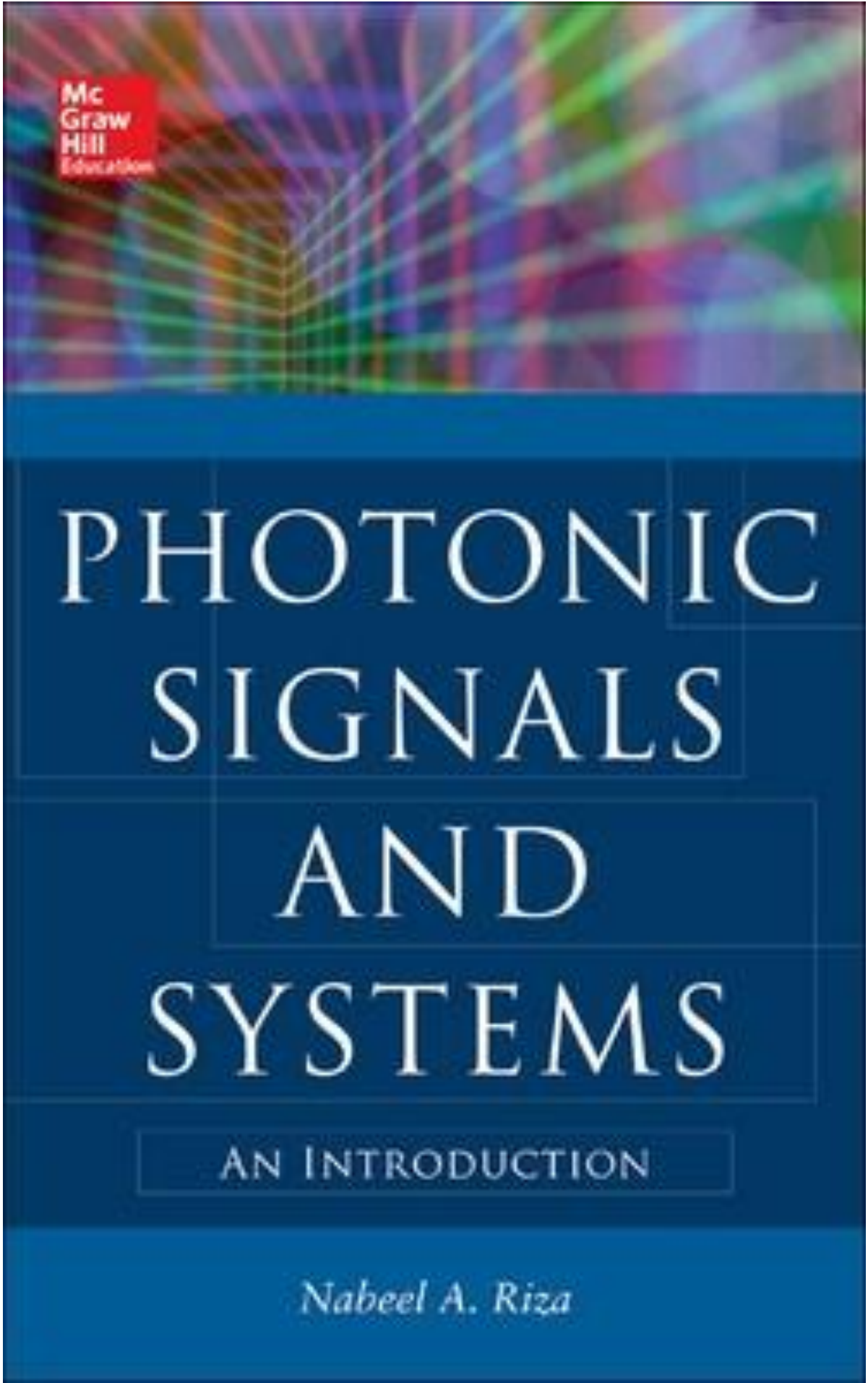




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PHOTONIC SIGNALS AND SYSTEMS

AN INTRODUCTION

Nabeel A. Riza

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BUILD THE SKILLS NEEDED TO ENGINEER NEXT-GENERATION SYSTEMS USING LIGHT

Photonic Signals and Systems: An Introduction presents essential and current knowledge of light applied in the design of innovative photonic systems that engage both optical and electrical signals. The book demonstrates how to design photonic systems operating within the required approximations of the deployed photonic devices, mathematics of signal processing, and optical phenomena.

Systems problems are solved using a variety of mature optical technologies, such as acousto-optics, liquid crystals, liquid optics, optical micro-electro-mechanical systems (MEMS), bulk optics, integrated optics, and optical fibers. End-of-chapter problems and solutions reinforce a thorough understanding of the material.

CONTENTS INCLUDE:

- Nature of light
- Electromagnetic waves, light, and polarization
- Interference, coherence, and diffraction
- Optical building blocks—components
- Photonic systems using optical micro-electro-mechanical systems devices
- Photonic systems using acousto-optic devices
- Photonic systems using liquid crystal and liquid devices
- Optical experiments
- Chapter problems and solutions



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Photonic Signals and Systems

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Photonic Signals and Systems

An Introduction

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Cork, Ireland*



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*Dedicated to my sons
Mehdi and Shems*



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Foreword

This book addresses the new discipline of “photonic engineering,” which refers to the engineering of photonic devices, subsystems, and systems—even system-on-a-chip. Photonic engineering has already played a major role in developing optical network “nodes” within the globally deployed long-haul and short-reach fiber-optic communications networks that benefit our everyday lives. This engineering is likely to be the backbone of applications in microwave photonics, sensing, and imaging that are coming on-stream now. As a photonics researcher, I find that photonics is a rich and diversified field with “open frontiers.” There are new phenomena to be discovered, new inventions to be made, and new uses to be found in medicine, energy, the environment, computing, signal processing, process control, and cryptography. Professor Riza is himself a superb inventor who wants to transmit this artful science to the next generation, and here he has aptly illuminated the fundamental aspects of photonics and has shared his expertise on system design. The possibilities and versatility of *free-space* optical systems are covered in depth, unlike other books that target guided-wave optics. The “photonic ‘signals’” in the title means that light beams are treated as bearers of information. This integrated learning experience is intended to provide a strong foundation for undergraduates, empowering them to participate creatively in the global “phenomenon” of photonics. The chapters on “basics” cover the nature of light, lasers, EM waves, polarization, interference, coherence, and diffraction. Key optical building blocks for free-space systems, mainly active components, are elucidated with analytic support. The emphasis on acousto-optics (AO), liquid-crystal electro-optics (LC-EO), and opto micro-electro-mechanics (O-MEM) shows that photonics draws on materials science, electrical engineering, and mechanical engineering, as well as physics. An important highlight of the book is the problem set at the end of each chapter, which is linked with its solution set. The heart of this book is the study of O-MEM, AO, and LC-EO systems presented in three chapters. A system design problem is posed, then solved in an elegant way. Engineering issues

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and tradeoffs are skillfully shown. Real-world design problems are tackled to impart true understanding and practical knowledge—making these chapters a unique and valuable approach. A surprise is contained in the last chapter, where detailed procedures are given for experiments that “bring to life” the foundation principles and capabilities of photonics.

Richard Soref
University of Massachusetts Boston

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I would like to thank all my fellow researchers, from my General Electric days to my more recent University College Cork days, who have contributed to the many applied research innovations that form the bases of the photonic design examples in this book. In particular, I would like to thank my esteemed colleague and friend, and the father of the field of silicon photonics, Dr. Richard Soref, for inspiring many of my inventive pursuits. A special thanks to McGraw-Hill Senior Editor Taisuke Soda, who gave me the opportunity to write this book, and Senior Editor Michael Penn, who saw this book through to its completion. Foremost, I would like to deeply thank my immediate family members for the immense patience and support they showed over the book writing period.

Nabeel A. Riza, Ph.D.



CHAPTER 1

Introduction

Why You Should Read This Book

The modern world is exploding with omnipresent signal flow. Some signals are visible to us as humans, whereas others flow quietly in hidden channels. These signals typically are interconnected with systems that perform specific functions. For example, some systems implement the task of communications, whereas others enable object detection, such as identification of specific human diseases or fast-moving airplanes. Some systems help us measure vital parameters, such as temperatures in power-plant turbines, whereas others measure chip thickness in semiconductor processing of computer chips. In short, the modern world is highly engaged with signals crisscrossing continents, cities, offices, homes, individuals, all interfaced through systems performing certain predesigned functions to enable the free-flowing global economy and human endeavors.

Signal flow in the 1900s was dominated by the flow of electrons and electronic systems. The new century is different as both electrons and photons (or light waves) play a joint role in realizing the new world economies. Specifically, the field of modern optics, commonly also referred to as photonics, plays a major role in applications ranging from communications, medicine, security, energy, the environment, defense, and entertainment. In order to be a contributing member to dynamic societies, it is vital that the next generation of undergraduate students in engineering and science worldwide have a common appreciation and understanding for both the basic principles of optics and optics direct application for designing photonic systems. I am attempting to write an entry-level undergraduate book with this specific goal in mind that it can empower the next generation of engineering and science graduates with the power to invent new systems using light. The basic prerequisite for studying from this book is entry college-level mathematics and physics common to most undergraduate science and engineering curriculum around the world. The topics covered in this book will provide students with the basic and current knowledge of light and its application using a

2 Chapter One

device toolset to design innovative photonic systems that engage both optical and electrical signals. The focus is on application specific photonic systems design using both optical and optoelectronic devices that form a mature and reliable technology to build confidence in future innovative designs by readers of this book. The book provides end-of-chapter problems for practice and confidence building. The chapters dealing with photonic systems designs for processing signals include additional references provided for further reading. The goal of the book is not to provide an exhaustive coverage of photonics and its applications engaging typical signals and system applications but, more importantly, to cover what I believe are key topics to educate a career-building engineering or science bachelor's degree student. Given the acquired knowledge from the book, the reader will have the confidence to design and experimentally build systems and eventually innovate by designing novel improved systems. Today's student is tomorrow's teacher or master practitioner. The objective of this book is to empower young minds with the engineering aspects of light.

Undergraduate education in electrical engineering around the world includes a core course called Signals and Systems focused on electrical signals and systems with a mathematical bent. The purpose of this book is to introduce an equivalent course that teaches photonic signals and systems with a physical (physics-based via light flow) or visual bent, illustrating the process of optical design using multiple components, hence the title of the book.

This book focuses on diverse signals and systems applications within the modern optical context. Specifically, it lays the key engineering foundations of light and then uses them to design and illustrate systems applications that range from the communications, aerospace/defense, biomedical, and test and measurement sectors. Moreover, the book solves given systems problems by engaging a host of mature optical technologies such as acousto-optics, liquid crystals, liquid optics, optical micro-electro-mechanical systems (MEMS), bulk optics, and optical fibers, simultaneously providing a student with a wide toolset to design next-generation systems. This book concentrates on problem solving for systems applications and does not restrict itself to one or two technologies such as free-space/Fourier optics, fiber optics, or integrated optics.

Science does not equal engineering, and this book is about engineering. Science deals with the verifiable knowledge that explains nature and the universe. Engineering is the action of problem solving within scientific laws where known pieces of the scientific infrastructure (e.g., optical, optoelectronic, and electronic components) are organized and interconnected to make new inventions that solve the given problem. A student should appreciate that engineering is, in fact, the study of approximations to real-world systems. These approximations obey the various known laws of science and the

mathematics and relevant models also operate well within certain mathematical and physical limitations. The quality of the engineering approximations can be considered very good, leading to highly reliable engineered systems that handle the chosen signals. Thus, engineers must be careful to operate well within the mathematically and physically engineered limits of engineering design and its signal constraints if reliability is key to achieving system success. Note that repeated experimental verifications of engineered systems give robustness to the deployed engineering hardware and its relevant engineering design, allowing system designs to be pushed for improved performance. This book describes relevant scientific facts about light and its implementations into photonic systems via various interconnected photonic devices, e.g., lasers, detectors, lenses, spatial light modulators, and optical fibers. The book designs photonic systems operating within the required approximations of the deployed photonic devices, mathematics of signal processing, and optical phenomena, resulting in well-engineered and reliable photonic systems that meet their application goals, e.g., 7-bit 0 to 2π phase control of 1-GHz radio frequency signals.

The Book Subject: Photonic Signals and Systems

Signals can be one-dimensional (1D) signals, such as time signals, or two-dimensional (2D) signals, such as spatial information or images. For example, a television set picks up electromagnetic waves from the surrounding air and electronically processes a 1D video signal represented in time that eventually displays as a 2D signals or optical image on a TV picture screen. Signals can also be three-dimensional (3D), that is, using the two dimensions of space and the third dimension as time. An example of a space-time signal is time-sequenced 2D image slices taken of a 3D object by a medical diagnostic system, such as a magnetic resonance imaging (MRI) machine.

Defining Signals

In general, a signal can be mathematically represented in N -dimensions, i.e., as a function of N -independent variables (see Figure 1.1). In this book, we mainly restrict ourselves to the three dimensions.

Signals represent information that needs to be communicated, processed, transformed, controlled, and utilized in a certain way that benefits the end user. These operations are performed by the *system* or

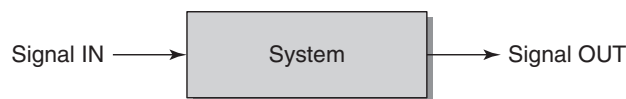


FIGURE 1.1 Basic block diagram of signals and system interaction.

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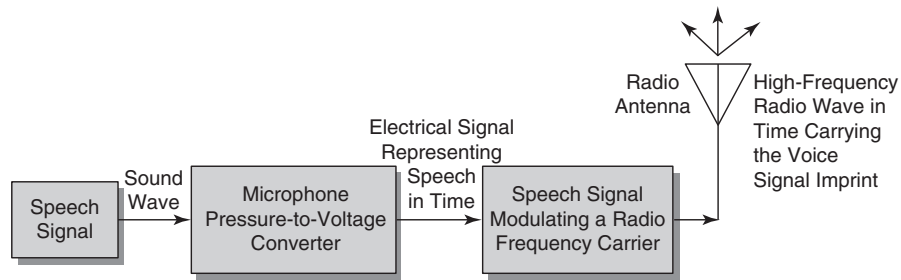


FIGURE 1.2 Radio link transmitter system for speech transmission.

black box as shown in Figure 1.1. For example, a simple voice radio link signal eventually requires several signal manipulations to complete successful two-way human conversation between the two end users.

Figure 1.2 shows a simple transmit-mode single-user system in which the original 1D voice signal that exists as sound or pressure waves is first converted by a piezoelectric transducer to an electrical signal (typical time oscillator) **or** frequency content for human voice **at** < 3 kHz (hertz = 1 cycle/second), which then modulates (or multiplies) with a high-frequency carrier signal (e.g., 600 MHz) before being transmitted as EM-waves generated by the antenna. In this case, we can note the electrical frequency translation the original signal must go through (i.e., voice sound-wave frequencies to very high electrical frequencies) to be able to communicate effectively. The motivation and need for all the “signal processing” is clear. It is impossible for a human sound-wave signal to travel several miles to the end user for clear communication. On the other hand, if the voice imprint is somehow transformed and translated to a high radio-frequency electrical modulation signal, then it can travel for thousands of miles as radio waves. The lesson to be learned is that signal information might have to undergo several manipulations before being optimized for use in a particular application.

This book concentrates on the use of photonics for processing or manipulating information signals, such that the end user’s and application goals are met while operating under the desired or required design constraints and requirements. Some typical design constraint basics for system design are listed as:

- Performance (e.g., electrical signal-to-noise ratio > 100 dB)
- Size/volume
- Weight
- Power consumption
- Electromagnetic interference (EMI)/electromagnetic pulse (EMP) sensitivity
- Environmental safety—water hazard, electrical shock hazard

- Cost
- Remoting
- Large-scale manufacturability
- Repair and assembly time
- Weather operation range (temperature, moisture, shock pressure, stability)
- Military specifications (MILSPEC)
- Robustness/tolerance to changes—power supply voltage variations/mechanical vibrational stability

Applications

The typical system application areas using photonic and optoelectronic building blocks are:

1. *Filtering.* Applications: cellular communications, medical imaging. (See Figure 1.3.)

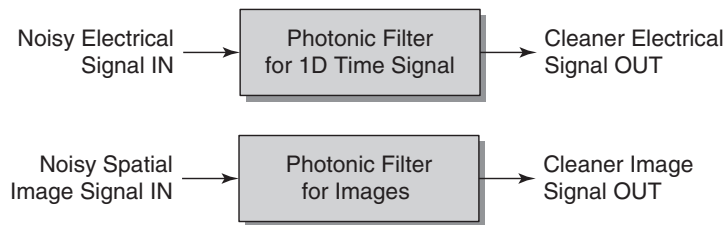


FIGURE 1.3 Photonic filters for 1D time signals and images.

2. *Recognition.* Applications: security systems, radar systems, air traffic controller, military identify friend or foe (IFF) target recognition—tank, road/vehicle, for example. (See Figure 1.4.)

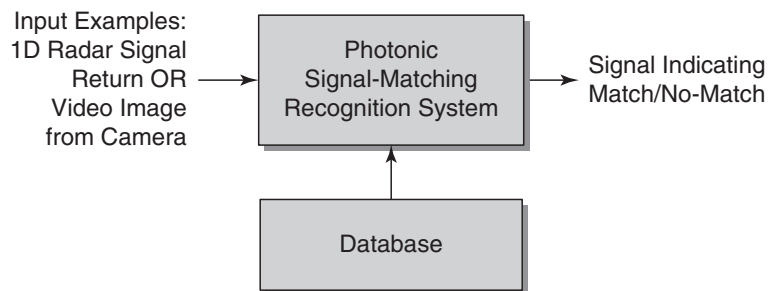


FIGURE 1.4 Photonic signal-matching recognition system.

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3. *Controls.* Applications: radar, sonar, ultrasound, wireless communications, lidar, astronomy. (See Figure 1.5.)

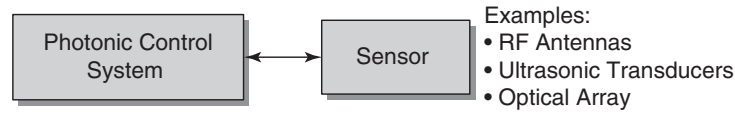


FIGURE 1.5 Photonic control system for sensor.

4. *Test and measurement.* Applications: nondestructive testing (NDT), combustion and shockwave studies, wind tunnel test, fluid dynamics, interferometry, and holography. (See Figure 1.6.)

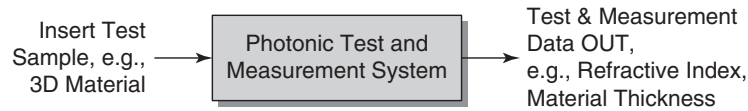


FIGURE 1.6 Photonic test and measurement system.

5. *Information analysis.* Applications: radar, adaptive antenna for cellular communication (for interference cancellation or nulling). (See Figure 1.7.) Also, medical diagnostics, inverse synthetic aperture radar (ISAR) image formation. (See Figure 1.8.)

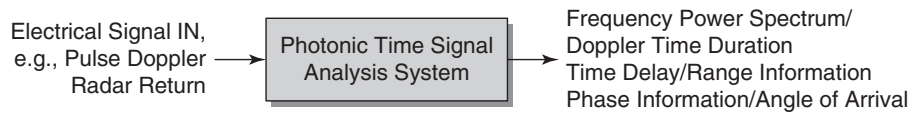


FIGURE 1.7 Photonic time signal analysis system.

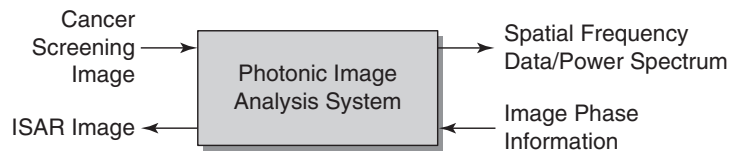


FIGURE 1.8 Photonic image analysis system.

6. *Communications*. Applications: secure remote communications, high-power optical satellite communications, fiber-optic communications. (See Figure 1.9.)

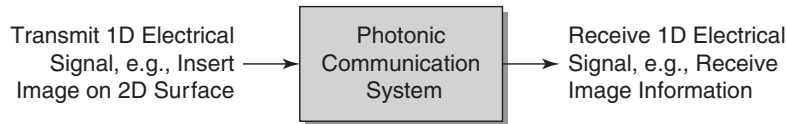


FIGURE 1.9 Photonic communication system.

7. *Computing and interconnects*. Applications: high-speed vector-matrix multiplication, logic operations in silicon photonics, chip-to-chip, processor-to-processor, board-to-board interconnects. (See Figure 1.10.)

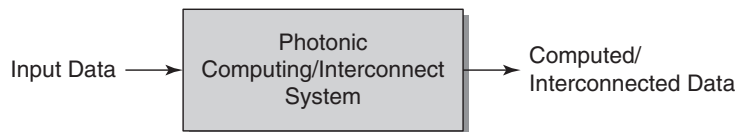


FIGURE 1.10 Photonic computing/interconnect system.

8. *Storage system*. Applications: database storage, write once read many (WORM) storage and compact disks (CDs). (See Figure 1.11.)

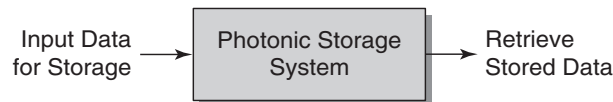


FIGURE 1.11 Photonic storage system.

9. *Image capture and display system*. Applications: visible cameras, infrared imagers, multicolor imagers, image displays, 3D displays. (See Figure 1.12.)

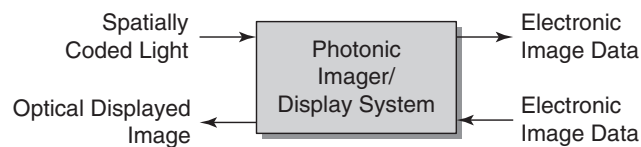


FIGURE 1.12 Photonic imager/display system.

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There are many photonic, optoelectronic, and electronic tools (i.e., physical effects and components that are used to construct photonic systems) such as:

1. *Classic passive bulk optical components*; examples include lenses, prisms, mirrors, stops, splitters, and lenses.
2. *Properties of free-space optical propagation*; examples include geometrical, Fraunhofer/Fourier, and Fresnel optics.
3. *Integrated passive optical components*; examples include fibers, fiber lenses, waveguide couplers, splitters, combiners, fiber gratings, wavelength multiplexers and demultiplexers, 2D gratings.
4. *Properties of integrated-optic (IO) waveguide propagation*; examples include single-mode low-loss optical communication fibers, sensitivity of fibers to polarization, such as good for making remote sensors.
5. *Active bulk optical components*; examples include acousto-optic (AO) crystal-based devices, electro-optic (EO) crystal-based devices, photorefractive (PR) crystal-based devices. AO, EO, and PR effects can be used to manipulate optical beams, such as frequency shifting, deflecting, and filtering.
6. *Active large-area optical components*; examples include liquid crystal (LC) arrays, magneto-optic (MO) arrays, and micromirror arrays. LC birefringence effects can be used in polarization-based optical switching and wavelength filtering.
7. *Active IO devices*; examples include IO waveguide high-speed modulators for phase modulation (PM), amplitude modulation (AM), and frequency modulation (FM) for low-power light beams.
8. *Active liquid micro-devices*; examples include electrically controlled fluidic optical lenses, waveguides, mirrors, etc., used for optical switching, attenuation, and wave-front controls.
9. *Active light sources and detection components*; examples include coherent light sources, such as laser types that can be defined by laser wavelength, power, tuning, CW or pulsed mode, size, weight, modulation speed, noise, etc. Other examples are light detection components defined by sensitivity, integration speed, photosensitive area, noise, dynamic range, etc.
10. *Electrical hardware*; examples include cables, connectors, splitters, mixers, filters, power amplifiers, low noise amps (LNAs), power supplies, signal generators, differential amplifiers, AGC amplifiers, A-D converters, D-A converters, frame grabbers, and PC-based data storage and processing.

The Concluded Learning Experience

The power of communicating and processing electrical signals in the optical domain can be seen by comparing *electrical signal-to-noise ratio* (E-SNR) versus *optical signal-to-noise ratio* (O-SNR). The notation used is that R is the termination electrical circuit resistance, $i_s(t)$ is the signal current, and $i_N(t)$ is the noise current in the electrical circuit. For the optical scenario, where photodetection is used to convert from the optical domain to the electrical domain using a photodetection circuit, P_s is the optical signal power falling on the photodetector and P_N is the noise optical power falling on the photodetector, then the E-SNR versus O-SNR can be analyzed as follows:

$$\begin{aligned} \text{E-SNR in decibels (dB)} &= 10 \log \frac{\text{electrical signal power}}{\text{electrical noise power}} \\ &= 10 \log \frac{i_s^2(t)R}{i_N^2(t)R} = 20 \log \frac{i_s(t)}{i_N(t)} \end{aligned}$$

In electrical circuits via Ohm's law, the current is proportional to the electrical field strength (or electric voltage). In the case of light shining on a photodetector connected to an electrical circuit, the photocurrent produced is proportional to the square of the optical (i.e., the electrical) field of the incident optical frequency wave (this relationship to be shown in Chapter 4). Specifically, electrical current $i(t)$ produced by a photodetector is proportional to the optical power, P , incident on the photodetector and not the optical (i.e., the electrical) field strength. Therefore, this can be written as

$$\begin{aligned} \text{O-SNR in dB} &= 10 \log \frac{\text{optical signal power}}{\text{optical noise power}} \\ &= 10 \log \frac{P_s}{P_N} = 10 \log \frac{i_s(t)}{i_N(t)} \end{aligned}$$

Comparing the two SNR expressions:

$$\text{E-SNR} = 2 \times \text{O-SNR in dB}$$

This doubling of SNR between the electrical and optical signal-processing domains is very significant as, for example, an optical switch that gives an interport isolation of 30 dB in fact gives an electrical signal switch port isolation of 60 dB. Processing electrical signals in the optical domain using optical hardware requires less stringent component specifications than when the electrical signal is processed and communicated in the electrical domain using electrical/electronic signal conditioning/processing components,

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such as electrical switches, attenuators, filters, etc. This brief analysis highlights the power of photonics for communication and processing of electrical signals that constitutes much of the world's infrastructure.

The summarized outline of the book is as follows: First, the fundamentals of light and the basic components used to design photonic systems are explained. Next, students experience application-focused photonic system design examples using these fundamentals in order to empower them for future self-implemented designs. A visual and physical approach to optical design innovation is followed in a step-by-step logical problem-solving and design-improvements mode with mathematical analysis used when needed to quantify or optimize photonic design. Chapters have end-of-chapter problems and their solutions so students can readily challenge themselves knowing the solutions are available. References related to the photonic design innovation examples and the chapter problem sets are provided to enable further reading and detailed photonic design analysis. The reading references include U.S. patents as they are easily accessed via Internet patent databases such as the U.S. Patents and Trademark Office (PTO) site and Google patents search.

It is envisioned that students, after studying this book, will be ready to embark on further and confident study of advanced topics in optics and photonics. Importantly, they will have received a foundational engineering design, experience that will positively cultivate valuable problem-solving and photonic design skills in order to help them confidently design and build future novel photonic systems that apply to many diverse fields in engineering and science.

CHAPTER 2

Nature of Light

Light Propagation

A natural question for a beginning student of light is to ask: *Does light travel in a straight line?* The answer is basically yes, and this scientific fact has been known as one of the fundamental properties of light or more generally for all *electromagnetic (EM)* waves.

Then naturally, the next question to ask is: *Why does light travel in a straight line?* Is there something special about the light wave's behavior in time and space that leads light to travel in a straight line, and are there any limits to this straight-line behavior.

We start with a geometrical picture of a straight line or ray that also forms the directional $\mathbf{k}$ or *propagation vector* for the traveling light wave under observation over a given travel distance. Note that this travel distance may be considered extremely short, (e.g., a few wavelengths of light), or extremely long (e.g., many trillions of wavelengths of light). This ray mathematically originates from a point on the light travel map and ends at a point on the light travel map, thus forming a line. A physical wave can be represented using a minimum of two parallel straight lines (see Figure 2.1) or rays over a given distance to represent a light wave traveling in a straight line. As the wave over the entire cross section between the defining rays/lines at the first observation plane are said to be parallel and straight, a wave front at this plane will have equal phase values over the entire defined plane, forming a normal phase front to the entire beam of light. This uniform-value phase front forms the classic plane-wave front. The phase value at this plane-wave front can be from 0° to 360° or 2π intervals. This first observation-plane phase front can be chosen to be a 0° phase-value front. Given that the light wave is a traveling wave in space and time, at a given spatial distance called the light wavelength, another phase front with a 0° phase value can be found. The concept of phase value or phasor implies that the wave function representing the light wave is purely sinusoidal in nature with a given spatial wavelength and temporal period or optical frequency linked by the

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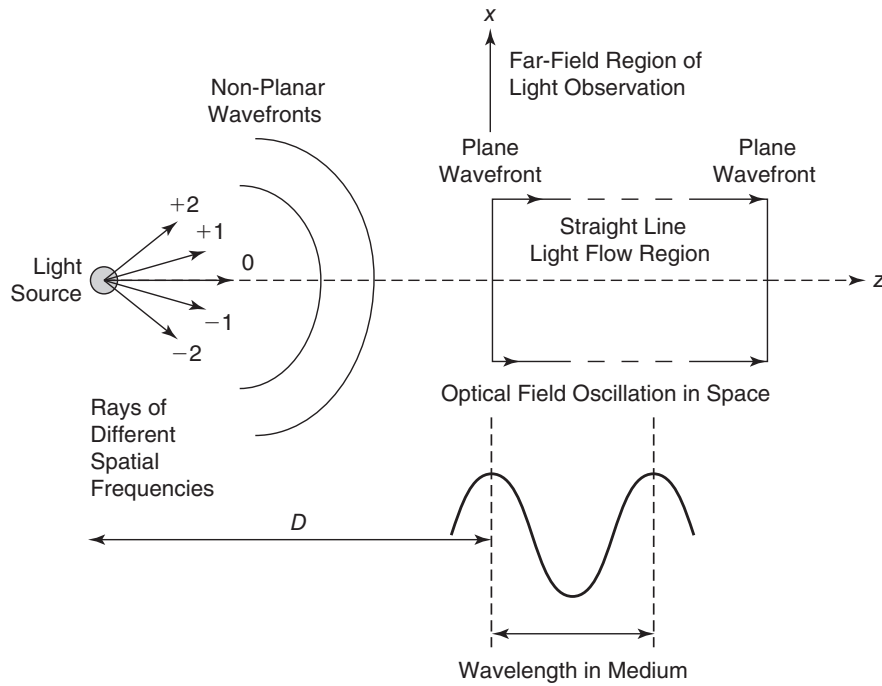


FIGURE 2.1 Nature has designed light to travel in straight lines.

classic expression of speed of light in the medium of *refractive index* n is equal to the optical frequency f times the wavelength in that medium λ_n , i.e.,

$$\frac{c}{n} = f \times \lambda_n$$

Here, c is the classic speed of light in vacuum. Hence, a light beam called a plane wave between the defined first and second observation planes follows the defined straight-light behavior with same valued phase fronts repeating after every spatial wavelength of travel along the $\mathbf{k}$ -vector. Therefore, light of a single optical frequency, a pure tone, like a pure color, will naturally produce propagation in a straight line. For that matter, any sum of optical frequencies will also naturally produce propagation in a straight line as superposition applies in space and time. Thus, the Sun, which is a natural source of many light temporal frequencies, produces the required straight-line travel behavior of the light beams that reach the Earth via straight-line travel. It is important to note that *Maxwell's equations*, which completely describe EM waves, produce a mathematical wave equation representing the flow of EM waves, in which the equation's fundamental solution is a

plane-wave function represented by a sinusoidal function in space and time with a given propagation direction represented by the $\mathbf{k}$ -vector or ray of light that is the straight line the light path follows. With the $\mathbf{k}$ -vector pointing in the Cartesian z -direction, and the optical (electric field) defined to be in the Cartesian x -direction, the plane-wave function representing the traveling wave/ray of light is generally written as

$$E_x(z, t) = E_{0x} \cos(2\pi ft - kz)$$

where the propagation constant is

$$k = 2\pi/\lambda_n$$

and E_{0x} is the optical field maximum value. Whether we start from the theory of EM waves or basic geometrical principles of what represents a wave's straight-line motion via formation of plane-wave fronts, the same basic conclusion is that the nature of light as defined within today's ideal mathematical and physical frameworks is such that it travels in a straight line.

The distance over which this straight-line behavior is observed (i.e., the distance between the two observation planes) will depend on the phase stability of the light over the entire spatial region defined as the plane-wave-front region (the left side of rectangular box in Figure 2.1). In essence, the propagating wave front must continue to produce flat equiphase or plane-wave fronts as it moves between the observation planes. Thus, the spatial coherence properties of the light beam are directly connected to how straight and for how long the beam traveling is in a straight line. *Coherence* here refers to the extent to which the light's temporal behavior is in-phase (or in-time synchronization) with other spatial parts of the wave defined by the observed wave front. All light radiation can be mathematically considered as coming from a point or delta function source. A practical source, of course, is made of many such point sources. EM diffraction theory stipulates that for a given point source to observation plane far-field distance, the presence of a plane-wave front can be observed. Thus, the spatial shape and size of the optical source and its distance to an observation plane dictates how coherent or plane the observed plane-wave front is. Note that a point source in its near field has many diverging nonplanar wave fronts, but a point source far enough from an observation plane looks like a source of a straight ray or plane wave. Thus, *spatial coherence* of a source is intimately connected to the source-to-observation distance. The Sun is a spatially coherent source on Earth but not near the Sun. The Sun also has many optical temporal frequencies, but each acts as an independent co-located point source, and superposition applies in

the observation plane. Many in-line plane waves can be observed but with different optical temporal frequencies. Thus, nonsingle frequency optical light (or multicolored light) also observes the travel-in-straight-line principle, indeed true for all EM waves. Figure 2.2 shows a flowchart indicating the logical steps to this straight-line-principle conclusion. Apart from its temporal frequency content description, an optical source can also be described by its spatial frequencies content. As shown in Figure 2.1, spatial frequencies can be defined as the angular spread of a light source. Typically, the on-axis ray is defined from the source as a zero spatial-frequency ray with higher-angle rays defined as the higher-positive or -negative spatial-frequency rays (e.g., positive-numbered rays for above-optical axis and negative-numbered rays for below axis). The angular- or spatial-frequency space is continuous, although for simplicity, it is shown by discrete rays and their numbering in Figure 2.2.

The laser-optical source is a great example of a manmade *high temporal coherence* (i.e., high temporal-spectral purity or near-pure tone) and high spatial coherence (i.e., near plane wave) optical generator. This coherence feature of the laser makes it possible to make a near-ideal point-like source of extreme optical power and

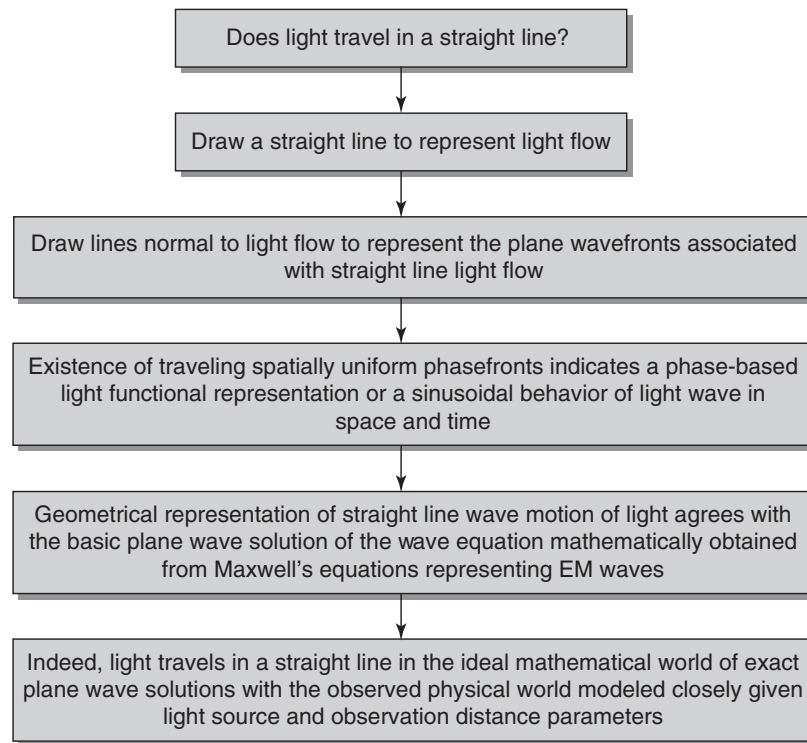


FIGURE 2.2 Flowchart concluding that light does travel in a straight line.

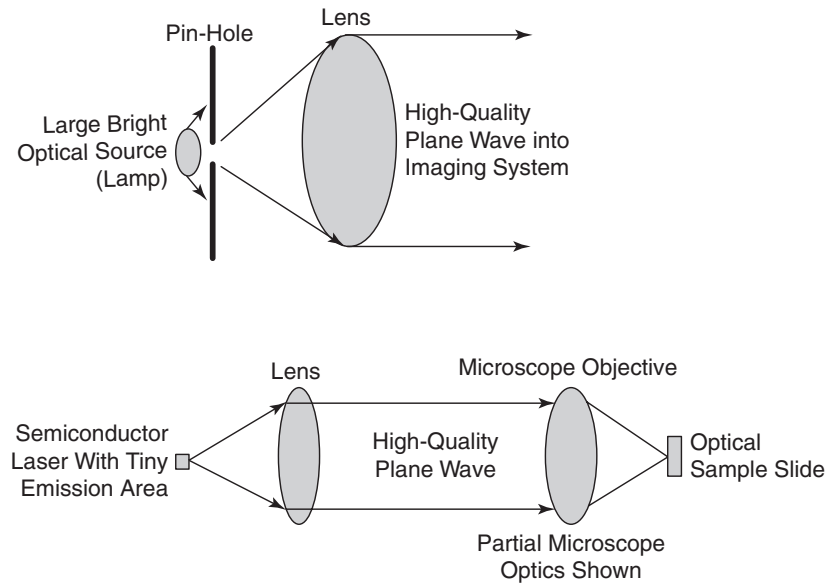


FIGURE 2.3 High spatial coherence produced by static mechanical means by using a pinhole in front of a large optical source while a semiconductor laser naturally produces a point-like emission point to produce a high-quality plane wave. In both cases, the lens produces the far-field plane wave within a short distance from source.

spectral purity, thus making the laser a most powerful building block for many optical systems, such as wireless laser communication systems and optical microscopes.

As an example, Figure 2.3 highlights the spatial coherence (or point-like) power of the laser and a mechanically filtered large optical source. First note that you can construct a high-resolution optical-imaging system, such as a microscope, when a white light source such as a high-power lamp is spatially filtered. In this case, mechanically producing the point-like source enables high spatial-resolution microscopy by using a tiny pinhole (or slit) in front of the rather large (compared to wavelength) source, but this of course leads to a power-inefficient system with a small fraction of light being used for microscopy. In comparison, modern microscopes now also use laser sources to enable high-resolution imaging, thus making power-efficient systems. To obtain the color diversity of white-light imaging, some systems now use tunable lasers or multiple lasers, thus providing high-versatility microscopy systems.

Light traveling in a straight line is a mathematically ideal situation. In the physical world, light previously traveling in a defined straight line displays light-bending behavior called *diffraction* once the light encounters a given physical aperture (e.g., window) or boundary, inducing light to make bends in travel versus pure

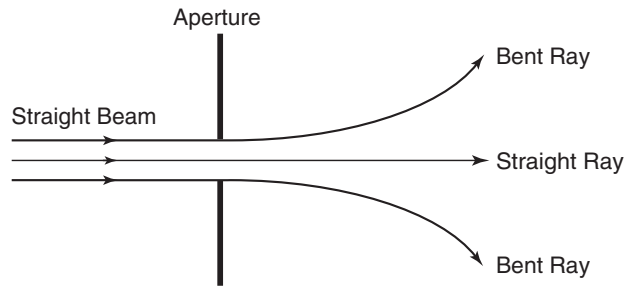


FIGURE 2.4 Straight-line light travel transforming to light-bending travel via light interaction with aperture. This phenomenon is known as diffraction.

straight-line travel for the entire light-beam propagation distance under observation (see Figure 2.4). This non-rectilinear propagation behavior was first observed by Italian professor Francesco Grimaldi (1618–1663). A simple example of this phenomenon is the graceful beam expansion or spatial spreading of a laser beam in freespace once launched from a small aperture of the laser cavity. Although the central ray for the laser can be defined as the straight-line beam, rays, particularly those close to the aperture, follow a non-straight trajectory, producing the beam-spreading effect.

From another point of view, a pure single-tone frequency of an EM wave does not exist in the physical world (even the purest color laser cannot be a single frequency), and thus one cannot expect a light wave to travel in a straight light forever as this would imply that the sinusoidal light signal existed in time forever. Thus, diffraction or bending of light is an eventual consequence for a beam of light with a defined physical cross-sectional aperture and spectral purity. Given the practical constraints of an optical system, the engineer must decide when to engage ray optics and diffraction light theories to approximate the designed performance of the optical system.

NOTE *It is now known that presence of matter (and dark matter) warps spacetime, causing light to bend as it travels past the matter. Also known as gravitational lensing, the presence of gravitational fields caused by massive objects (e.g., galaxy clusters) bends the light in the cosmos, allowing astronomers to take measurements to study the time-evolution of the universe. Dark matter and gravitational lensing were conceived by Swiss-born Caltech professor Fritz Zwicky in the 1930s.*

Nature of Light from Its Early Beginnings

Over centuries, experiments conducted on the nature of light have shown that it is both a particle (now called a photon) and an EM wave. Early models of light were based on space or geometry. Starting



FIGURE 2.5 First law of geometrical optics, i.e., light travels in a straight line. It is also called the law of rectilinear propagation.

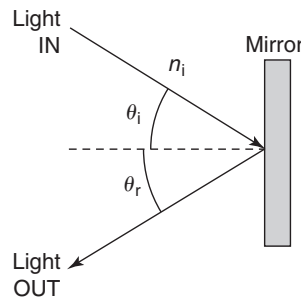


FIGURE 2.6 Second law of geometrical optics has two parts, i.e., $\theta_i = \theta_r$ and the reflected ray lies in the plane of incidence; here it is the plane of the paper with the mirror oriented normal to this plane of incidence.

with Euclidean optics around 280 B.C., the Greek philosopher Euclid laid the foundations of geometry (definition of point, straight line, etc.) and postulated that in homogenous media (e.g., air, glass) light travels in a straight line—and the incorrect concept that light comes out of the eye. Another Greek philosopher, Hero of Alexandria around 100 B.C., laid the foundations of the early laws of rectilinear optics based on the postulate that given two points, A and B, light travels via the shortest path (or straight line) from point A to B (see Figure 2.5). This fact became known as the *first law of geometrical optics*.

Using this postulate, Hero and also Euclid showed that the angle of incidence θ_i is equal to angle of reflection θ_r forming the first part of the *second Law of geometrical optics* called the law of reflection (see Figure 2.6).

Light described via a *particle model* was put forth by Persian Arab scientist Alhazen (965–1039 A.D.), now also known as the father of optics. He concluded in his studies that (a) light travels at finite speed, (b) the speed of light is slower in denser media, (c) light is a stream of particles, (d) and the reflected ray lies in the plane of incidence, thus providing the second part of the law of reflection. Alhazen (also known as Ibn al-Haytham) used mechanical analogies such as surface forces to produce reflection and refraction that turned out to be incorrect. Alhazen wrote fourteen books on optics, including the classic *Kitabl al-Manazir* or *Book of Optics* that in 1270 was translated into Latin as *Opticae Thesaurus Alhazen*. The English scientist Sir Isaac Newton (1642–1727) also proposed the corpuscular or stream of particles force-oriented theory for light. Newton maintained that if light is a wave, much like sound, it should go everywhere and bend

around corners, and there should be no shadows. This stronghold of Newton to not believe in the wave nature of light as proposed by his contemporary, the Dutch scientist Christian Huygens (1629–1695) led to wave theory being not accepted for many years. Ironically, it was Englishman and experimentalist Dr. Thomas Young (1773–1829) who conducted a series of experiments to conclusively show that light, indeed, behaves like a wave and produces an interference pattern with shadows, much like water waves. Young used his experiments also to measure the wavelength of light for the first time. The French scientist Augustin Fresnel (1788–1827) independently developed the *wave theory* for light.

One notes with interest that it was centuries later with respect to the early Greeks that the *third law of geometrical optics* came into being, partly in works by Johannes Kepler (1571–1630) who showed that angles of incidence and transmission angles are proportional for small angles, indeed a version of the refraction law for small angles. Later, Dutch professor Willebrord Snell at Leiden University experimentally discovered (see Figure 2.7) the law of refraction in 1621, where the transmitted ray lies in plane of incidence and

$$n_t \sin \theta_t = n_i \sin \theta_i$$

with n_t and n_i given as the refractive indices of the transmission and incidence media, respectively. Englishman Thomas Harriot also independently discovered this law of refraction in 1601, and there is some recent evidence that Arab scientist and mentor of Alhazen named Ibn Sahl also suggested light behavior, now well-known as Snell's law of refraction.

The 1600s also produced contributions to light by two French greats, namely, Rene' Descartes (1596–1650) and Pierre de Fermat (1601–1665). Descartes proposed the Cartesian geometry-oriented theory of light stating that light is a tendency towards movement, and light travels instantaneously in ether, and no void can exist for light to travel. Descartes arrived at the law of refraction by treating light as a pressure disturbance traveling in an elastic material. His

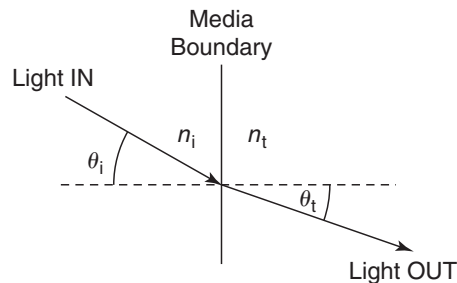


FIGURE 2.7 Third law of geometrical optics (now commonly known as Snell's law). The plane of incidence is the plane of the paper with the multi-media boundary surface oriented normal to this plane of incidence.

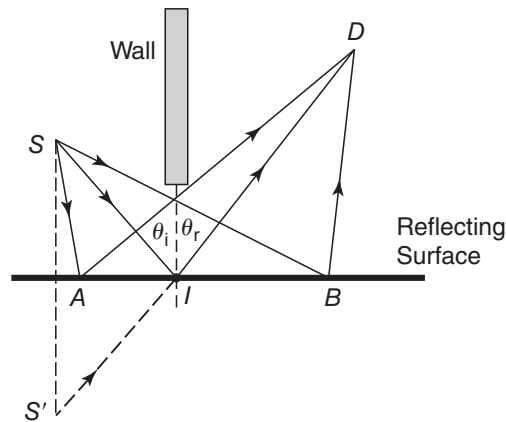


FIGURE 2.8 Fermat's principle of least time for travel allows selection of which rays apply in the physical world for light reflection.

contemporary, Fermat produced a vital breakthrough in the theory of light by proposing the principle of least-time or resistance to flow of light with the speed of light being inversely proportional to Fermat's optical resistance (now known as the material index of refraction). Unlike the principle of shortest path for light that is consistent with the law of reflection, Fermat correctly deduced that light will take the path of least time. Using this principle, Fermat was able to derive both the law of reflection and law of refraction. In the case of refraction, light going from point S in medium 1 to point D in medium 2 does not take the direct straight line from S to D or the shortest path; nevertheless, light does take the path of least time using two different but connected straight paths.

Figure 2.8 shows a light source, S , placed near a reflecting surface with a partial wall blocking direct line of sight from source to optical detector, D . As an example, three ray paths are shown: Path 1 of line segments SA and then AD ; Path 2 of line segments SI and then ID ; and Path 3 of line segments SB and then BD . I is the defined interface point directly below the wall-line normal to the reflection plane. The position I also provides the only point on the reflecting plane where the angle of incidence is equal to the angle of reflection. Geometry of path lengths measured confirms that Path 1 is indeed the shortest path or path of least time for light from S to D . This confirms that Fermat's principle (and Hero's principle) both produce the law of reflection.

There are other ways to describe *Fermat's principle*, such as a light ray in going from point S to point D must traverse an *optical path length* (OPL) that is stationary with respect to variations of that path where path stationary implies the first derivative of the OPL vanishes in its Taylor series expansion. This brings us to the most important concept of OPL, which not only includes the physical-path length of light travel but also contains the speed-of-light effect on that light-travel path.

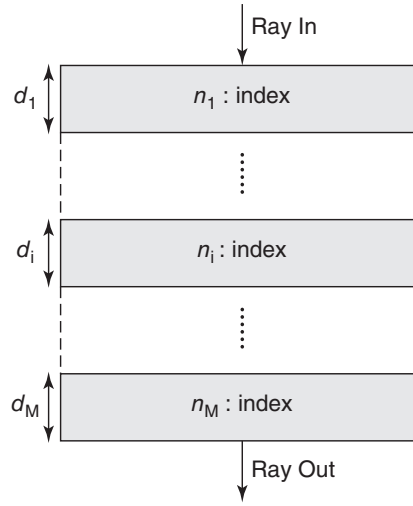


FIGURE 2.9 Light travel through a discrete-layered medium of different refractive indices and thicknesses.

OPL in a discrete-layered media (Figure 2.9) is defined as

$$\text{OPL} = \sum_{i=1}^M n_i d_i$$

where for the i th layer of thickness d_i , the refractive index is n_i .

In the case of a medium with a spatially varying refractive index, like $n(z)$, where z is the direction of light travel (see Figure 2.10), the OPL in an inhomogeneous medium for light traveling from point S to point D along the z -direction is given by

$$\text{OPL} = \int_S^D n(z) dz$$

An example of such an engineered material like shown in Figure 2.10 is a graded-index (or GRIN) optical-fiber lens commonly used for assembling fiber-optical components.

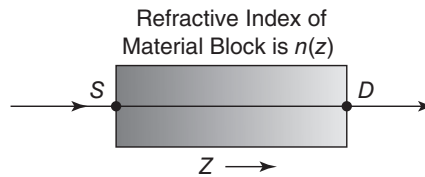


FIGURE 2.10 Light travel through an inhomogeneous medium of a spatially continuous refractive index.

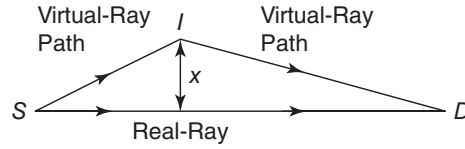


FIGURE 2.11 Defining a spatial-error parameter between the real-ray and virtual-ray path to express the general OPL between point S and point D.

OPL definitions contain the material refractive indices, thus OPL, unlike physical optical-path distance contains the effect of the different speeds of light in different media. Fermat correctly incorporated the effect of media in his least-time principle, which is mathematically equivalent to minimizing the light OPL.

Figure 2.11 shows that OPL must be expressed in terms of a variable, such as a spatial-error parameter (e.g., x , indicating the difference between a real-ray path and the virtual-ray path with x following a second-order or higher behavior). $\text{OPL}(x)_{S-D}$ implies OPL from point S to point D is a function of the defined spatial-error parameter, x . To mathematically exercise Fermat's principle, the following condition must be satisfied:

$$\frac{d}{dx} [\text{OPL}_{S-D}] = 0$$

This expression can be used to derive both the law of reflection and law of refraction. Equivalently, minimizing the time of travel from S to D given by $T(x)$ can also be used to derive the laws of reflection and refraction, in this case using the expression:

$$\frac{d}{dx} [T_{S-D}] = 0$$

Now we ask the question: Why is OPL important?

The OPL parameter is highly useful in designing a variety of optical systems, such as optical sensor systems. As shown in Figure 2.12, one can place a given test medium (e.g., sensor chip of optical thickness, d , at temperature, T) in a given environment in which a remote temperature measurement is required. As the temperature changes, the chip thickness changes because of thermal expansion, leading to a change in OPL for the light passing through and then reflected by the chip material-air interface. This OPL change can be measured by processing the received light information from the chip using an optical detector and signal processor, thus forming a remote temperature-measurement system. Note the chip naturally forms a reflector producing a reference beam that does not enter the chip.

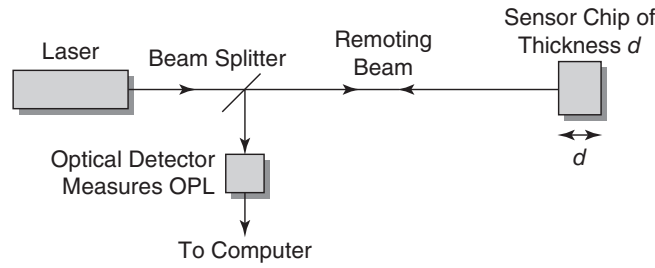


FIGURE 2.12 The changing OPL concept used to make a remote optical sensor of a physical parameter measurement such as temperature.

Note also that the OPL contains the material parameter called refractive index n . In general, n is dependent on the light wavelength, λ , and is written as $n(\lambda)$. The material is considered a dispersive material with an empirically computed $n(\lambda)$ given by the Sellmeier equation found in optical constants data books. Optical systems must be designed within given wavelength limits to engage or minimize material dispersive behavior. As an example, air is considered a highly nondispersive media for light wavelengths with $n = 1$. Similarly, typical $n = 1.5$ glass, used to design eyeglass lenses, is considered highly nondispersive for visible light wavelengths. On the contrary, glass used to design optical fibers for long-distance telecommunications induces material dispersion effects because of the long light-travel distances. Thus, optical-system designers have to take fiber material dispersion effects into account given data signal bandwidths.

Negative Refractive Index

In general, the material parameter refractive index, n , is defined as $n = \pm \sqrt{\mu_r \epsilon_r}$, where μ_r is the material relative magnetic permeability given by the ratio μ/μ_0 , where μ and μ_0 in units of henry/meter are the material and freespace magnetic permeability, respectively. In a similar fashion, ϵ_r is the material relative electric permittivity given by the ratio ϵ/ϵ_0 , where ϵ and ϵ_0 in units of farads/meter are the material and freespace electric permittivity, respectively. For most media, n is a real number (not complex), and for all known optically transparent media, ϵ_r and μ_r are positive valued. By convention, the positive square root is used for n . For most cases, $n > 1$, but it is possible for $n < 1$ such as in X-ray frequencies. In 1968, Russian physicist Victor Veselago theorized a material (today engineered as a so-called meta-material) in which simultaneously $\epsilon < 0$ (hence $\epsilon_r < 0$) and $\mu < 0$ (hence $\mu_r < 0$) and thus n is real. But choosing the negative sign in the square-root expression, such that the material is now called a negative-index material with n defined as $n = -\sqrt{\mu_r \epsilon_r}$. Veselago

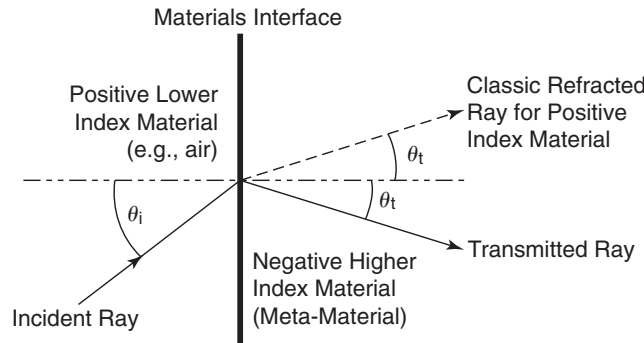


FIGURE 2.13 Behavior of a light ray at a positive refractive index and negative refractive index materials interface. The absolute value of the positive index is lower than the negative index value. The dashed ray is for the case when the transmission medium has a positive higher refractive index.

was the first to theoretically study the propagation of electromagnetic waves in a negative-index material.

As shown in Figure 2.13, with negative index materials, Snell's law still works except that the refracted ray stays on the same side of the normal as the incident ray. This aspect can also be shown mathematically, as follows, by starting with Snell's law $n_i \sin \theta_i = n_t \sin \theta_t$. Now assume the incidence medium is a regular positive lower-index material (e.g., air), whereas the transmitted ray medium is a negative index (e.g., meta-material). In this case, one rewrites Snell's law as $n_i \sin \theta_i = -n_t \sin \theta_t$ or $n_i \sin \theta_i = n_t \sin(-\theta_t)$. Thus, the transmitted ray bends below the interface normal with an θ_t angle, unlike a normal positive-index material in which the refracted ray is above the normal showing the classic ray bending or refraction operation. This type of optical behavior can be exploited to design new optical elements, such as diffraction-free imaging via a super-lens optical element. No naturally occurring material, due to its composition and structure, has shown a negative refractive index. On the contrary, certain engineered meta-materials at certain wavelengths (e.g., microwave wavelengths) have shown a negative index using a material structure with open rings (C-shape) and wires.

Metals, such as gold and silver, have negative electric permittivity, ϵ , at visible wavelengths, but with positive magnetic permeability, μ , thus producing a complex index of refraction with a real term and an imaginary term. The material is considered opaque to electromagnetic (EM) radiation, although this gives rise to surface plasmon EM waves on a metal-dielectric (nonconductor) interface, such as a gold film on a glass substrate. When light of a particular frequency is incident on a metal-dielectric interface, the mobile electrons on the surface of the metal also begin to resonate at the optical frequency. This process of optically activated resonance can produce density waves of electrons

that propagate along the metal-dielectric interface and can even be engineered to have wavelengths shorter than the light wavelength. This field of light–electron surface wave interaction is known as *plasmonics* and has potential for applications such as optical sensing and medical treatments. Materials engineering makes possible the manipulation of the signs (i.e., positive or negative values) of a material's electric permittivity, ϵ , and magnetic permeability, μ , thus allowing the realization of new devices and EM effects.

Photon: The Light Particle and Its Application—Photonics

Depending on the physical constraints determining an optical design, an optical designer has a number of options to model the light behavior within the designed component, module, or system. Rays and waves have already been mentioned as viable models to study light, but an equally important model is that of light as a particle called a *photon*, hence the modern application of light particles is commonly referred to as *photonics*. As mentioned, Alhazen and Newton both suggested light as particles, but it was Max Planck and Einstein in the early 1900s who put photon optics on a solid mathematical and physical footing. There were several experimentally observed phenomena that could not be explained with the wave theory of light such as the photoelectric effect and spectral content of black-body radiation. In particular, at very high EM-wave frequencies [or low wavelengths, e.g., ultraviolet (UV), X-rays, gamma rays], the wave-nature picture of light cannot explain physically measured effects. Max Planck conducted blackbody (hot-body) radiation spectrum studies to correctly conclude that EMR emitted by matter is emitted in packets or quanta of energy called photons, where the quantum energy, E , of a photon is given by

$$E = h \times f$$

with f the optical frequency in hertz of the **EMR** and h called the Planck's constant with $h = 6.62 \times 10^{-34}$ joule-second. The *photoelectric effect* involves the emission (ejection) of electrons from a metal surface when irradiated with light above a given optical threshold frequency that corresponds to a minimum energy level called the work function of the metal (e.g., 4.5 eV for iron). Thus kinetic energy in the ejected electron is the incident photon energy minus the metal work function. Einstein explained the photoelectric effect with the use of Planck's equation for discretized light energy that assumes that light is indeed a stream of photons with discrete quanta of energy.

Note that at lower frequencies photons have smaller energies, and typically light energy is made up of a huge number of photons that can be modeled as a continuous wave; hence the wave-theory picture. On the other hand, at very high EM frequencies corresponding to very

small scales of matter (and wavelength), such as atomic or nuclear distances, the discrete photon model of light becomes effective.

Einstein discovered the relation between energy and matter linked via the speed of EM waves in a vacuum. Specifically, that rest energy, E_{rest} (in joules), and mass, m_{rest} (in kg) of matter at rest are connected by the speed, c (3×10^8 m/s), of light in vacuum and given by the classic relation:

$$E_{\text{rest}} = m_{\text{rest}} c^2$$

Because photons and electrons are linked together via the photoelectric effect, we can pose the question: What equation should be used for a particle of total energy, E , if the particle has a rest mass, m_{rest} , and a total mass, m , with the particle in motion at speed v ? In this case, we use the more general relation from Einstein:

$$E = mc^2 = \frac{m_{\text{rest}}}{\sqrt{1 - \frac{v^2}{c^2}}} c^2$$

Note that as v increases, m increases, and in fact, as v approaches c , E goes to infinity indicating that an infinite amount of energy is required to get the higher-mass particle moving at the much faster speed of light. To generalize, the total energy of matter is given by its rest mass energy plus the particle's kinetic energy of $0.5 m_{\text{rest}} v^2$ when $v \ll c$.

Light as a photon particle is considered to be a mass-less particle already traveling at the very fast speed of light. Ironically, the photon represents energy linked with the speed of light and mass, and yet it is considered massless. On the contrary, Planck's equation gives the energy of the photon without the use of mass, but instead uses the photon frequency or equivalently a wave property called wavelength, hinting at the notion of *particle-wave duality* for light. Nevertheless, the photon does carry the energy, E , representing matter, m , and one can equate the two energy equations from Planck and Einstein to write

$$\begin{aligned} E = mc^2 &= hf = \frac{hc}{\lambda} \\ mc &= \frac{h}{\lambda} \\ \lambda &= \frac{h}{mc} = \frac{h}{p} \end{aligned}$$

Here $p = mc$ is known as the particle's linear momentum, indicating that the photon particle's wavelength (a wave property) is inversely proportional to the particle's linear momentum (a particle property), indicating the dual particle-wave nature of light. In 1924, the French scientist Louis de Broglie concluded that the charged-particle electron

also should display the wave-particle duality and not just the known particle behavior. In fact, the moving electron should exhibit wave-like behavior like diffraction and interference with the electron wave's wavelength known as the *de Broglie wavelength* given by $\lambda = h/p$ as predicted by the Einstein and Planck energy relations for a photon. Early electron guns were able to produce electrons with high enough kinetic energies to produce *matter waves* of de Broglie wavelengths on an atomic scale (e.g., $1 \text{ \AA} = 10^{-10} \text{ m}$), thus experimental observation of electron diffraction was realized when electron beams passed through periodic matter structures like single crystals of graphite. Compared to light (e.g., equivalent wavelength X-rays), matter waves can have their wavelengths controlled by changing the particle energy in the accelerator guns. Moreover, in the case of charged particles, such as electrons, the matter waves can be spatially focused using electrical and magnetic means to lead to imaging beyond the light-based diffraction limit. Hence, electron microscopy is a very powerful tool for nanoscopic imaging, although requiring complex and expensive electron beam controls compared to optical microscopes. Because e-beams can be harmful to some materials, such as biological materials (human tissue), the much friendlier light-based imagers are vital imaging tools for human beings. Nevertheless, it is important to realize that apart from light, matter waves such as electron beams or atom beams (called atom lasers) can also display wave-like properties.

Realizing that both photons and matter particles show this wave-particle duality, new mathematics called *wave mechanics* (or quantum mechanics) was developed. German scientist Max Born proposed representing the photon by an amplitude wave-function $\psi(x, y, z)$, where the intensity of the photon $|\psi|^2$ at the given physical location represents the probability of finding a photon in this given small volume in space. In reality, measurements indicate the presence of the full photon, not partial photons, so the probability at that location after successful detection is 1 and no detection is zero. This is called wave-function collapse and only occurs after the act of photon detection that, in reality, indicates that a photon was present or absent. Nevertheless, the spatial distribution of the wave function does convey the location of the photon probabilities for successful detection. Again, the wave-function $\psi(x, y, z)$ representation is applicable to all particles, not just photons. This wave function, in essence, behaves like the classical EM wave function as it passes through the optical system, yet preserves the particle and probabilistic nature of photon travel and detection in space. In classical physics, the known initial conditions of light and the optical system give a deterministic output for the light from the system. In the quantum theory of light, the output of the same system with the same initial conditions for the light can take on many possible states.

The *quantum optical* or probabilistic nature of light can be exploited in some applications like optical quantum cryptography and

quantum optical communications to deliver special system features such as super-high security. In addition, following R. P. Feynman's 1981 suggestion, computers could also operate using quantum-mechanical laws that could lead to super-computing powers. Unlike classic digital computers in which transistors switch between one (on) and zero (off) states, in these *quantum computers*, the information is represented by quantum bits or q-bits that simultaneously have a value of both one and zero. Semiconductor devices using standard microelectronic manufacturing processes with the device using superconducting layers of rhenium or niobium at cooled near-absolute zero temperatures have shown quantum behavior of a simultaneous one and zero called super-position, and thus such a device can be used to represent a q-bit in hardware. Many such interconnected q-bit devices can form a quantum-state-based computer processor that can have much more processor power than a digital logic computer processor. One way to understand the increased processing power of a quantum computer is the fact that processing occurs simultaneously for both the zero and one states of the q-bit device so a two-q-bit processor implements processing for all four states simultaneously and a five-q-bit processor implements processing for all $2^5 = 32$ ($N = 5$) states simultaneously, thus giving an exponentially faster processing speed with higher-q-bit processor states compared to the required digital computing mathematical operation via a classic N-bit digital computer. The act of measuring the q-bit in a given q-bit device, such as by measurement of a particle- (e.g., photon)-specific property (e.g., spin, polarization), implies corrupting the actual q-bit state when considering the classic Heisenberg uncertainly principle in quantum mechanics. To solve this problem, the principle of quantum entanglement of particles is used where a q-bit device is represented by quantum-entangled physically-separated particles where, for instance, one particle acts as the processing q-bit while its quantum-entangled particle also carries the processing q-bit particle's processing information. Then by measuring the entangled particle, the processed data can instantly be measured without affecting the quantum-mechanical properties of the processing q-bit particle.

Thus, engineers must design and fabricate q-bit devices that can demonstrate entangled states so the processing power of quantum-state particles is used but also the processed q-bit data is measured to eventually provide a computer-processed real-signal output. Example ways to generate q-bit devices include using charged atomic particles trapped by EM-fields or ions with lasers to create the entanglement between the ions. Quantum dots embedded in electrically-driven light sources, namely, semiconductor light-emitting diodes (LEDs) also form a source for entangled photon pairs and have the potential for use as q-bit devices to form quantum computers that will rely on generating many entangled photon pairs.

Mechanical Motion of Matter with Light

Unlike sound waves, light waves are not usually associated with mechanical effects. For example, the flow of a light wave is not used to rotate a wind-turbine blade like a wind wave can be used to generate energy. Similarly, a fast-flowing water wave from a dam can impart its mechanical energy to a rotating shaft in a water-driven electrical turbine to generate electrical energy. Nevertheless, today's world of nanoscale systems requires another look at light-matter interaction from a mechanical point of view.

Around the year 1600, German astronomer Johannes Kepler observed tails of comets pointed away from the Sun. However, it was not until 1871 that Scottish scientist James Maxwell theorized EM radiation pressure that linked mechanical effects to EM-waves and matter interaction. Russian physicist Peter Lebedev in 1900 experimentally observed the phenomenon of EM radiation pressure, although extremely small with macroscale matter, it becomes an observable reality with microscale or ultralight objects like ultra-thin metal vanes and microparticles like latex beads or metal nano-shells. As mentioned in the previous section on the quantum nature of the photon and its wave-particle duality, EM-waves like mechanical waves carry both energy, E , and momentum, p .

EM radiation pressure exerted by an EM-wave is given by

$$P_{\text{RAD}} = \frac{F}{A} = \frac{dp/dt}{A} = \frac{C_R}{c} \frac{1}{A} \frac{dE}{dt} = \frac{C_R}{c} I$$

Here $F = dp/dt$ is the force exerted by the EM-wave over an area, A , transverse to the light-propagation direction, E is the energy of the photon, C_R is called the coefficient of radiation pressure that quantizes what fraction of the incident photon energy and momentum transfers to the matter-light interface, and I is called the irradiance or intensity of the light given in units of power-flow per unit area or W/m^2 . C_R can be the ratio of the momentum acquired by the matter versus the momentum of the incident photon. Let us consider the extreme cases of light-matter interaction in which light imparts all or no momentum to the matter. When $C_R = 0$, light simply passes through the matter without being reflected or absorbed. When $C_R = 1$, light gets completely absorbed by the matter without being reflected or transmitted, and thus all the photon momentum is transferred to the momentum of the matter particles. The case of all the incident light being totally reflected from the matter interface implies $C_R = 2$ as the reflected photon travels in the opposite direction to the incident photon, and thus the momentum transferred to the matter is twice that present in the incident photon.

To get a quantitative idea for the radiation pressure, note the presence of a very large number c in the denominator of the radiation

pressure expression. For example, on the earth surface, the irradiance of sunlight is 1370 W/m^2 giving a radiation pressure with complete absorption (i.e., $C_R = 1$) of $4.6 \mu\text{N/m}^2$ or a very small $4.6 \mu\text{Pa}$. This minuscule level of radiation pressure from sunlight is too small to affect systems on a macroscale. To increase the radiation pressure, the light irradiance must increase. One source of exceptionally high irradiance is the laser. This can be seen by a very simple example of a typical continuous wave (CW) 1-W green or 514-nm wavelength argon ion laser with a $1 \text{ mm} \times 1 \text{ mm}$ transverse area beam giving an amazing 10^6 W/m^2 irradiance level, nearly a 1000 times stronger than the sunlight on the Earth's surface. In effect, compared to radiation pressure caused by sunlight on Earth, a laser beam on Earth could produce a 1000 times higher radiation pressure. In fact, American scientist Arthur Ashkin, in the 1970s, discovered and demonstrated the use of laser beams to manipulate micron-sized particles, such as latex spheres in water. Specifically, Ashkin showed that as light passes from the low-refractive index material, such as water, into the higher-index material, such as the latex sphere, the light beam changes direction because of refraction, and this change in direction of momentum-carrying photons linked to EM-wave radiation pressure causes a force to be extended in the transverse direction (to light travel) that causes the sphere to be pulled in the transverse plane (see Figure 2.14). Typically laser beams have a non-uniform irradiance distribution with the central part of the beam having a higher irradiance. Thus the microsphere particles gravitate towards the central part of the laser beam because of the radial pressure difference. In the same light, the incident photon momentum conservation principle or radiation pressure propels the particles to travel along the light-beam direction (shown in Figure 2.14). In effect, this forms a laser-driven particle transfer pipeline, a tool for next-generation biological particle manipulations. In fact, using highly focused laser beams, it is possible to hold and physically manipulate and move a microparticle, hence the term, *laser tweezers*, a new invention for nanotechnology instrumentations. Furthermore, since the laser beam can be used to hold in position or restrict the motion of a particle, the laser can be used to implement the cooling of the chosen matter; thus the term *laser cooling*.

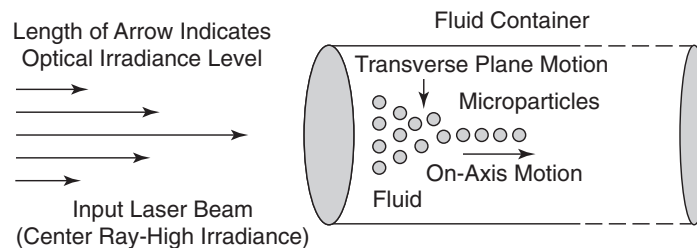


FIGURE 2.14 Laser-driven pipeline for noncontact microparticles transfer. The fluid container acts as the pipeline for microparticles.

Optoelectronics: Photons and Electrons

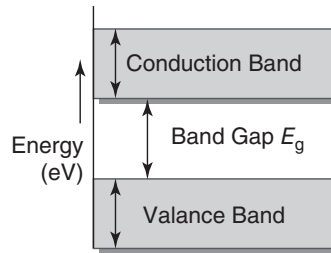
In electronics, energy of an electron is often described in units of electron-volts (eV). This is because the basic unit of joule for energy is a very large energy number of motion of small mass particles like electrons. Specifically, 1 eV is equal to the work done to move an electronic charge through a potential of 1 V. Hence, $1 \text{ eV} = 1.602 \times 10^{-19} \text{ coulomb} \times 1 \text{ V} = 1.602 \times 10^{-19} \text{ joule}$ —a very small number in joules. The material lattice electron vibrational energy in the bulk materials is intimately connected to the Boltzmann constant and the materials bulk temperature giving rise to the thermal excitation energy of an electron. The electron and its energy unit eV are intimately connected with photon emission and detection via matter, thus a discussion is relevant. For an approximation, the energy of a photon in eV is given by $E \sim 1.24/\lambda$, where the wavelength is in micrometers. Typical approximate photon energies for common wavelength bands are shown in Table 2.1. To operate a photon-assisted optoelectronic system with both photons and electrons as the signaling particles, the photon energies should be much higher than the thermal excitation energies of the electrons to form stable systems (see Problems section).

Matter can be described by the energy states of the electrons composing the atoms of the given material. Specifically, energy diagrams (see Figure 2.15) in discrete levels of eV units portray the differences (or band gaps) in energy levels of the electrons distributed in the outermost shell of atoms. Matter can be classified using these

EM Spectral Band	Wavelength (μm)	Photon Energy (eV)
Ultra-Violet (UV)	0.01–0.4	3.1–124
Visible	0.4–0.7	1.77–3.1
Near-Infrared (NIR)	0.7–1.0	1.24–1.77
Short-Wave Infrared (SWIR)	1–3	0.413–1.24
Medium-Wave Infrared (MWIR)	3–8	0.155–0.413
Long-Wave Infrared (LWIR)	8–15	0.155–0.083
Far-Infrared (FIR)	15–100	0.083–0.0124
Terahertz (Submillimeter Wave to Millimeter-Waves)	100–1000	0.0124–0.00124
Microwaves	1000–1,000,000	0.00124–0.00000124

TABLE 2.1 Photon Energies at Different Bands of the EM Spectrum

FIGURE 2.15 Band-gap energy diagrams in eV that determine electronic and optical properties of given material.



band gaps, E_g , divided into three major categories: *conductors*, *semiconductors*, and *insulators*. In the case of conductors such as metals, there is no band gap between the nonmobile valance band electrons and the highly mobile conduction band electrons (called charge carriers) ($E_g = 0$), as there is an overlap region between the two bands. Hence, electrons can easily travel between the valance and conduction bands within this overlap energy zone. For semiconductors, there is a small energy-level region between the conduction and valance bands so valance electrons, after absorption of energy such as via photon interaction, can jump to the higher conduction band. For typical semiconductors such as silicon (Si) and germanium (Ge), E_g for Si is 1.1 eV and E_g for Ge is 0.7 eV. It is common practice to use group-IV periodic table elements like Si and Ge as efficient photosensors (e.g., camera-type imagers) for today's available light sources. Other important semiconductor materials in optics are group-III-V compounds like gallium arsenide (GaAs) with an $E_g = 1.4$ eV. In the case of insulators, the band gap is so large (e.g., > 10 eV) that it basically prevents the presence of any conduction electrons by absorption of typical energy sources, including thermal sources. *Optoelectronics* is the field dealing with the interaction of photons and electrons in semiconductors and is the basis of the building blocks of many modern optical systems, such as optical fiber communication systems. For example, doped semiconductors like a p-type semiconductors with excess electrons when sandwiched with n-type semiconductors with excess holes can be used to make LEDs in the forward-bias state. In effect, a forward-bias voltage, V_b , applied to the diode p-n junction causes electrons in the p-doped area to jump to the lower-energy level n-type zone, causing the electrons of charge q to give up energy $E = qV_b$ as an emitted photon of energy $E = hf$, thus forming a light source at frequency f . In a similar fashion, a reverse-biased p-n diode can produce a current on absorption of photons to make an *optical detector*.

Note that the photon is an indivisible particle; hence, all its energy is transferred to only one electron in matter. Increasing the power of the laser does not increase the energy of the electron; it only produces more electrons of the same energy as high-optical power means more photons per second and thus a higher current from a photodetector device. Only a shift in the optical frequency can change the transferred

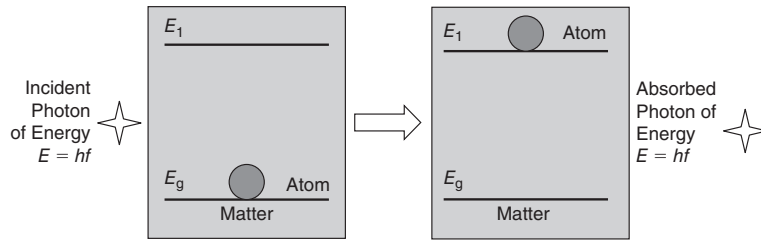


FIGURE 2.16 Stimulated absorption of a photon (normal absorption) in matter.

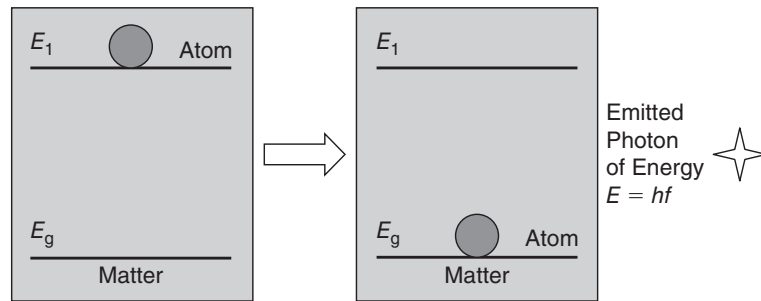


FIGURE 2.17 Spontaneous emission of a photon in matter.

energy of the electron. Figure 2.16 shows the process of stimulated absorption of a photon in matter, also called normal absorption. In the case, the photon has sufficient energy to transfer matter/atom to its higher energy state.

Next, Figure 2.17 shows that matter can release a photon when it relaxes to its lower-energy state.

The Laser

The word *LASER* stands for *Light Amplification by Stimulated Emission of Radiation*. Einstein, while studying classic light-matter interaction of light absorption (Figure 2.16) and emission (Figure 2.17) discovered a new process (see Figure 2.18) in which matter and radiation are in an equilibrium state, laying the foundations for the laser based on the process of stimulated emission. In this case, an incident photon of the correct energy when interacting with matter also present in a higher-energy or excited state can be coerced to produce two coherent photons of the same energy state as the incident photon, forming the basis for coherent amplification that leads to a laser. From a practical point-of-view, a multiple energy-level (e.g., four-level) laser material

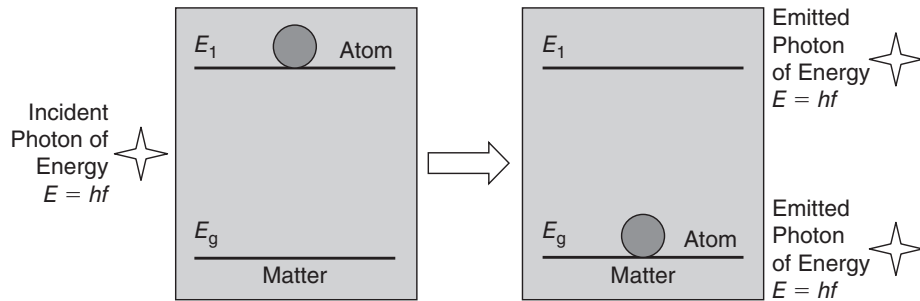


FIGURE 2.18 Stimulated emission of a photon in matter. Two photons are produced in the process, leading to light of increased intensity or optical amplification, the basis for the laser.

system can be used to realize a stable laser operation in which electrons sit with appropriate count distributions amongst the four energy levels in the material. From a simplistic view point, consider a two-level system, one level with the excited electrons and one level with the lower-energy-state electrons. The difference in this energy level corresponds to the emitted coherent photon.

Typically, a lasing material is placed in an optical cavity within mirrored facets (see Figure 2.19), and incident pump photons are injected from an external light source, such as a flash lamp or laser diode, forming a laser source that produces a single-frequency

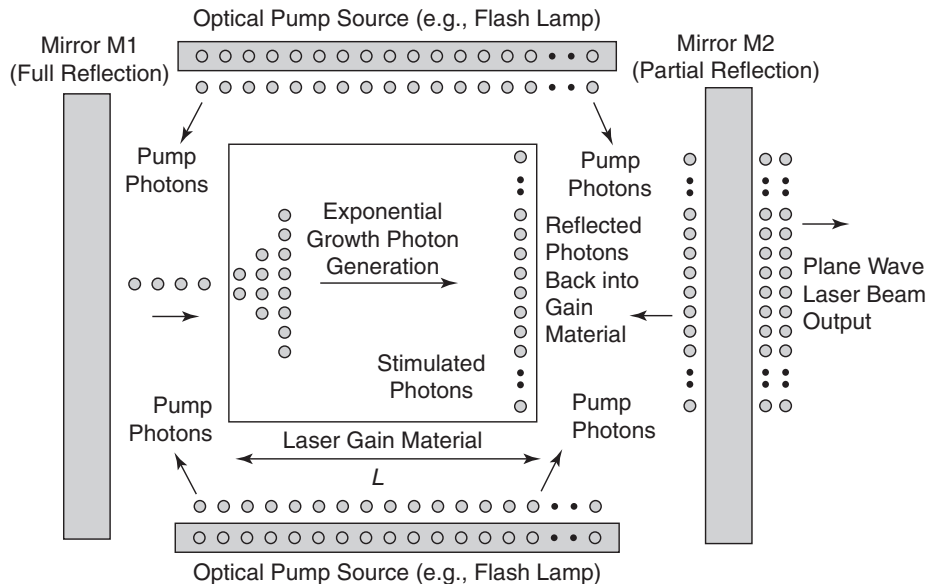


FIGURE 2.19 A basic laser design using a solid-state lasing material (e.g., ruby crystal) and an external flash lamp optical pump. Balls represent photons.

(energy) photon stream or a plane-wave beam. The external pump light moves electrons in the lasing material from its lower-energy state to its higher-energy state so a high population of excited electrons always exists in the material (causing a population difference, N) to enable steady-state lasing operations to generate a coherent beam of light. The electron excitation can also be done by electrical means via external electrical sources, such as done in semiconductor and gas lasers. The incident-pump photons travel along the laser material of length, L , stimulating emission of more coherent (or in-phase) photons along the material, thus an exponential growth of coherent photons occurs along the lasing-material beam-propagation direction. Because of the lasing-material placement within a cavity structure of length, L_1 , with mirrors, M1 and M2, forming the cavity walls, the photons traveling within the cavity are reflected back into the cavity, causing photons to travel and produce optical gain many times through the material. The material optical gain per unit-length is represented as G and represents the coherent photon-multiplication factor per unit distance travelling in gain medium. When these photons also satisfy the cavity in-phase condition, such that a photon-acquired roundtrip phase due to cavity optical-path-distance travel and the phase imparted by the laser-amplification process is a multiple of 2π , then a coherent summation of all photons occurs to produce a strong-intensity laser beam at a laser-material chosen wavelength, λ , that exits through the cavity mirror, M2. Note that M2 has a finite but small transmission coefficient T_2 at the lasing wavelength, λ . In general, the laser-light intensity produced by the laser after n roundtrips of the photons in the cavity can be simply expressed by

$$I(n) = [R_1 e^{2GL}]^n R_2^{n-1} T_2 I_0$$

where R_1 and R_2 are the M1 and M2 mirror-reflection intensity coefficients, respectively. T_2 is the M2 mirror-transmission intensity coefficient, and I_0 is the initial laser-cavity input-light intensity. R_1 , R_2 , and T_2 have values that range from 0 to 1. The factor of 2 in the exponential gain term occurs because the photon travel is a cavity roundtrip. The photon that exits the laser suffers n reflections from M1 and $n - 1$ reflections from M2, hence the term R_2 with $(n - 1)$ multiplications. Also, this photon must pass only once through M2 to form the external laser beam, thus the single use of T_2 in the basic laser operation equation. Of course, any loss of photons in the cavity due to material absorption, laser output beam, and other effects is compensated by the gain in the laser medium over steady-state lasing operations.

Figure 2.19 shows that the photons bounce back and forth in the laser cavity to produce the final output beam that is a single-frequency (or wavelength) high-quality plane wave for which the lasing

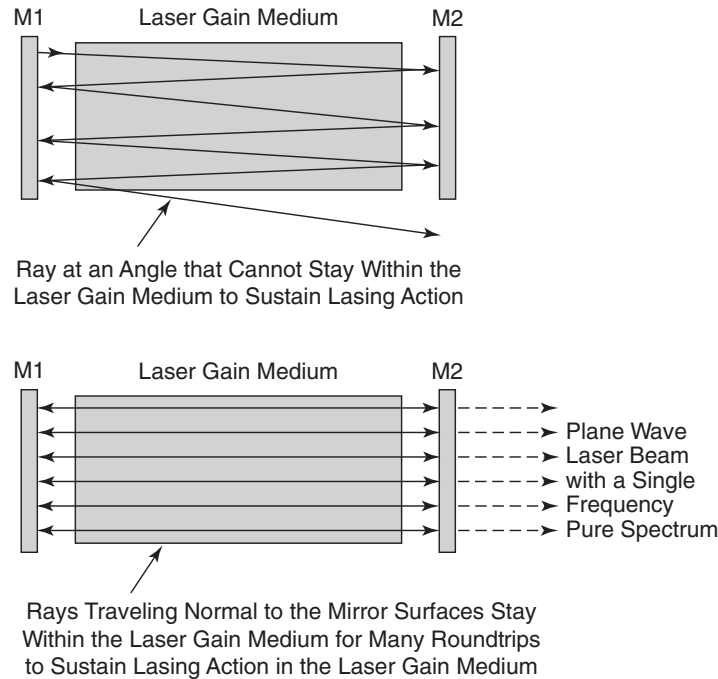


FIGURE 2.20 Plane-wave generation via geometry of laser-optical structure and cavity-traveling rays. Top figure shows ray at an off-axis angle to the mirror faces that is not sustained in the laser-gain cavity. Bottom figure shows that rays normal to the mirror surfaces are fully sustained in the cavity to sustain lasing action.

material is optimized. Simply by looking at the laser-cavity optical-design structure, we realize that for a beam path of photons (or ray) to sustain itself in the cavity for many roundtrips, the angular freedom of beam motion of the ray is highly limited. In essence, only the photons that travel as rays that are near or at normal incidence to the mirrors are able to sustain laser gain effects and eventually produce the coherent plane-waves (or rays) that exit the output mirror at an angle normal (or near-normal) to mirror surface. Figure 2.20 indeed shows what happens to on-axis versus off-axis angled rays within a laser cavity. Thus, by its very design and operational requirements, a laser produces a highly directional beam that forms a source of excellent coherent EM energy. Note that different optical frequencies can satisfy the cavity photon in-phase condition; hence the lasing material energy levels can be engineered to produce the desired frequencies. In addition, external or internal cavity-tuning optics can be deployed to select frequencies from the lasing spectrum, leading to tunable lasers. Such lasers can be highly useful in designing photonic signal-processing systems for various RF and digital-signaling applications.

The Fundamental Forces of Matter and Photonics

The purpose of this section is to put the role of the photon and the EM-field within perspective view of the known fundamental constituents of the universe. There are four fundamental particles of matter or types of chunks of matter that makes the universe, as elegantly narrated by the Pakistan-born Nobel Prize-winning physicist Abdus Salam as described next. The particles are:

1. Electrons
2. Protons
3. Neutrons
4. Neutrinos

The neutrino, also called the little neutral one when compared to the much heavier neutron, was postulated in 1932 by Wolfgang Pauli and named by Italian-born Enrico Fermi. The neutrino has no charge and so has no EM force effect on it. The neutrino has a very small non-zero mass similar to an electron and travels close to the speed of light and can pass through matter almost unaffected. They are produced in nuclear reactions, such as radioactive decay or nuclear reactions in the Sun. They travel from the sun through space and hit the Earth and these are called solar neutrinos. They have also been detected in experiments of beta decay in which a neutrino combined with a proton to produce a neutron and positron (also called an anti-electron as it has same mass as electron, but has a positive charge unlike the negative charge of an electron). There are many types of neutrinos like the muon neutrino found in 1962 by Leon Lederman's team.

Between pairs of the four fundamental particles, (i.e., electron, proton, neutron, and neutrino), there exists a specific fundamental force of nature that describes all phenomena associated with matter such as hardness/softness, color, thunder/lightening, etc. These forces are:

1. *Electromagnetic (EM) forces.* A static electron produces an electric field. When the electron moves in space, the electron produces a magnetic field, and at this point an electromagnetic force is present via the presence of an electromagnetic wave. In the 19th century, James C. Maxwell put forward the complete theory describing EM waves that encompasses the modern practice of photonics engineering. Thus, the force of electromagnetism is between electrically-charged objects, the protons and electrons. The EM force is a long-range force and the effect of this force can be felt for millions of miles using sensitive EM-wave detectors, giving photonics systems a unique power. An example of electric currents producing a magnetic field is the presence of electric currents in the core

of the Earth that result in the Earth's magnetic fields with its North and South magnetic poles. A magnetic field does not exist by itself (and also is not considered a fundamental force like gravity), but is an effect caused by electron motion. The total EM force F_{EM} attributed to electron motion (of charge e and velocity v) can be given by the Lorentz equation as

$$F_{\text{EM}} = F_{\text{E}} + F_{\text{M}}$$

where the force $F_{\text{E}} = qE$ is due to the electric field, E , and the force $F_{\text{M}} = qvB$ is due to the magnetic field B . In vector form, it is written with a vector cross product (given by the symbol $\times$) between the velocity vector $\mathbf{v}$ and the magnetic field vector $\mathbf{B}$. The vector force caused by the magnetic field is given as $\mathbf{F}_{\text{M}} = q \mathbf{v} \times \mathbf{B}$. Vectors here are written in boldface. The electron motion at a constant velocity represents a direct current (DC) and produces a magnetic field. The electron motion with acceleration (or deceleration) in space (and time) creates the same rate oscillating EM-field in space (and time). Thus, the non-uniform (i.e., changing speed) motion of the electron is tied to the EM force within the EM-wave.

2. *Strong nuclear forces.* The strong nuclear force exists between the proton and the neutron in the nucleus of an atom. To see this force, we would have to travel to the stars like the Sun. The strong nuclear force keeps the protons and neutrons together bound inside the nucleus. Protons and neutrons are made up of quarks and there are two types of quarks—the up quark and the bottom quark. Strong nuclear forces hold quarks together.
3. *Weak nuclear forces.* The weak nuclear force exists between any pair of the four fundamental particles in nature. Radioactivity, first observed by Madam Marie Curie, is a manifestation of the weak nuclear force and is also called the force of radioactivity. Radioactive decay of one element of matter to another element of matter is a nuclear reaction. The weak nuclear force causes the transformation of matter (called radioactive decay) with neutrons transformed into protons, electrons, and neutrinos. Unlike the EM force, the weak nuclear force is a very short-range force and manifests only when the proton and neutron and the electron and the neutrino that are engaged in the force production are within typically 10^{-16} cm relative distance to each other.
4. *Gravitation force.* Sir Isaac Newton first discovered the gravitation force. This force exists between all the four particles taken in pairs.

Unification of Forces

In the beginning of the 19th century, there were two distinct forces: the electric force and the magnetic force. Then the unification of these two forces occurred to form the single basic force called the electromagnetic force. The magnetic force is not a fundamental thing, but is connected to the electric force through the state of motion of the electron. The second unification occurred in 1949 between the unification of the EM force and the weak nuclear force. Also called electro-weak unification, the EM force and the weak nuclear force unify at extremely high temperatures (over a billion degrees centigrade). The Higgs boson has been postulated to give mass to fundamental particles and is recently claimed to be experimentally detected.

Problems

- 1 Using geometry, explain why Hero's principle of shortest-path length for light travel violates the law of refraction.
- 2 Show that Hero's shortest-path Principle and Fermat's least-time principle are equivalent for the process of light reflection.
- 3 Show mathematically that Fermat's principle of minimizing to shortest optical-path length and Fermat's least-time principle are equivalent, i.e., $\frac{d}{dx} [\text{OPL}_{S-D}] = 0$ and $\frac{d}{dx} [T_{S-D}] = 0$ impose the same condition on light travel.
- 4 Use Fermat's principle to derive the law of reflection. Use Figure 2.21. Hint: Use Problem 3.

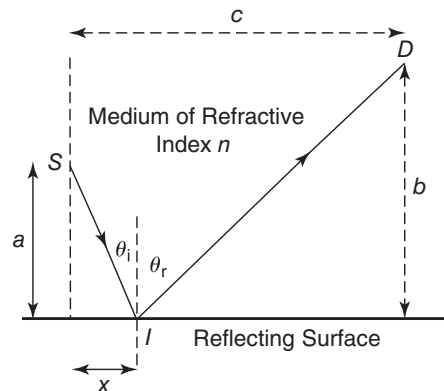


FIGURE 2.21

- 5 Use Fermat's principle to derive the law of refraction. Use Figure 2.22. Hint: Use Problem 3.

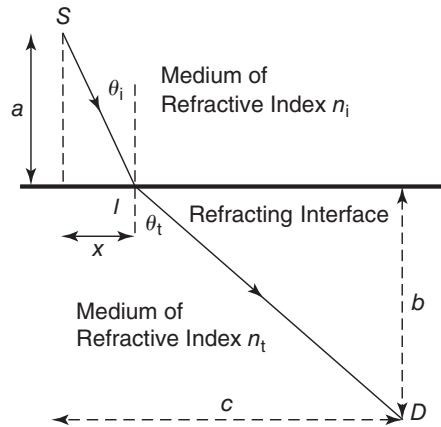


FIGURE 2.22

- 6 Give five examples of what kinds of sensors can be realized when exploiting the OPL change of a chosen optical material.
- 7 Given the incident angle, θ_a , and output angle, θ_b , for the ray shown in Figure 2.23, show steps and write an expression linking the two labeled angles. The ray is passing through media of different refractive indices given by n_0 , n_1 , n_2 , and n_3 .

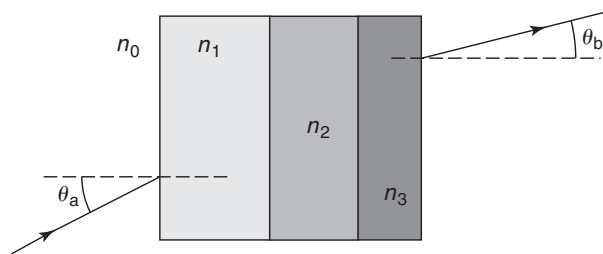


FIGURE 2.23

- 8 Write an expression for the optical-path length from the laser to the detector. The square-beam splitter is an optical device that can split the ray into paths that are orthogonal to each other. The same device also acts as a beam combiner for two input rays physically at 90° to each other. See Figure 2.24.



10 Given a light wave of frequency, f , wavelength λ_n in a medium of refractive index n , with c being the speed of light in vacuum and λ the free-space wavelength, write an expression for:

- (a) f in terms of medium wavelength
- (b) the change in optical frequency, f , as a function of freespace-wavelength change
- (c) the change in optical frequency, f , as a function of medium-wavelength change

In addition, comment (d) on whether the light frequency and wavelength changes once the wave enters the medium from freespace.

11 What single hardware modification to the Figure 2.12 system could be implemented to measure the optical-chip material dispersion $n(\lambda)$? Assume the chip temperature is stable, implying that chip thickness, d , is also fixed. Explain how to use the measured OPL values to determine $n(\lambda)$.

12 Refractive index, n , is given by the classic expression $n = c/v$, where c is the speed of light in a vacuum and v is the speed of light in the medium of index n with $v^2 = 1/\mu\epsilon$. Show that the refractive index can be written as $n = \pm \sqrt{\mu_r \epsilon_r}$, where μ_r and ϵ_r are the material relative-magnetic permeability and relative-electric permittivity, respectively.

13 An air-material interface has an incident angle of 30° . The material is a negative-index material with an absolute value of index equal to 2. Compute and explain what happens to the transmitted ray in the negative-index material.

14 Semiconductor materials silicon and germanium have band gaps of 1.1 eV and 0.7 eV, respectively. Calculate what optical-wavelength ranges of light can these materials be used for optical detection.

15 Given a light source of power 1 mW and green wavelength of 514 nm, how many photons per second are emitted by the source. If all the light strikes a photodetector with ideally no thermal losses, how many electrons can this detector produce per second?

16 Given a silver metal with a work function of 4.7 eV and incident photons of 1.5×10^{15} Hz, what is the maximum kinetic energy of the ejected electrons via the photoelectric effect?

17 Given matter waves with a de Broglie wavelength of 0.5 angstrom ($1 \text{ \AA} = 10^{-10} \text{ m}$), what photon frequency can produce the equivalent diffraction pattern produced by these matter waves? What photon band is this frequency?

18 The material lattice electron vibrational energy, E , in the bulk materials is intimately connected to the Boltzmann constant k_B and the materials bulk temperature T in Kelvins (K), giving rise to the thermal excitation energy of an electron. Specifically, $E = k_B T$ where $T = 273 \text{ K} + \text{Material Temperature in Centigrade}$ = $1.38 \times 10^{-23} \text{ J/K}$. Calculate the thermal excitation energy in eV

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of an electron in a 27° C room temperature material. Compare the electron thermal energy to a visible green 0.5 μm wavelength light photon energy.

19 In the basic laser equation $I(n) = [R_1 e^{2GL}]^n R_2^{-1} T_2 I_0$, can you explain the use of R_2 and T_2 in the equation?

20 Given a laser system, find the output laser intensity, I , after two complete roundtrips. The initial laser intensity $I_0 = 0.01 \text{ W/cm}^2$. The cavity mirror intensity reflectivities are 95 percent and 100 percent. The gain of the laser medium is $G = 2 \text{ cm}^{-1}$ and the cavity length is $L = 1 \text{ cm}$. Also specify which mirror reflectivity corresponds to the output beam mirror and why.

21 Describe the direct links of how the fundamental physics of nature is manifested in the field of photonics engineering. Hint: Start with a fundamental particle of nature.

Additional Reading

1. M. Born and E. Wolf, *Principles of Optics*, 7th Edition, Cambridge University Press, Cambridge, MA, 2001.

CHAPTER 3

Electromagnetic Waves, Light, and Polarization

Electromagnetic Waves and Polarization

Electromagnetic (EM) waves exhibit the special property of polarization. In general, polarization refers to the vector direction of the time and space oscillating electric field in the EM wave. For light waves, the vector direction of the electric field is also called the optical polarization vector of the light wave. Any EM wave can naturally show or be designed to show a particular polarization behavior, and photonic system designers can use light's polarization properties in synergy with various materials' polarization properties to form functional engineering systems. Indeed, an EM-wave's polarization and that of a medium in which the wave travels are linked together. To understand this polarization vector linkage, we should have a foundational understanding of Maxwell's equations, which mathematically describe electromagnetism and EM wave propagation.

Scottish mathematician James Clerk Maxwell in 1864 was able to unify various experimentally known results between electricity and magnetism into four classic equations that completely explained the mathematical relationship between time and space varying electric and magnetic fields and their relationship to charge and current densities. In fact, using his four equations, Maxwell was able to show that the electric and magnetic fields were completely interconnected as the EM field of a traveling wave, with the wave having the classic speed of a light wave in freespace or a vacuum and the wave showing a transverse EM-wave behavior (i.e., electric and magnetic fields are normal to each other and the wave travel direction). This was indeed a great achievement showing how mathematics produced a result observed in physics and electrical engineering.

Mathematical Formalization of Traveling Waves

A traveling wave is a disturbance in space represented by vector $\vec{r}$ and time, t , that can be written mathematically as a function $\psi(\vec{r}, t)$ that obeys the wave equation and carries momentum (a vector) and energy (a scalar). A simple nondispersive case of the wave represents a wave function that propagates with a constant velocity, v , without changing its shape, such as in a nondispersive medium like air. In effect, all frequency components of the wave function travel at the same speed, v ; hence the nondispersive wave representation. A light wave traveling through freespace or certain glass optics is an example of nondispersive wave propagation.

There are two main kinds of waves: longitudinal waves and transverse waves. In longitudinal waves, the disturbance and wave-travel direction are the same. An example is the sound wave traveling in an acousto-optic device shown in Figure 3.1a, where the sound-wave direction and the stresses and strains disturbance in the glass material are along the same direction. On the contrary, in transverse waves, the disturbance and wave-travel direction are in orthogonal planes. An example is the EM wave, such as a light beam traveling in a freespace shown in Figure 3.1b, where the wave electric $\vec{E}$ or magnetic $\vec{H}$ field disturbance direction and the wave-travel direction are normal to each other. Waves can exist in one dimension (like on a wire or string), two dimensions (like on a surface of a material, e.g., glass), or three dimensions (like a beam of light propagating in air). In its mathematically simple 1D form, a general wave function $\psi(z, t)$ can be written as

$$\psi(z, t) = g(z \pm vt)$$

where v is the wave velocity of the wave in the positive z -direction and negative z -direction. To test if this representation is appropriate

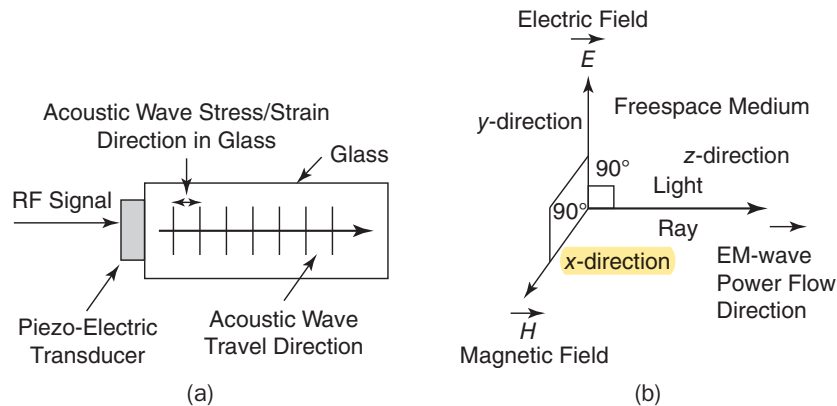


FIGURE 3.1 (a) Example of a longitudinal wave consisting of a bulk acoustic wave in an acousto-optic crystal like glass. (b) Example of a transverse wave like a light beam in air.

for a wave representation, check that if after a time, Δt , when the wave $\psi(z, t) = g(z - vt)$ has travelled a distance Δz at speed v in the z -direction, the shape of the wave function is the same as it was at time, t . Problem 3.1, indeed, asks to prove this test of a basic traveling-wave representation. The general wave function can also be written as a weighted sum of $+z$ -direction and $-z$ -direction wave functions such as

$$\psi(z, t) = C_1 g(z - vt) + C_2 g(z + vt)$$

where C_1 and C_2 are constants.

As asked in Problem 2, the general 1D nondispersive media wave equation can be derived by simply taking the time and space derivatives of the wave function to get the 1D nondispersive equation:

$$\frac{\partial^2 \psi}{\partial z^2} = \frac{1}{v^2} \frac{\partial^2 \psi}{\partial t^2}$$

that represents the wave-propagation basis for the wave function. Here, all frequencies in the wave function travel at the same velocity, v . As a general wave can be represented as a sum of different frequencies (e.g., harmonics of a fundamental frequency also known as a Fourier-series sum) and the wave equation is linear in linear media, the general-wave-function propagation property is simply a sum output of each frequency processed by the wave equation.

An example mechanical wave represented by the 1D nondispersive-medium wave equation is the compressional wave in a fluid where $\psi(z, t)$ represents the local mechanical displacement from a stationary (or equilibrium) point and the velocity, v , is given by $v = \sqrt{\alpha/\beta}$, where α is the fluid compressibility and β is the fluid density. An example of a nonmechanical wave represented by the 1D nondispersive-medium wave equation as proven by Maxwell is the EM wave in a linear medium, such as a vacuum, where $\psi(z, t)$ represents the local electric field or the local magnetic field and the velocity, v , is the speed of light in the linear medium.

A fundamental function $g(z, t)$ that can be used for the 1D wave function $\psi(z, t)$ is the harmonic- or sinusoidal-wave function; hence,

$$\psi(z, t) = g(z, t) = C_0 \sin[k(z - vt)]$$

where C_0 is the amplitude of the wave, and k is the wave number (or spatial frequency) given by $k = 2\pi/\lambda_m$, where λ_m is the wavelength (or spatial period) of the wave in the travel medium. Recall from Chapter 2 that the sinusoidal function also represents the plane-wave solution of the EM wave based on plane phase-fronts for a traveling wave and straight-line ray optics. The sinusoidal wave function can be rewritten in a number of ways, and these include

$$\psi(z, t) = g(z, t) = C_0 \sin[kz \mp \omega t]$$

$$\psi(z, t) = C_0 \sin\left[2\pi\left(\frac{z}{\lambda_m} \mp \frac{t}{T}\right)\right]$$

$$\psi(z, t) = C_0 \sin\left[\frac{2\pi}{\lambda_m}(z \mp vt)\right]$$

$$\psi(z, t) = C_0 \sin\left[\omega\left(\frac{z}{v} \mp t\right)\right]$$

$$\psi(z, t) = C_0 \cos[\omega t \mp kz]$$

As polarization studies deal with the polarization vector, and most optical waves exist in three dimensions (3D), in vector notation, the 3D plane-wave function traveling in the $\vec{k}$ direction can be written as

$$\vec{\psi}(\vec{r}, t) = \vec{C}_0 \cos[\omega t \mp \vec{k} \cdot \vec{r}]$$

Note that $\cdot$ represents the vector-dot product between $\vec{k}$ and $\vec{r}$, and $\vec{C}_0$ is the amplitude vector of the wave that, in the case of an EM wave, can represent the electric field polarization vector. The wave angular frequency in radians/s is

$$\omega = 2\pi/T = 2\pi f$$

where $f = 1/T$ is the wave temporal frequency in hertz and $T = \lambda_m/v$ is the wave-temporal period in seconds. Both sine and cosine representations of the real-wave function are valid harmonic wave representations. Also, the classic relationship of

$$v = \lambda_m f$$

between the harmonic-wave velocity, wavelength, and temporal-frequency holds for the sinusoidal plane-wave function. Do note that when travel media change, the wave changes in v and λ_m , while f stays at the given fixed value in linear media. In Cartesian coordinates, the wave propagation and position vectors can be written as

$$\vec{k} = k_x \vec{i} + k_y \vec{j} + k_z \vec{k} \quad \text{and} \quad \vec{r} = x\vec{i} + y\vec{j} + z\vec{k}$$

where (k_x, k_y, k_z) and (x, y, z) are the $\vec{k}$ -vector and position-vector coordinates, respectively, and $\vec{i}, \vec{j}, \vec{k}$ are the unit vectors in the x, y , and z , directions, respectively. The dot product of two vectors such as $\vec{k}$ and $\vec{r}$ gives the scalar quantity $|\vec{k}||\vec{r}|\cos\theta$, where θ is the angle between

the $\vec{k}$ and $\vec{r}$ vectors and $|\vec{k}| = \sqrt{k_x^2 + k_y^2 + k_z^2}$ and $|\vec{r}| = \sqrt{x^2 + y^2 + z^2}$. Note that for all spatial-position points in the plane normal to the wave $\vec{k}$ vector, $\theta = 90^\circ$ and the dot product $\vec{k} \cdot \vec{r} = 0$, implying that the wave's phase in radians is uniform (constant) in this plane; hence the notation, plane-wave. Indeed, for an EM-wave in freespace or linear media, a plane-wave solution exists, and the temporally oscillating electric and magnetic fields are in this plane, which is normal to the light-propagation direction.

EM Radiation, Media, and Polarization

EM radiation is generated by moving charges. If the charges, such as electrons, move at a constant velocity in a straight line in a wire to provide the DC current, a magnetic field is generated around the wire, an effect experimentally observed by A. M. Ampere and called Ampere's law. When these electrons form accelerating charges (such as via an AC-drive signal to an antenna wire), the produced magnetic field changes in time and thus an EM wave is generated. In optical-wave propagation in a medium that is polarizable (i.e., where the charges can move ever so slightly within an atom or molecule), the incident-EM waves' oscillating electric field can cause the electrons in the material atom to physically accelerate and oscillate at the same temporal frequency as the incident-EM wave. Thus, an oscillating electric dipole antenna is formed as a wave-scattering center in the material atoms, and this dipole antenna on a microscale re-radiates the incident-optical wave as it has an oscillating material polarization state (also provides the material polarization-based displacement current), thus forming a propagation wave in the medium on a macroscale. The direction of the electron acceleration is along the incident-EM wave electric field or polarization direction, but the radiated EM wave propagates normal to the electron-motion direction. In a freespace (nonpolarizing) medium, the time varying electrical field of the propagating EM wave represents what is now known as a displacement current. Maxwell defined a displacement field $\vec{D}$ (coulomb/m²) in terms of the electric field $\vec{E}$ (V/m) and material polarization field $\vec{P}$ (coulomb/m²) as

$$\vec{D} = \epsilon_0 \vec{E} + \vec{P}$$

Electric polarization in the linear isotropic media can be expressed as $\vec{P} = \epsilon_0 \chi \vec{E}$ where χ is the electric susceptibility of the medium. As $1 + \chi = \epsilon_r$ is the relative permittivity, with $\epsilon_r = \epsilon/\epsilon_0$ and ϵ the media permittivity, and ϵ_0 the freespace permittivity, we can write

$$\vec{D} = \epsilon_0 \vec{E} + \epsilon_0 \chi \vec{E} = \epsilon_0 (1 + \chi) \vec{E} = \epsilon_0 \epsilon_r \vec{E} = \epsilon \vec{E} \quad (C1)$$

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A similar treatment for the magnetic induction field $\vec{B}$ (tesla T or Wb/m²) gives a relationship with the EM-wave magnetic field $\vec{H}$ (A/m) and the induced magnetic polarization field $\vec{M}$ (also called the magnetic dipole moment per unit volume in units of tesla) in the propagation material to be

$$\vec{B} = \mu_0 \vec{H} + \vec{M} = \mu_r \mu_0 \vec{H} = \mu \vec{H} \quad (\text{C2})$$

where μ_0 and μ are the permeability of freespace and the medium, respectively. $\mu_r = 1 + \chi_M$ is the relative permeability of the medium, where χ_M is the magnetic susceptibility of the medium and $\vec{M} = \mu_0 \chi_M \vec{H}$. For most light-material interactions with nonmagnetic material, $\vec{M} = 0$ and $\mu_r = 1$, giving the common relationship for optical waves to be

$$\vec{B} = \mu_0 \vec{H}$$

It is possible to operate an optical material in its nonlinear regime:

$$\vec{P} = \vec{P}_L + \vec{P}_{NL} = \epsilon_0 \chi \vec{E} + \vec{P}_{NL}$$

where $\vec{P}_L$ and $\vec{P}_{NL}$ are the EM-wave induced linear and nonlinear polarization fields, respectively. $\vec{P}_{NL}$ vector has three components in the unit-vector directions noted by units $i = 1, 2$, and 3 and can be expressed via the quadratic dependence of the optical fields (also the intensity of the beam) and written as

$$P_{NL}^i = \sum_{k=1}^3 \sum_{j=1}^3 d_{ijk} E_j E_k$$

where d_{ijk} is the nonlinear susceptibility of the medium for given field directions within the 3D material geometry. For small optical-intensity levels, an optical material can be kept within its linear polarizability region of operation, as is deployed for most of this book.

Note that media can also conduct a current in the presence of an electric field (static or temporally varying), such as a DC current in amperes (A) in a wire connected to a voltage source such as a battery. Experimentally observed, the vector form of Ohm's law is

$$\vec{J} = \sigma \vec{E} \quad (\text{C3})$$

where σ is the electrical conductivity of the medium in mho/m (mho is 1 A/V and is the inverse of the ohm unit). Note that the modern unit for electrical conductivity is siemens per meter (S/m). $\vec{J}$ is the conventional current density vector in A/m² representing the flow of

electrons per unit time per unit volume. If the electrons are traveling at a velocity vector, $\vec{v}$, this conventional current density $\vec{j}$ can also be written as

$$\vec{j} = \rho \vec{v}$$

Metals have high σ and lead to high-current densities with the application of small electrical fields. Optical-frequency materials are generally considered nonconductive (e.g., glass), and hence, are insulators for electrical currents.

The three constitutive Equations C1, C2, C3 for an isotropic linear nonmagnetic media describe the interaction of the media with an EM wave.

Maxwell's Equations for Travelling Waves and Polarization

In the macroscopic media domain, the four Maxwell's equations that completely describe the relationship between electric and magnetic fields in the media and their wave-propagation properties are given in their derivative forms by

$$(\text{Curl of Electric Field}) \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (\text{M1})$$

$$(\text{Curl of Magnetic Field}) \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{j} \quad (\text{M2})$$

$$(\text{Divergence of Displacement Field}) \nabla \cdot \vec{D} = \rho \quad (\text{M3})$$

$$(\text{Divergence of Magnetic Induction Field}) \nabla \cdot \vec{B} = 0 \quad (\text{M4})$$

where ρ is the electric charge density (coulombs/m³) in the media. Maxwell formulated these equations from known experimental results and laws and added critical modifications (e.g., concept of displacement field, $\vec{D}$, leading to displacement current density, $\partial \vec{D} / \partial t$, to complete the mathematical and physical description of EM fields and waves. Specifically Equations M1, M2, M3, and M4 arise from the Faraday's law of EM induction, Ampere's circuital law, Gauss's law of electrostatics, and Gauss's law of magnetostatics, respectively. Statics in the electro/magneto sense, as represented by the Maxwell Equations M3 and M4 refers to non-time-varying fields, such as a fixed field from a magnet or a fixed voltage between the terminals of an electric charge-containing battery. On the other hand, Maxwell Equations M1 and M2 contain time-varying fields and indeed show that M1 is connected to M2, indicating that time-varying electric and magnetic field are closely connected as part of the EM wave.

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For isotropic, nonmagnetic, electrically insulating, linear media typical for optical propagation of EM waves and using their material constitutive equations, the Maxwell's equations can be rewritten as

$$\text{(Curl of Electric Field)} \quad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (\text{M1})$$

$$\text{(Curl of Magnetic Induction Field)} \quad \nabla \times \vec{B} = \mu_0 \epsilon \frac{\partial \vec{E}}{\partial t} \quad (\text{M2})$$

$$\text{(Divergence of Displacement Field)} \quad \nabla \cdot \vec{E} = \frac{\rho}{\epsilon} \quad (\text{M3})$$

$$\text{(Divergence of Magnetic Induction Field)} \quad \nabla \cdot \vec{B} = 0 \quad (\text{M4})$$

The vector curl and divergence operators on the electric field with respect to 3D Cartesian spatial coordinates can be written as

$$\nabla \cdot \vec{E} = \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z}$$

$$\nabla \times \vec{E} = \left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} \right) \hat{i} + \left(\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} \right) \hat{j} + \left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} \right) \hat{k}$$

As mentioned earlier, Maxwell's equations lead to the EM-wave equation that completely describes optical propagation in media including vacuum. To achieve this goal, we can take the curl on both sides of Equation M1 giving

$$\nabla \times (\nabla \times \vec{E}) = -\frac{\partial}{\partial t} (\nabla \times \vec{B})$$

Next using M2, we obtain

$$\nabla \times (\nabla \times \vec{E}) = -\frac{\partial}{\partial t} \left(\epsilon \mu_0 \frac{\partial \vec{E}}{\partial t} \right) = -\epsilon \mu_0 \frac{\partial^2 \vec{E}}{\partial t^2}$$

Using the vector identity, $\nabla \times (\nabla \times \vec{E}) = \nabla(\nabla \cdot \vec{E}) - \nabla^2 \vec{E} = -\nabla^2 \vec{E}$ for a charge-free region ($\rho = 0$) and using Equation M3. Hence, a further simplification is possible, leading to the desired EM-wave equation representing space-time variations of the electric- and magnetic-induction fields giving

$$\nabla^2 \vec{E} = \epsilon \mu_0 \frac{\partial^2 \vec{E}}{\partial t^2}$$

This equation can be further rewritten using $\epsilon = \epsilon_r \epsilon_0$ and $\mu_r = 1$ for nonmagnetic media encountered in optics with the speed, v , of the EM wave given as $v = 1/\sqrt{\epsilon_r \epsilon_0 \mu_r \mu_0}$ as

$$\nabla^2 \vec{E} = \frac{1}{v^2} \frac{\partial^2 \vec{E}}{\partial t^2}$$

The Laplacian operator acting on the electric field with respect to 3D spatial coordinates can be written as

$$\nabla^2 \vec{E} = \frac{\partial^2 \vec{E}}{\partial x^2} + \frac{\partial^2 \vec{E}}{\partial y^2} + \frac{\partial^2 \vec{E}}{\partial z^2}$$

Inserting $\vec{E} = E_x \vec{i} + E_y \vec{j} + E_z \vec{k}$ into the wave equation and matching the left- and right-hand sides of the components of the unit vectors generates the equations:

$$\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} = \frac{1}{v^2} \frac{\partial^2 E_x}{\partial t^2}$$

$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial y^2} + \frac{\partial^2 E_y}{\partial z^2} = \frac{1}{v^2} \frac{\partial^2 E_y}{\partial t^2} \quad \text{and}$$

$$\frac{\partial^2 E_z}{\partial x^2} + \frac{\partial^2 E_z}{\partial y^2} + \frac{\partial^2 E_z}{\partial z^2} = \frac{1}{v^2} \frac{\partial^2 E_z}{\partial t^2}$$

These are second-order partial differential equations, and their solution represents an EM-wave function for an optical wave propagating in an isotropic, nonmagnetic, charge-free, insulating, linear medium. A simple harmonic plane-wave solution called the transverse EM-wave (TEM-wave) solution **exists** for this EM-wave equation. For example, without loss of generality, we can assume a TEM wave with the electric field in the y -direction, wave travel in the z -direction, and B-field in the x -direction; in other words, we can write

$$E_y = E_{y0} \cos [k(z - vt)] = E_{y0} \cos(2\pi ft - kz) \quad \text{and}$$

$$E_y = vB_x = E_{y0} \cos(2\pi ft - kz)$$

In this case where only the E_y component exists for the TEM wave traveling in the z -direction, the optical field obeys the wave equation given by

$$\frac{\partial^2 E_y}{\partial z^2} = \frac{1}{v^2} \frac{\partial^2 E_y}{\partial t^2}$$

In general, if a plane wave is traveling in the $\mathbf{k}$ -vector direction, then the E-field oscillating in time is in the plane normal to the propagation direction. The E-field plane-wave solution in 3D space-vector $\vec{r}$ can be written as

$$\vec{E}(\vec{r}, t) = \vec{E}_0 \cos(2\pi f t - \vec{k} \cdot \vec{r})$$

where $\vec{E}_0$ is the peak amplitude vector of the wave. In general, a wave can have an amplitude that is dependent on $\vec{r}$ (called an inhomogeneous wave) and written as $\vec{E}_0(\vec{r})$, such as a spherical harmonic wave where $\vec{E}_0(\vec{r}) = \vec{E}_0/r$, where $|\vec{r}| = r$ and the argument of the cosine stays the same as for the plane-harmonic wave. Hence, plane waves are not the only solutions of the EM-wave equation. For example, spherical and cylindrical waves are also solutions to the EM-wave equation.

Note that the curl of Equation M2 also leads to a wave equation for the magnetic induction field given by

$$\nabla^2 \vec{B} = \frac{1}{v^2} \frac{\partial^2 \vec{B}}{\partial t^2}$$

that also gives three scalar equations connected to the three components of the magnetic induction field $\vec{B} = B_x \vec{i} + B_y \vec{j} + B_z \vec{k}$. Hence, both the E-field and the B-field follow the same EM-wave propagation characteristics. In electrical engineering and optics and photonics studies, it is the E-field and its interaction with media compared to the B-field that is chosen for propagation and analysis studies, and it is the direction of the E-field vector that is defined as the wave polarization vector.

Real- and Complex-Wave Representations

Without loss of generality, the optical field can be written as the real sinusoidal traveling-wave signal in the z -direction given as

$$\vec{E}(z, t) = \vec{E}_0 \cos(2\pi \nu t + \phi)$$

where $\vec{E}_0 = E_0 \vec{j}$, with E_0 the scalar amplitude of vector-field strength in the $\vec{j}$ unit vector (or y -direction) of space for the optical wave. $\phi = -kz$ in radians is the optical phase of the wave referenced to the $z = 0$ travel position and $k = 2\pi/\lambda$ is the wave propagation constant. As the real electric field has both a magnitude term given by $r = E_0$ and a phase term given by $\psi = 2\pi \nu t + \phi$, the electric field can also be expressed as complex number $z = r e^{j\psi}$ representing a phasor or vector rotating in the complex z -plane (see Figure 3.2) with $r = |z| = \sqrt{(r \cos \psi)^2 + (r \sin \psi)^2}$. By applying Euler's formula,

$$z = r e^{j\psi} = r \cos \psi + j r \sin \psi$$

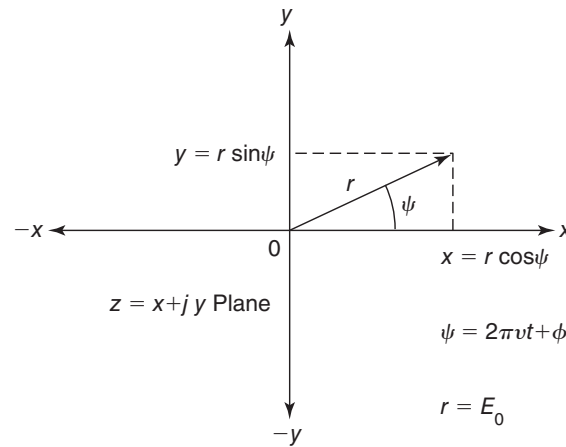


FIGURE 3.2 A view of the complex number z -plane and its relationship to optical-field amplitude and phase parameters in the real- and complex-field representations.

This means that the following holds:

$$\text{Re}[z] = r \cos \psi = E_0 \cos(2\pi\nu t + \phi)$$

$$\text{Im}[z] = r \sin \psi = E_0 \sin(2\pi\nu t + \phi)$$

where $\text{Re}[z]$ stands for the real value of z and $\text{Im}[z]$ stands for the imaginary value of z . Thus, we can use the complex notation to represent the electric field and after computations, in many cases, take either the real or imaginary value of the complex field to give the desired processed electric field. Common practice is to take the real value of the complex field to represent the field in reality. This approach of using the complex number representation of the field simplifies the mathematical analysis for most field-media interactions, (e.g., isotropic linear media like air and glass commonly used in optics); hence, this is deployed in engineering analysis. We can write this complex field representation for a plane wave with fixed-field amplitude as

$$E = E_0 e^{j[2\pi\nu t + \phi]}$$

or in complex vector notation as

$$\vec{E} = \vec{E}_0 e^{j[2\pi\nu t + \phi]} = \vec{E}_0 e^{j[2\pi\nu t - \vec{k} \cdot \vec{r}]}$$

This complex vector field representation is helpful when doing polarization analysis for optical fields given that light can have its E-field strength and direction oscillating in time and space.

Complex Index of Refraction and Evanescent (Surface) Waves

For a given material, the electric permittivity, ϵ , and magnetic permeability, μ , can also be complex numbers. This means that $\vec{E}$ and $\vec{D}$ will be out of phase, and $\vec{H}$ and $\vec{B}$ will be out of phase. The net result is that we must define a complex index of refraction $\tilde{n}$ given by

$$\tilde{n} = n[1 - j\chi] = n - j\kappa$$

where $\chi = \text{Im}[\tilde{n}]/\text{Re}[\tilde{n}]$ is the material attenuation index, $\text{Im}[\tilde{n}] = \kappa$ and $n = \sqrt{\epsilon_r \mu_r}$, where ϵ_r and μ_r are the material relative electric permittivity and magnetic permeability, respectively. $\text{Re}[\tilde{n}]$ and $\text{Im}[\tilde{n}]$ are the real and imaginary part of $\tilde{n}$, respectively. In general, we can write $n = \sqrt{\tilde{\epsilon}_r \tilde{\mu}_r}$, where $\tilde{\epsilon}_r$ and $\tilde{\mu}_r$ are the material complex relative electric permittivity and magnetic permeability, respectively. Maxwell's equations continue to provide the harmonic-wave solution, where we write the propagation constant as $\tilde{k} = \tilde{n}\omega/c$ with the optical field as

$$\begin{aligned} E &= E_0 e^{j[\omega t - \tilde{k}z]} \\ &= E_0 e^{j\left[\omega t - \frac{\tilde{n}\omega}{c}z\right]} \\ &= E_0 e^{j\omega t} e^{-j\frac{n\omega}{c}(1-j\chi)z} \\ &= E_0 e^{j\omega t} e^{-j\frac{n\omega}{c}z} e^{-\frac{\chi\omega}{c}nz} \\ &= E_0 e^{j[\omega t - kz]} e^{-\frac{z}{\delta}} \end{aligned}$$

where $k = n\omega/c$, and the material skin depth, δ , for the nonconducting dielectric is defined as

$$\delta = \frac{c}{\omega \text{Im}[\tilde{n}]} = \frac{c}{\chi\omega n}$$

Hence, a material with a complex index of refraction exhibits an exponential attenuation of the propagating optical field into the material controlled by the material attenuation index. Specifically, as the wave enters the material by one skin-depth δ , the optical field attenuates by 1/e of its value on the surface. It is possible that the EM wave propagation constant $\tilde{k}$ becomes purely imaginary, leading to a near-field standing wave solution with a harmonic time oscillation at frequency, ω . The wave with an exponentially attenuating optical field at the surface of a material is called an evanescent wave. In

optics, the materials for interaction are generally dielectrics with no electrical conductivity (i.e., $\sigma = 0$ mho/m).

For conductors such as metals, the complex index can be rewritten as

$$\tilde{n}_c = \sqrt{\epsilon_r \mu_r - j \frac{\sigma}{\epsilon_0 \omega}}$$

and the skin depth is given by

$$\delta_c = \sqrt{\frac{2c^2 \epsilon_0}{\sigma \omega}} = \frac{1}{\sqrt{\pi \nu \mu \sigma}}$$

As an example for a typical metal material such as copper with $\sigma = 5.8 \times 10^7$ A/V-m used in electrical engineering, the EM-wave skin depth is a rather large 1 cm for a typical $\nu = 50$ Hz EM-wave frequency used for power transmission systems. As power is related to the square of the electric field, the power drops to 13.5 percent of its peak for one skin depth into the material. At 10 GHz frequency, the skin depth in a copper wire is about 660 nm, indicating that at higher frequencies, the EM-wave power mostly travels on the skin of the copper waveguide, and the copper waveguide interior simply acts as a directional guide for the EM wave. If the EM-wave frequency goes extremely high like into the optical regime (e.g., visible green light at 500 nm), the skin depth for the copper conductor is only a very small 1.7 nm, indicating that light will not penetrate into the metal for an appreciable depth to form a good guide for carrying EM-wave optical power.

It can be shown (see Problem 7) that for electrically conducting materials with material parameters and EM-wave frequency that satisfies the condition $\sigma/\epsilon\omega\mu_r < 1$, the material complex index of refraction can be written as

$$\tilde{n}_c \approx n \left[1 - j \frac{\sigma}{\epsilon\omega\mu_r} \right]$$

where the material attenuation index is $\chi = \sigma/2\epsilon\omega\mu_r$. For most nonmagnetic materials, $\mu_r = 1$, so $\chi = \sigma/2\epsilon\omega$. Table 3.1 gives approximate material constants for typical metals and dielectrics encountered in photonics.

The genius of James C. Maxwell can be seen by his equation (M2) that provides a link between expected current densities in an electrical circuit containing an electrical capacitor. A capacitor is a passive electrical component made by sandwiching an electrical

Material	Relative Permittivity ($\nu < 10$ kHz) $\epsilon_r = \epsilon/\epsilon_0$	Conductivity (at $\nu = 0$) σ Siemens/m	Optical Refractive Index (at 633 nm)
Air	1.0	0.8×10^{-14}	1.0
Germanium	16	0.22×10^7	5.48
Glass (Silicon Dioxide)	4 to 7	2×10^{-14}	1.46
Silicon	11.8	1200	3.88
Fused Quartz	3.8	10^{-14}	1.55
Diamond		2×10^{-13}	2.41
Aluminum		3.82×10^7	1.37
Silicon Carbide			2.64
Aluminum Oxide (Sapphire)		1×10^{-1}	1.77

(Approximate Values given in Table.) (W. H. Hayt, Jr., "Engineering Electromagnetics," McGraw-Hill, 4th Edition, 1981).

TABLE 3.1 Material Constants for Typical Metal and Dielectrics.

insulator (e.g., dielectric material) between two electrical conductors (e.g., metal plates). The capacitor is electrically connected to an electrical transmission line, such as a coaxial cable, that is connected in series to an electrical current source, such as shown in Figure 3.3. First consider an oscillating electric field source such as a radio frequency (RF) signal generator that provides a time-varying current $i(t)$. This current $i(t)$ flows in the capacitor circuit with the electrical wire of conductivity σ forming the guide for EM-wave propagation induced by $i(t)$. The current density in the RF transmission line is given by $J = \sigma E$, where E is the oscillating electric field of the EM wave in the wire. Recall that the capacitor contains an electrically insulating material connected to the metallic contacts of the capacitor that connects to the transmission line. Given that insulators have $\sigma = 0$, a conventional electrical current cannot flow through the capacitor and into the connecting electrical transmission line. Yet we know that a current flows in the capacitor-connected electrical circuit. To solve this kind of dilemma, Maxwell

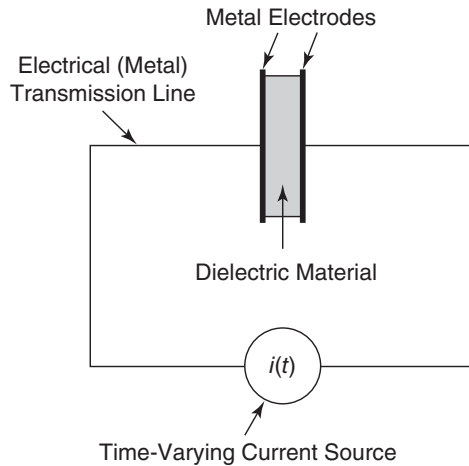


FIGURE 3.3 EM-wave propagation in a circuit containing a metallic transmission line serially connected to an electrical component called a capacitor that is formed using an electrical insulator such as the dielectric Mylar (polyester).

proposed the existence of the displacement current density, $\partial D/\partial t = \epsilon \partial E/\partial t$, which exists in a dielectric of permittivity, ϵ , subjected to an oscillating electric field, E , to explain the continuity of EM-wave propagation in the electrical circuit. Indeed, the conventional current flowing in the circuit becomes the displacement current flowing in the dielectric of the capacitor, thus allowing the continuous flow of EM-wave in the circuit. Hence, we can write the current density $J = \sigma E$ in the electrical wire becomes equal to the displacement-current density $\partial D/\partial t = \epsilon \partial E/\partial t$ in the capacitor. This genius insight of Maxwell forms the basis of EM-wave propagation in both metals and dielectric media and their interfaces, a critical aspect of both electrical and photonic engineering where EM waves propagate in media with a variety of electric material properties of conductance and dielectric constants.

Total Internal Reflection and the Evanescent Wave

The refractive index can be postulated to be complex. In this case, the evanescent wave via the complex index part of the incident media index is produced when the incident-beam incidence angle equals or exceeds the critical incidence angle to produce total internal reflection (TIR) (i.e., both reflected and transmitted waves are in the denser medium with the transmitted wave at the interface of the media called an evanescent wave). Then the transmit beam angle in Snell's law is also postulated to being called a complex angle.

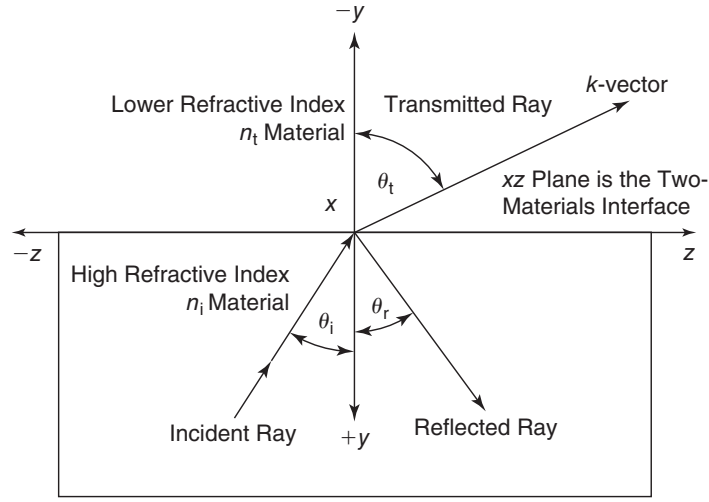


FIGURE 3.4 Light ray propagation from a high-refractive index material (e.g., glass) to a lower-refractive index material (e.g., air). The incident, reflected, and transmitted rays all are in the yz -plane. The xz -plane is the interface plane between the two media.

Figure 3.4 shows the classic application of Snell's law of refraction (i.e., $n_i \sin \theta_i = n_t \sin \theta_t$) and the law of reflection (i.e., $\theta_i = \theta_r$) to describe the direction of the reflected and transmitted rays. Specifically, using $\mathbf{k}$ -vector notation with the geometrical angles of the transmitted wave with the optical two media interfaces starting optical-field strength of E_0 , the transmitted wave can be expressed as

$$E = E_0 e^{j[\omega t - kz \sin \theta_t + ky \cos \theta_t]}$$

where $k = 2\pi/\lambda_t = 2\pi n_t/\lambda_0$, and λ_0 is the freespace wavelength. Hence, the transmitted ray partly travels in the z -direction and partly travels in the negative y -direction as also seen by observing the transmitted-ray $\mathbf{k}$ -vector direction. For the specific case of a ray traveling from a high-incidence refractive index n_i medium to a lower-refractive index n_t medium (i.e., $n_i > n_t$) via Snell's law, we get $\theta_t > \theta_i$ as shown in Figure 3.4. As θ_i increases until it reaches the critical angle, $\theta_i = \theta_c$, the transmission angle $\theta_t = 90^\circ$, thus implying that the transmitted ray now is in the xz -plane and hence, is a surface wave at the two media interface. In this case, the transmitted wave can simply be written as

$$E = E_0 e^{j[\omega t - kz]}$$

Note that at critical angle, both the transmitted and reflected waves are in the incident media, hence the term TIR. The question is what happens to the transmitted wave when the incident angle exceeds the critical angle (i.e., $\theta_i > \theta_c$). In this case, we must study the general optical-field expression for the transmitted ray and, in particular, the $\cos \theta_t$ term of its $\mathbf{k}$ -vector. Using a trigonometric identity and Snell's law, we can write

$$\cos \theta_t = \sqrt{1 - \sin^2 \theta_t} = \sqrt{1 - \frac{n_i^2}{n_t^2} \sin^2 \theta_i}$$

For TIR, when $\theta_i > \theta_c$, one also has $\frac{n_i}{n_t} \sin \theta_i > 1$ and then $\frac{n_i^2}{n_t^2} \sin^2 \theta_i > 1$. For example, for a glass-air interface with $n_i = 1.5$ and $n_t = 1$ and $\theta_i = 45^\circ$, $\frac{n_i}{n_t} \sin \theta_i = 1.0607$ and $\frac{n_i^2}{n_t^2} \sin^2 \theta_i = 1.125$. Hence, the term under the square root for the $\cos \theta_t$ expression becomes negative for the case of TIR and θ_t in the Snell's law expression can be said to be a purely complex angle. More importantly, $\cos \theta_t$ becomes purely complex and can be written as

$$\cos \theta_t = j \sqrt{\frac{n_i^2}{n_t^2} \sin^2 \theta_i - 1}$$

Define the interface skin depth, δ , as

$$\frac{1}{\delta} = k \sqrt{\frac{n_i^2}{n_t^2} \sin^2 \theta_i - 1} = \frac{2\pi n_t}{\lambda_0} \sqrt{\frac{n_i^2}{n_t^2} \sin^2 \theta_i - 1}$$

For $\theta_i \geq \theta_c$, we can use $\sin \theta_t = 1$ and express the transmitted wave as

$$\begin{aligned} E &= E_0 e^{j[\omega t - k z \sin \theta_i + k y \cos \theta_t]} \\ &= E_0 e^{j[\omega t - k z]} e^{y j k \cos \theta_t} \\ &= E_0 e^{j[\omega t - k z]} e^{y \frac{j}{\delta}} \\ &= E_0 e^{j[\omega t - k z]} e^{-\frac{y}{\delta}} \end{aligned}$$

The transmitted wave for the TIR case is now called an evanescent wave that exists as a surface-like wave on the interface along the z -direction with an optical-field exponential decay in the

$-y$ -direction in the lower-index material with the skin-depth, δ , giving the $1/e$ optical-field decay location. We can define an *evanescent wave* as a wave that has a real exponential decay in one spatial direction. Thus, the evanescent wave is also an inhomogeneous plane wave.

The skin depth can be re-expressed as

$$\delta = \frac{\lambda_t}{2\pi \sqrt{n_i^2 \sin^2 \theta_i - n_t^2}} = \frac{\lambda_0}{2\pi n_t \sqrt{n_i^2 \sin^2 \theta_i - n_t^2}} = \frac{\lambda_0}{2\pi \sqrt{n_i^2 \sin^2 \theta_i - n_t^2}}$$

Note that the concept of skin depth via TIR also leads to the concept of frustrated TIR (FTIR) and can be explained as follows. When light is undergoing TIR within a first two-material interface (e.g., glass-air) and another second two-material interface (air-glass) is brought within a skin-depth range of the first interface, then light can be made to undergo a frustrated operation in which the evanescent wave at the first material interface can couple into

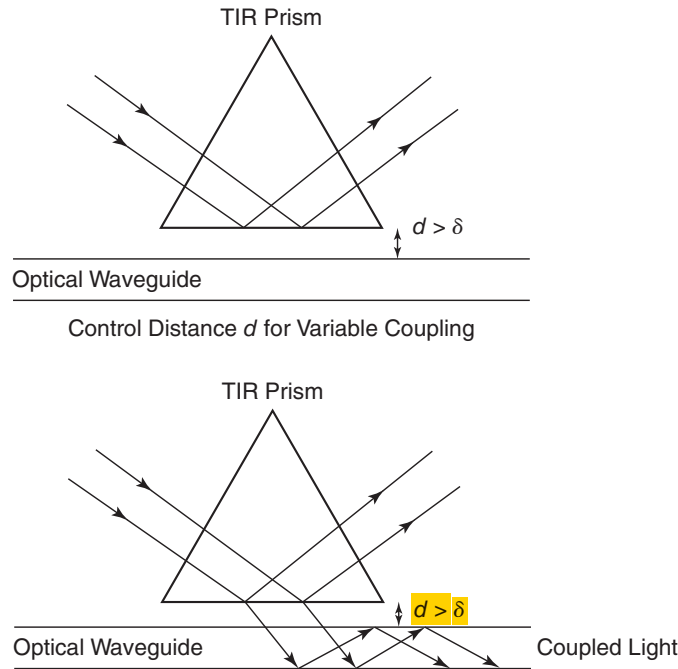


FIGURE 3.5 The figure shows how TIR and evanescent-wave coupling with a TIR prism and optical waveguide can be used for coupling light from a freespace laser beam into a miniature optical waveguide. The amount of light coupled can be controlled by varying the prism-waveguide gap distance, d , compared to the prism-air interface skin-depth.

the second two-material interface, thus forming a light-leaking mechanism via FTIR. From an applications point of view, FTIR is a very useful effect and can be used to engineer many types of optical modules such as shown next in Figures 3.5–3.8.

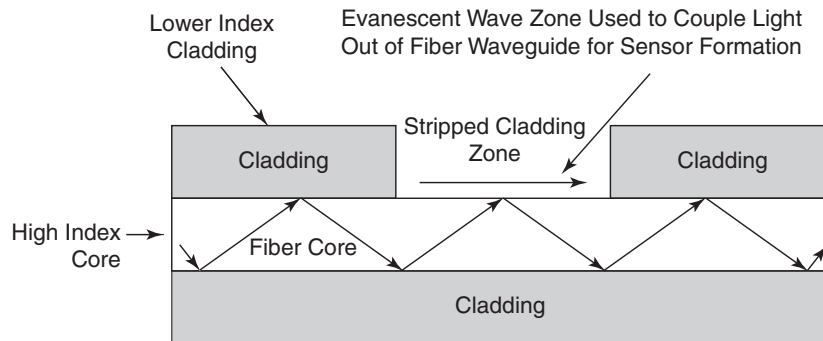


FIGURE 3.6 This figure shows how TIR and evanescent-wave coupling within the cladding-stripped optical-fiber waveguide region can be used for coupling light from the fiber core into an external sensing region. Depending on the material index and density of the sensing region such as due to flow of biological molecules and cells, a different level of evanescent-wave coupling occurs.

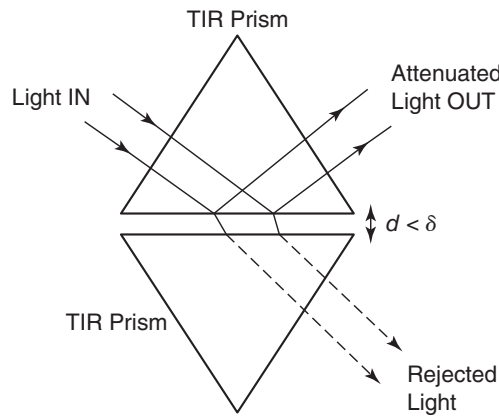
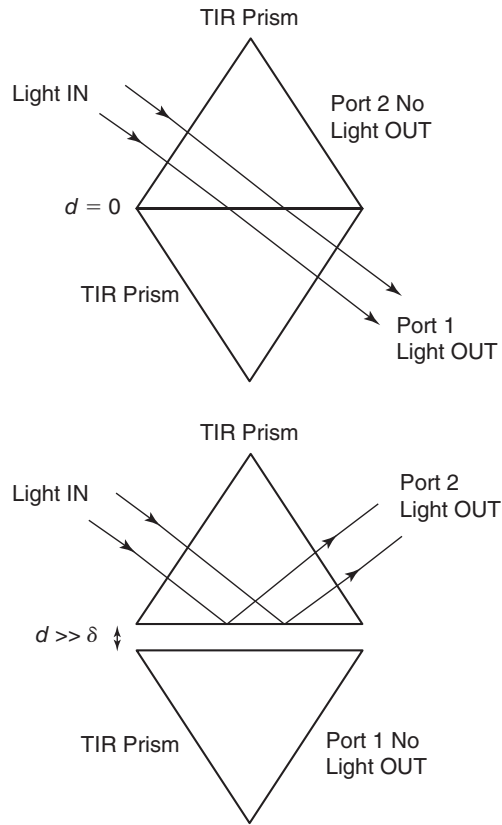


FIGURE 3.7 This figure shows how TIR and evanescent-wave coupling with two TIR prisms can be used for variable attenuation of freespace laser beam. The amount of light attenuated can be controlled by varying the prism-air-prism gap distance, d , compared to the prism-air interface skin-depth. Note that input light entered via the upper TIR prism exists as an evanescent standing wave in the gap between the TIR prisms. When the prism gap is closed, light energy in the evanescent standing wave is coupled into the lower TIR prism to exit as a traveling wave that is the rejected light.

FIGURE 3.8 This figure shows how TIR and evanescent-wave coupling with two TIR prisms can be used for a 1×2 optical switch for a freespace laser beam. The two switch states can be controlled by changing the prism-air-prism gap distance, d , compared to the prism-air interface skin-depth.



Group Velocity and Dispersion

As mentioned, for EM-wave interaction with isotropic materials, both electrically-conducting (such as metals) and nonconducting (such as insulators or dielectrics), we rely on the complex index of refraction, $\tilde{n}$, of the material that also provides for a complex propagation vector $\tilde{k} = \tilde{n}\omega/c$ for the plane-wave solution in the medium. In insulators (i.e., contains no free-charges), the EM-wave fields cause motion-of-bound charges in the material nuclei to form microscopic oscillators (via electric dipoles forming damped harmonic oscillators representing induced electric polarization) that re-radiate a part of the incident-EM wave to produce propagation in the material. In conductors, the free charges (electrons) have the stronger influence on the material constants relating to optical and electrical/RF band frequencies of EM-waves. In either case, a complex index of refraction occurs and includes a complex index term that produces the electric-field attenuation term χ for the propagating-EM wave that leads to the skin-depth notation. From the prior equations, it is clear that these EM-wave-related material constants

depend on the EM-wave frequency, in other words, the material constants are dispersive in temporal frequency domain. Specifically, the complex-refractive index of the material is EM-wave-frequency-dependent and generally exhibits resonance frequencies when the material is highly absorptive of the incident photons while being highly transparent (non-absorptive) for other frequencies. For example, glass is transparent for visible-band optical frequencies while having resonances in the infrared and UV bands.

Recall that when only the E_y component exists for the TEM wave traveling with velocity, v , in the z -direction of a linear-isotropic medium, the optical field obeys the wave equation given by

$$\frac{\partial^2 E_y}{\partial z^2} = \frac{1}{v^2} \frac{\partial^2 E_y}{\partial t^2}$$

This equation is considered a nondispersive wave equation as the wave function, E_y , does not change its form (e.g., shape) as it propagates along the z -direction, so all temporal frequencies of the wave function travel at the same velocity, v . A specific solution of the nondispersive wave equation is the sinusoidal or harmonic wave (the plane wave) at a given frequency, f . In this case, we say that the given plane wave at the frequency, f , travels with a phase velocity, v , determined by the refractive index, n , of the material at the frequency, f . For nondispersive linear media like air, the refractive index, n , is considered to be equal to one for the EM-wave spectrum, hence v is the same for all frequencies that may make up the group of traveling-wave frequencies of the optical field. In reality, most linear media have refractive indices that are different for different EM-wave frequencies or $n(f)$, hence called dispersive linear media. In this case, we must use a dispersive-wave equation with the velocity of the wave called the group velocity, v_g , in essence representing the travel velocity of the entire group of frequencies of spectrum, δf , centered around a given central frequency, f_c . Consider the general harmonic plane-wave solution for the traveling light wave given by the optical field:

$$E_y(z, t) = E_{0y} \cos(2\pi ft - kz) = E_{0y} \cos(\omega t - kz) = E_{0y} \cos \phi$$

where ϕ is the instantaneous phase of the wave with optical frequency, f . It is well-known that a general wave function can be approximated as a weight sum of optical frequencies that instantaneously add up to produce a wave packet/pulse. This pulse will have a peak amplitude when all frequencies in the wave packet add up in phase (i.e., have an instantaneous phase value $\phi = 0$). In essence, we can follow the speed of the signal-packet envelope peak as it travels in the z -direction to gauge an average speed of the group of optical angular frequencies

represented mathematically by $d\omega$. Hence, we can take the derivative of the instantaneous phase shift with respect to the propagation vector k to derive the result for the wave-group velocity. Specifically, we follow the steps:

$$\begin{aligned}\phi &= \omega t - kz \\ \frac{d\phi}{dk} &= t \frac{d\omega}{dk} - z \frac{dk}{dk} \\ 0 &= t \frac{d\omega}{dk} - z \\ \frac{z}{t} &= \frac{d\omega}{dk} \\ v_g &= \frac{d\omega}{dk}\end{aligned}$$

In general, the group velocity is not a constant and should be evaluated for a central $\mathbf{k}$ -vector value corresponding to the wave-packet central frequency (or wavelength). Recall that all the individual frequencies, f , that make up the packet will have their distinct phase velocities, v , that are not equal to the group velocity. Hence, the ability for a media to be linear and dispersive for a given range of optical frequencies can be considered an engineer's nightmare, such as causing optical-signal degradation in an optical-fiber communications channel or an engineer's delight, such as by providing frequency-coded time-delay signal processing for an RF radar.

Knowledge of optical signal-packet group-velocity calculations allows designers to compute accurate valuations for signal degradation or enhancement after traveling through the given linear dispersive media. The group velocity, v_g , can also be related to the phase velocity, v , and optical wavelength, λ , in the media by the expression (see the Problems section):

$$v_g = v - \lambda \frac{dv}{d\lambda}$$

where we make use of the relations $\lambda = 2\pi/k$, $v = \lambda f$, $\omega = 2\pi f$, and $v = \omega/k$. Note that for a nondispersive medium, $dv/d\lambda = 0$ and hence, $v_g = v$, so the wave-group velocity is equal to wave-phase velocities with $v = c/n$, where n is the optical-frequency independent refractive index. Furthermore, we can consider a group refractive index, n_g , of the linear-dispersive media to be related to the group velocity, v_g , by

$$v_g = \frac{c}{n_g}$$

where n_g can be evaluated at the central frequency, f_c , of the group of frequencies with spectrum Δf . Using the definition of group velocity, we can show the relationship between refractive index and optical frequency (see Problem 3.12 as

$$n_g = n + \omega \frac{dn}{d\omega}$$

For a nondispersive medium, the refractive index does not change with optical frequency and hence $dn/d\omega = 0$, and so all frequencies have a given fixed-refractive index, n . We choose to use the optical-frequency notation for the refractive index because optical frequencies do not change in the linear-dispersive media, whereas wavelengths in media do change based on their given optical-phase velocity.

Polarization Representations

Polarization is a vector quantity linked to the direction in which the optical field oscillates in space and time. One extreme case of *polarized light* occurs when the optical field follows a defined direction of space-time oscillation, such as the fundamental TEM_{00} mode from a laser producing a plane-linear polarized-EM wave. The other extreme is the designation of *unpolarized light*, such as natural light from the Sun where the resultant measured/observed light polarization is indiscernible and there is no single defined state of polarization (SOP) of the EM wave. In the Sun, each atom radiates polarized light for a short time, but when many atomic radiations are added up in time, the resultant optical field does not have a specific preferred electric field direction and is hence considered unpolarized light. Here the resultant optical field at a measurement point in space has random phase and direction fluctuations in time. In reality, EM waves are partially polarized where the resultant optical field is a superposition of both unpolarized light and polarized light, and the degree of polarization depends on the mixing ratio of polarized versus unpolarized light.

There are a number of ways to mathematically represent polarized light and polarization effects via optical components. Depending on the engineering problem, one method can be a more direct way to arrive at the system solution. Earlier descriptions of light in the book used optical-field representations in which the light is *linearly polarized*; in other words, the optical-field vector oscillates in space in a straight line represented by a vector of given strength and direction with the vector lying in a plane normal to the wave direction. Note that it is also possible for the oscillating optical field to trace an ellipse or circle in the plane normal to the wave direction when traveling through space. Hence, the names *elliptically* or

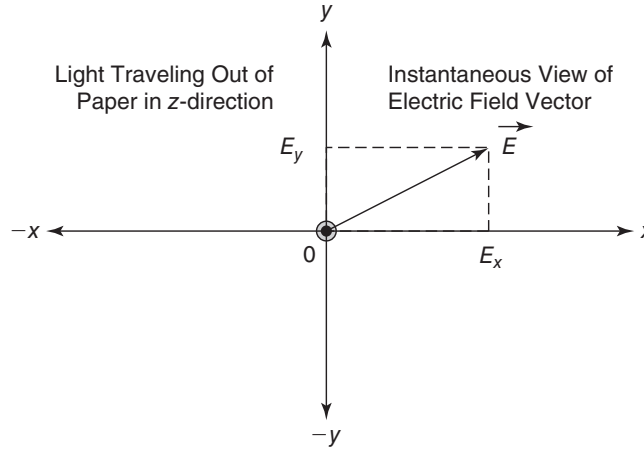


FIGURE 3.9 Instantaneous view of the oscillating optical-field vector as the polarized light wave travels in the z -direction (out of the paper).

circularly polarized light. When dealing with linear, circular, and elliptically polarized light in photonics system design, the *Jones vector* and *matrix notation* come in very handy to describe the light polarization from the input to the output of a photonic system. As we are dealing with polarized light with the optical field in the plane normal to the wave direction, the resultant optical field can be completely described by the magnitude and phase of the in-plane orthogonal field components. For a wave traveling in the z -direction in the Cartesian coordinate system as shown in Figure 3.9, the x and y direction optical field magnitude and phase components provide the SOP of the wave.

The polarized light wave in Figure 3.9 can be written as

$$\vec{E} = E_x \vec{i} + E_y \vec{j} \quad \text{where}$$

$$E_x = E_{0x} e^{j\phi_x} e^{-j[\omega t - kz]} \quad \text{and}$$

$$E_y = E_{0y} e^{j\phi_y} e^{-j[\omega t - kz]}$$

Here E_{0x} and E_{0y} are the amplitude values of the optical fields along the x and y directions, respectively. ϕ_x and ϕ_y are the phase values of the optical fields along the x and y directions, respectively.

The Jones vector representation of polarized light is defined as

$$\vec{J} = \begin{bmatrix} E_{0x} e^{j\phi_x} \\ E_{0y} e^{j\phi_y} \end{bmatrix}$$

Note that for a vector $\begin{bmatrix} A \\ B \end{bmatrix}$ to be normalized, we must satisfy:
 $1 = \sqrt{|A|^2 + |B|^2}$

The normalized Jones vector representation of polarized light is defined as

$$\vec{J} = \frac{1}{\sqrt{E_{0x}^2 + E_{0y}^2}} \begin{bmatrix} E_{0x} e^{j\phi_x} \\ E_{0y} e^{j\phi_y} \end{bmatrix}$$

Depending on the type of polarized light, the optical-field amplitude and phase quantities have particular values. Linearly polarized light requires the relative phase $\phi_y - \phi_x = m\pi$ with $m = 0, 1, 2, \dots$, so the Jones vector for linearly polarized light is

$$\vec{J} = \frac{1}{\sqrt{E_{0x}^2 + E_{0y}^2}} \begin{bmatrix} E_{0x} \\ E_{0y} \end{bmatrix}$$

Circularly polarized light requires equal field components (i.e., $E_{0x} = E_{0y} = E_0$). In addition, right circular light requires the relative-phase condition of $\phi_y - \phi_x = -\pi/2$ while left circular light requires the relative-phase condition of $\phi_y - \phi_x = \pi/2$. Hence, the normalized Jones vectors for right (clockwise rotation of field) and left (anti-clockwise rotation of field) circularly polarized light can be written as

$$\vec{J}_{\text{RCP}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -j \end{bmatrix} \quad \text{and} \quad \vec{J}_{\text{LCP}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ j \end{bmatrix}, \text{ respectively.}$$

Elliptical polarization requires that $E_{0x} \neq E_{0y}$. A special case of elliptical polarization that has the same phase-shift conditions as circular light (i.e., $\phi_y - \phi_x = -\pi/2$ for right elliptical or $\phi_y - \phi_x = \pi/2$ for left elliptical) causes the optical-field vector to trace an ellipse on wave propagation along z -direction with the ellipse axes aligned with the x and y axes. Hence, the normalized Jones vectors for right (clockwise rotation of field) and left (anti-clockwise rotation of field) elliptically polarized light can be written as

$$\vec{J}_{\text{REP}} = \frac{1}{\sqrt{E_{0x}^2 + E_{0y}^2}} \begin{bmatrix} E_{0x} \\ -jE_{0y} \end{bmatrix} \quad \text{and} \quad \vec{J}_{\text{LEP}} = \frac{1}{\sqrt{E_{0x}^2 + E_{0y}^2}} \begin{bmatrix} E_{0x} \\ jE_{0y} \end{bmatrix}, \text{ respectively.}$$

The most general case of elliptically polarized occurs when $\phi_y - \phi_x \neq m\pi$ and $|\phi_y - \phi_x| \neq \pi/2$ (the ellipse axes are no longer aligned with the x and y directions), and the Jones vector for this special case

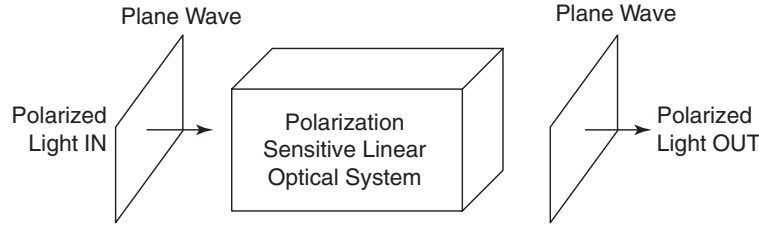


FIGURE 3.10 Plane-optical wave is input to the linear-optical system that also produces a plane-optical wave at its output, conditions required for application of Jones matrices for input/output system polarization analysis.

of elliptically polarized light with $\phi_x = 0$ with no loss of generality can be written as

$$\vec{J}_E = \frac{1}{\sqrt{E_{0x}^2 + E_{0y}^2}} \begin{bmatrix} E_{0x} \\ E_{0y} \cos \phi_y + j E_{0y} \sin \phi_y \end{bmatrix}$$

The key is to recognize the types of Jones vectors that are being provided as the input to the system and the Jones vector format of the produced system outputs. Hence, simply by looking at the vector output, we can realize what has happened to the processed input light.

Under plane-wave conditions of incident input and output light to a linear-optical system as shown in Figure 3.10, we can represent polarization components such as polarizers and wave plates via their systems matrices called Jones matrices. Hence, the output of such a linear system/component (where superposition of optical field applies) is given by a Jones vector $\vec{J}_{\text{OUT}}$ that is produced by multiplying the Jones input vector $\vec{J}_{\text{IN}}$ with the Jones matrix T_M of the optical system, such as a single optical polarization component. Mathematically, this operation is written as

$$\vec{J}_{\text{OUT}} = T_M \vec{J}_{\text{IN}}$$

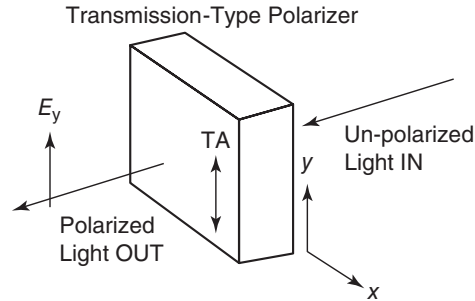
$$\begin{bmatrix} E_{2x} \\ E_{2y} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} E_{1x} \\ E_{1y} \end{bmatrix}$$

Figure 3.11 shows the operation of a transmission-type polarizer where the light passing through the polarizer contains only the vertical polarization component of the input light. The Jones matrix for this polarizer can be computed to be

$$T_M = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \text{ Linear Polarizer TA Vertical}$$

In this case, as one knows the Jones vectors for horizontal and vertical linear polarization input light and the expected output from the

FIGURE 3.11 Shown is a transmission-type polarizer component with a vertical direction or y -direction transmission axis (TA).



polarizer, two sets of simultaneous equations with the four unknown components of the Jones matrix can be generated and solved to give the components of the Jones matrix for the polarizer TA vertical. The same is true for a linear polarizer TA horizontal, and in this case, we get the Jones matrix:

$$T_M = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \text{ Linear Polarizer TA Horizontal}$$

In the same way, for a linear polarizer with its TA making an angle θ with the horizontal axis, we can get the Jones matrix:

Linear Polarizer TA at angle θ with Horizontal

$$T_M = \begin{bmatrix} \cos^2 \theta & \sin \theta \cos \theta \\ \sin \theta \cos \theta & \sin^2 \theta \end{bmatrix}$$

Figure 3.12 shows how an optical-phase retarder component operates on input polarized light, such as an input linearly polarized light. Fundamentally, this optical component has two different refractive indices along the x - and y -directions of the optical material, such as an optical crystal. The fast axis (FA) corresponds to the component axis where the refractive index is lower compared to the refractive index along the component slow axis (SA). Hence, the words fast and slow corresponding to the speed of light for the optical-field components aligned along these axes. In Figure 3.12, the FA is along the y -direction, whereas the SA of this retarder is along the x -direction. Hence, when in-phase optical field components enter the component, the optical field along the FA exits first compared to the optical field along the SA, as also shown in Figure 3.12. Thus, we can add an optical phase between the two orthogonal optical field components and hence modify the SOP of the output light versus the input light. Hence, an optical retarder is a very useful component in photonics system design. We can designate the input x -direction optical-field amplitude and phase values to be E_{0x} and ϕ_x , respectively. We can also designate the

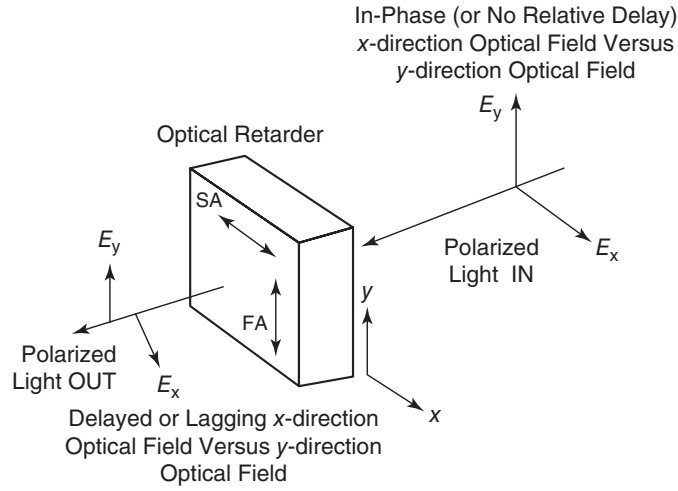


FIGURE 3.12 Shown is an optical retarder component with a vertical direction or y -direction fast axis (FA) and horizontal direction or x -direction slow axis (SA).

input y -direction optical-field amplitude and phase values to be E_{0y} and ϕ_y , respectively. After passing through the optical retarder, the optical-phase values β_x and β_y are acquired by the x -direction and y -direction optical fields E_{0x} and E_{0y} , respectively. Using Jones vector-matrix polarizer analysis for the input/output polarized light and the retarder acting as an optical system, we can write:

$$\begin{bmatrix} E_{0x} e^{j[\phi_x + \beta_x]} \\ E_{0y} e^{j[\phi_y + \beta_y]} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} E_{0x} e^{j\phi_x} \\ E_{0y} e^{j\phi_y} \end{bmatrix}$$

where it can be shown that the Jones matrix for the optical retarder can be written as

$$T_M = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} e^{j\beta_x} & 0 \\ 0 & e^{j\beta_y} \end{bmatrix}$$

For the example shown in Figure 3.12, E_x is the slow or lagging optical field compared to the E_y optical field as the SA is horizontal (x -direction). If this lag is $\pi/2$ or 90° , then we can write $\beta_x - \beta_y = \pi/2$ and the optical retarder is called a quarter-wave plate (QWP) as the optical field experiences a relative quarter-wave optical delay. The QWP is a highly useful photonic system-design component as, for example, linear polarization can be converted to circular polarization using a QWP and vice versa. Circularly polarized light is useful in

photonic system design as it contains equal parts of vertical and horizontal polarization thus reducing the impact of optical effects that are sensitive to linear polarization directions. The half-wave plate (HWP) is another useful optical design component and can be used to rotate linear polarized light to a desired linear polarization angle. The key is aligning the incoming linear polarization at an angle θ with an axis (e.g., FA) of the HWP retarder, and this leads to the output light linear polarization rotating an angle 2θ such that this output linear polarization is at an angle θ with the axis (e.g., FA). Jones vector polarization analysis can be used to prove this useful optical component operation (see Problem 3.17). For example, the linear polarization direction from an output laser beam may not match the transmission axis of polarizer physically fixed to some fixture in an optical package. In this case, a HWP can be inserted between the laser and the polarizer to rotate the laser linear polarization to match the transmission axis of the polarizer.

Some photonic system design useful Jones matrices for retarders are given next.

$$T_M = e^{j\frac{\pi}{4}} \begin{bmatrix} 1 & 0 \\ 0 & -j \end{bmatrix} \quad \text{QWP SA Horizontal and FA Vertical}$$

$$T_M = e^{-j\frac{\pi}{4}} \begin{bmatrix} 1 & 0 \\ 0 & j \end{bmatrix} \quad \text{QWP SA Vertical and FA Horizontal}$$

$$T_M = e^{j\frac{\pi}{2}} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \quad \text{HWP SA Horizontal and FA Vertical}$$

$$T_M = e^{-j\frac{\pi}{2}} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \quad \text{HWP SA Vertical and FA Horizontal}$$

Another useful component is the optical polarization rotator such as a Faraday rotator device that, for instance, takes an linear polarization input of amplitude E_0 making an angle α with the x -axis to a linear state of polarization making an angle $\alpha + \beta$ with the x -axis. Using Jones polarization analysis, this means

$$\begin{bmatrix} E_0 \cos[\alpha + \beta] \\ E_0 \sin[\alpha + \beta] \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} E_0 \cos \alpha \\ E_0 \sin \alpha \end{bmatrix}$$

where it can be shown that the Jones matrix for the optical polarization rotator with power of β angle rotation can be written as

$$T_M = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{bmatrix}$$

Problems

1 The wave function for a traveling wave in the z -direction at velocity, v , is classically written as $\psi(z, t) = g(z - vt)$. A simple test for this representation as being appropriate for a wave representation is to check that if after a time Δt when the wave has travelled a distance Δz at speed v , the shape of the wave function is the same as it was at time t .

2 Derive the general 1D nondispersive media wave equation $\frac{\partial^2 \psi}{\partial z^2} = \frac{1}{v^2} \frac{\partial^2 \psi}{\partial t^2}$ that represents the wave propagation basis for the wave function $\psi(z, t) = g(z \pm vt)$, where v is the wave velocity in the z -direction in the medium of travel.

3 Given a plane-harmonic wave traveling in the z -direction at velocity v is classically written as $\psi(z, t) = \sin[k(z - vt)]$, shown that by virtue of the definition of wavelength λ_m of wave in the medium representing the distance the wave has travelled when it repeats itself, one comes to the definition for the wave propagation constant as $k = 2\pi/\lambda_m$.

4 Consider the following mathematical expressions, where distances are in meters and time is in seconds.

(a) $E(z, t) = E_0 \sin^2[\pi(5t + z)]$

(b) $E(x, t) = E_0(3x - t)^2$

(c) $E(y, t) = E_0 \cos[2\pi(y/\alpha + t/\beta)^4]$

Which ones qualify as traveling waves? If they qualify, give the magnitude and direction of the wave velocity.

5 A plane harmonic linearly polarized lightwave has a magnetic field given by $E_y = E_0 \sin[\pi 10^6(4 \times 10^8 t - 2z)]$ while traveling in a piece of glass. Find the frequency of the optical field, its wavelength, and the index of refraction n of the glass.

6 The complex index of refraction of a material is $5.1 - j0.3$. Find the attenuation index and skin depth for the optical frequency of 4.4×10^{14} Hz.

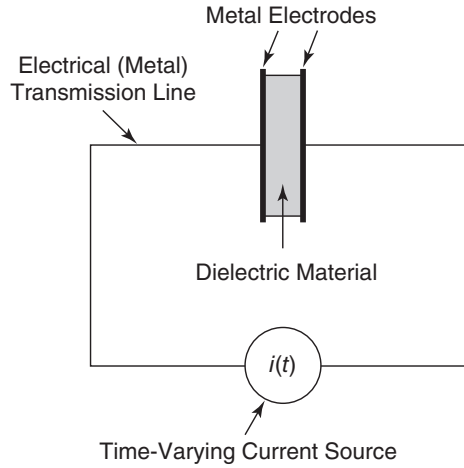
7 Show that for a conducting material with material parameters and EM-wave frequency that satisfies the condition $\sigma/\epsilon\omega\mu_r < 1$, the material complex index of refraction can be written as

$$\tilde{n}_c \approx n \left[1 - j \frac{\sigma}{\epsilon\omega\mu_r} \right]$$

where the material attenuation index is $\chi = \sigma/2\epsilon\omega\mu_r$.

8 Figure 3.13 shows a Circuit with a current source given by $i(t) = a(t) + A_0$ where A_0 is a constant. Using Maxwell's equations, specifically, the displacement-current density interpretations, explain what is the current flowing in the circuit. Can you give a functional name for the capacitor operations for the given circuit conditions?

FIGURE 3.13 Capacitor electrical circuit driven by a current source.



9 Find the skin depth for a silicon carbide-air interface where the silicon carbide (SiC) refractive index is 2.57 and the freespace-laser wavelength is 1550 nm. The angle of incidence of the laser beam in SiC is 50° .

10 Using TIR prisms, design a 2×2 freespace optical switch for directing two input laser beams. A 2×2 switch has two input-beam labeled ports called port 1 and port 2 and two output beam ports labeled as $1'$ and $2'$. The switch operates with two states, namely state of port 1 to port $1'$ and port 2 to $2'$ and the state of port 1 to port $2'$ and port 2 to $1'$.

11 Show that group velocity $v_g = d\omega/dk$ can be related to the EM-wave phase-velocity v and optical wavelength λ in the linear dispersive media by the expression:

$$v_g = v - \lambda \frac{dv}{d\lambda}$$

To arrive at the results, you may use the relations $\lambda = 2\pi/k$, $v = \lambda f$, $\omega = 2\pi f$, and $v = \omega/k$.

12 Using the definition of group velocity $v_g = d\omega/dk$ and $v_g = c/n_g$, show the relationship between refractive index and optical angular frequency as

$$n_g = n + \omega \frac{dn}{d\omega}$$

13 Deduce the Jones vectors for the following types of light polarizations.

- Vertical linear optical field (along y -direction) with amplitude of 5 V/m.
- Horizontal linear optical field (along x -direction) with amplitude of 2 V/m.
- Linear optical field with amplitude of 2 V/m and making an angle β with the $+x$ -direction.
- Linear optical field with amplitude of 4 V/m and making an angle 30° (as shown in Figure 3.14) with the $-x$ -direction.

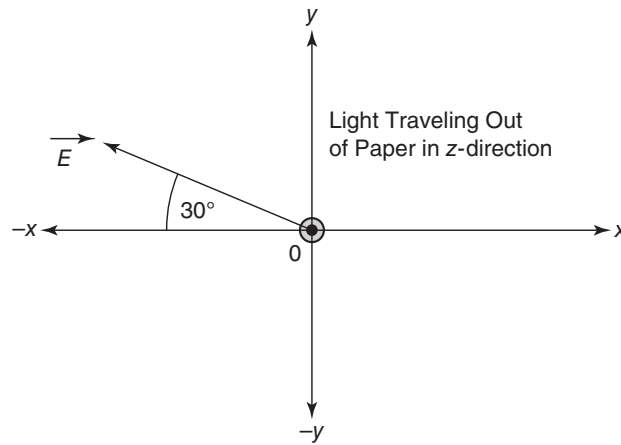


FIGURE 3.14 Direction of linear polarization in the xy -plane.

14 Given are two coherent optical beams that have optical fields of equal amplitude but different polarizations. These independent polarizations are given as

- (a) Left-circular polarization (LCP) and right-circular polarization (RCP)
- (b) Vertical linear polarization (VLP) and horizontal linear polarization (HLP).

Given the two cases of (a) and (b), for each compute the resultant coherent optical field produced by the summation of the two beams.

15 Derive the Jones matrices for the given optical components.

- (a) $T_M = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ Linear Polarizer TA Vertical
- (b) $T_M = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$ Linear Polarizer TA Horizontal
- (c) $T_M = \begin{bmatrix} \cos^2 \theta & \sin \theta \cos \theta \\ \sin \theta \cos \theta & \sin^2 \theta \end{bmatrix}$ Linear Polarizer TA at angle θ with Horizontal

HINT There are four unknown components (T_{11} , T_{12} , T_{21} , T_{22}) of the component Jones matrix. The polarization component is expected to produce a known result given a known input polarization Jones vector. For example, input light with vertical polarization passes all through a polarizer with TA vertical giving one set of two equations involving (T_{11} , T_{12} , T_{21} , T_{22}). With input light of horizontal polarization, no light passes through the polarizer to give another set of two equations involving (T_{11} , T_{12} , T_{21} , T_{22}). Solve the four equations to find (T_{11} , T_{12} , T_{21} , T_{22}).

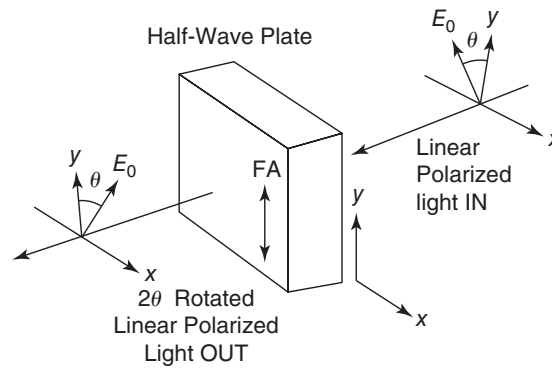


FIGURE 3.15 Linearly polarized light traveling through a HWP.

16 Derive the Jones matrices for the given optical components.

(a) $T_M = \begin{bmatrix} e^{i\beta_x} & 0 \\ 0 & e^{i\beta_y} \end{bmatrix}$ Optical Retarder

17 For the photonic system configuration shown in Figure 3.15, use Jones polarization analysis to show that the output linear polarization is rotated by an angle 2θ after passing through the HWP with FA vertical.

Additional Reading

1. F. T. Ulaby, *Fundamentals of Applied Electromagnetics*, Prentice Hall, NJ, 1997.



CHAPTER 4

Interference, Coherence, and Diffraction

Electromagnetic (EM) waves exhibit the special properties of coherence, interference, and diffraction. To realize the property of interference, the waves must exhibit some degree of the wave-coherence property. For example, two interfering sinusoidal EM waves should have relative stability in time during the interference observation interval. Interference of waves is a mathematical idealization of the physical process of interference called diffraction. Diffraction theory takes into account the physical limits of apertures through which the waves travel and interact to produce the interference pattern that shows special characteristics via finite-edge effects. For example, a mathematically deduced uniform-interference pattern shows up as a non-uniform interference pattern representing the influence of the physical constraints of the experiment approximated by diffraction theory that indeed produces better engineering results for photonic-system design.

Interference

The interference phenomena is common when using radio-wave equipment, such as mobile/cell phones and satellite television. During electrical storms, the TV picture can deteriorate with snowing or completely losing the video signal. Similarly, while walking in a busy downtown with many tall buildings and heavy cell-phone traffic, cell-phone users can pick up unwanted audio chatter or simply have their audio signal fade away and disconnect (see Figure 4.1). Even advanced electronic systems like radars in airport air-traffic control, weather reporting, military-aircraft guidance, and missile targeting can experience the effect of interference. These are examples of annoying interference or, more specifically, interference in the radio band of the EM-waves spectrum.

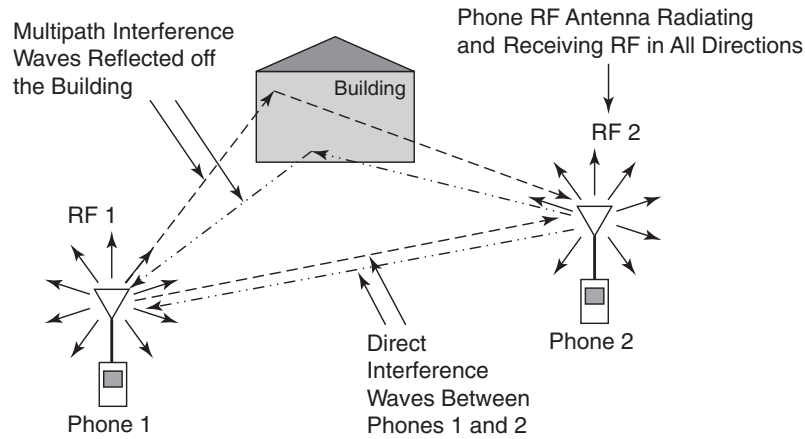


FIGURE 4.1 EM-interference phenomena commonly observed in the modern mobile-phone (cellular-phone) communications world of densely populated metropolitan cities. Each phone antenna acts as an RF detector.

Turning to light waves, in particular, laser-produced waves, we often hear about the interference capability of laser beams. In fact, it is common practice to use laser interference-based machines to non-invasively inspect the surface flatness of substrates, such as glass, used for the manufacture of LCDs and silicon deployed for manufacturing electronic integrated circuits. Given that light waves are also EM waves, it is safe to say that all EM waves can exhibit the interference phenomena. Oddly, when endorsing the use of light waves to build a photonic system, designers often boldly state that light is immune to EM interference (EMI), and light waves are not affected by the surrounding RF environment. We can say that one light beam can physically pass through another light beam in air without one beam interfering with the operations of the other light beam. In fact, millions of light beams can crisscross each other in air without affecting each other. Given light beams are just a fractional part of the EM wave spectrum of waves, this aspect of beams passing physically through each other and not so-called speaking to each other is true for all EM waves. This aspect of interwave indifference is a very fortunate occurrence for us as in any given room, where hundreds of EM waves from various manmade or other sources might bounce in the room and not interfere with each other. So radio signals from hundreds of transmitting stations in a city are not interfering in the air of the room where the possible radio-signal listener is sitting. So it is bit strange that, on the one hand, we complain about the interference problem of radio waves and then boast about the EMI immunity of light waves. This paradox of the EMI phenomena can be understood by studying the physical process involved in realizing interference.

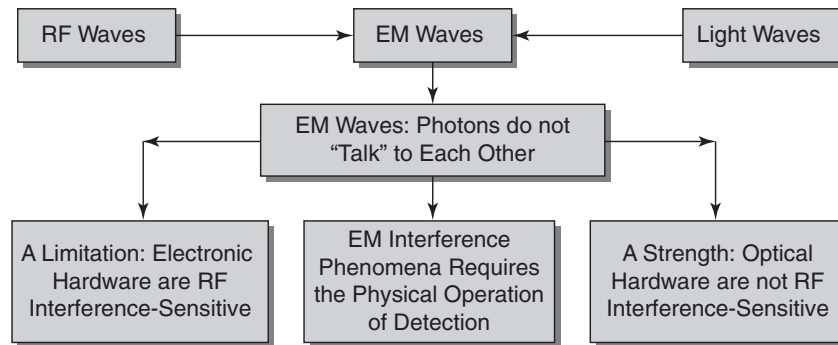


FIGURE 4.2 RF and light interference interconnection and its requirements flowchart.

Figure 4.2 shows a flowchart linking RF and optical-wave behavior within electronic- and optical-hardware context and its required interference conditions. EM waves in a linear infinite-transmission media like air, metal, glass, and silicon, will not interact or engage with another EM wave flowing in the same medium. In other words, as shown in Figure 4.3, EM Wave A will not interfere with EM Wave B, and both waves will continue to flow unperturbed in the medium. The act of interference occurs when we actually try to “observe” or “capture” these waves at a physical location where the two waves spatially overlap. Specifically, this happens when we place an EM-wave detector in this overlap region so the EM-wave detector can simultaneously respond to the presence of both Waves A and B.

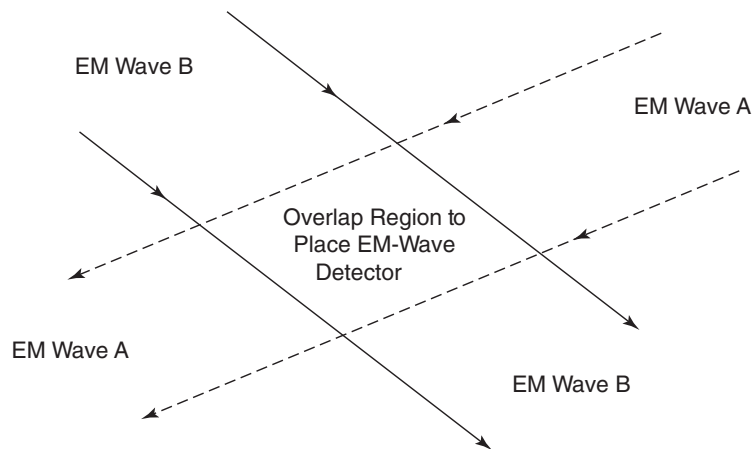


FIGURE 4.3 Two EM waves traveling through each other without interfering with each other. EM-wave interference happens when an EM-wave detector is placed in the wave-overlap region. Waves shown are simple highly directional plane waves, much like light beams made from a collection of parallel light rays.

Interference in the RF Regime of the EM Spectrum

To observe, measure, or witness RF interference, we must deploy the EM detector called the RF antenna in the physical path of the incident EM waves. Specifically, the RF antenna circuit produces a current flow or voltage oscillation at the given frequencies of the incident radio signals.

NOTE Diffraction does not require the EM-wave detector to operate; this is unlike an interference operation that requires a summing device or EM detector.

Figure 4.4 shows the operation of an RF signal detector that allows the implementation of the EM-wave interference operation. Shown are two EM waves labeled as Wave A and Wave B that strike at normal incidence to the vertically-oriented antenna wire pair. It is shown that the time-oscillating electric fields of the two waves point along the vertical direction of the wires causing maximum interaction between the electron flow in the antenna wires and the incident electric fields.

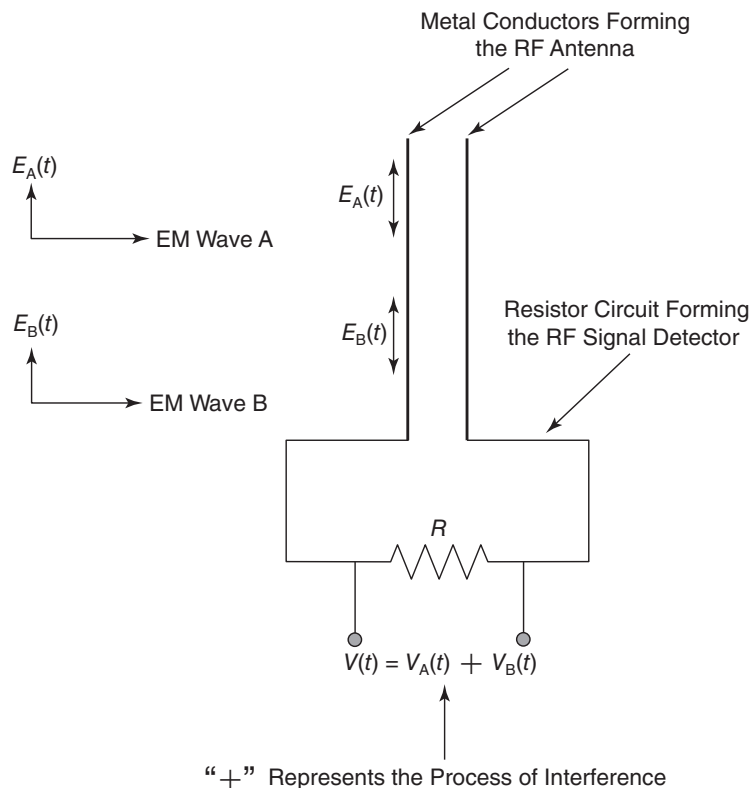


FIGURE 4.4 The RF signal detector, also known as RF antenna, operating as an RF-interference implementing device with antenna resistance, R .

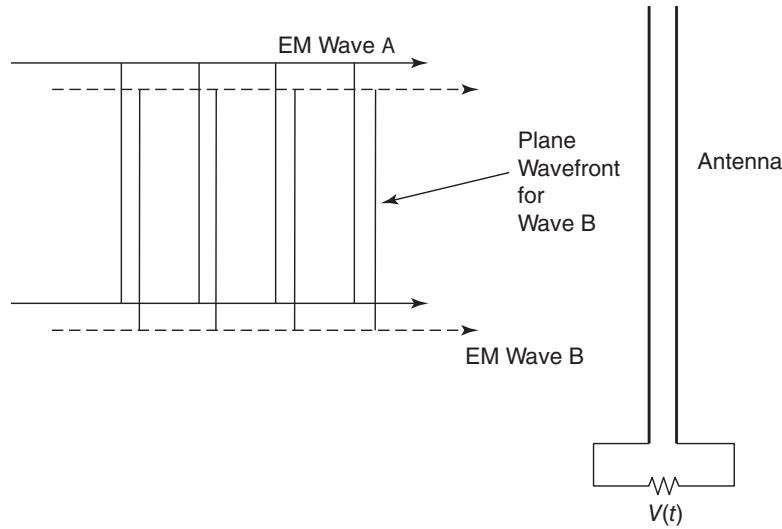


FIGURE 4.5 The need for plane wave fronts for high-quality interference via an EM-wave detector.

It is assumed that the EM wave fronts that fall along the length of the antenna are plane wave fronts (see Figure 4.5) along the same wave-propagation direction, an important physical wave attribute needed for high-quality or high-coherence interference over the RF antenna structure. If this were not so, a spatially varying relative phase between the two interfering EM waves exists over the antenna structure that on average washes out the antenna-detected interference signal. For the interference studies presented in this chapter, the ray optics model holds, in other words, plane wave fronts are assumed to arise because of ray or straight-line EM-wave propagation.

Each traveling-wave electrical field in units of volts/meter produces an equivalent voltage in the antenna wire; for example, $V_A \propto E_A$ and $V_B \propto E_B$. More specifically, $V_A = G_a E_A$ and $V_B = G_a E_B$, where G_a can be called the antenna gain figure in units of 1/m. The electric fields are oscillating up and down along the antenna-wire direction as two time-synchronized (or mutually coherent) temporal sinusoids at the RF of f_{RF} . Note that it is also possible for the EM Waves A and B to have different oscillation frequencies. The real electrical-field signals of the EM waves can be written as

$$E_A(t) = E_{A0} \cos[2\pi f_{RF}t + \phi_A] \quad \text{and}$$

$$E_B(t) = E_{B0} \cos[2\pi f_{RF}t + \phi_B]$$

where $[E_{A0}, \phi_A]$ and $[E_{B0}, \phi_B]$ are the signal-amplitude phase values for the electric fields $E_A(t)$ and $E_B(t)$, respectively. These $E_A(t)$ and $E_B(t)$ electric fields cause conduction electrons in the antenna metal wires to flow and produce electric currents $i_A(t)$ and $i_B(t)$, respectively.

Via the linear transformation of Ohm's law in the antenna circuit, the RF signal addition or interference is implemented as

$$v(t) = i(t)R = [i_A(t) + i_B(t)]R = V_A + V_B = G_a [E_A + E_B]$$

Hence, the RF voltage signal produced by the antenna detector with two impinging EM Waves A and B can be written as

$$v(t) = V_{A0} \cos[2\pi f_{RF}t + \phi_A] + V_{B0} \cos[2\pi f_{RF}t + \phi_B]$$

where the voltage amplitudes are $V_{A0} = G_a E_{A0}$ and $V_{B0} = G_a E_{B0}$. Note that the EM-wave relative phases are preserved by the linear antenna detector and this phase information can provide mechanisms for powerful signal processing of incident EM waves. Without loss of generality, we can write $\phi_A = 0$, thus defining a time-reference position. In the simple case when $V_{A0} = V_{B0} = V_0$, we can write

$$\begin{aligned} v(t) &= V_{A0} \cos[2\pi f_{RF}t] + V_{B0} \cos[2\pi f_{RF}t + \phi_B] \\ &= V_{A0} \cos[2\pi f_{RF}t] + V_{B0} \cos[2\pi f_{RF}\{t + \tau_B\}] \end{aligned}$$

It is possible that the EM waves have a relative time delay that satisfies the condition where $\phi_B = n2\pi$ with $n = 0, \pm 1, \pm 2, \dots, N$, where N is an integer. In effect, the EM Wave B relative-time delay compared to Wave A that satisfies $\tau_B = n(1/f_{RF}) = nT_{RF}$, where T_{RF} is the time period of the sinusoidal RF signal. Under these special interfering waves condition, the antenna generates the stronger RF signal as shown in Figure 4.6 to be

$$v(t) = \{V_{A0} + V_{B0}\} \cos[2\pi f_{RF}t]$$

Notice that the received signal has an amplified voltage value of $V_{A0} + V_{B0}$. Depending on the application, this amplification can be a

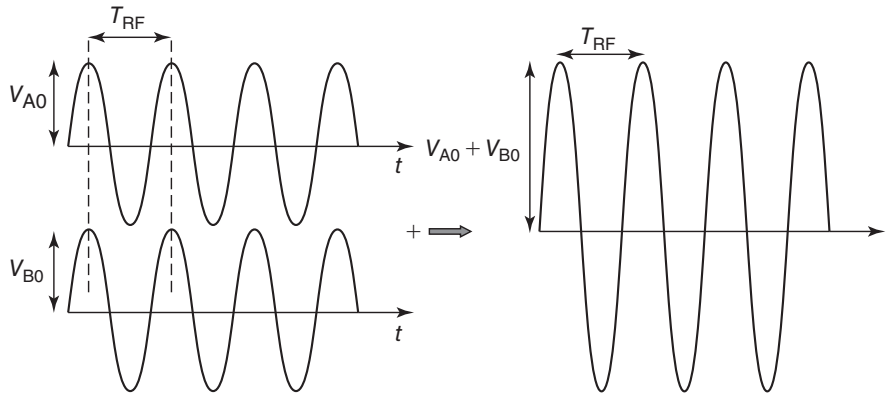


FIGURE 4.6 Constructive RF interference of two EM waves via an RF antenna that generates the electrical sum of the two detected in-phase RF voltage signals. Time axis represents the zero-volts position with above axis being positive voltage and below axis being negative voltage.

good thing or a bad thing. This condition of relative time delay or phase between the interfering EM waves is called the *positive interference* or *constructive interference* condition because the gain factor in the summed signal is detected.

For example, if V_{A0} is the desired radar signal and V_{B0} is the radar jammer signal, it would not be good for V_{B0} to be a strong signal versus V_{A0} , as it would dominate the received RF signal and, thus “jam” the radar. On the other hand, if V_{B0} is a friendly signal, such as from a desired RF source, this just amplifies a desired RF signal. In fact, constructive interference via an array of RF antennas can be used to produce a strong transmit or receive RF signal that otherwise would be very difficult using a single RF antenna. Such an RF system using constructive interference is called a phased-array antenna (PAA) and is used in various applications, such as radar, communications, and even astronomy via an array of radio telescopes as shown in Figure 4.7. In this case, each RF-antenna element is connected to its independently controlled RF phase-shift device that is used to remove any relative phase shifts between the produced RF signals from all the antenna elements to induce the RF

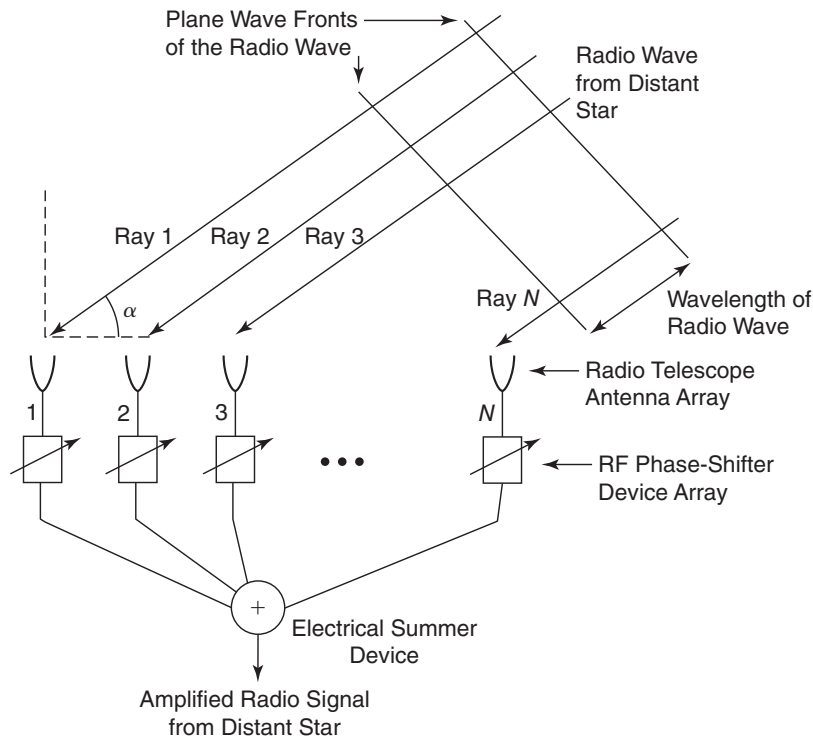


FIGURE 4.7 Constructive RF interference of many mutually coherent EM rays incident on an array of RF-antenna elements implemented via an array of RF phase-delay devices that generate in-phase RF signals that electrically sum to produce a highly amplified RF voltage signal.

constructive-interference condition of adding in-phase RF signals via the summer circuit (device shown with the plus sign) in the RF system. The RF wave can be coming from a distant star that acts as a point source of a radio wave that generates an inclined plane wave that is incident on the radio-telescope array implementing stellar interferometry.

The plane-wave illumination can be treated as mutually time-coherent RF rays/beam incident on the different RF antenna elements. As the wave is inclined at an angle, α , to the axis of the antenna-array spatial distribution, each RF antenna generates an RF signal that has a relative time- or phase-delay with respect to the adjacent antenna. To implement constructive RF interference, the RF phase-delay devices are electronically configured to eliminate the relative-phase delay or make the RF signals from all the antenna elements in-phase with each other.

Opposite to constructive interference, it is also possible that the interfering EM Waves A and B on the RF antenna have a relative time delay that satisfies the condition where $\phi_b = (n + 1/2)2\pi$ with $n = 0, \pm 1, \pm 2, \dots, N$, where N is an integer. In effect, the EM Wave B relative time delay compared to Wave A that satisfies $\tau_b = (n + 1/2) (1/f_{RF}) = (n + 1/2)T_{RF}$, where T_{RF} is the time period of the sinusoidal RF signal. Under these special interfering waves condition, the antenna generates the weaker RF signal as shown in Figure 4.8 to be

$$v(t) = \{V_{A0} - V_{B0}\} \cos [2\pi f_{RF} t]$$

Notice that the received signal has a weakened voltage value of $V_{A0} - V_{B0}$. Again, depending on the application, destructive interference can be a positive feature or a detrimental system attribute. In fact, if the

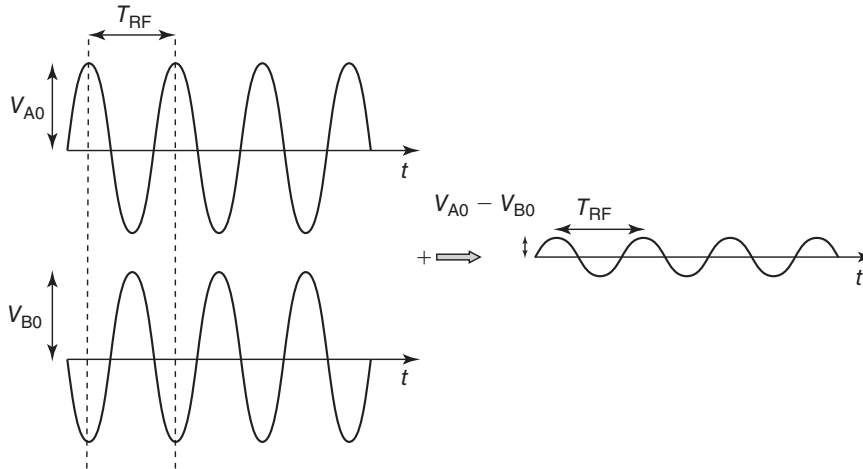


FIGURE 4.8 Destructive RF interference of two EM waves via an RF antenna that generates the electrical sum of the two detected out-of-phase RF voltage signals.

strengths of the two EM waves are the same, in other words, if $V_{A0} = V_{B0}$, then the antenna-produced RF signal disappears or $v(t) = 0$. Destructive interference can be a nuisance in RF systems, particularly when reflections of a desired RF signal combine out-of-phase to diminish or completely null the RF signal causing the effect of RF signal zeroing.

On the other hand, signal delays of a given value depending on the jammer signal frequency and direction relative to the antenna-array axis can be introduced to produce destructive interference for the identified jammer signal. Thus, the RF phase-shifters in an RF phased-array antenna can be programmed to form a directional spatial filter that places a zero or null at the jammer frequency in the antenna far-field pattern direction of the jammer location. Figure 4.9 shows destructive RF interference of the two mutually coherent jammer RF-signal EM rays incident from an α direction relative to the two-element array distribution of an RF antenna. The RF phase-delay device is used to generate an out-of-phase jammer RF signal that electrically sums to the jammer signal from the other antenna element to produce a nulled RF-voltage signal due to the jammer frequency. In order to do so, the RF phase-shifter device must also equalize any α direction-dependent time/phase delay between the EM waves incident on the two antenna elements. When the RF signals are considered as sinusoids or typical narrowband carrier signals (versus broad-spectrum signals), one can

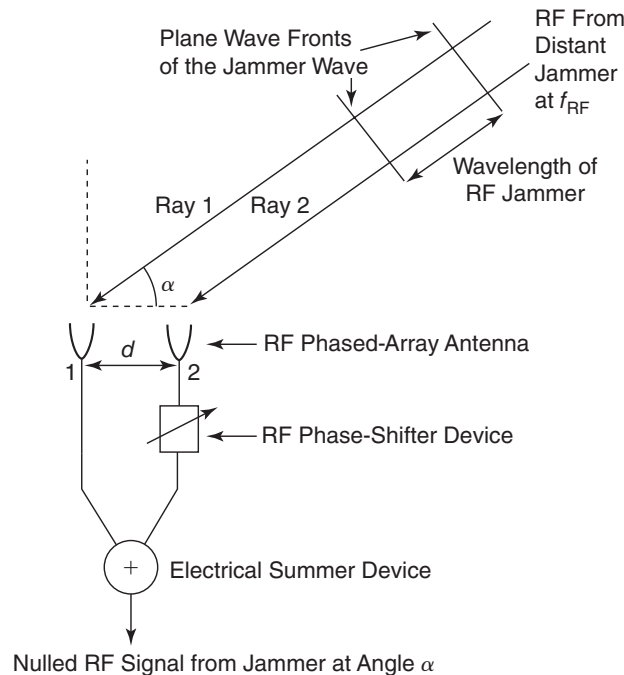


FIGURE 4.9 Example of a two-element RF phased-array antenna implementing a RF-jammer nulling filter via use of the reconfigurable RF time- or phase-delay device.

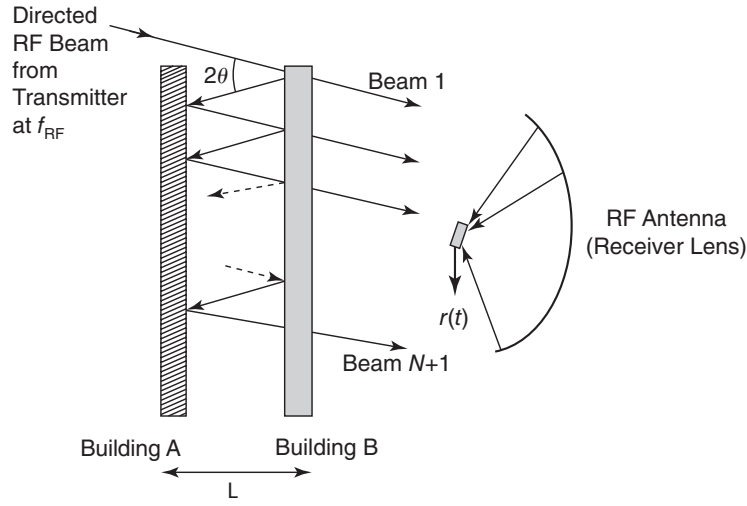


FIGURE 4.10 Example of a multipath RF-interference scenario created by multiple reflections of two building that are between the directional RF receiver and the directional RF transmitter, such as a RF beam from a satellite.

use 0 to 2π RF phase-shifters versus time-delay-based devices to provide the out-of-phase signal from antenna element 2. The Figure 4.9 system can also be called an RF transversal filter. Signal fading is also a result of varied interference when reflections of a signal come into and out-of-phase with the original received RF signal. In this case, we need an automatically changing RF phase-shifter to get signals in phase to reduce signal fading.

Figure 4.10 shows an example of a multipath RF-interference scenario where an RF beam at the RF of f_{RF} from a satellite suffers many equal-strength reflected beams that are incident of the receive antenna. The final RF received signal produced by the antenna circuit due to the multiple EM waves is a multibeam RF-interference signal given by

$$r(t) = \sum_{n=0}^N V \sin[2\pi f_{RF}t + n\alpha] = \left[\frac{\sin\left(\frac{N+1}{2}\alpha\right)}{\sin\left(\frac{\alpha}{2}\right)} \right] \sin\left[2\pi f_{RF}t + \frac{N\alpha}{2}\right]$$

or

$$r(t) = \sum_{n=0}^N V \sin[2\pi f_{RF}t + n\alpha] = \left[\frac{\sin\left(\frac{N+1}{2}\alpha\right)}{\sin\left(\frac{\alpha}{2}\right)} \right] \sin\left[2\pi f_{RF}t + \frac{N\alpha}{2}\right]$$

Here each incident EM-wave reflection produces a sine or cosine signal of strength “ V ” volts. Here α corresponds to a relative RF phase-delay in radians between two adjacent reflections where $\alpha = 2\pi f_{\text{RF}} \tau$ and τ is the relative time-delay between two closest-in-time reflections. As expected, the received signal $r(t)$ is on the RF of f_{RF} . The key point to note is that this received signal’s amplitude is modulated by a $[\sin(N\beta)]/\sin(\beta)$ expression that has a $\text{Sinc}\beta$ function-like behavior. Thus, α can be such that $r(t)$ is maximum or minimum or any value in between these max/min values. As α is determined by the physical scenario that creates the EM-wave reflections, such as distance between buildings, angle of incidence of the beam, and building-surface material properties, complex interference signals can be generated on detection by the EM-wave antenna.

Interference in the Optical Regime of the EM Spectrum

Note this observation in daily life. With eyelids open, humans can observe concentric bright and dark optical interference patterns on a wall that come from a typical spot beam from a flashlight (see Figure 4.11). The pattern, in reality, has shades of gray, but for simplicity only the fully bright and fully dark rings are shown. If someone closes their eyelids, the light is still present on the wall, but they do not see the pattern. To see the light pattern, the

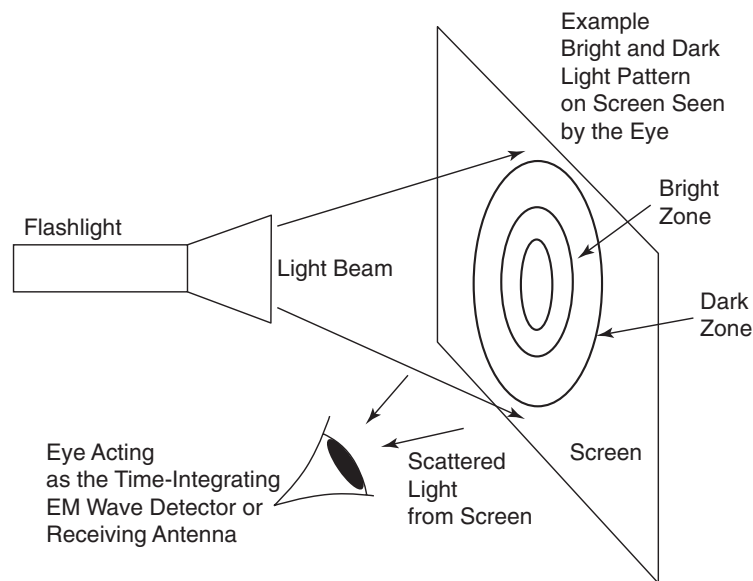


FIGURE 4.11 The human eye working as the EM wave detector in the optical spectrum that observes the bright and dark light pattern produced by the flashlight beam via the EM wave-interference phenomena captured by the eye detector.

wall-scattered light photons must enter the eye's sensor, the time-integrating retina, and the brain processor to "see" the pattern. Thus, observing, seeing, or recording the classic optical-interference phenomena requires a time-integrating light sensor like a CCD chip or the human retina, whose time response is much slower than the optical field frequency.

NOTE *Freespace cannot act as an EM field adder to implement interference. We need an EM field-sensitive material like a metallic antenna for RF bands or an optically absorbing material to produce EM field-induced charge carriers (e.g., electrons) to implement the summing EM fields' effect necessary to implement the interference process of EM waves.*

The electric field of an EM wave at a location due to interference can go to a maximum and can also go to a minimum and, in fact, can go down to zero. The total electric field is space and time at the observation/detection location is given by

$$E_T(r,t) = \sum_i E_i(r,t)$$

To get a zero total field at a spatial location means $E_T = 0$, and this can, for instance, happen when a positive electric field adds with the same-strength negative electric field (units of V/m) to give a zero sum of fields or a fully negative optical-interference result.

The natural questions to ask are:

1. Can two EM fields at one position completely destroy each other?
2. Can an EM wave at a position just disappear?

The answer to question 1 is "no" via the conservation of energy law and also as photons don't interact with each other in freespace to destroy each other. The answer to question 2 is "yes." In that case, the right question to ask is: If the light disappeared at a specific spatial location, where did it go? We can answer this question by thinking about EM wave antennas and their EM power-based radiation patterns in space. For a typical RF antenna, we can note that in the far field, the antenna has a received radiation power pattern (such as measured by another point-sampling RF antenna) that shows peaks and nulls with a given shape. In this case, the received RF antenna-power pattern is proportional to the square of the received electric field or $E_T^2(t)$ as Ohm's law applies in the RF antenna-detection circuit. Because the antenna beam power is distributed via the far-distance electric-field interference operation, a null location in the radiation pattern is compensated by a higher radiation level in some other part of the

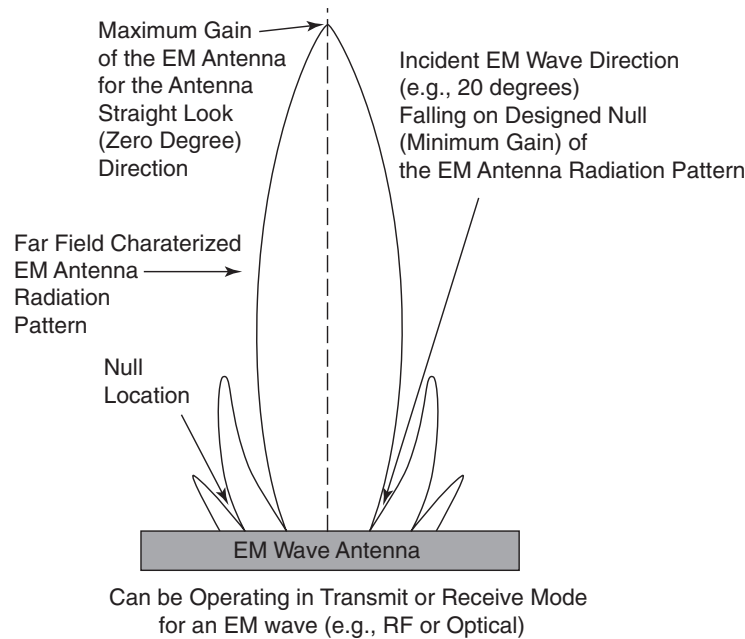


FIGURE 4.12 Shown is an EM wave transmit/receive-mode antenna having a designed far-field radiation pattern that has its maximum gain in the direction straight in front of the antenna aperture and gain nulls (or minima) at several off-axis angles of the radiation (e.g., 20° off the straight-look direction).

far-field beam. In effect, the photons have redistributed their positions in space, and this is the key aspect of EM waves' interference phenomena.

Specifically, if a null appears in the radiation pattern, no photons exist at this location as they have redistributed to another location indicating a higher-radiation power. Hence, as shown in Figure 4.12, an EM wave antenna (RF or optical) in space can be drawn with its specific far-field power radiation pattern resulting from far-field summations (via the act of EM fields interfering in the relevant EM wave detector) that can show how the beam behaves in angular space. For example, the radiated beam can have a radiation maximum at $\alpha + 30^\circ$ direction while have a radiation minimum at the $+5^\circ$ look direction. Hence, transmit antenna apertures can be synthesized by EM field-phase and amplitude control across the transmit antenna apertures to provide the far-field radiation pattern with peaks and null are the desired look angles.

Unlike RF frequencies using RF antennas for EM field and EM power detection, EM wave observation/detection at optical frequencies requires a different kind of EM field signal processing that involves the squaring of the time-integrated optical field. If the temporal frequency, ν , of the EM wave is considered in the classic

optical regime of the EM spectrum (e.g., 400 to 1700 nm wavelengths) that includes the visible and near infrared spectra commonly used in photonic system applications, ν is on the order of 10^{15} Hz or 10^6 GHz. With an oscillatory electric field $\vec{E}$ at such a high frequency, most optically absorbing materials (unlike RF antennas at much lower ν) are unable to respond at these fast optical-field variations. In effect, the optical wave-detection material is forced to respond by collecting optical energy over many time periods of the optical field cycle. In other words, the optically absorbing material implements optical field detection by time averaging the incident and then partly absorbed optical energy over the detection area, A_d . Note that for a nonmagnetic detection material, the classic 1884 Poynting vector is a cross product of two vector fields, namely, $\vec{S} = \frac{1}{\mu_0} (\vec{E} \times \vec{B})$ in Poynting's energy conservation law represents EM-wave energy flux in joules/second-meter², where $\vec{B}$ is the classic magnetic induction field, and μ_0 (equal to $4\pi \times 10^{-7}$ H/m) is the permeability of freespace media. The cross product of two vectors $\vec{E}$ and $\vec{B}$ is given by $\vec{E} \times \vec{B} = |\vec{E}| |\vec{B}| \sin \theta \vec{n}$. Here $\vec{n}$ is the unit vector normal to the plane containing the vectors $\vec{E}$ and $\vec{B}$, and θ is the angle between the two vectors.

Figure 4.13 shows a basic freespace interaction geometry between a plane optical wave and an optical detector. Without loss of generality, the optical field shown in Figure 4.13 can be written as the real sinusoidal traveling-wave signal in the z -direction given as

$$\vec{E}(z, t) = \vec{E}_0 \cos(2\pi\nu t + \phi)$$

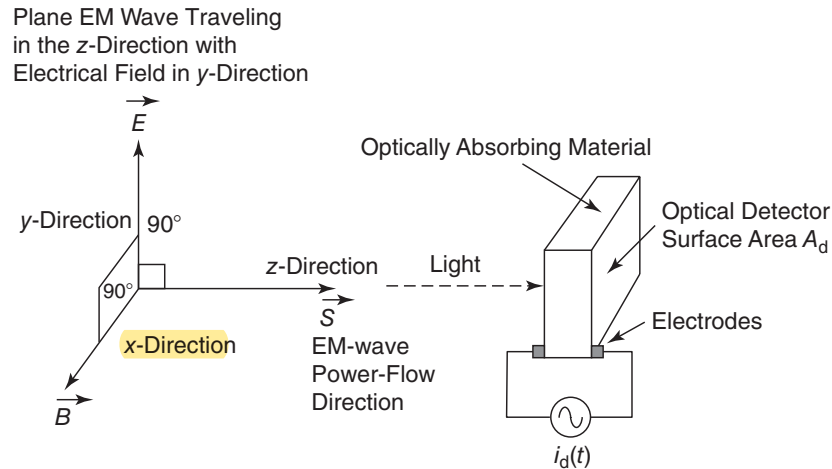


FIGURE 4.13 Free-space interaction geometry of a plane EM wave's optical field and an optical detector via the Poynting vector energy-flux absorption in the optically absorbing material.

where $\vec{E}_0 = E_0 \hat{j}$ with E_0 the scalar amplitude of vector field strength in the $\hat{j}$ unit vector (or y -direction) of space for the optical wave. $\phi = kz$ in radians is the optical phase of the wave referenced to the $z = 0$ travel position and $k = 2\pi/\lambda$ is the wave-propagation constant. In the basic case shown in Figure 4.13, to compute the Poynting vector in the z -direction given by the unit vector $\hat{k}$, the plane transverse EM wave solution exists and $\theta = 90^\circ$. The electric and magnetic induction fields are aligned along the y - and x -directions, respectively. Hence, the Poynting vector for this real optical-wave incident on the photodetector can be written as

$$\vec{S} = \frac{1}{\mu_0} (\vec{E} \times \vec{B}) = \frac{1}{c\mu_0} |\vec{E}|^2 \hat{k} = \frac{1}{c\mu_0} \vec{E} \vec{E}^* \hat{k} = \frac{1}{c\mu_0} \vec{E}^2 \hat{k}$$

where $\vec{E}$ and $\vec{B}$ are in phase in freespace (or linear isotropic media such as glass), $|\vec{E}| = c|\vec{B}|$, $\vec{E}$ is real, and hence, $\vec{E} = \vec{E}^*$, where $*$ stands for the complex conjugate operation on a given function. The magnitude $|\vec{S}|$ of the Poynting vector represents the power per unit area (W/m^2) carried by the electric field in the direction of the wave travel direction. This optical-power density is absorbed by the optical detector of surface area A_d (in m^2) for a significantly long time, T , compared to the time period of the optical frequency (i.e., $T \gg 1/\nu$). The electrical detection circuit connected to the optical detector temporally collects the photodetected electric current $i_d(t)$ that represents the information in the incident optical wave. The photodetected current can be written as

$$i_d(t) = G_d P_d = G_d A_d I = G_d A_d \langle |\vec{S}| \rangle = G_d A_d \frac{1}{T} \int_T |\vec{S}| dt$$

where the $I = \langle |\vec{S}| \rangle$ is the intensity or irradiance in W/m^2 of the photodetected optical wave, $\langle \rangle$ represents the time-averaging operation implemented with the photodetector in conjunction with the electrical charge-collection circuit, and P_d represents the power contained in the optical wave incident on the detector surface. G_d in A/W units is the spectral sensitivity of the optical detector and can be written as $G_d = (\xi e)/(\hbar \nu)$, where ξ is the unitless photodetector quantum efficiency with $0 \leq \xi \leq 1$, e the electronic charge in coulombs, $\hbar$ the Planck's constant, and $P_d = A_d I$. Hence, the photodetected current time averaged over T seconds can be given by

$$i_d(t) = \frac{1}{c\mu_0} G_d A_d \frac{1}{T} \int_{-T/2}^{T/2} \vec{E}^2(z, t) dt$$

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The speed of light in vacuum $c = 1/(\mu_0 \epsilon_0)$ where ϵ_0 (equal to 8.854×10^{-12} F/m) is the permittivity of freespace media. The real plane-wave optical field can also be expressed as

$$\vec{E}(z, t) = \frac{1}{2} [\vec{E}_0(z) \exp(-j2\pi\nu t) + \vec{E}_0^*(z) \exp(+j2\pi\nu t)]$$

where $\vec{E}_0(z) = E_0 \exp(-j\phi) \vec{j}$ where $\phi = kz$. Using this form of the optical field and squaring its representation, the photodetected current produced by the photodetector time integration is given by

$$\begin{aligned} i_d(t) &= \frac{G_d A_d}{4c\mu_0} \frac{1}{T} \int_{-T/2}^{T/2} [\vec{E}_0(z) \exp(-j2\pi\nu t) + \vec{E}_0^*(z) \exp(+j2\pi\nu t)]^2 dt \\ &= \frac{G_d A_d}{4c\mu_0} \frac{1}{T} \int_{-T/2}^{T/2} [\vec{E}_0^2(z) \exp(-j4\pi\nu t) + \vec{E}_0^{*2}(z) \exp(j4\pi\nu t) + 2\vec{E}_0(z) \vec{E}_0^*(z)] dt \\ &= \frac{G_d A_d}{4c\mu_0} \left[\vec{E}_0^2(z) \langle \exp(-j4\pi\nu t) \rangle + \vec{E}_0^{*2}(z) \langle \exp(j4\pi\nu t) \rangle \right. \\ &\quad \left. + 2\vec{E}_0(z) \vec{E}_0^*(z) \frac{1}{T} \int_{-T/2}^{T/2} dt \right] \end{aligned}$$

The time-averaging operation of the complex exponential representing a very fast 2ν optical frequency gives

$$\langle \exp(-j4\pi\nu t) \rangle = \frac{1}{T} \int_{-T/2}^{T/2} \exp(-j4\pi\nu t) dt = \frac{\tau_v}{T} \frac{\sin(2\pi\nu T)}{2\pi} \approx 0$$

As $\tau_v/T \ll 1$ where $\tau_v = 1/\nu$ is the time period of the optical cycle, which is much smaller than the photodetector integration time, T . Using the same mathematical and physical conditions, $\langle \exp(j4\pi\nu t) \rangle \approx 0$. Hence, the photodetected current is given by

$$i_d(t) = \frac{G_d A_d}{2c\mu_0} [\vec{E}_0(z) \vec{E}_0^*(z)] = \frac{G_d A_d}{2c\mu_0} |\vec{E}_0(z)|^2$$

where we use the identity $|\vec{E}_0(z)|^2 = \vec{E}_0(z) \vec{E}_0^*(z)$. For a general plane wave not necessarily in the z -direction, we can write the amplitude of the optical field in the form $\vec{E}_0(\vec{k} \cdot \vec{r})$, where $\vec{k}$ is the propagation vector and $\vec{r}$ is the optical field-position vector in Cartesian coordinate space, where the dot product of these two vectors sweeps a plane surface representing the plane wave front of the wave. Recall that for a plane incident optical wave traveling in the z -direction, $\vec{E}_0(z) = E_0 \exp(-j\phi) \vec{j}$, hence the photodetected current can be simply written as

$$i_d(t) = \frac{G_d A_d}{2c\mu_0} E_0^2 = \frac{G_d A_d}{c\mu_0} E_{\text{rms}}^2$$

where the root-mean-square (RMS) value of the optical field amplitude is $E_{\text{rms}} = E_0/\sqrt{2}$. Thus, an optical plane wave such as from a continuous wave operation laser-beam incident on a photodetector produces a DC or constant value current that is proportional to the square of the optical field strength E_0 of the wave. Hence, the photodetector is unable to follow the fast temporal oscillations of the inherent optical field and in turn gives a time-averaging produced square of the RMS value of the optical field strength. Hence, the optical detection operation implements a *nonlinear* or specifically a squaring operation on the incident optical field. The optical detector performs an *electric-field mixing* or multiplier operation.

Recall in the case of an EM RF wave of electric field amplitude E_{A0} falling on an RF antenna, the detected current produced is

$$i_A(t) = \frac{V_A(t)}{R} = \frac{G_a}{R} E_A(t) = \frac{G_a}{R} E_{A0} \cos[2\pi f_{\text{RF}} t + \phi_A]$$

Thus, unlike the RF antenna detector, the optical detector does not linearly track the incident time-varying electric field. In fact, it is the photodetected current that is linearly proportional to the optical power (or optical irradiance) and written as

$$i_d(t) = G_d P_d \propto P_d \quad \text{where} \quad P_d = \frac{A_d}{2c\mu_0} E_0^2$$

Thus, one can implement linear mapping from the optical power domain to the photodetected current (or voltage) domain.

An isotropic media is one where the material properties are the same in every direction, like in vacuum, air, and glass. A linear media is one where the affect between the applied electric field $\vec{E}$ and the induced electric polarization field $\vec{P}$ (or electric dipole moments per unit volume) in the medium have a linear relationship, and the applied magnetic field $\vec{H}$ and the induced magnetic polarization field $\vec{M}$ (or magnetic dipole moments per unit volume) in the medium have a linear relationship.

Note that the irradiance (also called intensity) of a plane optical beam with electric field strength, E_0 , traveling at speed, v , in a linear isotropic medium of refractive index, n , is given by (see Problem 6)

$$I = \frac{n}{2c\mu_0} E_0^2$$

where the refractive index of the medium is given by

$$n = \sqrt{\epsilon_r \mu_r} = \frac{c}{v}$$

where the medium relative permeability is $\mu_r = \mu/\mu_0$ and the medium relative permittivity is $\epsilon_r = \epsilon/\epsilon_0$. The media permeability and permittivity are μ and ϵ , respectively. It can also be shown (see Problem 7) that the speed of light (EM wave) in the medium of index, n , can be written as

$$v = \frac{1}{\sqrt{\mu\epsilon}}$$

ϵ and μ represent the electric and magnetic polarization properties of a medium caused by the EM-wave incident electric E and magnetic H fields, respectively. As mentioned, in a linear isotropic media, the relationship with the induced polarization field and the incident EM wave electric and magnetic fields is linear, in-phase, and direct, and encompassed in the media relations:

$$\vec{D} = \epsilon \vec{E} = \epsilon_0 \vec{E} + \vec{P} \quad \text{and} \quad \vec{B} = \mu \vec{H} = \mu_0 \vec{H} + \vec{M}$$

where $\vec{D}$ is the displacement field that James Maxwell defined and used when coming up with his equations to describe electromagnetism. Most optical materials are nonmagnetic and hence $\mu = \mu_0$ and $\mu_r = 1$ and there are no induced magnetic dipole moments so $\vec{M} = 0$. Electric polarization in the linear isotropic media can also be expressed as $\vec{P} = \epsilon_0 \chi \vec{E}$, where χ is the electric susceptibility of the medium. Note that $1 + \chi = \epsilon_r$ as we can also write

$$\vec{D} = \epsilon_0 \vec{E} + \vec{P} = \epsilon_0 \vec{E} + \epsilon_0 \chi \vec{E} = \epsilon_0 (1 + \chi) \vec{E} = \epsilon_0 \epsilon_r \vec{E} = \epsilon \vec{E}$$

The case of the optical plane wave discussed earlier uses a beam of light with a fixed optical-field strength implying a light beam of fixed optical power, hence a DC or fixed-level current produced by the photodetector. To usher in the age of light-based communications and information processing, the light power can be temporally and/or spatially varied, thus forming the basis of information transfer. A basic operating of information mapping occurs when a laser power is temporally varied in a linear fashion to give a photodetected current that also varies in a linear fashion, thus tracking the temporal optical-power variation and thus forming the basis of linear signal processing via optical means. To achieve this result, the photodetector integration time, T , should be short enough (satisfy Nyquist rate) to sample the temporal optical power modulation but long enough to time integrate over many optical carrier cycles to meet the $\tau_v/T \ll 1$ condition.

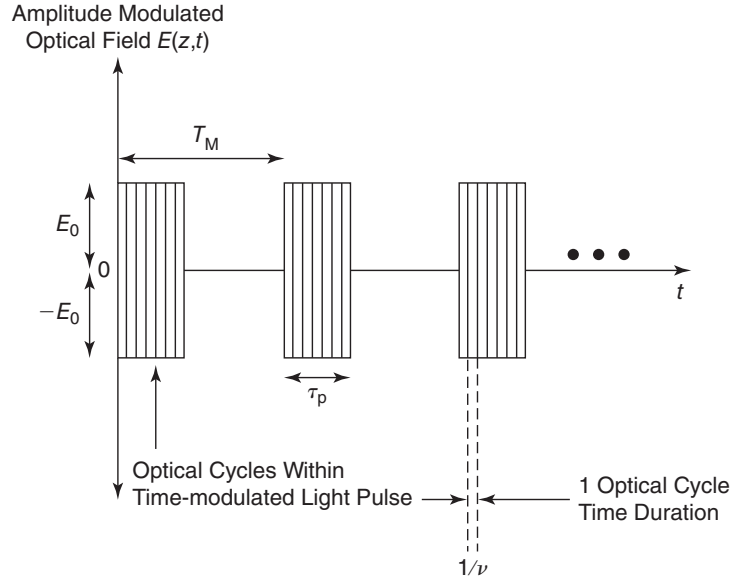


FIGURE 4.14 On-off temporally modulated laser optical field $E_0(t)$ such as using a fast optical shutter that blocks the laser beam for a $T_M - \tau_p$ seconds period and allows the optical beam through for a τ_p duration period with a shutter operation repetition rate of $1/T_M$ Hz.

Consider the simple case off on-off digital light modulation shown in Figure 4.14 with a laser on pulse width of τ_p seconds and a temporal modulation rate of $1/T_M$ Hz. In this case, the photo-detector integration time $T < \tau_p$ to enable adequate capture of the optical power modulation envelope. In the case of an analog signal modulation of the laser power, $T \ll \tau_p$ to satisfy adequate sampling speed for proper analog-signal recovery. In short, an engineer needs to choose a fast enough photodetector to capture the optical carrier-modulation signal, but a slow enough detector to properly implement the Poynting vector magnitude time averaging operation to preserve the linear electrical to optical power mapping in the photodetector.

To consider temporal modulation of an optical field's amplitude and instantaneous phase parameters, we can rewrite the plane wave optical field as

$$\vec{E}(z,t) = \vec{E}_0(t) \cos[2\pi\nu t + \phi(t)]$$

In this case, the photodetected current is given by

$$i_d(t) = \frac{G_d A_d}{2c\mu_0} E_0^2(t) = G_d P_d(t)$$

where $\vec{E}_0(t) = E_0(t) \exp[-j\phi(t)]\vec{j}$. Thus, when the laser power $P_d(t)$ is temporally modulated, the detected current $i_d(t)$ is also temporally

modulated at the same rate. Note that direct irradiance (optical power) detection via the photodetector does not recover any phase modulation the optical field may have undergone, only the field amplitude modulation $E_0(t)$ via its square field representation is recovered. As will be seen later, to recover the optical phase modulation $\phi(t)$, an additional reference optical wave will have to fall on the photodetector.

In many cases, lasers operate in a non-CW mode, such as a repetitive short-pulse mode such as used for eye surgery or parts machining. For such a temporally pulsed optical field, such as shown in Figure 4.14, it is useful to consider the optical properties of the light source, such as peak power per pulse, average power, and energy per pulse. Using Figure 4.14 notation, we can write the following expressions:

$$\text{Duty Cycle of Light Source} = \tau_p / T_M$$

$$\text{Energy per Light Source Pulse} = \text{Average Power of Source} \times T_M$$

$$\text{Peak Power per Pulse} = [\text{Energy per Pulse}] / \tau_p$$

It is common to have laser sources with very high peak powers (e.g., 100 W) using low (e.g., 1 W) average powers as one can adjust source duty cycles to optimize application impact.

Interference of Two Optical Beams

Without loss of generality, the two co-propagating (or collinear) optical beams at the same optical frequency, ν , and provided from the same laser source and shown in Figure 4.15 can be written as the real sinusoidal traveling waves in the z -direction with optical fields given as

$$\vec{E}_1(z, t) = \vec{E}_{01} \cos(2\pi\nu t) \quad \text{and} \quad \vec{E}_2(z, t) = \vec{E}_{02} \cos(2\pi\nu t + \phi_{12})$$

$\vec{E}_{01} = E_{01} \vec{j}$, with E_{01} the scalar amplitude of vector field strength in the $\vec{j}$ unit vector (or y -direction) of space for the optical wave 1, and $\vec{E}_{02} = E_{02} \vec{j}$, with E_{02} the scalar amplitude of vector field strength in the $\vec{j}$ unit vector (or y -direction) of space for the optical wave 2. ϕ_{12} (in radians) is the relative optical phase between the two interfering waves and indicates that the two beams are phase-locked or temporally phase stable (or coherent) with respect to each other. Using the analysis conducted earlier for the optical irradiance provided by the optical detector, the irradiance provided by optical detection of the two optical beams can be written as

$$\begin{aligned}
 I &= \frac{1}{c\mu_0} \langle \vec{E}^2 \rangle = \frac{1}{c\mu_0} \langle [\vec{E}_1 + \vec{E}_2]^2 \rangle = \frac{1}{c\mu_0} \langle \vec{E}_1^2 + \vec{E}_2^2 + 2\vec{E}_1 \cdot \vec{E}_2 \rangle \\
 &= \frac{1}{c\mu_0} \langle \vec{E}_1^2 \rangle + \frac{1}{c\mu_0} \langle \vec{E}_2^2 \rangle + \frac{1}{c\mu_0} \langle 2\vec{E}_1 \cdot \vec{E}_2 \rangle \\
 &= I_1 + I_2 + I_{12}
 \end{aligned}$$

where $I_1 = \frac{E_{01}^2}{2}$ and $I_2 = \frac{E_{02}^2}{2}$ & $I_{12} = \frac{1}{c\mu_0} \langle 2\vec{E}_1 \cdot \vec{E}_2 \rangle$

is the interference term.

Hence, we must compute the key relation relating the two real fields in the optical interference term, namely:

$$\begin{aligned}
 \langle 2\vec{E}_1 \cdot \vec{E}_2 \rangle &= \frac{1}{T} \int_T \{ E_{01} E_{02} 2 \cos[2\pi\nu t] \cos[2\pi\nu t + \phi_{12}] \} dt \\
 &= \frac{1}{T} E_{01} E_{02} \left\{ \int_T \cos[4\pi\nu t + \phi_{12}] dt + \int_T \cos \phi_{12} dt \right\} \\
 &= E_{01} E_{02} \cos \phi_{12}
 \end{aligned}$$

Here, one has used the trigonometric identity: $2 \cos(A) \cos(B) = \cos(A + B) + \cos(A - B)$ with $A = 2\pi\nu t + \phi_{12}$ and $B = 2\pi\nu t$. Here the photodetector implemented long-time averaging over T seconds of the very fast (at 2ν) optical frequency sinusoid corresponding to the first integral in the interferometric term analyzed earlier, which leads to a zero value leaving only the cosine of the phase difference between the two interfering optical fields to be left in the fields' product term. Hence, the irradiance provided by optical detection of the two optical beams can be further written as

$$\begin{aligned}
 I &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos \phi_{12}] \\
 &= I_1 + I_2 + I_{12} \\
 &= I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \phi_{12} \\
 &\propto E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos \phi_{12}
 \end{aligned}$$

The presence of the cosine in the detected irradiance implies that a changing relative optical phase between the interfering fields will produce an oscillatory sinusoidal behavior of the detected optical irradiance as the cosine value varies between $+1$ and -1 value (see Figure 4.15). Note that the photodetector-generated irradiance cannot be of negative value and this is consistent with the fact that an optical beam does not carry negative power. In contrast, the RF signal generated

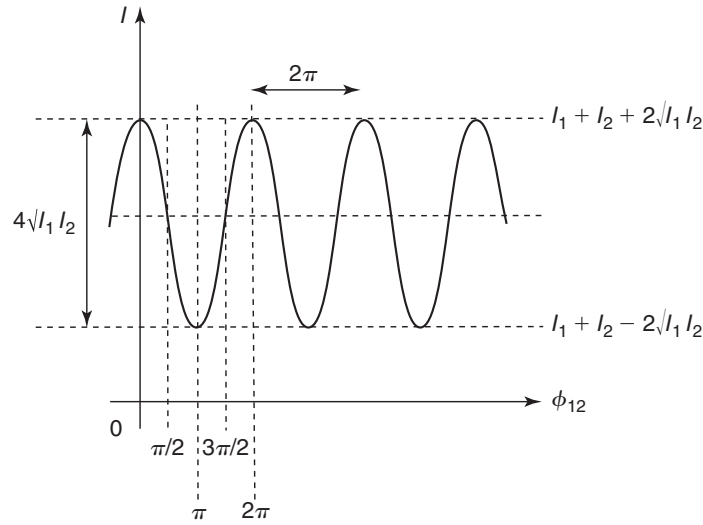


FIGURE 4.15 Two beam-generated photodetected irradiance as the relative phase between the two beams changes. Both beams are at a fixed and mutually coherent optical frequency, such as from a single-color laser.

from an RF antenna can have negative values, namely, oscillations with both positive and negative voltages about a ground or zero volts level.

The current generated by the point photodetector is coded with the phase-difference ϕ_{12} between the two optical fields, and we can write the total current to be

$$i_d(t) = G_d A_d \left[I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \phi_{12} \right]$$

Thus, by monitoring the photodetector current amplitude variation, we can determine ϕ_{12} . Hence, if one optical beam undergoes a physical perturbation that induces an optical phase-shift, interference with a second unperturbed reference beam can capture the relative phase between the two beams, thus forming the foundations of optical-sensing technology using optical-interference phenomenon.

A good measure of the optical-interference quality is called modulation depth, fringe contrast, or fringe visibility given by

$$M_F = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} = \frac{\text{Half of AC Level of } I}{\text{DC Level of } I}$$

Figure 4.15 shows the two beam-based irradiance oscillation with varying relative-beam phase shift, indicating the detected irradiance signal has a given AC level and a DC level, much like the notation used in electrical engineering for signals where AC means alternating-current and DC refers to direct-current levels. Given the definition for

irradiance-modulation depth, we note that modulation depth can vary from one to zero with $M_F = 1$ indicating the best interference possible. Specifically, there are specific optical-field amplitude and irradiance conditions that must be satisfied for the interfering beams to produce the best interference fringe visibility (see Problem 10). Thus, when designing an optical sensor under certain environmental conditions, the engineer can select interfering beam properties to get the best interference result

An important question to ask is what happens to the detected interference irradiance when the optical-phase difference ϕ_{12} between the two interfering beams is a random fluctuation with time at the spatial point of photodetection. In other words, $\phi_{12} = \phi_{12}(t)$ is a random variable in time or a random process, and the photodetected irradiance interference term will be given as

$$\begin{aligned} \langle 2\vec{E}_1 \vec{E}_2 \rangle &= \frac{1}{T} \int_T \{ E_{01} E_{02} 2 \cos[2\pi\nu t] \cos[2\pi\nu t + \phi_{12}(t)] \} dt \\ &= \frac{1}{T} E_{01} E_{02} \left\{ \int_T \cos[4\pi\nu t + \phi_{12}(t)] dt + \int_T \cos \phi_{12}(t) dt \right\} \\ &= \frac{1}{T} E_{01} E_{02} \int_T \cos \phi_{12}(t) dt \\ &= 0 \end{aligned}$$

The cosine of the randomly fluctuating phase oscillates randomly between +1 and -1 with a long T time-averaged value of zero; hence, the interference term in the photodetected irradiance disappears and the two beam-interfering total irradiance can be written as

$$\begin{aligned} I &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2] \\ &= I_1 + I_2 \end{aligned}$$

The resulting total irradiance is simply the sum of the irradiances of the two optical beams. This case can occur when using two separate lasers of the same frequency to form the interfering beams as the two lasers produce beams with random relative-phase values. Hence, the total power detected by the detector is simply the sum of the powers of the two separate laser beams as no interference occurs between these two beams. Note that these two lasers are not time/phase-locked to each other as if they were phase-locked; their relative phase would be stable and one, indeed, would produce optical interference. Optically interfering beams of the same optical frequency is commonly called *homodyne interferometry*.

Visualizing Coherence of a Wave

Do recall that to produce a stable photodetected current in time, the relative phase between the two interfering optical fields must be also fixed and stable, like two synchronized clocks. One way to insure this condition within certain engineering limits is to produce the two interfering light beams from the same optical source, thus maintaining a high degree of a criterion called *temporal coherence* and using an optical detection area that is small enough to preserve an interfering wave front's relative phase-stable localized delta-function spatial-sampling operation, thus maintaining a criterion called *spatial coherence*. One way to visualize light-wave coherence properties is to think of marching soldiers viewed through a window (see Figure 4.16).

A side view of the soldiers shows the soldiers in perfect time synchronization at both edges of the window, indicating the traveling wave of soldiers have excellent temporal coherence within the viewed spatial window. This train of soldiers can be made up of a row that is five soldiers deep. A side view of the soldiers marching in perfect synchronization does not show the number of soldiers in each row, also called the columns of the marching contingent. A top or angled

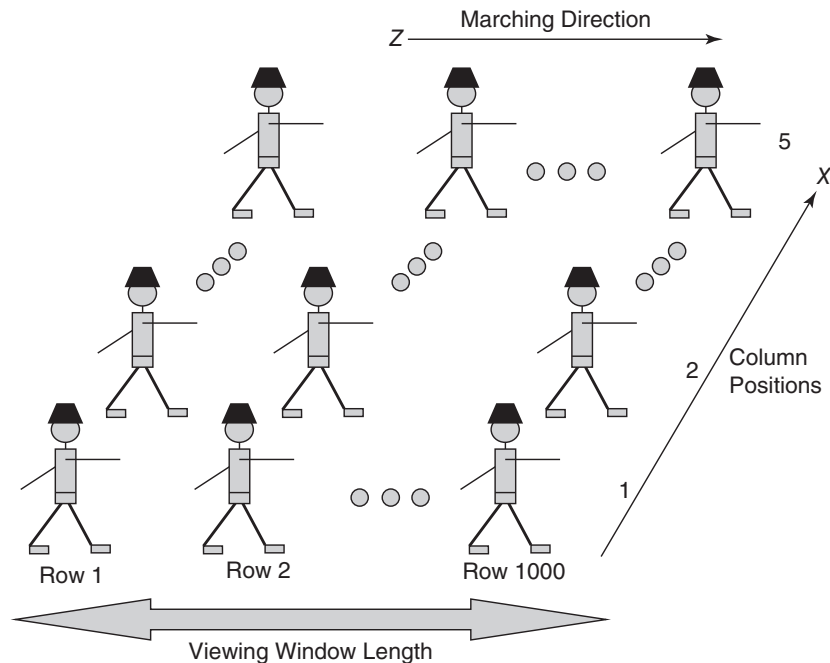


FIGURE 4.16 Three-dimensional view of a traveling wave made of marching soldiers. This shows the wave to have perfect temporal (along z-direction) coherence and spatial (along x-direction) coherence.

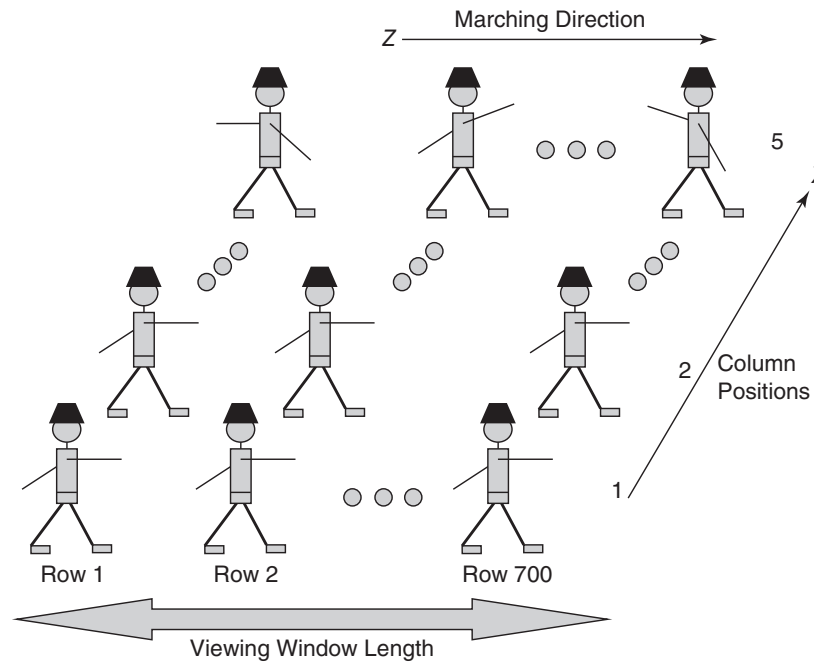


FIGURE 4.17 Three-dimensional view of a traveling wave made of marching soldiers. This shows the wave to have perfect temporal (along z -direction) coherence and less than perfect spatial (along x -direction) coherence. Column 5 of soldiers is the undesired wave part that decreases the coherence of the shown wave.

view through the window shows the soldiers in each row, and this gives an idea of the spatial coherence or spatial wave front quality of the soldier marching train. If the spatial coherence of the soldier's wave is excellent, all soldiers in each row have same hand and leg positions (see Figure 4.16). When the spatial-coherence quality of the wave drops, we could say that the column number 1-, 2-, 3-, and 4-position soldiers in the observed row have perfect hand and leg synchronization whereas soldiers in column-position 5 are out-of-sync with the rest of the row (see Figure 4.17). For the figures shown, soldier position in column 1 would be closest to the viewing window. Ideally, if we wanted to implement perfect interference using this soldier wave, we would somehow block the soldiers in column 5 to be not part of the wave that is sent forward for the eventual interference operation in the system. This process of wave spatial blocking is often called *spatial filtering*.

The window at any instant, for example, may show 1000 rows of soldiers. It is possible that when viewing the soldiers from the left side of the window, we notice that only 700 rows of the soldiers are in perfect marching sync, and after row 700, the rows appear out of sync as soldiers march past the window view. In this case, to

implement perfect interference, we should use a viewing window that is 700 rows long as then, all rows viewed via this shorter time window will always be in sync and hence, have the high temporal coherence required for interference. In other words, soldiers from the first row can strongly interfere with soldier's up to the 700th row and no farther. Another way to look at temporal coherence is via a time-measured window as the soldiers' marching is a traveling wave with a given speed. Once the spatial viewing window is selected, the window size in time duration can be measured and called a wave *coherence time* indicating for what maximum instantaneous time window that the soldiers maintain their exceptional synchronization. Recall that interference and coherence of waves is intimately connected and observing interference of waves requires some degree of wave coherence. **Additional** formalization for coherence will be covered later in the chapter.

Plane-Wave Interference via the Plane-Wave Function

We have so far considered detection of optical interference by a delta function-like point sampler or the point photodetector that samples in space and time at a given (x, y, z) point in space. In general, an optical wave is 3D wave, and interference of light beams is often captured over a surface zone like the photosensitive area of a large multipoint detector device like a -2D pixelated charge coupled device (CCD) chip. Thus, it is important to study the interference of waves over planar surfaces. In this respect, we should first consider the basic interference of two plane waves, and to do so we must understand the notations used to represent a plane wave front and its associated phase value.

The stationary plane-wave function in space is commonly written as $f(\vec{k} \cdot \vec{r})$, where f is a cosine function, hence the term $\cos(\vec{k} \cdot \vec{r})$. As seen in Figure 4.18, $\vec{k}$ is the propagation vector, and $\vec{r}$ is the optical field position vector in Cartesian coordinate space. The dot product of these two vectors sweeps a plane surface representing the plane wave front of the wave when $\vec{r}$ is in a plane that is normal to $\vec{k}$. In this case, the angle between $\vec{r}$ and $\vec{k}$ is 90° and $\vec{k} \cdot \vec{r} = |\vec{k}| |\vec{r}| \cos 90^\circ = 0$, indicating that all points with position vector in this plane provide a zero dot product and $\cos(\vec{k} \cdot \vec{r}) = 1$ or a fixed value corresponding to a zero degree reference phase for the wave. In general, $\vec{k} \cdot \vec{r}$ represents a given phase value of a plane wave with respect to a reference-phase origin for the wave (the zero point of the Cartesian coordinate system); we can write

$$\vec{k} \cdot \vec{r} = |\vec{k}| |\vec{r}| \cos \theta = kr \cos \theta = \frac{2\pi}{\lambda_m} r \cos \theta = 2\pi \frac{r \cos \theta}{\lambda_m}$$

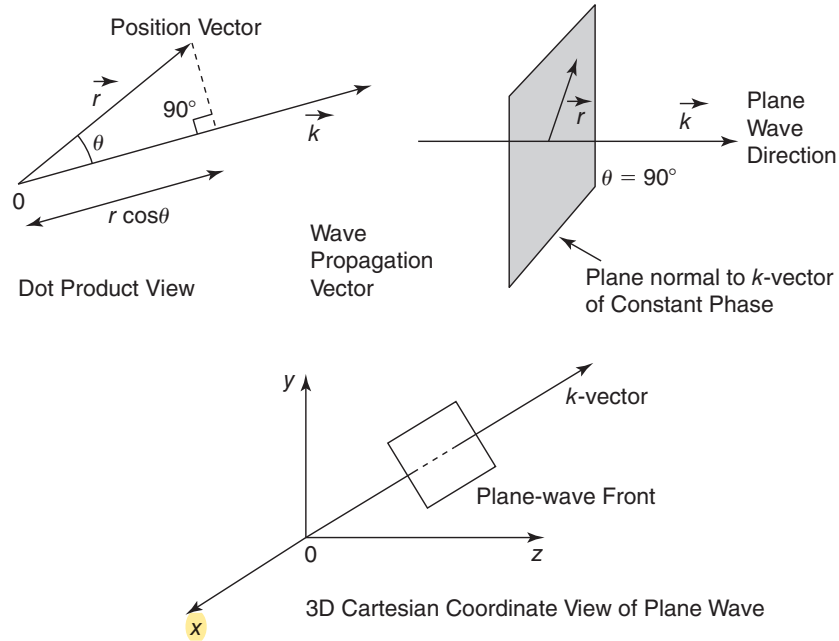


FIGURE 4.18 Views of the vector notation of position and propagation of a plane wave.

Note that the plane-wave optical phase is measured as a 2π product of a material wavelength normalized travel distance of the plane wave front located at the given $\vec{r} = [x\vec{i} + y\vec{j} + z\vec{k}]$ vector. Note that the plane-wave vector can also be written with unit vector notation as

$$\begin{aligned}
 \vec{k} &= [k_x\vec{i} + k_y\vec{j} + k_z\vec{k}] = [k\alpha\vec{i} + k\beta\vec{j} + k\gamma\vec{k}] \\
 &= k[\alpha\vec{i} + \beta\vec{j} + \gamma\vec{k}] = \frac{2\pi}{\lambda_m}[\alpha\vec{i} + \beta\vec{j} + \gamma\vec{k}] \\
 &= n\frac{2\pi}{\lambda}[\alpha\vec{i} + \beta\vec{j} + \gamma\vec{k}] \\
 &= n\frac{\omega}{c}[\alpha\vec{i} + \beta\vec{j} + \gamma\vec{k}] \\
 &= n\frac{2\pi\nu}{c}[\alpha\vec{i} + \beta\vec{j} + \gamma\vec{k}]
 \end{aligned}$$

$$\text{where } |\vec{k}| = k\sqrt{\alpha^2 + \beta^2 + \gamma^2} = k$$

$$\text{as } \sqrt{\alpha^2 + \beta^2 + \gamma^2} = 1 \text{ per unit vector notation}$$

So $\vec{k}/k$ represents a unit-size vector pointing in the direction of the wave k -vector. Hence, a traveling plane wave can be written as

$$\begin{aligned}\vec{E} &= \vec{E}_0 \cos[2\pi\nu t - \vec{k} \cdot \vec{r}] = \vec{E}_0 \cos[2\pi\nu t - kr \cos\theta] \\ &= \vec{E}_0 \cos\left[2\pi\nu t - 2\pi \frac{r \cos\theta}{\lambda_m}\right]\end{aligned}$$

For the simple case of a wave traveling in the z -direction with the electric field-position vector located also along the z -direction at a distance z_0 from the Cartesian coordinate origin giving $r = z_0$ and $\theta = 0$, we can write the field at $z = z_0$ as

$$\begin{aligned}\vec{E}(z_0, t) &= \vec{E}_0 \cos\left[2\pi\nu t - 2\pi \frac{z_0}{\lambda_m}\right] = \vec{E}_0 \cos\left[2\pi\nu t - 2\pi \frac{z_0\nu}{v}\right] \\ &= \vec{E}_0 \cos\left[2\pi\nu\left(t - \frac{z_0}{v}\right)\right]\end{aligned}$$

indicating that the optical field is simply a delayed wave that has acquired a time delay $\Delta t = z_0/v$ because of the travel-path length, z_0 , where v is the speed of the wave in the given medium. The concluded mathematics indicates how time delay gets represented within a plane-wave representation within a Cartesian coordinate framework. In the most general framework, it is not necessary that the wave at the time-coordinate origin (i.e., $t = 0$) have zero-phase contribution. In fact, we can use a general starting phase, for example, ε_1 at the time origin. Hence, we can write the most general pair of independent optical fields required for interference as

$$\vec{E}_1 = \vec{E}_{01} \cos[2\pi\nu_1 t - \varepsilon_1 - \vec{k}_1 \cdot \vec{r}] \quad \text{and} \quad \vec{E}_2 = \vec{E}_{02} \cos[2\pi\nu_2 t - \varepsilon_2 - \vec{k}_2 \cdot \vec{r}]$$

We can think of the two optical fields E_1 and E_2 having wave-travel start times that are different with respect to some reference time clock, thus giving the different phase value of ε_1 and ε_2 within the wave-cosine arguments. For both waves, the phase contribution caused by wave-distance travel to a measurement point comes from the $\vec{k} \cdot \vec{r}$ term in the cosine. We should also note that E_1 and E_2 have different optical frequencies, such as beams, coming from two different-colored lasers that are frequency-locked to make them phase-coherent.

As shown in Figure 4.19, consider the case of interference of two collinear beams, in other words, beams that travel in a straight line overlapping each other so their k -vector directions are the same. In this case, the beams can be considered as overlapping rays and the interference photodetection zone a point. Hence, the interference zone corresponding to the full-beam cross section produces the same

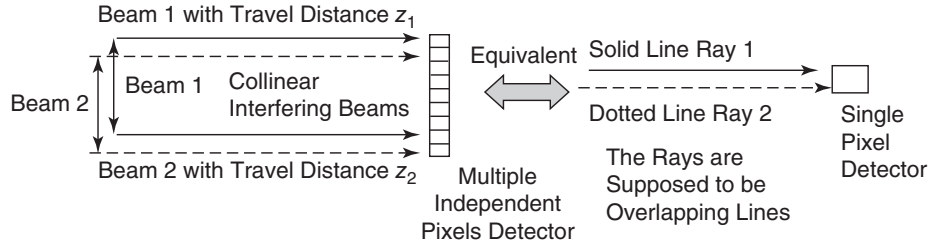


FIGURE 4.19 View of the two collinear beams from a laser interfering on a photodetector after the beams have traveled different relative distances. The large cross-section beams can be treated as two physically overlapping rays to determine their interference.

result as the point detector over the beam cross-sectional space. Take the simple case of both beams traveling along the z -axis and coming from the same laser. With respect to the laser position marking the $z = 0$ origin, one beam travels a distance z_1 in freespace while the other beam travels a longer distance z_2 in freespace before falling on the point detector. In this case, the optical fields incident on the photodetector is written as

$$\vec{E}_1 = \vec{E}_{01} \cos[2\pi vt - kz_1] \quad \text{and} \quad \vec{E}_2 = \vec{E}_{02} \cos[2\pi vt - kz_2]$$

Using the two-beam interference caused photodetected irradiance expression with the optical-field relative-phase term $\phi_{12} = k(z_2 - z_1) = k\Delta z$, we can write the photodetected irradiance for a two-collinear beam interference as

$$\begin{aligned} I &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos \phi_{12}] \\ &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos(k\Delta z)] \\ &= \frac{1}{2c\mu_0} \left[E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos\left(2\pi \frac{\Delta z}{\lambda}\right) \right] \end{aligned}$$

Clearly if the relative optical-path length Δz changes for the interfering collinear beams, the irradiance-coded current produced by the point photodetector (or single-pixel detector) will oscillate between a maximum and minimum value showing the classic sinusoidal wave behavior in time as the relative path-length changes in time, for example, like that caused by motion of a mirror that interacts with one of the interfering beams.

Unlike Figure 4.19 where the rays were collinear, Figure 4.20 shows two noncollinear rays from a point light source (e.g., laser diode) interfering on a pixel of a multi-pixel photodetector after the beams have travelled a relative distance of Δz . This ray geometry is

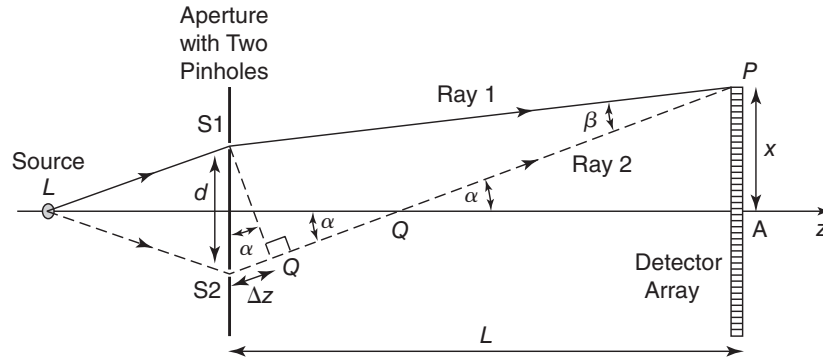


FIGURE 4.20 View of the two noncollinear rays from a point light source (e.g., a laser diode) interfering on a pixel of a multi-pixel photodetector after the beams have traveled a relative distance of Δz . This interpretation is the classic Young's double-slit experiment.

also the classic Young's double-slit experiment with the pinholes positioned symmetrically about the z -axis giving both light sources, S_1 and S_2 , on the aperture the same phase values ε_1 and ε_2 relative to the originating light source, L . Without loss of generality, we can use $\varepsilon_1 = \varepsilon_2 = 0$. The location of a general pixel on the photodetector is marked by the x -value on the x -axis scale. In such an experiment, we assume that the maximum x -value $\ll L$, the distance of the detector from the aperture, thus meeting the small- α angle or paraxial approximation condition that leads to several geometrical approximations such as $\sin \alpha \sim \alpha$ radians, AQ segment $\sim L$, $\tan \alpha \sim \alpha$ radians. This allows the computation of Δz to be $\Delta z = d \sin \alpha \sim d \alpha \sim d \tan \alpha = dx/AQ \sim dx/L$. Because of symmetry, the optical fields at S_1 and S_2 will have equal strengths and hence, the expected photodetected irradiance at the x -position on the photodetector will be given by

$$\begin{aligned}
 I &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos \phi_{12}] \\
 &= \frac{1}{2c\mu_0} [E_0^2 + E_0^2 + 2E_0E_0 \cos(k\Delta z)] \\
 &= \frac{E_0^2}{c\mu_0} \left[1 + \cos \left(2\pi \frac{d}{\lambda L} x \right) \right] \\
 &= \frac{E_0^2}{c\mu_0} [1 + \cos(2\pi f_x x)]
 \end{aligned}$$

So as x varies along the photodetector, the interference generated along the detector x -axis also follows a sinusoidal variation at a *spatial frequency* $f_x = d/(\lambda L) \sim (\sin \beta)/\lambda$ as $\sin \beta \sim \beta \sim d/L$ where β is the angle at point P between Ray 1 and Ray 2. Hence, interference in space has now introduced the existence of a spatial frequency or sinusoidal

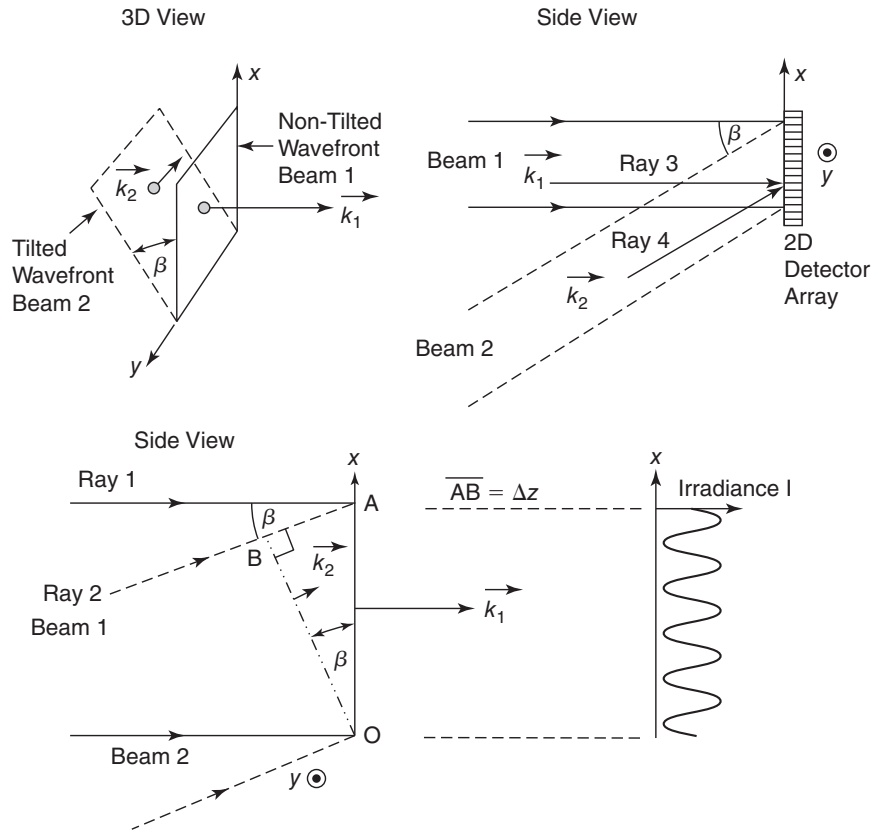


FIGURE 4.21 Interference scenario of two angled plane waves in freespace falling on a 2D photodetector array like a CCD chip. The two beams may be coming from a single-frequency laser source.

variation in space by the simple fact that varying angles between two interfering rays also corresponds to the changing relative path lengths travels (via geometry) and hence, gives rise to changing relative- $k\Delta z$ values within the cosine argument of the two beam interference term.

Instead of simply considering two angled rays, let us consider the case shown in Figure 4.21 of two large cross-section plane waves (made up of many rays) labeled as Beam 1 and Beam 2 interfering at an angle of β between their k -vectors labeled as $\vec{k}_1$ and $\vec{k}_2$. The plane wave fronts interference picture will show how the spatial-frequency concept comes to being in the detected interference-based irradiance, commonly called the fringe pattern.

Consider the location given by A-point on the detector aligned along the x -axis with its origin marked by the O-point. At A-point, Ray 1 from Beam 1 and Ray 2 from Beam 2 meet to produce interference via the photodetector pixel. Ray 1 traveling with the Beam-1 flat wave front reaches the A-point first, while Ray 2

traveling with the Beam-2 tilted wave front reaches A-point after traveling an extra path length of $AB = \Delta z$. Both beams have a common wave-front origin marked by the O-point where the rays from both beams have zero relative delay caused by relative wave-front tilt angle, β . For the A-point location and interference for Ray 1 and Ray 2, we can write via geometry that $\Delta z = x \sin \beta$. Assume that the light source is a single-frequency light wave and Beam 1 and Beam 2 have optical field strengths of E_{01} and E_{02} , respectively. Then the expected photo-detected irradiance at the x -position on the photodetector without loss of generality at the A-point will be given by

$$\begin{aligned}
 I(x) &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos \phi_{12}] \\
 &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos(k\Delta z)] \\
 &= \frac{1}{2c\mu_0} \left[E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos\left(\frac{2\pi}{\lambda} x \sin \beta\right) \right] \\
 &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos(2\pi f_x x)]
 \end{aligned}$$

The A-point without loss of generality can be moved along the detector and the appropriate pair of rays (e.g., Ray 3 and Ray 4) for the given x -location will be used from the beams to deliver the required interference. Hence, we see that interference between two relative tilt plane wave fronts from a single-frequency coherent source produces on the spatial domain of the time-integrating detector like a CCD chip, a spatial-frequency pattern (or sinusoidal fringe pattern) at a spatial frequency $f_x = \sin \beta / \lambda$ in units of cycles per distance (e.g., cycles/mm with 1 cycle = 1 complete interference fringe). Given a general beam 2 can be made up of wave fronts that have many different tilt angles, the expected interference with a reference plane wave will produce an interference pattern with many different spatial frequencies. Hence, the existence of beam components at angles with respect to a reference plane wave front implies the existence of varied spatial frequency content for a general light wave and is a highly useful attribute for photonic signal processing applications using beam interference effects. Right away we see a mapping of the incident-beam angle (for Beam 2) to a spatial frequency map detected by a high spatial resolution optical array detector, thus realizing an angle detection sensor. For example, Beam 2 could strike a mirror whose angle changes, and this angle change requires accurate and fine measurement, which can now be done by an optical sensor using interference.

Heterodyne Interferometry—RF Generation via Photo-Detection

Figure 4.22 shows the significant difference between electrical field direct-mixing operations via the electrical mixer component versus indirect optical field mixing operations implement by a time-integrating photodetector component that produces a current on an RF carrier when the optical fields have different frequencies. As mentioned previously, optically interfering beams of the same optical frequency are commonly called *homodyne interferometry*. On the other hand, optically interfering beams of different optical frequencies are commonly called *heterodyne interferometry*. Homodyne interferometry produces time-stationary electrical signals from the photodetector, such as a stationary gray-scale fringe pattern image produced by a 2D CCD detector imager where the detector-integration time is considered very long compared to the light-wave time period. Recall that the photodetector implements a multiplication operation of the two incident real optical fields producing electrical currents from the sum and difference frequencies of the light waves. When the light-wave frequencies are the same, the difference frequency component of the photodetector current is time stationary or a DC-current value. In heterodyne interferometry, this difference frequency component of

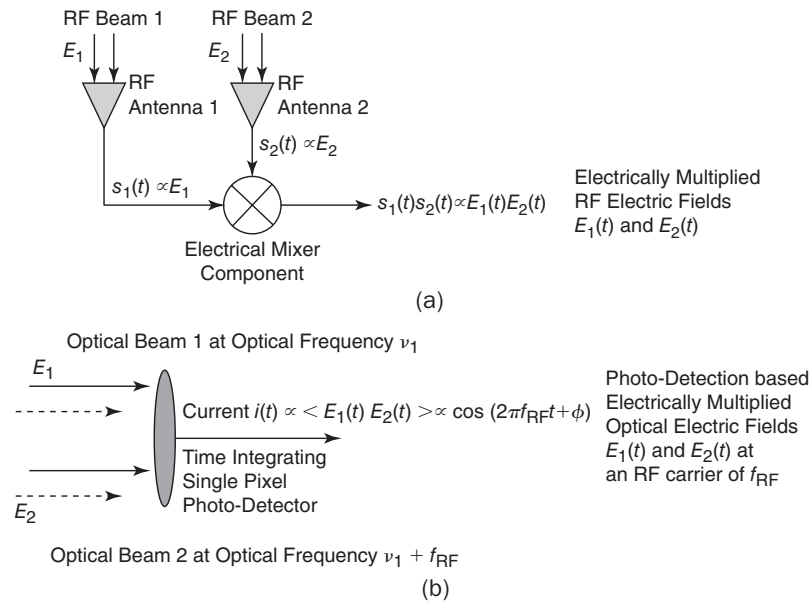


FIGURE 4.22 (a) RF mixer component-produced electrical mixing operation of electrical fields of two RF signals such as detected by separate RF antennas. (b) Photodetector component-produced electrical mixing of electrical fields of two optical signals having different optical frequencies with a frequency difference of f_{RF} .

the photodetection current has a time-oscillatory behavior at the frequency difference between the two light waves. To capture this frequency-difference time-oscillatory behavior, the photodetection integration time has to be short enough to sample this difference frequency signal; hence, an adequately fast-speed photodetector must be used to produce the difference frequency-produced RF signal. Hence, the fundamental feature of heterodyne interferometry is the heterodyne photodetection operation of the detector that produces the optical interference-coded signal on an RF carrier or AC signal versus a time-stationary DC signal as in homodyne interferometry. As higher-speed detectors are more complex and expensive devices, the natural question is, what is the benefit of going to heterodyne interferometry? Given the interference signal is produced on a nonzero RF carrier, the $1/f$ noise in the electrical detection circuits is lower for higher-RF values. Thus, to produce very high SNR interference-based systems, we resort to heterodyne interferometry for highly sensitive interference readings using such powerful electrical signal processors as RF phase meters, RF amplifiers, and RF filters, such as used in sophisticated aerospace radar systems. Given that heterodyne interferometers also use temporally faster response photodetectors, they can capture temporally fast interference-coded effects such as the minute sub-micron scale vibrations of a micromachine part under observation for part-quality verifications in a nondestructive testing (NDT) operation using light waves.

Without loss of generality, the two co-propagating (or collinear) mutually coherent optical beams at the different optical frequencies ν_1 and ν_2 can be written as the real sinusoidal traveling waves in the z -direction with optical fields given as

$$\vec{E}_1(z, t) = \vec{E}_{01} \cos(2\pi\nu_1 t) \quad \text{and} \quad \vec{E}_2(z, t) = \vec{E}_{02} \cos(2\pi\nu_2 t + \phi_{12})$$

$\vec{E}_{01} = E_{01} \vec{j}$ with E_{01} the scalar amplitude of vector field strength in the $\vec{j}$ unit vector (or y -direction) of space for the optical wave 1 and $\vec{E}_{02} = E_{02} \vec{j}$ with E_{02} the scalar amplitude of vector-field strength in the $\vec{j}$ unit vector (or y -direction) of space for the optical wave 2. ϕ_{12} in radians is the relative optical phase of between the two interfering waves and indicates that the two beams are phase-locked or temporally phase stable (or coherent) with respect to each other. Using the analysis conducted earlier for the optical irradiance provided by the optical detector, the irradiance provided by optical detection of the two optical beams can be written as

$$\begin{aligned} I &= \frac{1}{c\mu_0} \langle \vec{E}^2 \rangle = \frac{1}{c\mu_0} \langle [\vec{E}_1 + \vec{E}_2]^2 \rangle = \frac{1}{c\mu_0} \langle \vec{E}_1^2 + \vec{E}_2^2 + 2\vec{E}_1 \vec{E}_2 \rangle \\ &= \frac{1}{c\mu_0} \langle \vec{E}_1^2 \rangle + \frac{1}{c\mu_0} \langle \vec{E}_2^2 \rangle + \frac{1}{c\mu_0} \langle 2\vec{E}_1 \vec{E}_2 \rangle \end{aligned}$$

$$= I_1 + I_2 + I_{12} \quad \text{where} \quad I_1 = \frac{E_{01}^2}{2} \quad \text{and} \quad I_2 = \frac{E_{02}^2}{2} \quad \&$$

$$I_{12} = \frac{1}{c\mu_0} \langle 2\vec{E}_1 \vec{E}_2 \rangle \text{ is the interference term}$$

Hence, we must compute the key relation relating the two real fields in the optical interference term, namely:

$$\begin{aligned} \langle 2\vec{E}_1 \vec{E}_2 \rangle &= \frac{1}{T} \int_T \{ E_{01} E_{02} 2 \cos[2\pi\nu_1 t] \cos[2\pi\nu_2 t + \phi_{12}] \} dt \\ &= \frac{1}{T} E_{01} E_{02} \left\{ \int_T \cos[2\pi(\nu_1 + \nu_2)t + \phi_{12}] dt \right. \\ &\quad \left. + \int_T \cos[2\pi(\nu_2 - \nu_1)t + \phi_{12}] dt \right\} \\ &= \frac{1}{T} E_{01} E_{02} \int_T \cos[2\pi(\nu_2 - \nu_1)t + \phi_{12}] dt \\ &= \frac{1}{T} E_{01} E_{02} \int_T \cos[2\pi f_{\text{RF}} t + \phi_{12}] dt \end{aligned}$$

Here we have used the trigonometric identity: $2\cos(A) \cos(B) = \cos(A+B) + \cos(A-B)$ with $A = 2\pi\nu_2 t + \phi_{12}$ and $B = 2\pi\nu_1 t$. Here the photodetector implemented long-time averaging over T seconds of the very fast (at $\nu_2 + \nu_1$) optical frequency sinusoid corresponding to the first integral in the interferometric term analyzed earlier leads to a zero value leaving only the cosine of the optical frequencies difference $\nu_2 - \nu_1 = f_{\text{RF}}$ and phase difference ϕ_{12} between the two interfering optical fields to be left in the fields product term. At this stage, one must make an assumption on the temporal response of the photodetector with respect to the optical frequencies' difference, namely, the detection integration time is much shorter than the period of the generated RF or specifically, $T \ll 1/f_{\text{RF}}$. Under these fast photodetector response conditions, the photodetector acts as a delta function $d(t)$ time sampler of the RF beat signal and the photodetected interference term can be written as

$$\begin{aligned} \langle 2\vec{E}_1 \vec{E}_2 \rangle &= \frac{1}{T} E_{01} E_{02} \int_T \cos[2\pi f_{\text{RF}} t + \phi_{12}] dt \\ &= E_{01} E_{02} \cos[2\pi f_{\text{RF}} t + \phi_{12}] \frac{1}{T} \int_T dt \\ &= E_{01} E_{02} \cos[2\pi f_{\text{RF}} t + \phi_{12}] \end{aligned}$$

Hence, the irradiance provided by optical detection of the two optical beams with an optical frequencies difference of f_{RF} can be further written as

$$\begin{aligned}
 I &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos[2\pi f_{\text{RF}}t + \phi_{12}]] \\
 &= I_1 + I_2 + I_{12} \\
 &= I_1 + I_2 + 2\sqrt{I_1 I_2} \cos[2\pi f_{\text{RF}}t + \phi_{12}] \\
 &\propto E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos[2\pi f_{\text{RF}}t + \phi_{12}]
 \end{aligned}$$

The current generated by the point photodetector is coded with the phase difference, ϕ_{12} , between the two optical fields, and we can write the total current to be

$$i_d(t) = G_d A_d [I_1 + I_2 + 2\sqrt{I_1 I_2} \cos[2\pi f_{\text{RF}}t + \phi_{12}]]$$

The presence of the time-modulated cosine in the detected irradiance implies that the useful interference information in the photodetected signal is on an RF carrier. Hence, we can use RF electronics such as DC blocks (eliminates the DC level in the signal), AC filters (reduces out-of-band RF frequency noise in the signal), RF amplifiers (increases the signal strength of the interference term), and RF phase meters (measures the relative RF phase between the photodetected RF signal and a stable RF phase reference). In short, by monitoring the photodetector current RF phase-shift variation, we can determine ϕ_{12} . Hence, if one optical beam undergoes a rapid physical perturbation that induces a fast optical phase shift, interference with a second unperturbed RF frequency shifted reference optical beam can capture via heterodyne detection the relative optical phase between the two beams, thus forming the foundations of RF carrier-based fast temporal response highly phase sensitive optical sensing technology.

Diffraction

As mentioned in the beginning of the chapter, interference of waves is a mathematical idealization of the physical process of interference called diffraction. Diffraction theory takes into account the physical limits of apertures through which the waves travel and interact to produce the interference pattern that shows special characteristics via finite edge effects. For example, a mathematically deduced uniform interference pattern shows up as a non-uniform interference pattern representing the influence of the physical constraints of the experiment approximated by diffraction theory that indeed produces better engineering results for photonic system design. Another way

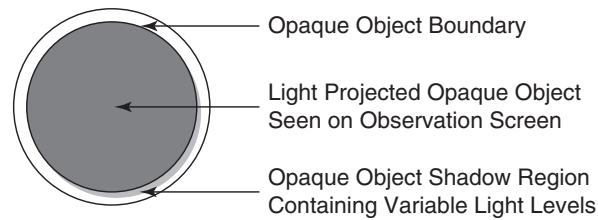


FIGURE 4.23 The light-diffraction process in action by observation of shadow region around opaque object boundary. With no diffraction, there is no shadow region.

to describe diffraction is the deviation of a wave from straight line or rectilinear propagation. A simple observation of diffraction (see Figure 4.23) is the presence of a shadow made of dark and bright regions around an opaque object that obstructs light. If there was no diffraction, the shadow around the object would not exist. To essentially have no diffraction effects, the aperture size in the EM-wave obstructing object should be much bigger than the EM-wave wavelength (see Figure 4.24). In this case, the plane wave through the aperture continues its approximately rectilinear or straight line propagation.

Huygens explained diffraction (the process of wave propagation) by saying that every point on a given wave front can be considered as a source of secondary wavelets. The aperture size dictated the maximum distance between the furthest coherent point sources in the aperture wave front that interfere in the far field to produce the diffraction pattern. Fresnel extended Huygens interpretations by adding that the actual optical field at any point beyond the wave front is a superposition of all these wavelets taking into account both

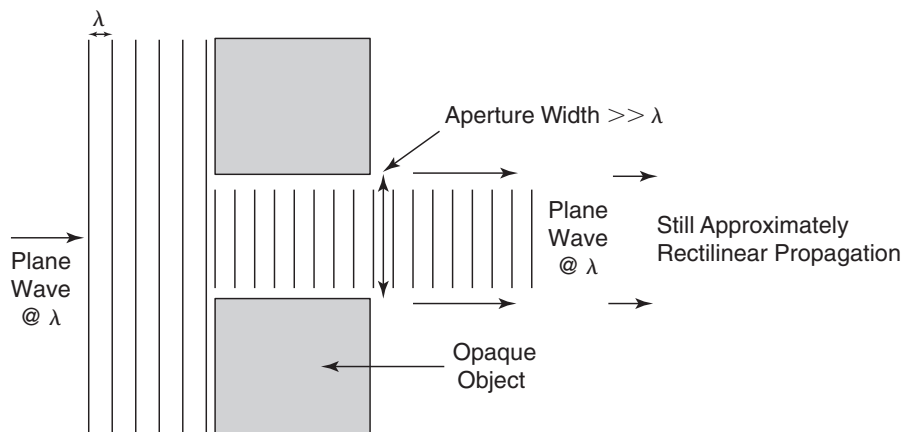


FIGURE 4.24 Conditions when light diffraction can be basically ignored to enable simpler geometrical or ray-optics based photonics system design. Hence, an input plane wave stays an output plane wave; in other words, a ray of light stays a ray of light.

the amplitudes and phases of the wavelets. This presentation of diffraction is called the Huygens-Fresnel principle of diffraction and is an approximate theory as it does not take into account the contribution to the diffraction field of the electronic oscillators in the edges of the diffracting aperture material. These edge effects are important when the diffraction field observation point is very near the aperture.

Interference analysis uses the sum of isolated but mutually coherent point sources on a wave front at the obstructing aperture to compute the interference spatial signal. For example, the Young's double-slit experiment treats the two aperture slits in the opaque obstruction as two point sources of light whose optical fields add in the far field. Hence, interference studies use discrete summations of optical fields, like N -fields for N -beam interference in a Fabry-Perot optical cavity, for example, parallel-faces optical glass block in air. On the other hand, diffraction studies treat the slit zone as a continuous array or distribution of point sources, and hence integrals are used to produce diffracted beam outputs.

Apart from the wavelength compared to the aperture size, the distance of the light source to the aperture and the distance of the aperture to the observation point plays a key role in determining which diffraction approximation is suited for providing the observed diffraction pattern. As shown in Figure 4.25, if both the light source and observation screen are effectively far enough from the aperture so that the wave fronts arriving at the aperture and screen are plane waves, then one is in the *far-field* or *Fraunhofer diffraction* regime. In this regime, a point source at the diffraction aperture shows up as a plane wave at the screen. In effect, light propagation between diffraction aperture and screen behaves as if an optical lens was placed mid-way between the aperture and screen. From an ideal mathematical point of view, a spatial delta function (ideal point source) at the aperture becomes a uniform (flat-top) rectangular (or rect) function (or a parallel/collimated beam of light) at the screen. In effect, a *Fourier transform* operation has been implemented optically via the process of light propagation in the Fraunhofer diffraction regime. In effect, we might travel 10 km to reach the screen location that meets the Fraunhofer condition. A more practical way to reach the Fraunhofer regime and observe the Fraunhofer diffraction pattern would be to place an optical lens at a focal distance from the aperture that would produce the Fourier transform or Fraunhofer diffraction pattern of a screen placed a focal length away from the lens. In these cases, we illuminate the aperture with a plane-wave light source, such as from a laser. We can apply the Huygens-Fresnel principle by treating the aperture zone as a source of secondary spherical wavelet electric fields that add up at the observation screen point. Given the distance between the aperture source points and the observation point varies for each

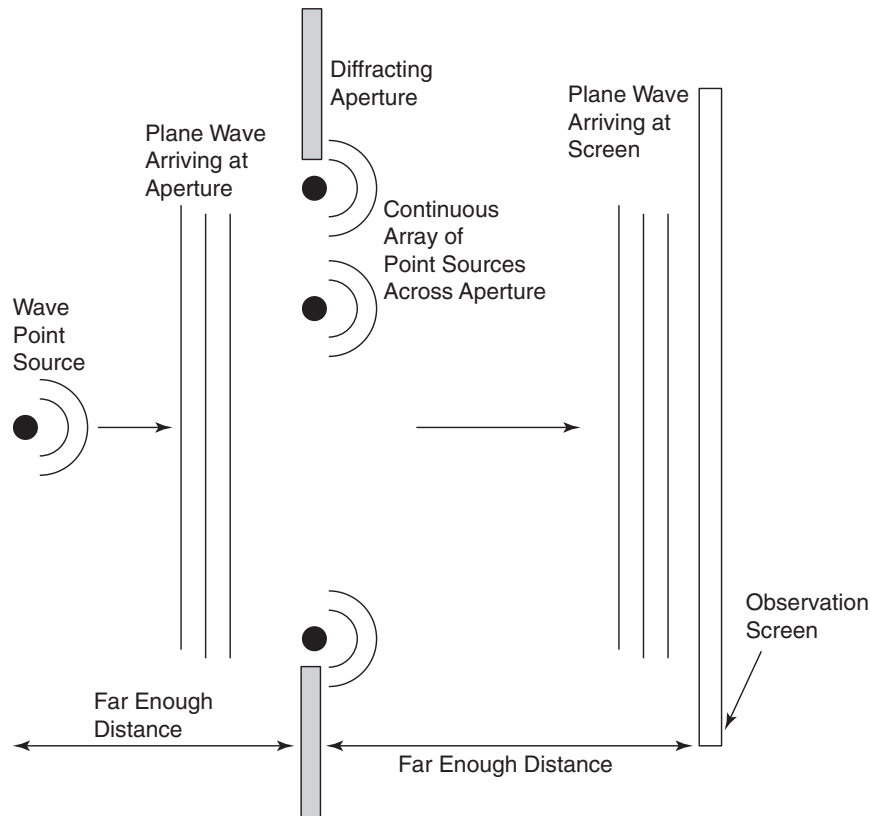


FIGURE 4.25 Conditions for far-field or Fraunhofer light diffraction where distances between source, aperture, and screen are long enough to have plane waves present at aperture and screen.

source point, the light from the different source points suffer relative optical phase shifts leading to a unique diffraction pattern resultant optical field.

Specifically as shown in Figure 4.26, Fraunhofer diffraction assumes that the phase of the diffracting wave from the aperture varies linearly across the aperture. This is indeed the case if we draw light rays from the different source points on the aperture to the observation point and notes the linearly increasing/decreasing distances as we move along the aperture axis. Specifically, choose a general screen observation point D that is an x' distance above the optical axis. Pick two point sources A and B on the aperture with A treated as the reference point located at $x = 0$, while B is located a distance x away from A. Draw a plane wave front AC for the BD ray. It is critical to assume that the distance R between the aperture and screen is large compared to aperture and screen dimensions, so $R \gg x$ and $R \gg x'$. This means that the wave propagation stays close to the optical central axis, a condition called the paraxial

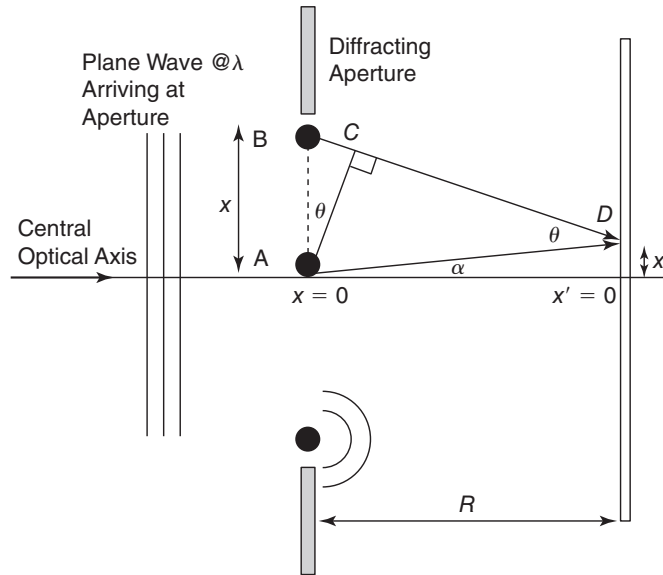


FIGURE 4.26 Rationale for the linear phase factor in the far-field or Fraunhofer light diffraction integral.

approximation. We must obey this approximation if the Fourier transform equivalent produced by Fraunhofer diffraction is to be expected on the screen. Using this approximation leads to several mathematical simplifications in the diffraction analysis starting with the optical path difference between the AD and BD rays is the distance $BC = x \sin \theta$, $\sin \theta \sim \theta$, $\alpha \sim \theta$, and $x' \sim R \theta$. The optical-phase shift between rays AD and BD is given by $\exp[-j(2\pi/\lambda)BC] = \exp[-j(2\pi/\lambda) x \sin \theta] \sim \exp[-j(2\pi/\lambda) x \theta] \sim \exp[-j(2\pi/\lambda) x (x'/R)]$. This linear phase shift factor derived in 1D Cartesian space (x to x' mapping) is embedded in the Fraunhofer diffraction integral as an exponential function. Hence, the integral giving the diffracted optical field can be written as

$$E_d(x') \propto \frac{1}{R} \int_{\text{aperture}} E_a(x) \exp\left[-j \frac{2\pi}{\lambda R} x' x\right] dx$$

where $E_a(x)$ is the diffracting aperture optical field function that can be complex (i.e., has both amplitude and phase terms representing the complete aperture optical transmittance function). One can write a spatial frequency f_x along the x' direction as $f_x = x' / (\lambda R)$, then one can write the Fraunhofer diffracted field as

$$E_d(f_x) \propto \frac{1}{R} \int_{\text{aperture}} E_a(x) \exp[-j 2\pi f_x x] dx$$

Note that the diffracted field expression is simply the 1D spatial Fourier transform of the aperture optical field. Recall that one can also satisfy the plane-wave conditions by placing a spherical lens midway between the aperture and screen with the aperture in the front-focal plane of the lens and the screen at the back focal plane of the lens. In this case, the same 1D Fourier transform is achieved with $R = F$, where F is the focal length of the lens. Use of the spherical lens for image spectrum analysis is often referred to as Fourier transform optics or just Fourier optics. As noted earlier, the fidelity of this optical Fourier transform is closely tied to meeting the paraxial approximation conditions for the physical system, including the spatial frequency content relative to lens and imager size in the system. Electronic-computing Fourier transform systems have no such limitations and hence dominate for accurate computation of image Fourier transforms.

As an example, given a clear optical aperture of width, D , centered around the $x = 0$, we can write $E_a(x) = \text{rect}(x/D)$. Then the Fraunhofer diffracted optical field is the 1D spatial Fourier transform of the aperture field and given as $E_d(f_x)$ a $D \text{ sinc}(f_x D) = D [\sin(\pi f_x D)/\pi f_x D]$. The sinc function is maximum at $f_x = 0$, in other words, $x' = 0$ position on the screen (on the optical axis) while it has zeros when $f_x D = \pm p$ where $p = 1, 2, 3, 4$, and so on. As $f_x = x'/(\lambda R)$, we can write $x' = \pm p[(\lambda R)/D]$. The first zeros on either side of the optical axis occur at $p = \pm 1$ so at $x' = \pm(\lambda R)/D$ and we can write the zero-to-zero diffraction pattern central width as $W = (2\lambda R)/D$.

Figure 4.27 shows this optical field pattern for the given rect-function diffracting aperture. The optical irradiance of the diffraction pattern is simply the square of the diffracted optical field and in this case is a sinc-squared function. A key point to note in this Fraunhofer diffraction analysis is that the clear step edge of the optical aperture shows up in the far field as disturbed edge with wings or side lobes where the optical energy is spatially distributed over an infinite zone, although these contributions decrease greatly as one moves away

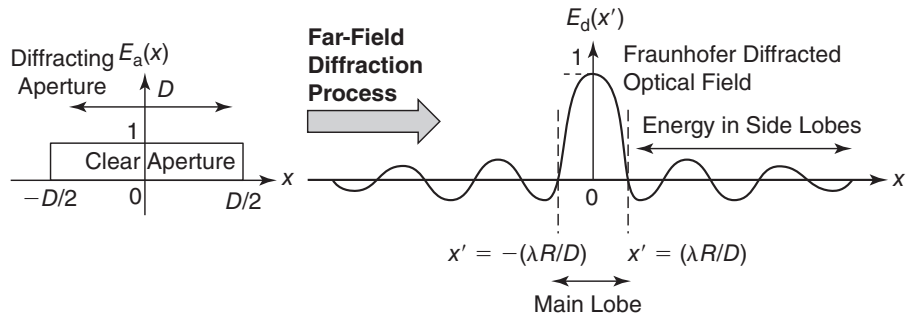


FIGURE 4.27 Fraunhofer optical field diffraction pattern for the given rect function diffracting aperture.

from the central optical axis on the screen. If geometric optics were to hold, there would be no wings, simply a step edge boundary like the aperture indicating a zone with light and a zone completely free of light. In reality, diffraction is always present, although the amount is highly dependent of the physical conditions in the photonic system. To compute the screen distance limit where geometrical optics holds, one can simply put $W = D$ in the $W = (2\lambda R)/D$ expression to get $R_{\min} = D^2/(2\lambda)$. So clearly one is in the far-field regime where $R \gg D^2/(2\lambda)$ or generally $R \gg (\text{Aperture Area})/\lambda$. For the most common circular aperture of diameter D , the Fraunhofer diffraction pattern produces a concentric rings pattern with one on-axis central main lobe circular zone called the Airy disc, whose width is given by $W = (2.44\lambda R)/D$, often called the diffraction-limited blur-spot size. For example, R can be the focal length of a microscope objective lens, and D can be the aperture of the lens; then W gives the smallest spot the objective can produce or see in its focus plane. Hence, diffraction plays a major role in the design of high-resolution microscopes and imagers.

The analysis conducted was for 1D space, but in reality, we have 2D space. Because 2D optical phase shifts can be represented separately as 1D optical phase shifts in the x - and y -directions that can be added easily when the exponentials representing the optical phase shifts in the two separate dimensions are multiplied, we can write the integral for the 2D diffracted optical field as

$$E_d(x', y') \propto \frac{1}{R} \iint_{\text{aperture}} E_a(x, y) \exp\left[-j\frac{2\pi}{\lambda R} x'x\right] \exp\left[-j\frac{2\pi}{\lambda R} y'y\right] dx dy$$

where $E_a(x, y)$ is the 2D diffracting aperture optical field function. Again we can use the spatial frequency notation $f_y = y'/(\lambda R)$ and write the 2D Fraunhofer diffracted field in a classic Fourier transform notation as

$$E_d(f_x, f_y) \propto \frac{1}{R} \iint_{\text{aperture}} E_a(x, y) \exp\left[-j2\pi(f_x x + f_y y)\right] dx dy$$

In the far-field regime, the diffraction pattern keeps its specific shape but changes uniformly in size as we move the screen relative to the aperture. This is clear from Figure 4.27 because the main lobe width is dependent of the distance, R , as its gets bigger (or smaller) as R increases (decreases), but keeps its sinc-like shape.

In the *Fresnel* or *near-field* diffraction case, the curvature of the wave front at the diffracting aperture and observation plane must be taken into account to predict the diffraction pattern. In this case, both the shape and size of the diffraction pattern changes as the screen is moved while in the Fresnel regime. In summary, as the screen moves away from the aperture, the light propagation analysis moves from

the *geometric optics* regime to the Fresnel regime to the Fraunhofer regime. In the Fresnel regime, the distance **between** R source (or screen) and diffracting aperture is such that $R < (\text{aperture area})/\lambda$. In the Fresnel regime, one no longer uses the linear phase shift change across the diffracting aperture made of continuous point sources. Now we must treat each point source on the aperture as a spherical wave front and hence a quadratic-phase variation of the diffracted wave across the aperture is applied to the wave propagation analysis. We can write the 2D Fresnel diffracted field as

$$E_d(x', y') \propto \frac{1}{R} \iint_{\text{aperture}} E_a(x, y) \exp \left[-j \frac{\pi}{\lambda R} \{ (x' - x)^2 + (y' - y)^2 \} \right] dx dy$$

or

$$E_d(x', y') \propto E_a(x, y) * h(x, y)$$

where $*$ is the convolution operator.

Here $h(x, y) = \exp[j\pi/R\lambda(x^2 + y^2)]$ is the impulse response of the freespace optical system where $E_a(x, y)$ is the input signal and $E_d(x', y')$ is the output signal of the Fresnel diffracting system. The convolution operation indicates that Fresnel diffraction is a linear-shift invariant (LSI) optical system in which the impulse response of the system is a quadratic phase shift representing a 2D Huygens-Fresnel spherical wavelet. Note that as many diffracting apertures can have complex shapes and unique amplitude and phase responses, photonic system designers using freespace propagation in a system deploy computer-based tools to compute Fresnel and Fraunhofer diffraction patterns to optimize system performance.

Problems

- 1 Given the simple case two equal-strength 1-GHz EM waves incident on a 1-GHz center-frequency RF antenna,
 - (a) When can the received electric power be quadrupled compared to a single EM wave-generated signal power? Explain how power is quadrupled.
 - (b) At what condition can the received RF signal suffer a nulling effect? This refers to when the received RF signal goes to zero.
- 2 Given a distant star inclined at an angle $\alpha = 60^\circ$ relative to a two-antenna array-distribution axis. The star is radiating a 100-MHz radio signal. The radio telescope antenna elements are separated by 1.5 m. Find the time delay and phase-shifter value that the antenna should be set to for constructive interference to generate the maximum radio signal from the star.

3 In the Figure 4.9 RF antenna nulling system, write an expression for the phase-shifter setting to satisfy destructive interference or RF nulling of the incident sinusoidal f_{RF} jammer signal.

4 Figure 4.10 shows an example multipath RF-interference scenario. Write the expression for the received RF signal $r(t)$ assuming all the RF beam reflections are of equal strength. Provide the expression for $r(t)$, given the physical scenario of the two building and the incoming direct RF beam.

5 Given a plane-wave optical beam $E(t)$ with electric field strength E_0 traveling in freespace, show that the irradiance, I , of this plane wave can be written as

$$I = \frac{E_{\text{rms}}^2}{Z_0} = \frac{E_0^2}{2Z_0}$$

where the freespace impedance is given by $Z_0 = \sqrt{\mu_0/\epsilon_0}$ and the speed of light in freespace is $c = 1/\sqrt{\mu_0\epsilon_0}$. Note that irradiance represents power in watts/unit area and the irradiance formula shows a similarity with the formula used for power in watts because of a sinusoidal voltage with strength E_0 in an electrical circuit with impedance Z_0 .

6 (a) Show that the irradiance of a plane-optical beam with electric field strength, E_0 , traveling in a linear isotropic medium of refractive index, n , is given by

$$I = \frac{n}{2c \mu_0} E_0^2$$

Hint: Use the relationship that the magnitude of the electric field in the medium is equal to the speed of the light in the medium times the magnetic induction field in the medium.

(b) In general, impedance of the EM wave in the medium is given as $Z_m = \frac{|E_m|}{|H_m|} = \frac{Z_0}{n}$, where n is the refractive index of the medium, and E_m and H_m are the EM-wave electrical and magnetic fields in the medium, respectively. Show that irradiance in the medium can be written as

$$I = \frac{E_{\text{rms}}^2}{Z_m} = \frac{E_0^2}{2Z_m}$$

7 Starting with a comparison with the speed of light, c , in vacuum (or freespace), mathematically show that the speed of light (EM wave) in the linear isotropic medium of index, n , can be written as

$$v = \frac{1}{\sqrt{\mu\epsilon}}$$

8 Given a pulsed laser with a peak power of 1 KW, calculate the energy stored per laser pulse given that the optical pulse width is 10 ns.

9 Consider two beams from a single wavelength (color) laser interfering on a point photodetector. Both beams pass through the same material with a temporally varying refractive index. Using the said beam conditions, can we design an interference-based optical sensor that measures the materials' changing refractive index? Explain your answer using two-beam field mathematics. Also state what optical design conditions for the beams must be met to realize the desired sensor.

10 Given the definition of irradiance modulation for two-beam optical interference, derive the condition for the irradiances for the two interfering beams to achieve a $M_F = 1$ indicating the best possible interference. Also indicate what optical-field amplitude strength condition should the two beams meet for $M_F = 1$ ideal interference.

11 Given two beams of equal irradiance, I_0 , and relative phase shift of ϕ , show that the total photodetected irradiance from the interference of these two beams is $4I_0 \cos^2(\phi/2)$.

12 Given are two interfering E_1 and E_2 optical fields from a single-frequency laser with $E_1 = 4 \cos[2\pi vt + \pi/2]$ V/m and $E_2 = 3 \cos[2\pi vt + \pi/6]$ V/m. The two beams are present on a point photodetector and the beams have their electric-field vectors in the same direction (e.g., vertical direction) called vertical-linear polarization.

- (a) Find the photodetected irradiance.
- (b) Find the fringe visibility of the detected irradiance.

13 Given are two interfering E_1 and E_2 optical fields from a single-frequency laser with $E_1 = 4 \cos[2\pi vt + \pi/2]$ V/m and $E_2 = 3 \cos[2\pi vt + \pi/6]$ V/m. The two beams are present on a point photodetector and the beams have their electric field vectors in orthogonal directions, for example, E_1 is in the horizontal linear polarization direction while E_2 is in the vertical linear polarization direction.

- (a) Find the photodetected irradiance.
- (b) Given that a polarizer oriented with its polarization axis at 45° to the horizontal and vertical polarization directions is placed just before the photodetector, compute the photodetected irradiance.

14 Given two beams are generated from a single laser of frequency, ν , and freespace wavelength, λ_0 , that are passed through different media before eventual interference on a point photodetector. One beam travels a distance z_1 in a medium of refractive index n_1 and the other beam travels a distance z_2 in medium of refractive index, n_2 .

- (a) Write an expression for the two collinear optical fields falling on the point detector.
- (b) Write an expression for the photodetected irradiance.

15 Consider the two-beam interference set-up of the Young's double-slit experiment shown in the chapter.

- Derive the conditions for the photodetected irradiance peaks and nulls positions given a single-frequency optical source.
- What is the physical distance between two consecutive peaks and two consecutive nulls in the irradiance?
- Explain what happens to the interference fringes (i.e., nulls and peaks) as the source wavelength increases.
- Explain what happens to the interference fringes (i.e., nulls and peaks) if the source is a broadband source like a white-light source.
- How can we measure an optical source wavelength using the given set-up?

16 As shown in Figure 4.28, given are two planes waves (Beam 1 and Beam 2) of green color produced from a single-wavelength 514-nm argon-ion laser. The two beams are produced using a beam splitting optic or BS that splits the laser beam to produce equal optical amplitude beams that meet at the CCD photodetector x - y plane. Beam 2 strikes a mirror, M , so that beam angle relative to Beam 1 can be varied both with respect to the x -axis and y -axis. Write the irradiance expression and compute the spatial frequency and spatial period of the irradiance pattern produced by the CCD detector for the following cases:

- Beam 1 and Beam 2 have a relative angle of $\theta_x = 1^\circ$ with respect to x -axis.
- Beam 1 and Beam 2 have a relative angle of $\theta_y = 2^\circ$ with respect to y -axis.
- Beam 1 and Beam 2 have relative angles of $\theta_x = 1.5^\circ$ and $\theta_y = 5^\circ$ with respect to x -axis and y -axis, respectively.

Hint: Treat the mirror angular motions θ_x and θ_y as independent tilt angles that lead to independently controllable spatial frequencies along the CCD x - and y -axes.

- Draw and describe the irradiance pattern produced in (c).
- As an engineer, what pixel size for the CCD should be picked for the experiment in (a) given the CCD system output can tolerate a 10 percent of a fringe-cycle phase accuracy (averaging).

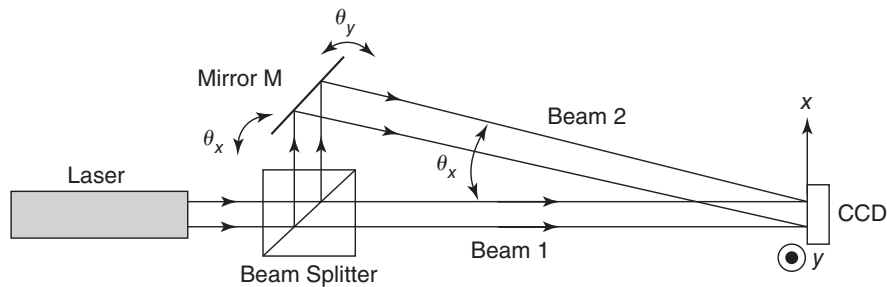


FIGURE 4.28 Two-beam optical system using a single laser.

17 Consider a two-beam heterodyne interferometry set-up in which the interfering beams on the photodetector are collinear and mutually coherent. One beam has an optical frequency of 1×10^{11} Hz while the other beam has an optical frequency of 1.001×10^{11} Hz.

- (a) Calculate the photodetected RF-carrier frequency.
- (b) Calculate the photodetector response condition such that the detector is fast enough to sample the heterodyne detection-produced RF carrier.

18 A laser beam exits a laser cavity aperture of width 1 mm. The wavelength of the laser is 500 nm or green light. Calculate the main lobe beam width of this laser after it travels a distance of 50 m.



CHAPTER 5

Optical Building Blocks: Components

Like electronic systems, photonic systems are designed and built using a host of optical components. These components have specific features that are engaged in the overall optical design to produce the required system output. Each component has its positive attributes, which are vital to the system design; nevertheless, each component also has some negative attributes that a good optical designer suppresses to produce the desired system results. The presented optical components are divided into four major categories based on the system designs presented in the book.

Acousto-Optic Devices

An optical device that engages the interaction of sound and light waves is called an acousto-optic (AO) device. The dominant device structure consists of a bulk optical crystal, like glass with a bonded piezoelectric transducer. When an electrical radio-frequency (RF) $s(t)$ signal is applied to the transducer, sound waves travel along the crystal causing the material refractive index to be varied by the drive signal, $s(t)$. Next if light is allowed to pass through the crystal volume undergoing mechanical and optical modulation, light-sound interaction occurs in the bulk medium causing the exiting light beam to be spatially and temporally modulated by the input $s(t)$. Thus, the AO device provides an excellent mechanism for converting an electrical signal, $s(t)$, into an optical signal imprinted with the same electrical signal, $s(t)$. For example, AO devices can have RF drive-signal frequency ranging from 20 MHz to 6 GHz, forming an excellent transduction platform for RF-to-optical conversion. This power also forms the basis for using AO devices for performing certain RF signal-processing functions.

A preferred mode of operation of an AO device is in *Bragg mode*. In this case, the light-wave propagation vector is oriented in such a way that interaction with the acoustic-wave vector produces a high diffraction-efficiency beam because of the Bragg-matched interference

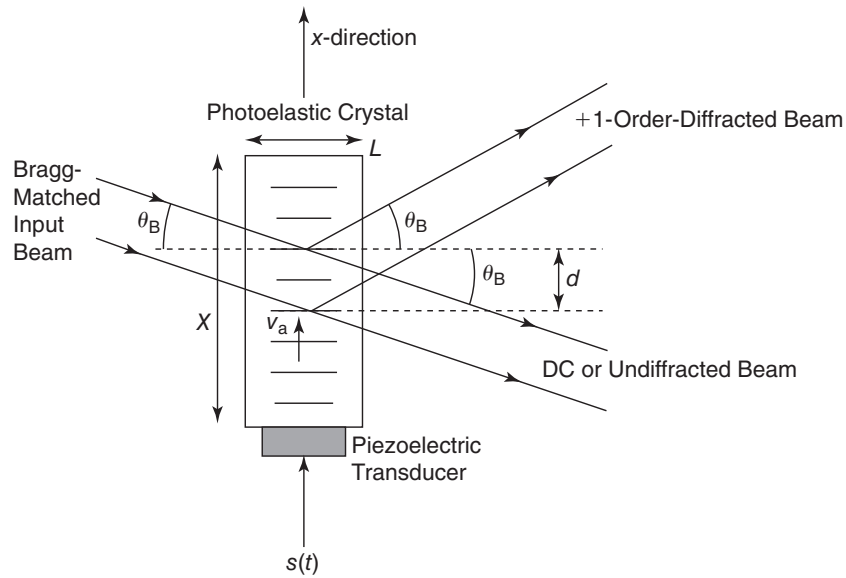


FIGURE 5.1 The AO Bragg cell device for electrical-to-optical signal conversion. In actuality, the acoustic wavelength is a much smaller fraction of the device length, X , and AO-interaction length, L .

condition. Such a Bragg cell device is shown in Figure 5.1, in which the Bragg diffraction-interference condition for maximum light diffraction (see Problem 1) requires the input laser beam at freespace wavelength, λ , to satisfy:

$$\sin \theta_B = \frac{\lambda}{(n2\Lambda_a)} \text{ within the Bragg cell and}$$

$$\sin \theta_B = \frac{\lambda}{(2\Lambda_a)} \text{ outside the Bragg cell}$$

where n is the refractive index of the AO medium. Typically we deal with incident and diffracted beams outside the Bragg cell; hence, the more common definition for the AO Bragg-cell angle does not include n . The traveling acoustic-signal wavelength, speed, and drive frequency are Λ_a , v_a , and f_a , respectively. Here $v_a = \Lambda_a f_a$. Note that for typical AO Bragg cells, the Bragg angle is typically smaller than a few degrees, making the first-order diffracted beam and undiffracted or DC beam closer in angular space than that depicted in Figure 5.1. The name DC beam refers to a beam with zero spatial frequency as this beam suffers no angular deflection and can be considered the on-axis beam.

The AO Bragg cell is commonly also called an *AO deflector* as the diffracted beam and straight or undiffracted beam are separated at

Bragg condition by the deflection angle defined as $\theta_D = 2\theta = 2\theta_B$ that can be varied by changing the device-drive frequency f_a . Here $\sin \theta = (\lambda f_a)/(2v_a)$. Typically, each AO-device transducer has a center frequency, f_c , with a given 3-dB bandwidth, B , so f_a goes from $-B/2 + f_c$ to $f_c + B/2$. Thus, we simply tune the RF to steer or deflect the input laser beam to different scan angles, θ_D , with a small angular $\Delta\theta$ spread in freespace medium approximately given by:

$$\Delta\theta \sim \frac{(\lambda B)}{v_a}$$

(see Problem 3) when the entire 3-dB RF bandwidth of the device is utilized. The angular 3-dB beam-deflecting resolution, $\Delta\theta_R$, is governed by the smallest temporal-frequency change spatially possible within the Bragg cell that occurs when the entire aperture of the Bragg cell contains 1 temporal cycle; thus the Bragg-cell frequency resolution is $\delta f = 1/T_a$. This also means the angular resolution of the optical beam that engages the full aperture of the Bragg cell via spatial diffraction theory is $\Delta\theta_R \sim \lambda/X$. Thus, the number of independently resolvable AO-device-based deflected beams, N_B , using temporal signal analysis that is equivalent to angular bandwidth analysis can be given by

$$N_B = \frac{\Delta\theta}{\Delta\theta_R} = \frac{B}{\delta f} = T_a B$$

In this operation, the entire aperture of the Bragg cell should be engaged to enable high-frequency-resolution controlled-beam deflection. Notice that the number of spatially resolvable deflected beams is a product of the device time aperture and the device temporal bandwidth, in other words the device *time-bandwidth product* (TBWP). Thus, we can increase the AO device time aperture and bandwidth if we desire a deflector with many beam deflection spots.

The storage capacity of the Bragg cell is $2BT_a$, as according the Nyquist theory, a signal of bandwidth, B , must be sampled at a $2B$ frequency to adequately preserve the signal information. In other words, two storage points are needed to complete a single frequency cycle. Thus, the Bragg cell of signal bandwidth, B , and aperture, T_a , must be able to hold $2BT_a$ independent signal data points within its cell, giving an *AO cell storage capacity* of $2 \times \text{TBWP}$. This storage capacity indicates the level of complexity of an information signal or information capacity of a signal channel within a chosen AO Bragg cell. When implementing photonic system design using Bragg cells, we must keep this storage capacity limit in mind to avoid signal spoiling effects.

Example 1: Beam Scanner

A typical flint glass AO device has a $10\text{-}\mu\text{s}$ aperture with a 50-MHz bandwidth. How many spots beam deflector can be formed with this device?

Solution

The numbers of spots produced by the given AO device beam scanner is given by $N_B = T_a \times B = 10\text{ }\mu\text{s} \times 50\text{ MHz} = 500$ spots.

Figure 5.1 also shows that the optical-beam size that interacts with the acoustic wave is d . To engage the AO device fully, the optical beam should be occupied by the new RF signal to produce a new deflection beam angle. Thus, the beam size-dependent temporal response of the AO device is given by $T = d/v_a$. To enable fast temporal modulation, we should use a small d ; hence we can use a focused light beam as shown in Figure 5.2, although at the expense of using a smaller AO-signal length leading to lower volume for Bragg diffraction thus leading to a lower-diffraction efficiency. Specifically, the shortest time RF signal modulation that the AO device can respond to given beam size d is $T = d/v_a$, giving a pulse-repetition

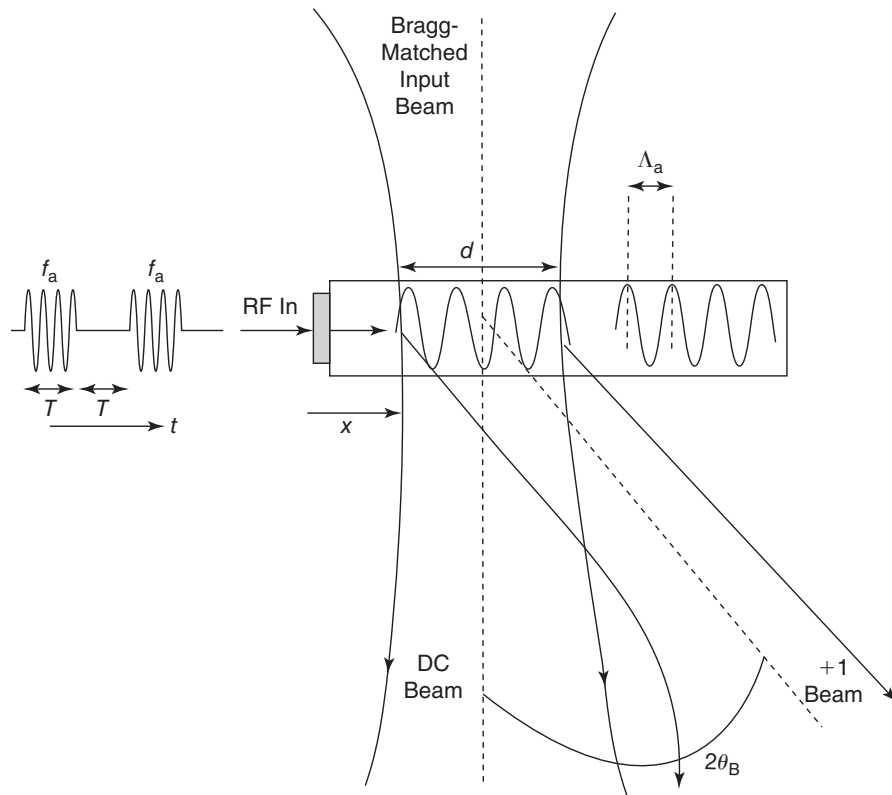


FIGURE 5.2 Operation of an AO Bragg cell as an on-off high-speed optical modulator.

frequency (PRF) of $1/2T$, given an equal time on/off duration square-wave modulation signal, also known as a 50 percent duty-cycle signal.

If the square-wave modulation off-period approaches zero, the fastest RF-frequency change the Bragg cell can respond to by producing the +1-order diffracted beam is $1/T = v_a/d$. The previous discussion assumes multiple (at least two acoustic wavelengths) within the beam size, d , as shown in Figure 5.2. To determine the ultimate limit in the fastest AO-device response time, the optical-beam size, d , must occupy one full acoustic-signal wavelength to enable beam diffraction. The smallest acoustic wavelength (and equivalently, the optical beam size) occurs when the RF drive is the fastest possible or $f_c + 0.5B$. In this case, the *fastest* AO device response time is $T = d/v_a = \Lambda_a/v_a = 1/f_a = 1/(f_c + 0.5B)$. Thus, if the fastest RF drive for a Bragg cell is $f_c + 0.5B = 1$ GHz, the fastest-response time of this AOD is $T = 1$ ns.

Monitoring the +1-diffracted beam that becomes spatially separated from the nondeflected or DC beam produces an on/off light point *AO modulator* (sometimes called an AOM) when the device is driven by the square-wave amplitude modulation (AM) signal with the carrier frequency, f_a , within the AO-transducer bandwidth. The DC beam also shows on/off temporal modulation, although the off-state does not correspond to a zero light level, as in a practical AO device. 100 percent Bragg diffraction is not possible into the +1 order. A more common number is 90 percent diffraction, implying 10 percent of light is the off-state and 100 percent light is the on-state, giving a 10:1 on-off optical-modulation contrast ratio. In comparison, the +1-order beam has a very low light-level off-state dictated by scattered light from the Bragg cell. A typical on-off ratio of 1000:1 or 30 dB can be attained at the +1-order beam position.

A crystal-based AO device is a bulk or 3D device where a 3D or volume grating forms caused by the AO interaction. A very important system-design parameter is system loss that is directly connected to an AO device parameter called diffraction efficiency (DE), characterized by $\eta = P_d/P_i = (\text{Optical Power in the Diffracted Beam}) / (\text{Optical Power in the Incident Beam})$. From coupled-mode theory of volume Bragg diffraction in isotropic AO medium, the ratio of the diffracted optical field amplitude $E_d(V)$ to the incident optical field amplitude $E_i(V)$ is given by

$$\frac{E_d(V)}{E_i(V)} = -j \frac{CV}{|CV|} \sin(|CV|L)$$

where C is a coupling constant per unit-applied voltage and coupling distance that depends on device parameters such as material photoelastic constant and piezoelectric coupling efficiency, V is the

acoustic signal drive voltage in volts, and L is the device AO interaction length (typically the length of the transducer). As optical power is proportional to the magnitude square of the optical-field amplitude, Bragg cell DE is given by

$$\eta = \frac{P_d}{P_i} = \frac{|E_d|^2}{|E_i|^2} = \sin^2(|CV|L)$$

As C and L are constants and the incident power P_i is also a constant, the AO device-drive voltage, V , shows a sine square-dependent diffracted-beam optical-power behavior (see Figure 5.3). In this mode, we can apply a DC or bias voltage, V_B , to the AC-modulating signal, V_s , such that the acoustic drive signal, V , occurs on a small linear part of the sine-square curve. The bias voltage, V_B , is adjusted to produce the half or $\eta = 0.5$ DE point that happens when $CVL = \pi/4$ rad. In this case, the drive voltage $V = V_B + V_s$ becomes linear with the Bragg-diffracted optical power varying from $P_i(0.5 - \eta_s)$ to $P_i(0.5 + \eta_s)$ for the condition $V_B \gg V_s$ providing a modulation mode called the *linear-intensity modulation mode* of the Bragg cell. This mode is much like the simple-to-use integrated-optic Mach-Zehnder interferometric linear-intensity modulator, in which the modulator is biased at a given drive voltage and the modulated optical power is linearly proportional to the electrical modulation voltage. For the Bragg cell,

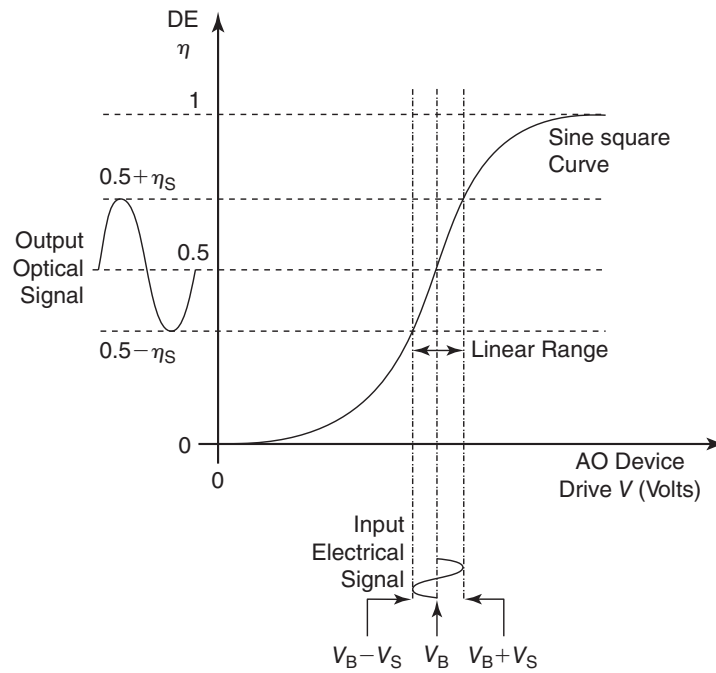


FIGURE 5.3 Linear intensity modulation-mode of AO Bragg cell.

this mode does not fully utilize the modulation swing of the device and also produces significant bias-optical power that can eat up the dynamic range of an optical-detection device, such as a CCD. Hence, this mode is used in limited applications where high dynamic ranges are not required.

Another mode of the AO Bragg cell is the *linear-amplitude modulation mode*, where the AO-drive voltage is approximately proportional to the diffracted-light optical-field amplitude. This condition occurs for low-diffraction efficiencies, typically under 10 percent (or D.E. $\eta < 0.1$) depending on the modulation linearity required. In this case,

$$\frac{E_d(V)}{E_i(V)} = -j \frac{CV}{|CV|} \sin(|CV|L) \approx -j \frac{CV}{|CV|} |CV|L = -jCLV \propto V$$

This linear-mode of AO Bragg-cell operation is a powerful mode to implement linear RF signal-processing operations using the optical carrier. In this case, the Bragg cell diffraction efficiency also becomes proportional to the acoustic drive power as

$$\eta = \frac{P_d}{P_i} = \frac{|E_d|^2}{|E_i|^2} \approx (CLV)^2 = (CL)^2 V^2 = R(CL)^2 \frac{V^2}{R} = R(CL)^2 P_a \propto P_a$$

where P_a is the acoustic drive power and R is the resistance of the piezoelectric transducer. Because D.E. η is small, the optical-drive voltage that is proportional to $\sqrt{\eta}$ is even smaller, implying a small signal-driving condition, much like small signal-based electronic signal-processing that consumes low electrical power and operates devices within linear signal-processing regimes. Thus the AO Bragg cell can be made to function as a small-signal linear electrical-to-optical modulator.

The AO Bragg cell is a traveling-wave device as an acoustic signal travels along the AO crystal attached to the piezoelectric transducer. As light is also a traveling wave, the interaction of the incident light wave with the acoustic traveling wave leads to the diffracted wave undergoing the Doppler effect that either increases (positive Doppler shift) or decreases (negative Doppler shift) its optical frequency by an amount equal to the acoustic frequency. Figure 5.4 illustrates two interaction geometries for the waves in the AO Bragg cell. Also shown are the particle (photon and phonon) momentum-conserving propagation ($\hbar \mathbf{k}_i \pm \hbar \mathbf{k}_a = \hbar \mathbf{k}_d$; h is Planck's constant, $+$ for positive Doppler and $-$ for negative Doppler) or $\mathbf{k}$ -vector diagrams showing the expected directions of the diffracted waves when observing the optimum diffraction-efficiency Bragg-angle condition. Considering the summation of $\mathbf{k}$ -vectors in the two different photon-phonon

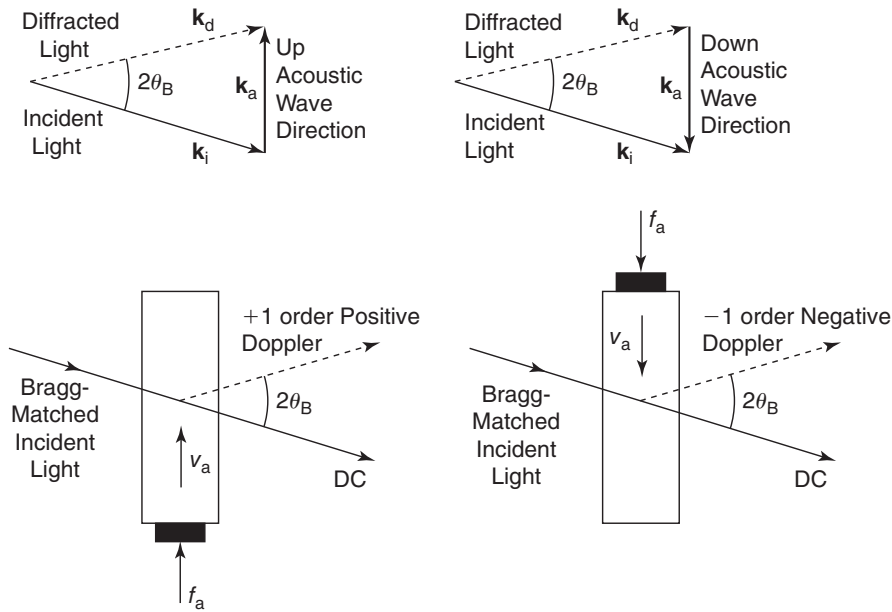


FIGURE 5.4 Illustration of Doppler effect in the diffracted light for two Bragg cell light-acoustic wave-interaction configurations.

interaction geometries, we can conclude that for the positive Doppler-shift case, $\mathbf{k}_i + \mathbf{k}_a = \mathbf{k}_d$. On the other hand, for the negative Doppler-shift case, vector summation leads to the condition $\mathbf{k}_d + \mathbf{k}_a = \mathbf{k}_i$ or $\mathbf{k}_i - \mathbf{k}_a = \mathbf{k}_d$. Figure 5.4 also shows that when the incident wave and acoustic wave are moving toward each other, the diffracted wave must possess a shortened wavelength; hence, the diffracted wave (called a +1 order) has a positive Doppler shift. Hence, if the incident light optical frequency is ν (Hz), the DC and +1-order diffracted wave have optical frequencies of ν and $\nu + f_a$, respectively. Similarly, when the incident wave and acoustic waves are moving away from each other, the diffracted wave must possess a longer wavelength; hence, the diffracted wave called a -1 order has a negative Doppler shift. Hence, if the incident-light optical frequency is ν (Hz), the DC and -1-order diffracted waves have optical frequencies of ν and $\nu - f_a$, respectively. In effect, the AO Bragg cell functions as a *frequency shifter*, a powerful feature of Bragg cells used for designing a variety of photonic systems.

The AO Bragg cell has another powerful property, that is, the AO cell temporal drive signal, $s(t)$, has a direct mapping to 1D optical space, in particular the acoustic wave direction, x . Figure 5.2 shows this traveling-wave spatial refractive index modulation in the AO device, where the index spatial modulation mirrors the RF temporal modulation $s(t)$. The drive signal, $s(t)$, is centered at a transducer center-frequency, f_0 , with a bandwidth generally limited to an

octave or $2f_0/3$ to limit transducer nonlinear second-harmonic intermodulation effects. The traveling-wave acoustic-signal space-time representation using the Figure 5.1 defined x -direction (i.e., the acoustic wave is in the same direction as x -direction) can be written as

$$s(x, t) = s\left(t - \frac{x}{v_a}\right) \text{rect}\left[\frac{x - X/2}{X}\right]$$

where $\text{rect}[x/X] = 1$, if $|x| \leq X/2$ and $\text{rect}[x/X] = 0$ otherwise. Because the traveling-acoustic signal via the AO effect induces a traveling refractive-index perturbation in the AO crystal, this optical 1D space-time modulation in the AO cell can be written as a pure optical-phase modulation or AO cell spatial light-modulation transmittance function:

$$\begin{aligned} t(x, t) &= \exp[jm_a s(x, t)] \\ &= \exp[jm_a s(t - x/v_a)] \text{rect}\left[\frac{x - X/2}{X}\right] \\ &= [1 + jm_a s(t - x/v_a) + \text{higher-order terms}] \text{rect}\left[\frac{x - X/2}{X}\right] \\ &\approx [1 + jm_a s(t - x/v_a)] \text{rect}\left[\frac{x - X/2}{X}\right] \end{aligned}$$

Here m_a is an index-modulation term that depends on AO material parameters, such as the photoelastic interaction efficiency. Note that for small diffraction efficiencies, the higher-order terms in the optical-phase modulation expansion can be neglected, giving the desired linear-modulation relationship between the AO cell drive signal and the optical spatial modulation in the device, in other words,

$$t(x, t) \approx \left[1 + jm_a s\left(t - \frac{x}{v_a}\right)\right] \text{rect}\left[\frac{x - X/2}{X}\right]$$

Do note that for the derivation of the just-described AO cell-transmittance function (see also Problem 8 for derivation steps), the AO cell for the moment is not considered operating in its Bragg operation mode. From signals theory, a real signal, $s(t)$, can be expressed as its upper $\tilde{s}(t)$ and lower $\tilde{s}^*(t)$ sideband complex conjugate terms, in other words, $s(t) = [\tilde{s}(t) + \tilde{s}^*(t)]$. The physical Bragg-diffraction process in the AO device naturally selects only one of the sidebands of the input-signal spectrum centered around the Bragg

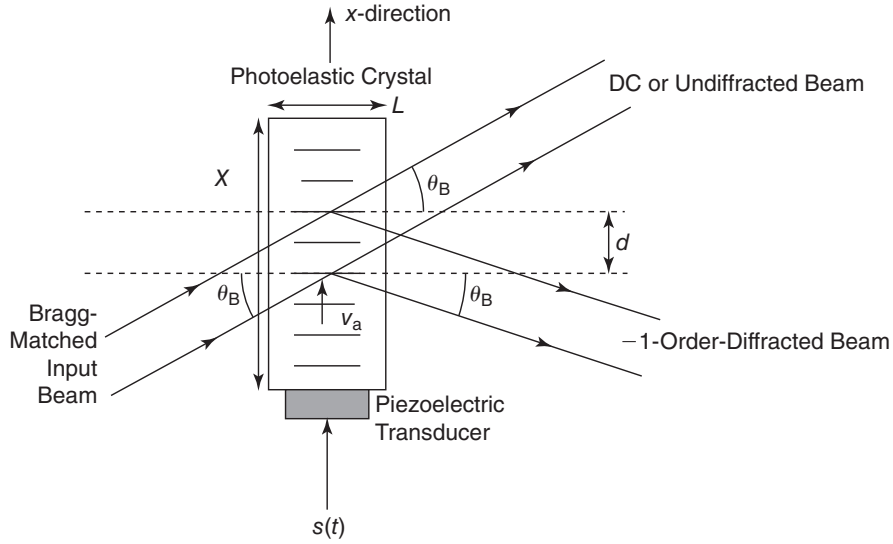


FIGURE 5.5 The AO Bragg-cell device operating in -1 -order negative Doppler mode. Incident beam has a positive spatial frequency by notation adopted.

cell center frequency associated with the specific first-order beam. Specifically, for $+1$ -order diffraction geometry as shown in Figure 5.1, the AO-cell transmittance function is associated with the positive Doppler upper sideband spectrum and is defined as

$$t_{+1}(x, t) = \left[1 + jm_a \tilde{s} \left(t - \frac{x}{v_a} \right) \right] \text{rect} \left[\frac{x - X/2}{X} \right] \quad (\text{This is a } +1\text{-order Bragg mode.})$$

Figure 5.5 shows an example of the -1 -order diffraction geometry within the same coordinate definitions of x -direction (bottom to top on the Figure 5.1). In this case of the -1 -order diffraction geometry, the AO cell-transmittance function is associated with the negative Doppler lower sideband spectrum and is defined as

$$t_{-1}(x, t) = \left[1 + jm_a \tilde{s}^* \left(t - \frac{x}{v_a} \right) \right] \text{rect} \left[\frac{x - X/2}{X} \right] \quad (-1 \text{ order Bragg Mode})$$

In effect, the AO Bragg cell operates as a *single-sideband modulator* (SSB) for the input RF signal, $s(t)$. Given the photonic-system design using a Bragg cell, the appropriate transmittance function is engaged with the incident optical field to characterize the output beams after passing through the cell. Using the Figure 5.5 geometry and notation and the representation of angular spatial frequencies to represent the

incident plane wave $E_i(x, t)$ that is Bragg-matched to the Bragg angle, $-\theta_B$, at cell center frequency, f_0 , we can write

$$E_i(x, t) = \exp\{-j2\pi\nu \cdot t\} \exp\left\{-j2\pi \frac{\sin \theta_B}{\lambda} x\right\}$$

The exponential refers to the optical frequency, ν , of the laser, whereas the second exponential term refers to the light spatial/angular frequency in the x direction. As the AO device is operated in the Bragg mode, we can write the AO device mid-band frequency-linked relationship:

$$\frac{\sin \theta_B}{\lambda} = \frac{f_0}{2v_a}$$

When Bragg-matched light interacts with the AOD with the +1-order orientation in Figure 5.6, the resulting optical field is given by the input optical field multiplied by the Bragg-cell transmittance function, in other words,

$$E_0(x, t) = E_i(x, t) \cdot t_{+1}(x, t) = E_{DC}(x, t) + E_{+1}(x, t)$$

where the undiffracted light beam represented as the DC-beam optical field is given by

$$E_{DC}(x, t) = \exp\{-j2\pi\nu \cdot t\} \exp\left\{-2\pi \frac{\sin \theta_B}{\lambda} x\right\} \text{rect}\left[\frac{x - X/2}{X}\right]$$

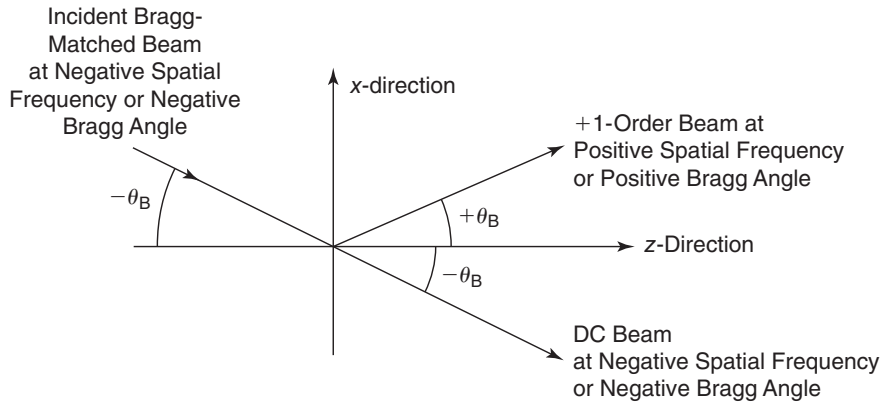


FIGURE 5.6 The geometry and notation for representing the positive and negative Bragg-angle beams shown for the +1-order AO Bragg diffraction.

while the +1-order positive Doppler-shifted beam is given as

$$E_{+1}(x, t) = jm_a \exp\{-j2\pi v \cdot t\} \exp\left\{-2\pi \frac{\sin \theta_B}{\lambda} x\right\} \tilde{s}\left(t - \frac{x}{v_a}\right) \text{rect}\left[\frac{x - X/2}{X}\right]$$

With the assumption of low diffraction efficiency, we can also write

$$|\eta| = \frac{P_d}{P_i} = \frac{|E_{+1}|^2}{|E_i|^2} = \frac{|E_{+1}|^2}{|E_{DC}|^2 + |E_{+1}|^2} \approx \frac{|E_{+1}|^2}{|E_{DC}|^2} = \frac{|0.5m_a \tilde{s}|^2}{1} = G \cdot |\tilde{s}|^2$$

where G is a constant scaling factor, such that η obeys the small diffraction-efficiency condition (e.g., $\eta < 0.1$ or $\text{DE} < 10$ percent). The mid-band frequency of the AO Bragg cell can be used in the Bragg-angle term for the +1-order optical field to write

$$E_{+1}(x, t) = jm_a \exp\{-j2\pi v \cdot t\} \exp\left\{-2\pi \frac{f_0}{2v_a} x\right\} \tilde{s}\left(t - \frac{x}{v_a}\right) \text{rect}\left[\frac{x - X/2}{X}\right]$$

If the spatial window function is centered in the center of the Bragg cell, the +1-order diffracted optical field can be rewritten as

$$E_{+1}(x, t) = jm_a \exp\{-j2\pi v \cdot t\} \exp\left\{-2\pi \frac{f_0}{2v_a} x\right\} \tilde{s}\left(t - \frac{x}{v_a} - \frac{T_a}{2}\right) \text{rect}\left[\frac{x}{X}\right]$$

where $T_a = X/v_a$ is the time aperture of the Bragg cell. To demonstrate the signal-processing capability of AO Bragg cells, example input drive signals $s(t)$ are next deployed.

Example 2: Frequency Shifter

Given a Bragg-cell drive signal, $s(t)$, of amplitude A at the transducer mid-band frequency, f_0 , in other words, $s(t) = A \cos(2\pi f_0 t)$, show the demonstration of a positive-Doppler shift to the input beam given +1-order diffraction. Also show that the +1-order diffracted-field strength is proportional to the drive signal voltage, A .

Solution

Express the single sideband signal $\tilde{s}(t) = 0.5A \exp(-j2\pi f_0 t)$; then we can insert this value for the +1-diffracted optical field to get

$$\begin{aligned} E_{+1}(x, t) &= j0.5m_a \exp\{-j2\pi v \cdot t\} \exp\left\{-2\pi \frac{f_0}{2v_a} x\right\} A \exp\{-j2\pi f_0 \left(t - \frac{x}{v_a}\right)\} \\ &= j0.5m_a A \exp\{-j2\pi(v + f_0)t\} \exp\left\{j2\pi \frac{f_0}{2v_a} x\right\} \\ &= j0.5m_a A \exp\{-j2\pi(v + f_0)t\} \exp\left\{j2\pi \frac{\sin \theta_B}{\lambda} x\right\} \end{aligned}$$

The first exponential shows that the +1-order-diffracted optical frequency is now $\nu + f_0$ compared to the input light of frequency, ν , indicating a positive Doppler shift. The multiplicative factor A in the diffracted optical field shows that the optical-field amplitude is proportional to the AO cell-drive voltage, A . The second exponential shows that the diffracted beam has a positive spatial frequency equivalent to the diffracted beam at a positive Bragg angle (above the z -axis). This example shows that the AO device forms an excellent amplitude controlled frequency shifter that finds many applications in laser systems requiring optical frequency shifts.

Example 3: Frequency-Controlled Beam Steerer

Given a Bragg-cell drive signal, $s(t)$, of amplitude A at the transducer mid-band frequency f_0 and a scan-angle frequency, f_s , in other words, $s(t) = A \cos[2\pi(f_0 + f_s)t]$, show the demonstration of a frequency-controlled positive-scan angle-beam steerer for the +1-order diffracted beam.

Solution

Express the single sideband signal $\tilde{s}(t) = 0.5A \exp[-j2\pi(f_0 + f_s)t]$, then one can insert this value for the +1-diffracted optical field to get

$$\begin{aligned}
 E_{+1}(x, t) &= j0.5m_a \exp\{-j2\pi\nu \cdot t\} \exp\left\{-2\pi \frac{f_0}{2v_a} x\right\} A \exp \\
 &\quad -j2\pi(f_0 + f_s)\left(t - \frac{x}{v_a}\right) \\
 &= j0.5m_a A \exp\{-j2\pi(\nu + f_0 + f_s)t\} \exp\left\{j2\pi \frac{f_0}{2v_a} x\right\} \\
 &\quad \exp\left\{j2\pi \frac{f_s}{v_a} x\right\} \\
 &= j0.5m_a A \exp\{-j2\pi(\nu + f_0 + f_s)t\} \exp\left\{j2\pi \frac{\sin \theta_B}{\lambda} x\right\} \\
 &\quad \exp\left\{j2\pi \frac{f_s}{v_a} x\right\}
 \end{aligned}$$

The last exponential term shows that the +1-order diffracted optical-beam spatial frequency is controlled by the scan-angle frequency, f_s . Specifically, the +1-diffracted beam is positioned at the start angle, θ_B , given by the second exponential term and the +1 beam scans up in angle for positive values of f_s . This example also shows that the Bragg cell acts as a RF-controlled spatial-frequency generator. If the optical system axis is defined as the positive Bragg-angle direction, we can drop the second exponential term. In addition, if the Doppler shift is

not of concern in the photonic system design, we can also drop the first exponential term and simply write

$$E_{+1}(x, t) \propto A \exp\left\{j2\pi \frac{f_s}{v_a} x\right\} = A \exp\left\{j2\pi \frac{\sin\theta_s}{\lambda} x\right\}$$

and for small angles, $\theta_s \approx \lambda f_s / v_a$. Hence a frequency-controlled beam steerer is formed.

Example 4: One-Dimensional (1D) Spatial-Light Modulator (SLM)

Given a Bragg-cell-drive signal, $s(t)$, of real amplitude, $a(t)$, and at the transducer mid-band frequency f_0 , in other words, $s(t) = a(t)\cos(2\pi f_0 t)$, also called a double-sideband modulation (DSB) signal, show that the +1-order diffracted field acts as a 1D SLM with the optical field proportional to the drive-signal voltage, $a(t)$.

Solution

Unlike a 2D SLM, such as a liquid crystal display (LCD), the AO Bragg-mode device is a line modulator also called a 1D SLM. The line aspect comes from the fact that the acoustic-signal modulation in the AO device travels like a 1D wave, and the optical beam that engages this 1D wave is approximately a line formed by optics, such as a cylindrical lens. Hence as shown in Figure 5.7, the signal-modulation sampler is a delta function in the direction orthogonal to the acoustic wave, while it is a line function in the acoustic wave direction, thus forming the suggested line modulator.

Express the single sideband signal $\tilde{s}(t) = 0.5a(t)\exp(-j2\pi f_0 t)$, then we can insert this value for the +1-diffracted optical field to get

$$\begin{aligned} E_{+1}(x, t) &= j0.5m_a \exp\{-j2\pi v \cdot t\} \exp\left\{-2\pi \frac{f_0}{2v_a} x\right\} a\left(t - \frac{x}{v_a}\right) \\ &\quad \exp\left\{-j2\pi f_0 \left(t - \frac{x}{v_a}\right)\right\} \\ &= j0.5m_a a\left(t - \frac{x}{v_a}\right) \exp\{-j2\pi(v + f_0)t\} \exp\left\{j2\pi \frac{f_0}{2v_a} x\right\} \\ &= j0.5m_a a\left(t - \frac{x}{v_a}\right) \exp\{-j2\pi(v + f_0)t\} \exp\left\{j2\pi \frac{\sin\theta_B}{\lambda} x\right\} \\ &\propto a\left(t - \frac{x}{v_a}\right) \exp\{-j2\pi(v + f_0)t\} \exp\left\{j2\pi \frac{\sin\theta_B}{\lambda} x\right\} \end{aligned}$$

The first term provides the 1D SLM operation; the second term provides the Doppler shift, and the third term represents the +1-order beam spatial/angular position at angle θ_B . For direct intensity $I(x, t)$ detection of the +1-order optical field, such as via a CCD camera, we can drop the two exponential terms as the time-integrated-charge

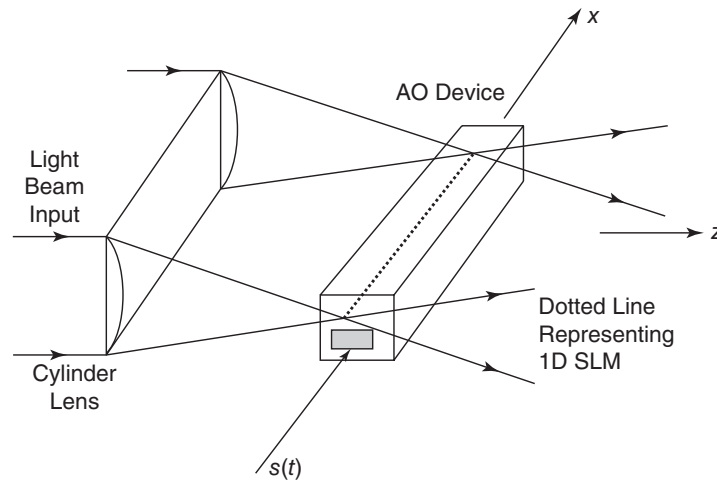


FIGURE 5.7 The geometry of the sampling light and acoustic-wave interaction in an AO Bragg cell that forms a 1D SLM line modulator.

distribution signal from the camera integrating for time, T , seconds can be written as

$$Q(x) \propto \int_0^T I(x, t) dt = \int_0^T |E_{+1}(x, t)|^2 dt = \left| a \left(t - \frac{x}{v_a} \right) \right|^2$$

Example 5: Time-to-Space Mapper

Can an AO device form a time-sequential line-signal generator?

Solution

Although the AO device is a traveling-wave device in which the input RF signal gets transformed into a spatially traveling signal seen within a finite time (or space) window with the AO crystal, it is possible to freeze the spatial signal in a time-sequential window by using stroboscopic or flash photography-like methods. Hence, as shown in Figure 5.8, a long time-duration 1D signal can be mapped to a space-time folded signal, much like a raster-scanned television image signal representation, in which the discrete time events occur when the light is pulsed to freeze the spatial signal in the Bragg cell. Specifically, the incident light acts like a repetitive short pulse of energy every time the AO device aperture fills up with a new spatial signal representing the aperture time of the cell. The short-pulse operation acts like a sampling delta function in time to take a snapshot of the spatial optical signal inside the Bragg cell that can be recorded by a 1D optical-image recording device like a CCD, a photographic film, a holographic material, or a 1D high-speed photodetector array. Thus a time signal of T_a duration is, mapped to a frozen spatial signal

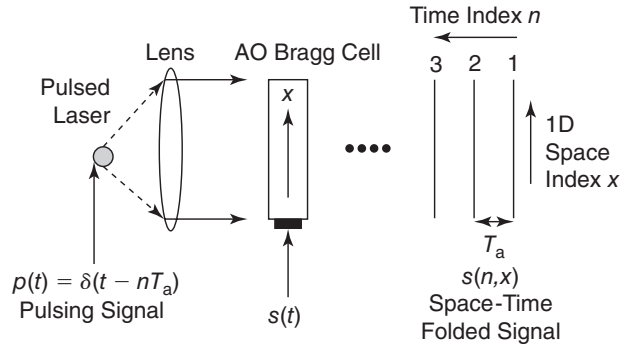


FIGURE 5.8 The AO Bragg-cell device shown in Figure 5.8 acting as a time-to-space mapper where a long $T = NT_a$ time-duration signal, $s(t)$, is converted to a space-time folded signal, where $n = 1, 2, 3, N$ represents the time-window number (an laser-pulse number), in which the signal $s(t)$ is captured.

of X spatial duration, forming a time to 1D space mapper, where $n = 1, 2, 3, \dots, N$, is the number of the laser pulse. For example, if the RF signal $s(t)$ is a long $T = NT_a$ time-duration signal, then N 1D spatial representations of the time signal seen in N time windows is produced in space, forming the space-time folded signal. To express this mapping operation mathematically for the case that the Bragg cell is driven by the AM signal $s(t) = a(t)\cos(2\pi f_0 t)$ with +1-order diffraction, the n th light-pulse-detected 1D spatial signal $Q(x, n)$ on the 1D imaging device can be expressed as

$$Q(x, n) \propto \int_0^{T_a} I(x, t) \delta(t - nT_a) dt = \int_0^{T_a} \delta(t - nT_a) |E_{+1}(x, t)|^2 dt = \left| a \left(nT_a - \frac{x}{v_a} \right) \right|^2$$

For example, $n = 1, 2, 3, \dots, N$ can represent the line number in a video signal, and T_a can be the video-line time duration with $1/T_a$ being the video-image line rate. In this way, a long time-duration (i.e., $T \gg T_a$) 1D time signal (called video signal) can be converted into independent 1D spatial signals representing the individual lines of the video signal where each line signal can be independently processed with its own spatial filter when implementing space-time photonic-processing using a programmable SLM to represent these filters. For example, high-resolution wide instantaneous-bandwidth temporal signal $s(t)$ RF spectrum analysis can be implemented via folded spectrum time and space processing via optics of a space-time folded or rastered signal $s(x, n)$ produced via an AO device operating with pulsed light. Using the pulsed-light viewing of the Bragg cell, we can even observe the 1D spatial-phase modulation in the AO cell if we use interferometric optical detection of the diffracted optical field, in other words, we can detect both a reference beam and the diffracted order on the same optical detector. Thus the AO Bragg cell provides system designers an option to exploit both its fast spatial and temporal-modulation strengths to reach system goals.

Example 6: Electronically Controlled Optical Tunable Filter

Can an AO device be used to rapidly filter light, such as following through an optical fiber or optical-imaging system?

Solution

The transverse spatial-light-modulation geometry for the AO device where the acoustic signal and optical beam are noncollinear, such as described earlier, behaves like a transmission grating interacting with a plane wave to deliver such AO Bragg-cell properties like RF-tuned beam deflection. The same geometry also forms a programmable grating spectrometer or *acousto-optic tunable filter* (AOTF) that via Bragg diffraction selects a given wavelength out of the incident light by controlling the RF. Although optical-filtering operations can be achieved with isotropic Bragg diffraction using isotropic-material AO devices like glass, these AOTFs have limited optical-resolving power. Specifically, resolving power R of the AOTF device is defined as $R = \lambda/\delta\lambda$, where λ is the incident wavelength and $\delta\lambda$ is the minimum resolvable-incident wavelength difference detectable by the AOTF. The wavelength selectivity of the AOTF is determined by the number of acoustic wavelengths Λ_a or optical grating periods produced in the AO interaction region.

For the traditional AO Bragg-cell deflector operated as an AOTF with f_a drive frequency, the maximum number of acoustic wavelengths in the AO interaction region is given by $R = T_a/(1/f_a) = T_a f_a$. Recall that T_a is the acoustic-wave transit time in the incident optical-beam aperture $X = v_a T_a$. Thus, for higher-wavelength selectivity or smaller values of $\delta\lambda$, we have to use as high an f_a as possible, implying that the acoustic attenuation in the crystal at high-electrical frequencies limits the classical Bragg cell from achieving good optical-tuning resolution. For a typical infrared-wavelength $\lambda = 1500$ nm AO deflector with $T_a = 10$ μ s and $f_a = 50$ MHz, the number of acoustic wavelengths in the AO interaction region is $R = T_a f_a = 500$, giving a moderate wavelength-tuning resolution of $\delta\lambda = \lambda/R = \lambda/(T_a f_a) = 1500$ nm/500 = 3 nm.

A more fundamental reason why isotropic Bragg diffraction limits AOTF performance is that the Bragg-matching condition is maintained for an exceedingly small incident-beam angular aperture or equivalently a very small optical bandwidth. It was discovered that anisotropic Bragg diffraction, more specifically AO diffraction in a birefringent medium like tellurium dioxide crystal, greatly alleviates this small incident-beam angular aperture limitation. Specifically, as shown in Figure 5.9, collinear AO interaction (i.e., acoustic and optical waves in same direction) in birefringent media (a medium with two refractive indices differing by Δn) achieves a wide-angular aperture for the incident beam and maintains the momentum (Bragg) matching condition for the fixed-direction acoustic-wave vector. In effect, the collinear geometry birefringent material AOTF provides a large optical bandwidth for

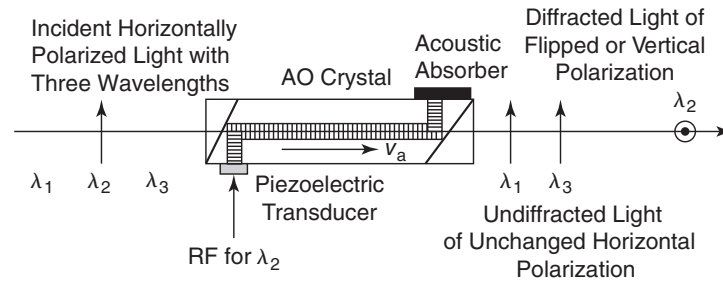


FIGURE 5.9 Collinear AOTF operation geometry where incident and diffracted beams are collinear. The AOTF acts as a wavelength selective-polarization switch. Shown for linear horizontal-polarization input light with three independent AOTF resolvable wavelengths.

optical tuning. In this case, $\delta\lambda = \lambda/R$ where $R = (X \Delta n)/\lambda$ implying $\delta\lambda = \lambda^2/(X \Delta n)$. Here X is the collinear AO interaction length. For a typical collinear AOTF design for $\lambda = 1500$ nm region, $X = 8$ cm, $\Delta n = 0.1$, we get a much-improved $\delta\lambda = 0.28$ nm.

As shown in Figure 5.10, an alternative AOTF design with particular noncollinear acoustic and optical-beam directions uses AO interaction (much like the classic AO deflector) in a birefringent crystal to also achieved good tuning results. For example, both collinear and noncollinear AOTF devices using birefringent materials have been designed to operate at spectral bands that range from visible to near infrared. A common AOTF device is for visible light (e.g., 400 to 700 nm) with applications such as white-light microscopy. Another AOTF device has been designed for fiber-optic wavelength-filtering applications in telecommunication bands of 1500 to 1600 nm.

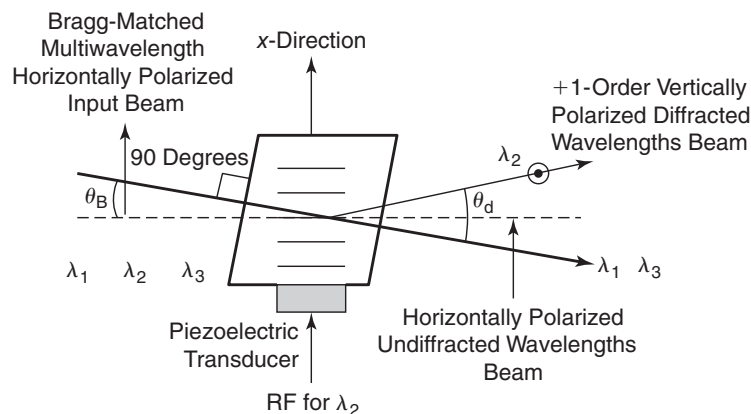


FIGURE 5.10 Noncollinear AOTF operation geometry where incident and diffracted beams are separated by a small angle. Shown for linear horizontal-polarization input light.

Typical $\delta\lambda$ resolutions range from 0.1 to 1 nm for many AOTFs. It has also been shown and demonstrated that AO diffraction in a birefringent crystal like tellurium dioxide produces a high-diffraction efficiency finely-tuned diffracted beam with an orthogonal polarization to the incident beam for a particular optical wavelength corresponding to a given AOTF-drive frequency. Thus a *wavelength selective-polarization switch* is formed that can be used to route or switch signals of the electronically chosen wavelengths.

Figure 5.11 shows the general noncollinear AOTF operation geometry where incident and diffracted beams are separated by a small angle. As shown, the input light has both horizontal and vertical polarization components that when passing through the birefringent crystal get a relative spatial displacement because of the differing refractive indices seen by the input plane waves of the different linear polarizations. Also shown are the appropriate Doppler-shift orders for the two diffracted beams indicating opposite Doppler shifts for the two orthogonal linear polarizations. These unique polarization and wavelength-dependent properties of the bulk crystal AOTF can be utilized for optimal system design, particularly since bulk AOTFs can handle high-watt-level optical powers and are mature commercial devices with great wavelength diversity.

An improved almost-collinear AOTF device design shown in Figure 5.12 uses acoustic and optical beams propagating in almost the same direction, producing incident and diffracted beams that are spatially separated and hence easily distinguishable, much like noncollinear design but with improved optical-tuning resolutions.

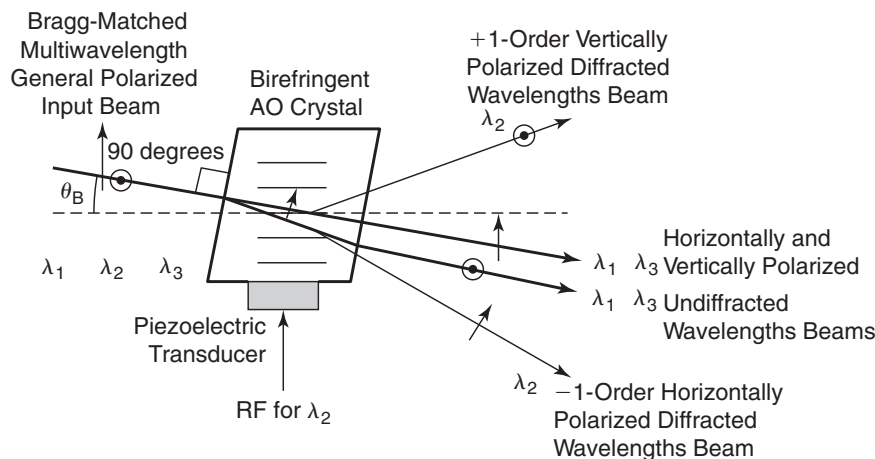


FIGURE 5.11 General noncollinear AOTF operation geometry where incident and diffracted beams are separated by a small angle. Shown for linear polarization-input light with both horizontal and vertical components. Also shows the appropriate Doppler-shift orders for the diffracted beams.

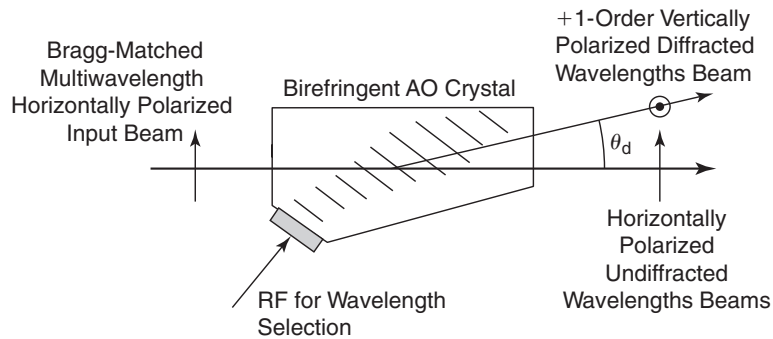


FIGURE 5.12 Almost-collinear AOTF operation geometry where incident and diffracted beams are separated by a small angle. Shown for linear horizontal-polarization-input light.

Liquid Crystal Devices

Liquid crystals (LCs) can be explained as follows. The classic three states of matter are determined by the degree of 3D spatial positional and orientational order of molecules. Solids have higher-order or tightly positioned and oriented molecules. Crystalline solids having a fixed pattern of molecules, and amorphous solids have no pattern. Liquids have medium order with very loosely positioned and oriented molecules. Gas has low ordering of molecules and so no positional order with the molecules having free molecular motion. As shown in Figure 5.13, LCs can be considered the fourth state of matter between a solid and liquid state determined by the LC material temperature, so LCs have no positional order and some orientational order and are more like liquids than solids.

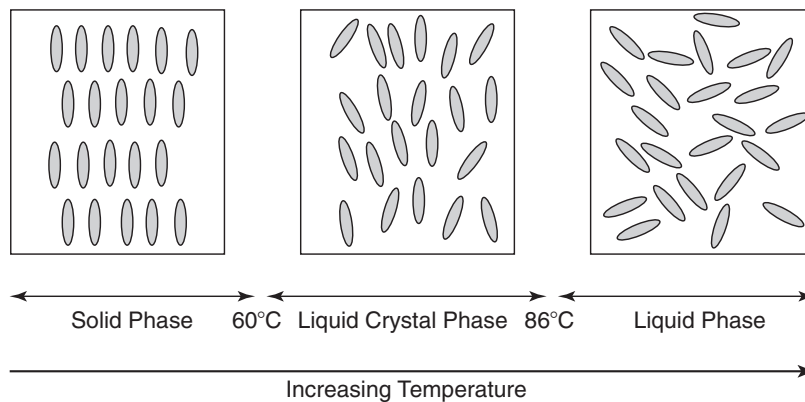


FIGURE 5.13 Molecular 3D spatial positional and orientation-order changes with temperature increases as the material passes from the solid phase to the liquid crystal phase to the liquid phase. The oblong-shaped objects represent the molecules in the material make-up.

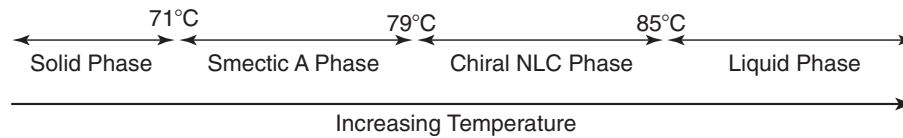


FIGURE 5.14 LC phases for the cholesteryl myristate LC material for increasing temperatures.

Figure 5.14 shows a variety of LC phases for the cholesteryl myristate LC material for increasing temperatures. In the nematic (Greek for thread) phase, on average, the molecules are oriented along one direction. In the chiral (Greek for handedness) twisted NLC phase, the nematic director undergoes a periodic twist about a horizontal axis. The nematic director represents the average direction/orientation of the molecules. In the smectic-A phase (smectic is Greek for soap), molecules are arranged in layers with the molecular director at 90° to the layer planes. In the smectic-C phase, molecules are arranged in layers with the molecular director not at 90° to the layer planes. The chiral smectic-C* (ferroelectric LC or FLC) phase is like the smectic-C phase, except the director rotates from one molecular layer to another layer, tracing a cone of a fixed angle with one complete rotation called a pitch or distance between layers. The FLC phase maintains molecules with a permanent inherent dipole moment sensitive to the direction of electric field.

Austrian botanist Friedrich Reinitzer is credited with the discovery of LCs in 1888. He observed two melting temperatures for cholesterol (a chiral nematic LC phase) in plants. German physicist Otto Lehmann (1850–1888) invented and developed a polarization microscope with a material-heating stage to study properties of LC materials. This instrument was critical to the study of LCs. French scientist Georges Friedel's 1922 paper described the different LC phases. Swedish scientist Carl Oseen and English scientist F. C. Frank, between 1922 and 1939, developed the elastic and continuum theory for LCs. American scientist (1969) James Ferguson, German scientist (1970) Wolfgang Helfrich and Swiss Scientist (1970) Martin Schadt co-pioneered twisted NLC (or TNLC) displays.

In the nematic phase shown in Figure 5.15, on average, the molecules are oriented in a direction given by the nematic director. The NLC material is made of long cigar-like molecules made by long chains of carbon, hydrogen, and oxygen.

One basic NLC device is the parallel-rub (also called anti-parallel rub) birefringent-mode (BM) NLC device. The device is made by sandwiching two thin glass plates that are rubbed (coated) with the long cigar-like NLC molecules. The device is sealed so the NLC molecules stay within the glass encasing. The inner surface of the glass plates also has a thin layer of transparent metal, such as made of indium tin oxide (ITO) that acts as electrodes to the device. The NLC molecule

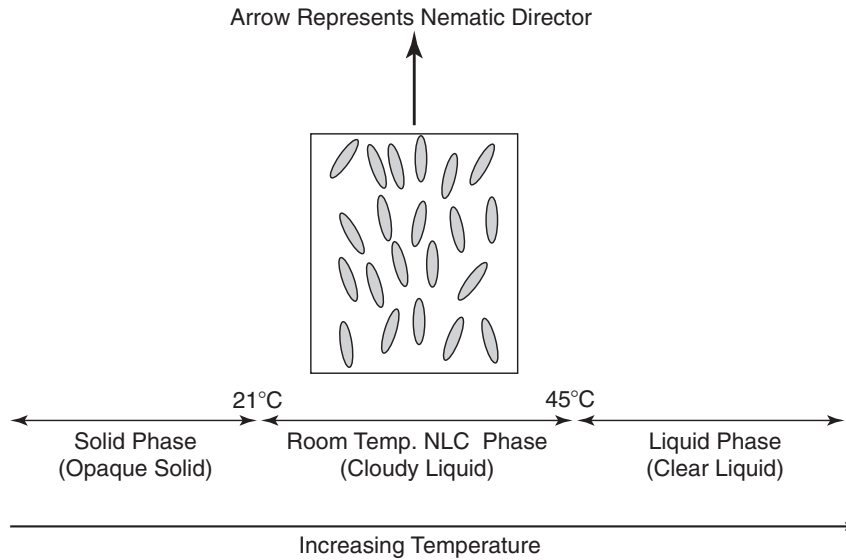


FIGURE 5.15 Transition to the nematic LC phase, most commonly used for the manufacture of LC displays.

sits in 3D space (see Figure 5.16) such that its nematic director (also the long axis of the molecules) points in a defined y -direction, where the material refractive index is n_e or the extraordinary index of the material. In other words, for a light beam with its polarization or E -field direction in the y -direction, the light field experiences the n_e index of refraction. In contrast, in the x - and z -directions, the refractive index of the material is the same and is n_0 , the ordinary index of the material. So if the incident optical field is in the x -direction (the beam travel is in the z -direction), the light field experiences the n_0 index of refraction. In effect, the NLC material in its natural state (when basically no voltage is applied to the device, i.e., $V = 0$) has two indices of refraction; hence, called the birefringent material. The external electric field, E , applied via the external voltage source, V , induces a dipole moment in the NLC molecules that rotates the molecular director towards the E -field direction. Hence a voltage-dependent refractive index, $n(V)$, is seen by the optical field with polarization in the y -direction. On the contrary, the polarization in the x -direction continues to see the n_0 index. The electric-dipole moment per unit LC volume is equal to the LC electric polarization, P , and the external E -field and LC polarization, P , are directly connected by the LC refractive index $n(V)$ seen by the incident optical field. Hence, a voltage-controlled optical phase-shifting device is formed when light incident has some polarization component in the y -direction of the shown device.

Figure 5.17 shows a basic 90° twist-mode NLC device. Unlike the BM-NLC device, the cell contains NLC molecules that undergo

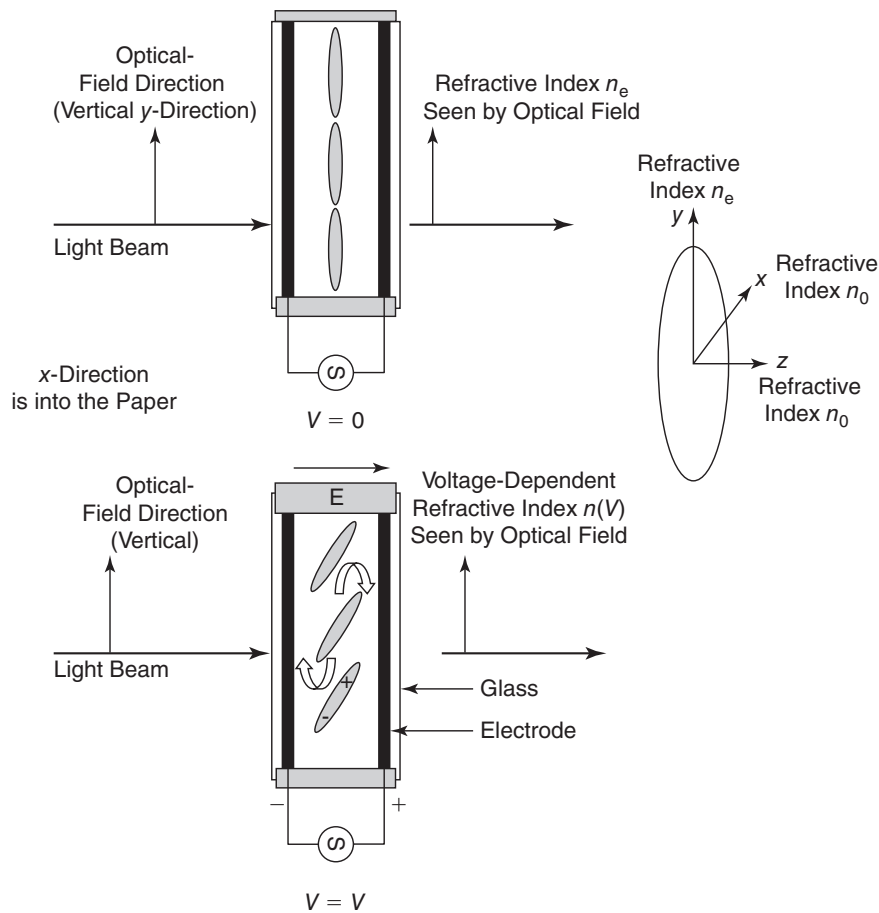


FIGURE 5.16 The design and operation of the parallel-rub birefringent-mode (BM) NLC device. This device, when placed between parallel or crossed polarizers, acts as a voltage-controlled shutter. In this case, the input-polarization axis is at 45° to the shown vertical/horizontal axis.

a 90° twist. This is achieved by using NLC-rubbed glass plates with orthogonal rub directions. When these plates are sandwiched together, there is a natural 90° rotation of the NLC molecules between the glass plates and incident-light linear polarization follows this twist when it passes through the device. As an example, when a 5-V drive is used, it basically removes the LC twist in the device and light linear polarization passing through stays unperturbed. When such a device is placed between crossed polarizers, it acts as a voltage-controlled variable optical shutter. The input-polarizer polarization axis is aligned with the device vertical axis to form a shutter, such as a pixel in an LC display. See problems at end of chapter for the design of attenuators using NLC devices.

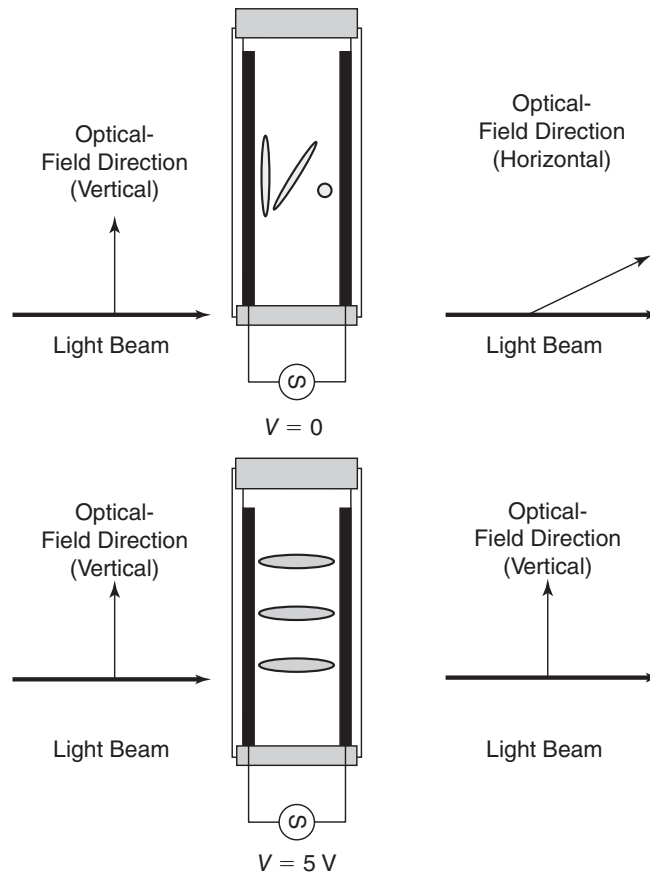


FIGURE 5.17 The basic 90° twist-mode NLC device operating in its two extreme states.

Because the BM-NLC device is fundamentally a polarization sensitive optical phase shifter device, the spatial zone in an NLC device can be electrically programmed to produce a desired map of optical-phase shifts imparted to an incident laser beam. The particular optical-phase values on the device can be encoded by having a multipixel device like an LC display design with each pixel electrode provided a specific voltage to produce a specific optical-phase shift. Depending on the NLC device design, including electrode and NLC material designs, the NLC device can exhibit both a linear and quadratic optical-phase shift response with linearly increasing voltage such as shown in Figure 5.18.

The linear optical-phase-shift response of a BM-NLC device can be used to design a variable tilt-angle prism for a laser beam that does not require the change of optic. As shown in Figure 5.19, the BM-NLC device can have its molecules programmed such that they produce a linear refractive-index change across its 1D spatial

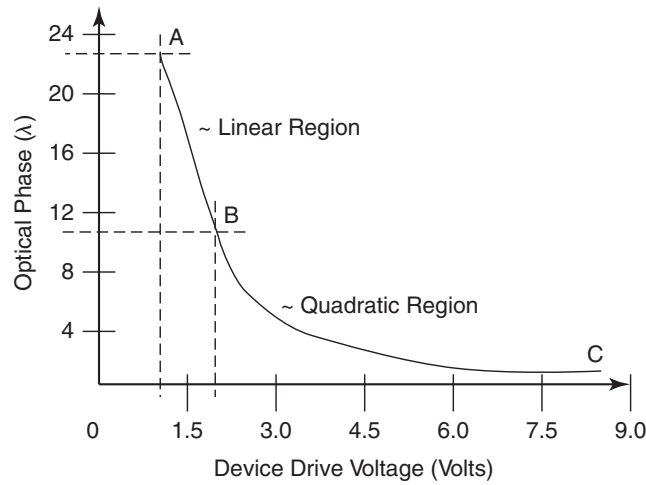


FIGURE 5.18 The optical-phase shift provided by a BM-NLC device can exhibit both a linear (from A to B) and quadratic (from B to C) region of optical-phase shifts versus drive voltage.

direction to allow the formation of a 1D beam-tilting optic. By controlling the electrical drive of the NLC device, the tilt angle across the device can be varied, allowing the variable tilt-angle deflection of the incident vertically polarized laser beam. For the horizontally polarized beam, only the ordinary index is seen at all

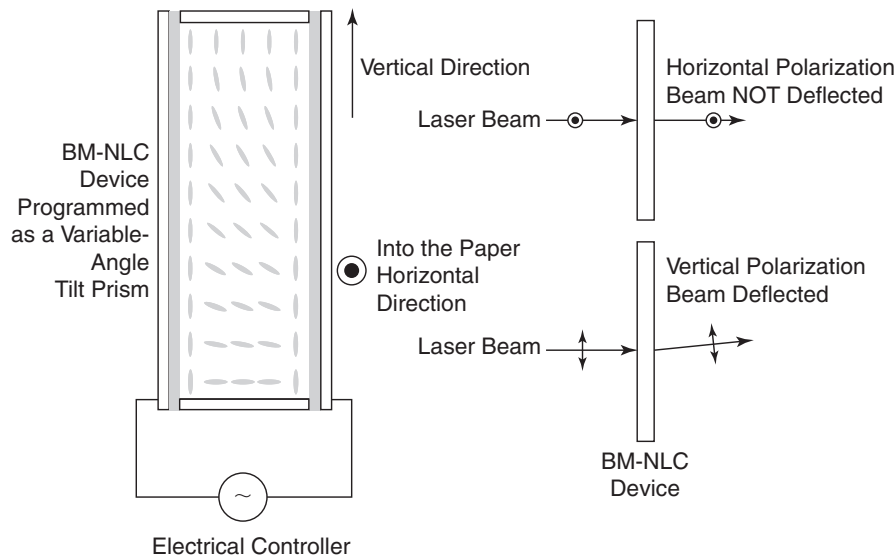


FIGURE 5.19 Electronically programmable BM-NLC beam deflector device.

times and so this beam is not deflected. Hence, a polarization-sensitive electronically controlled deflector is formed between two parallel sheets of glass, allowing the easy stacking of similar flat optics versus use of bulk prisms with nonparallel top and bottom surfaces. Note that based on the thickness of the BM-NLC device and the NLC material birefringence, a variety of tilt angles can be generated, but typically the angles are under a degree for the refractive-type device where the entire device acts as a refractive tilt plate. It is possible to get higher-tilt angles, but using the device in a diffractive grating-style mode that uses many repetitive index variations across the face of the device to produce the steeper-tilt angles reaching 50° depending on the pixel size and pitch in the BM-NLC device. The pixelated device can also be programmed as an x - y or 2D beam deflector with beam deflections in both the x - and y -directions in space.

Another BM-NLC device is an electronically controlled variable focal-length lens (ECVFL). In this case, we can use the quadratic phase-shift versus voltage regime of a BM-NLC device to produce a quadratic lens-like index variation across the device. Figure 5.20 shows such a variation and the vertically polarized laser beam sees this lensing and hence produces a focused beam spot. The horizontally polarized beam does not see this refractive index change and hence stays unchanged.

BM-NLC devices and TN-LC devices can be used to form a variety of photonic-engineering modules such as optical switches, equalizers, attenuators, and programmable processors. The key aspect is that LC devices are polarization-sensitive electronically-controlled devices, and they can be designed with other photonics to fulfill engineering functions.

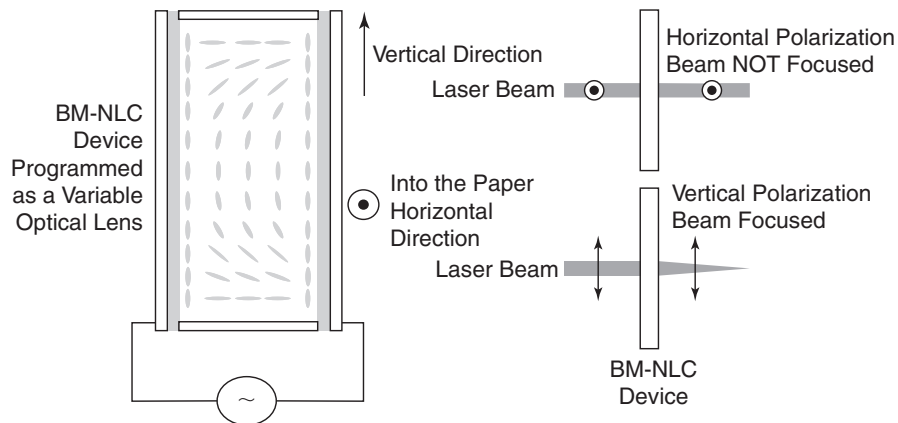


FIGURE 5.20 Electronically programmable BM-NLC beam-lensing device, also called a ECVFL.

Mechanical Devices

A number of mechanical devices have optical capabilities, prominent amongst them is the optical mirror placed within a mechanical-motion framework controlled by dedicated microelectronics. The mirror is probably the most-deployed optical element in photonic systems, as the mirror has many features including the leading feature of handling wide-spectrum light. Hence, Figure 5.21 shows a baseline design for such an opto-mechanical device based on the mirror-optic element. The device can scale from micrometers to meters depending on the application. For example, a scan mirror within an endoscope for medical imaging may be $100\text{ }\mu\text{m}$ in diameter while a large diameter telescope wave-front-control mirror-based device for astronomical-imaging applications can be several meters in diameter. The motion-mechanics actuator technology deployed to produce a desired mirror-motion such as tilt, piston in-out of mirror-plane translation, and mirror-positive or -negative curvature to induce lensing can be different ranging from micro-electro-mechanical systems (MEMS), nano-electro-mechanical systems (NEMS), piezoelectrics, to fluidic (using liquids).

The mirror-based baseline optomechanical device shown in Figure 5.21 is of rectangular shape, although any desired shape can be fabricated given fabrication-technology constraints. For example, a circular or elliptical device shape is suited for interaction with laser beams produced by various laser devices types that naturally produce circular-like or elliptical-shape beams. The Figure 5.21 device shown has multiple independently controlled square mirrors with a fixed pixel-pitch layout in a 2D grid. The number of mirrors can range from one mirror in the device to multiple mirrors of various shapes in the device. The mirrors can also be placed in a 1D grid, like parallel long ribbons on the device plane. The response time of a mirror on the device depends on many factors, such as size and weight of mirror, actuation technology, required mirror-motion range, and mirror stiffness. Hence response

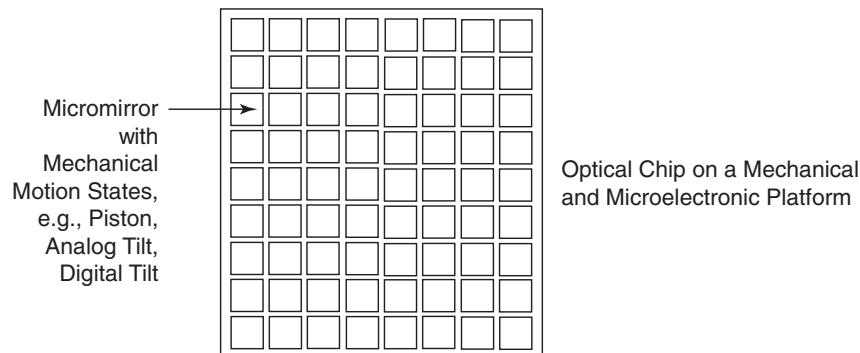


FIGURE 5.21 A baseline design of an opto-mechanical device based on the mirror-optic element with chip containing motion mechanics and its control microelectronics.

time can range from seconds to sub-microseconds. One type of opto-mechanical device is the deformable mirror (DM) membrane device, where a single piece of mirror-membrane surface can be deformed by multiple actuators behind the membrane to produce a near-smooth surface optical-beam manipulation device. Such a device is used in visual optical-imaging systems where the device forms an adaptive optic-wave-front control device. In this case, the mirror motion is of the piston type, moving in and out of the direction of the optical beam. A few optical wavelengths' piston motion is commonplace with small (under 1-cm diameter) devices using piezoelectric actuation. The single mirror device has also found use as a two-axis tilt mirror in optical-switching systems, and multiple arrays of such mirrors have been fabricated in a single device using MEMS technology.

The Figure 5.21 device as shown resembles the layout of the famed Texas Instruments (TI) Digital Micromirror Device (DMD) where over one million tiny mirrors are electrically actuated to produce one of two 1D tilt states, for example, $+10^\circ$ and -10° . Hence, a highly reliable digital-state optical device is formed. The DMD has been extensively used for color projectors, where time modulation of the microseconds reset time-digital micromirrors (each micromirror can have, for example, a $10\text{-}\mu\text{m}$ diameter) in the DMD have been used to produce light grayscale necessary in human-viewed imaging. Hence, the DMD forms a robust fault-tolerant device given its many micromirrors suitable for manipulating light in both its spatial and temporal dimensions.

Figure 5.22 shows how two liquids, such as oil and water, can be used to design a moving optical surface controlled by a voltage (e.g., via a process known as electro-wetting) to realize a programmable-

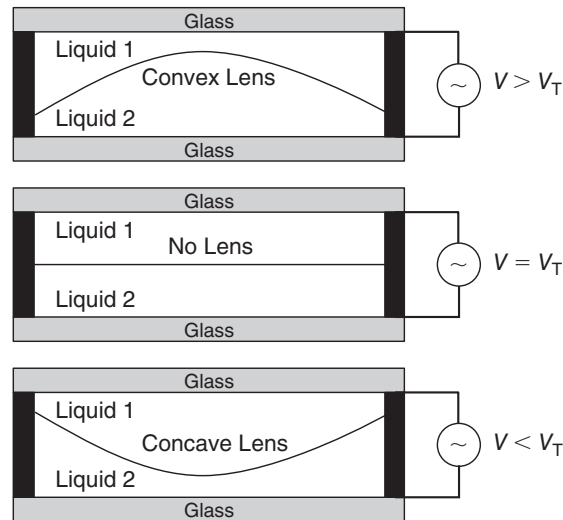


FIGURE 5.22 Opto-mechanical device using a moving two-fluid boundary to produce a variable focal-length lens.

lens optical element. In effect, a conductive fluid in contact with a nonconducting fluid can have its two liquids-interface surface tension electrically controlled, leading to change in the interface radius of curvature. Hence, a variable wave-front -control optical-lens element is formed. Compared to the large 3-mm-diameter NLC lens, the liquid lens is generally not polarization sensitive, but typically has a slower response time (e.g., ~ 1 s) versus milliseconds of NLC lenses. Such liquid-lens elements have been deployed in miniature-imaging systems amongst other applications, such as switches, attenuators, and 3D mapping sensors.

Fiber-Optic Devices

The optical fiber is one of the greatest inventions using light. Fundamentally, the optical fiber is a flexible light pipe that transports light energy from the input end of the fiber to the output end of the fiber. John Tyndall (1820–1893), the Irish scientist, was one of the early demonstrator's of light transport via total internal reflection (TIR) in a water pipe, the forerunner of the modern glass or plastic-optical fiber. As shown in Figure 5.23, the classic glass fiber is constructed using two glass materials of slightly different refractive indices, one used for the core of the fiber and one used for the cladding around the core to produce TIR via repeated application of Snell's law of refraction at the boundary of two different optical media.

The multi-mode fiber (MMF) has many independent angular rays (spatial modes) supported by fiber propagation. The MMF is considered a large-mouth (or large numerical aperture, or NA) fiber when compared to the light wavelength and hence accepts a large cone of rays into the fiber. Interfacing from external-light sources to MMFs is easier because of the tolerance to acceptance angle variations and, as such, MMFs are widely used in lower data-rate applications over moderate distances (e.g., within tens of meters depending on data rate, of say, 10 Mbps or 10 MHz). MMFs also are excellent for delivery of raw optical power to hard-to-get places via remote access.

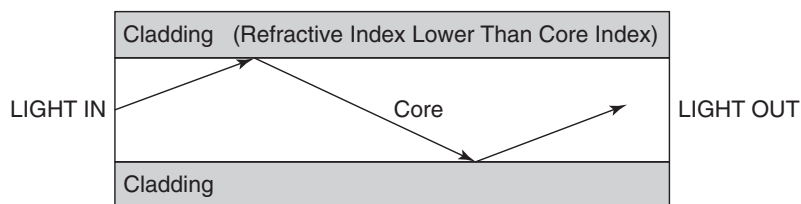


FIGURE 5.23 The basic principle behind the light pipe or modern-day optical fiber, in which light is guided in the core of the pipe via total internal reflections at the interface between the core and cladding. A curved water flow from an elevated tap can also guide light where water becomes the high refractive-index core and air becomes the lower-index cladding.

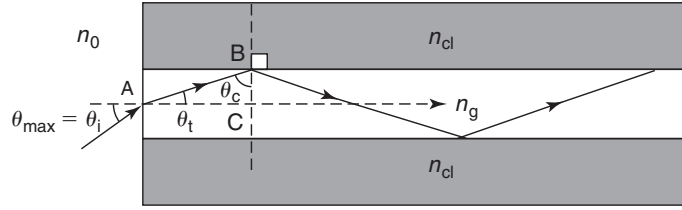


FIGURE 5.24 The maximum angle, $\theta_{\max}$, of a light ray a given optical fiber can accept for guiding within the fiber can be computed using Snell's law at the various interfaces in the fiber. The refractive indices for the air, core glass, and cladding are defined as n_0 , n_g , and n_{cl} , respectively.

Many laser ablation and damage systems deliver raw (watts) optical power for machining and cutting applications.

Figure 5.24 shows the maximum angle, $\theta_{\max}$, of a light ray a given optical fiber can accept for guiding within the fiber. NA of a fiber is given as $NA = n_0 \sin \theta_{\max}$. The angle $\theta_{\max}$ can be computed using Snell's law at the various interfaces in the fiber. First, we apply Snell's law at the fiber core-cladding boundary to get

$$n_{cl} \sin 90 = n_g \sin \theta_c$$

$$n_{cl} = n_g \sin \theta_c$$

Since $\theta_t = 90 - \theta_c$,

$$\frac{n_{cl}}{n_g} = \sin \theta_c = \sin(90 - \theta_t) = \cos \theta_t$$

Applying Snell's law at the air-core boundary,

$$n_0 \sin \theta_i = n_g \sin \theta_t$$

$$\sin \theta_t = \sqrt{1 - \cos^2 \theta_t} = \sqrt{1 - \left(\frac{n_{cl}}{n_g}\right)^2}$$

$$n_0 \sin \theta_i = n_0 \sin \theta_{\max} = n_g \sqrt{1 - \left(\frac{n_{cl}}{n_g}\right)^2}$$

$$NA = n_0 \sin \theta_{\max} = \sqrt{n_g^2 - n_{cl}^2} \quad \text{where} \quad NA \leq 1$$

Like a camera aperture, the speed or $F/\#$ of a fiber is inversely proportional to its NA and is specifically given as $F/\# = 1/(2NA)$. The light cone of acceptance into the fiber is symmetric about the fiber

axis and hence the $2\theta_{\max}$ factor is used in the $F/\#$. Optical-fiber fabricators can optimize the refractive indices for fiber fabrication to increase the NA where applications require large NA so many spatial fiber modes can propagate in the fiber. When the opposite is needed (e.g., a single spatial mode in the fiber is requested) the difference between the core and cladding indices is kept very small, for example, 0.01. Hence, a single-mode fiber (SMF) is formed. The SMF is the workhorse of the optical telecommunications industry and is suited for very high data-rate communications.

As shown in Figure 5.24, a fiber can support the central on-axis ray (along AC), as well as the steepest entry ray (along AB) at incidence angle $\theta_{\max}$ and all the rays in between the steepest ray and the on-axis ray. In the SMF, only the on-axis single ray exists as the single-spatial mode. In a MMF, many rays exist. Given that electrical data is represented as a light pulse (representing a 1 in a 1,0 digital data stream) that is input into the fiber, the input-pulse photons can take many different routes of the many spatial modes in a MMF. In effect, as shown in Figure 5.25, if the data photons travel different paths, then at the exit of the fiber when the pulses add up, they appear out of time and hence appear as a time spread of temporally dispersed broader pulse. This effect of spatial-mode dispersion in a MMF greatly limits data bandwidths for a given fiber length as pulses in sequence will begin to overlap and hence will be hard to separate in time for data recovery. Mathematically, we can compute the relative time delay between the axial mode (central ray) and the highest modes (steepest ray) per unit length of fiber. Using Figure 5.24, we can compute the propagation time for the axial ray over the length of fiber $AC = l_0$ to be given as

$$t_{\min} = \frac{AC}{v_g} = \frac{l_0 n_g}{c}$$

where c is the speed of light in vacuum/air. The propagation time for the highest-order ray over the length AB is given as

$$t_{\max} = \frac{AB}{v_g} = \frac{l_0}{\cos \theta_t} \frac{n_g}{c} = \frac{l_0 n_g}{n_{cl}} \frac{n_g}{c} = \frac{l_0 n_g^2}{c n_{cl}}$$

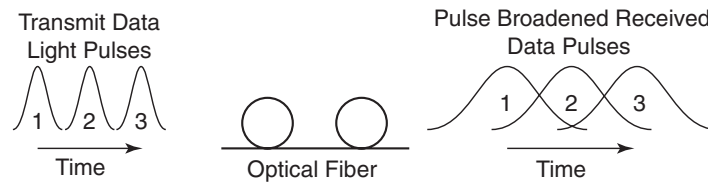


FIGURE 5.25 A data optical-pulse train input into an optical fiber shown to suffer pulse broadening due to spatial-mode dispersion effects in the fiber waveguide that supports multiple spatial modes as in the MMF.

The distance AB and AC are studied as the rays through the fiber follow a symmetrical path and repeat the travel of these distances along the fiber length. Hence, we can simply study the light travels along the defined paths AB and AC. The relative time delay, Δt , between the axial mode and the highest-order mode should be minimized to reduce pulse broadening and achieve the highest data rate per unit length of fiber. In other words, $\Delta t/l_0$ should be kept at a minimum. Using the derived time delays for the two extreme spatial modes, we can write

$$\Delta t = t_{\max} - t_{\min} = \frac{l_0 n_g^2}{c n_{cl}} - \frac{l_0 n_g}{c} = \frac{l_0 n_g}{c} \left(\frac{n_g}{n_{cl}} - 1 \right)$$

and hence,

$$\frac{\Delta t}{l_0} = \frac{n_g}{c} \left(\frac{n_g}{n_{cl}} - 1 \right)$$

Using index values of $n_g = 1.6$ and $n_{cl} = 1.5$, we compute a pulse temporal dispersion in a MMF to be $\Delta t/l_0 = 0.36 \mu\text{s}/\text{km}$. In effect, an input Delta function pulse (in theory with zero-time duration) will spread to $0.36 \mu\text{s}$ after a 1 km of travel in the MMF. Thus, assuming a data bit duration is Δt , then the maximum possible data rate for the given L km MMF would be

$$B_T = \frac{l_0}{\Delta t} \frac{1}{L}$$

With $L = 1$ km, we get $B_T = 1/0.36$ Mbps as $\Delta t/l_0 = 0.36 \mu\text{s}/\text{km}$. Typically, a data bit is smaller than the expected Δt broadening, so there is a guard band between two consecutive bits in a data stream. For example, if the guard band is $0.5\Delta t$, then the maximum bit rate is $0.5/\Delta t$; hence, lower than a zero-guard band stream. The design engineer can choose what is best for a desired bit error rate (BER).

Another useful parameter for an optical fiber is the optical attenuation factor given by L dB/km with optical loss in the fiber expressed in decibels as

$$\text{Optical Loss(OL) in dB} = 10 \log 10^{-L(l_0/10)}$$

where l_0 is the fiber length in kilometers. For example, for a 10-km fiber with the attenuation factor of 2 dB/km, the optical loss for light passing through the fiber length comes to be

$$\text{Optical Loss (dB)} = 10 \log 10^{-2(\text{dB/km})(10\text{km}/10)} = -20 \text{ dB}$$

High-quality SMFs have very low attenuation factors of <0.1 dB/km at the standard telecom wavelengths around 1550 nm. Recall that the SMF ideally has only one spatial mode so one can expect no pulse broadening due to spatial mode dispersion in the fiber. Nevertheless, the optical pulse representing a bit in time has a temporal-frequency spread about its light-carrier wavelength. From Fourier transforms of signals, note that the spectrum (or Fourier transform) of a square pulse in time shows up as a sinc function in the temporal (not spatial) optical-frequency domain. Hence, the shorter the bit time, the wider the optical spectrum centered on the carrier wavelength. Because the refractive index of the fiber is a function of the optical wavelength (or frequency), different signal frequencies experience different refractive indices and hence different parts of the signal-frequency content show up with a different time delay while passing through the fiber. This effect is termed *material dispersion*, as it is caused by the material properties of the waveguide. Related with atomic data and the light frequency f , the index of refraction, $n(f)$, of the material is given as

$$n(f) \approx 1 + k \frac{1}{(f_0^2 - f^2)}$$

where k represents a formula comprising the concentration of atoms in the material, electronic charge, electron mass, and the permittivity of freespace ϵ_0 . f_0 is the resonant frequency of the electrons in the material, and f is the frequency of the light. As an example, only one f_0 is chosen. As f increases, the index of refraction decreases. The opposite happens when the index variation is considered with respect to the wavelength λ . n is higher for blue light at $\lambda = 488$ nm than for red light at $\lambda = 633$ nm. As mentioned, on a fundamental level, material dispersion is related to the characteristic resonance frequencies at which the material absorbs the electromagnetic radiation. Far away from such resonant frequencies, the refractive index n is well approximated as a function of angular frequency $\omega = 2\pi f$ by the Sellmeier equation given as

$$n^2(\omega) = 1 + \sum_{j=1}^M \frac{B_j \omega_j^2}{\omega_j^2 - \omega^2}$$

where ω_j is the resonance frequency and B_j is the oscillator strength at the corresponding resonant frequency. In the case of the modern-day optical fiber, $n(\omega)$ can either be the core index or the cladding index. B_j and ω_j are obtained experimentally through fitting the measured dispersion curves to the general Sellmeier equation with $M = 3$. B_j is dependent on fiber dopants and for pure silica are $B_1 = 0.696$, $\lambda_1 = 0.068 \mu\text{m}$, $B_2 = 0.407$, $\lambda_2 = 0.116 \mu\text{m}$, and $B_3 = 0.897$, $\lambda_3 = 9.890 \mu\text{m}$ where $\lambda_j = 2\pi c/\omega_j$, $j = 1, 2, 3$. Figure 5.26 shows an example of the silica (BK7 glass) refractive-index behavior with optical wavelength.

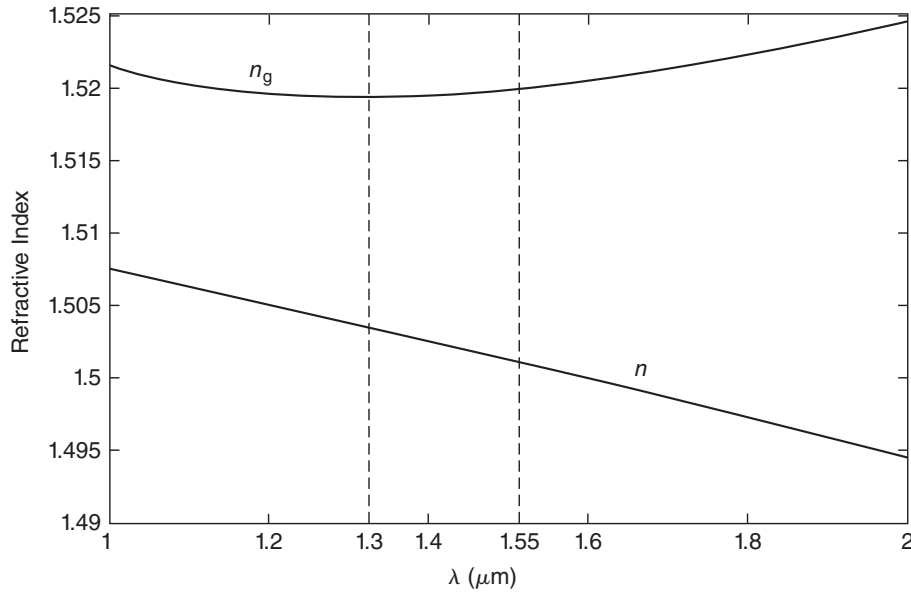


FIGURE 5.26 Silica (BK7 glass) refractive index behavior with optical wavelength.

Using the n experimental data with ω , we can compute the group refractive index, n_g , from $n_g = n + \omega \cdot (dn/d\omega)$. The group index is applied to experimental design when we are dealing with a simultaneous group of data-signal frequencies. Given that a typical data bit is a temporal pulse like a square-shaped pulse, then we know that the pulse is made up of many temporal frequencies. Hence the group index is critical to understanding how long a pulse takes to travel through the fiber. For a fiber made of silica (BK7 optical glass), the computed group index n_g is shown for the wavelength range $1\mu\text{m} < \lambda < 1.6\mu\text{m}$. The behavior of the group index is important to the design of fiber-optic telecommunication systems. An important parameter for a given fiber is its material dispersion D_M that is given by

$$D_M = \frac{1}{c} \cdot \left(\frac{dn_g}{d\lambda} \right)$$

It turns out that $dn_g/d\lambda = 0$ at $\lambda_{\text{ZD}} = 1.276\mu\text{m}$ (only for pure silica), where λ_{ZD} is called the zero dispersion (ZD) wavelength with

$$D_M = 0 \quad \text{at} \quad \lambda = \lambda_{\text{ZD}}$$

$$\lambda < \lambda_{\text{ZD}} \quad D_M: \text{Negative}$$

$$\lambda > \lambda_{\text{ZD}} \quad D_M: \text{Positive}$$

Figure 5.26 indicates where n_g has zero slope indicating a near 1300-nm wavelength position for zero material dispersion. Note that in the 1550-nm wavelength location, the slope is positive; hence fiber dispersion is a positive number. In the λ range of 1.25 to 1.66 μm , an experimental relation gives D_M as

$$D_M \approx 122 \left(1 - \frac{\lambda_{\text{ZD}}}{\lambda} \right)$$

In general, λ_{ZD} for a commercial optical fiber depends on the fiber-core radius and index step, Δn , between core and cladding. Both core- and cladding-material silica are doped to vary their refractive indices. Modern silica SMFs typically have λ_{ZD} of 1300 nm and hence to reduce signal distortions are the choice wavelength for transmission of analog signals, such as microwave-radar signals. For digital-signal communications, the 1550-nm band is the choice band where the optical-fiber loss is minimal compared to the 1300-nm band.

Another parameter used in fiber-optic system design is the fiber group velocity dispersion (GVD) parameter β_2 that is dependent on light temporal characteristics that come from both the original laser-source spectrum and the data time modulation imprinted on the laser light. Consider a SMF of length L (and not a MMF, which would have spatial modal dispersion). For data-modulated light with center frequency, ω , and spectral spread, $d\omega$, we can compute the time delay, T , in the fiber the data pulse experiences by using the group index with $T = L/v_g$. The group velocity v_g can also be given by $v_g = (d\beta/d\omega)^{-1}$, where $\beta = nk_0 = n\omega/c$. By using v_g and β , we can show that $v_g = c/n_g$, where n_g is the group index given by $n_g = n + \omega(dn/d\omega)$. The frequency dependence of the group velocity leads to pulse broadening because as mentioned earlier, different spectral components of the data pulse disperse during fiber propagation and hence do not arrive simultaneously at the fiber output. If $\Delta\omega$ is the spectral width of the pulse, the extent of pulse-broadening ΔT for a fiber of length L is given as

$$\Delta T = \frac{dT}{d\omega} \Delta\omega = \frac{d}{d\omega} \left(\frac{L}{v_g} \right) \Delta\omega = L \frac{d^2\beta}{d\omega^2} \Delta\omega$$

$$\Delta T = L\beta_2\Delta\omega$$

where the GVD parameter is defined as $\beta_2 = d^2\beta/d\omega^2$. For single-wavelength carrier-optical communications, $\Delta\omega$ is determined by source wavelength λ 's spread $\Delta\lambda$ as the electrical modulation data-spectral width is generally a small fraction of the laser-source spectral width. Thus, the laser spectrum dominates the data pulse-spreading

effect, and engineers make every effort to control this spectrum to minimize effects on data BERs. As angular frequency and wavelength are related, the pulse spread can be represented via the wavelength-spread domain and written as $\omega = 2\pi c/\lambda$, which after a derivative implies $\Delta\omega = (-2\pi c/\lambda^2)\Delta\lambda$. Using the earlier mentioned expression for ΔT , we can write

$$\begin{aligned}\Delta T &= L \beta_2 \Delta\omega \\ &= L \beta_2 \left(-\frac{2\pi c}{\lambda^2} \right) \Delta\lambda \\ \Delta T &= L D \Delta\lambda \quad \text{where} \quad D_M = \beta_2 \left(-\frac{2\pi c}{\lambda^2} \right) = \frac{d}{d\lambda} \left(\frac{1}{v_g} \right)\end{aligned}$$

D_M is the material dispersion parameter of the fiber typically expressed in ps/(km-nm).

The bit rate, B_T , of a digital data signal, as shown in Figure 5.27, also called the data rate, can be written as $B_T = 1/T$, where T is the bit period in seconds and $T = 1/B_T$. For error-free communications, two adjacent bits should not spread or stretch in time to reach the interbit discriminatory boundary, that is, the data-pulse spreading $\Delta T < T$ or $\Delta T \times (1/T) < 1$, which leads to the condition that $B_T \Delta T < 1$. Given that for a SMF, one can write $\Delta T = L D \Delta\lambda$, the condition for error-free communications in a SMF becomes

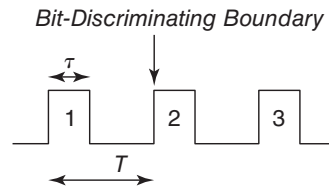
$$B_T L |D_M| \Delta\lambda < 1$$

In general, the dispersion parameter, D , for an optical fiber can be written as a sum of the fiber-material dispersion and the fiber-waveguide dispersion D_W giving $D = D_M + D_W$.

Many photonic systems use SMFs coupled with freespace optics, such as bulk micro-optical components. Figure 5.28 shows birefringent (e.g., made of calcite crystal) beam-displacing prisms (BDPs) that act as polarization components separating or combining the vertical (V) and horizontal (H) linear polarizations of a light-beam interfacing with the BDP. The size, wavelength, and refractive indices of BDP material dictates the physical separation at the exit of the BDP for the

FIGURE 5.27

Shown is a digital-bits data stream of 3 bits.



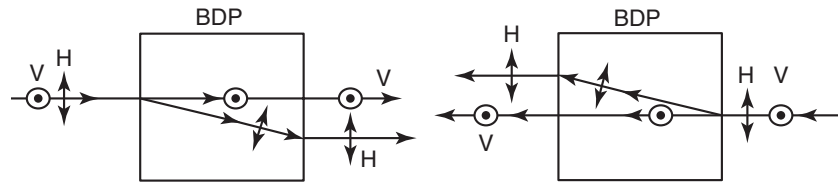


FIGURE 5.28 A solid-optic polarizing beam-displacing prism (BDP) operations for vertically (V) and horizontally (H) polarized light.

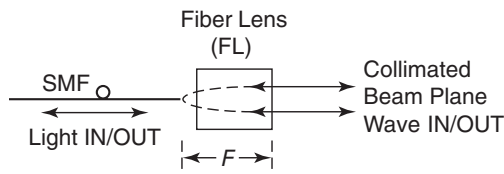
two orthogonal-linear polarizations. A typical separation distance can be 1.6 mm for a 10-mm long calcite BDP.

To couple light-in and -out of SMFs, we often use a fiber lens (FL) of the graded-index (GRIN) type that is made of a solid block of glass with a radial index variation to produce a lens via appropriate doping of the material. The GRIN lens because of its solid flat structure is easier to mass produce and package and is deployed in many SMF systems. Figure 5.29 shows a basic design of how a SMF is interfaced with a GRIN lens to form a collimated beam indicating that the core of the SMF is placed at a focal distance F from the exit of the fiber lens. The collimated beam in freespace can hence easily interface with a SMF for optimal photonic system design with both fiber and bulk-optical components. Note that standard-design SMFs do not preserve the polarization state of the input light. Nevertheless, special-design polarization-maintaining fibers (PMFs) are also available to designers that preserve both the single-spatial mode and the input polarization of the light launched into the fiber. Fiber cores can also use special designs, such as having a crystal-like array-patterned core or multimaterial core structures including air- or liquid-core structures. Such fibers are typically called photonic crystal fibers (PCFs) and have useful applications in fiber-laser design and optical sensing.

Another bulk-optic component used to design fiber-optic modules is the half-wave plate (HWP) that is commonly used to rotate the linear polarization of light. Specifically, as shown in Figure 5.30, when the HWP slow axis (SA) is at an angle θ with the input linear polarization, the light (left to right) after passing through the HWP has its polarization rotated by 2θ .

The HWP is known as a reciprocal device as input light at angle 2θ with the HWP SA when traveling back (right to left) as shown in

FIGURE 5.29 SMF coupled to a fiber lens to engage collimated beams in freespace.



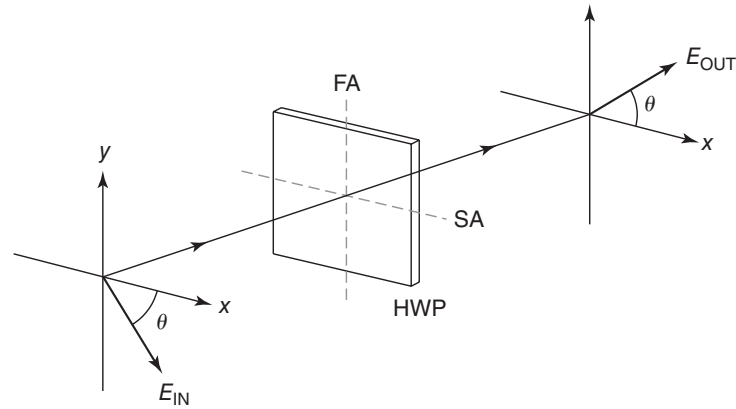


FIGURE 5.30 Rotation of linear polarization of light by angle 2θ when the input linear polarization makes an angle θ with the SA of the HWP. Light travel from left to right.

Figure 5.31) through the same device returns to its original input-light state of polarization (i.e., linear polarization at angle θ with HWP SA).

In contrast to the HWP, the Faraday rotator is a nonreciprocal device. As shown in the sequence of drawing in Figure 5.32, the light polarization of the beam returning to the input port is of a different polarization. The example used a Faraday rotator (FR) with a linear polarization rotation power of α . Clearly a photonics designer can use the reciprocity properties of the HWP and FR to design optical modules that demonstrate reciprocal and nonreciprocal behavior for light passage within the input/output ports of the module.

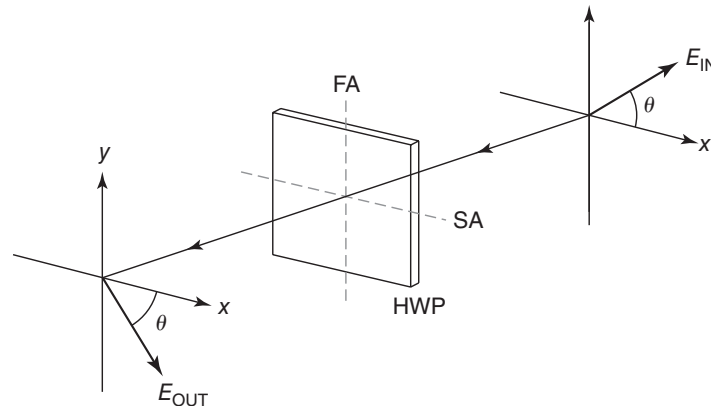


FIGURE 5.31 Shown is the reciprocal nature of the HWP as returning light from Figure 5.30 when going right to left through the same HWP returns to its original input state of polarization.

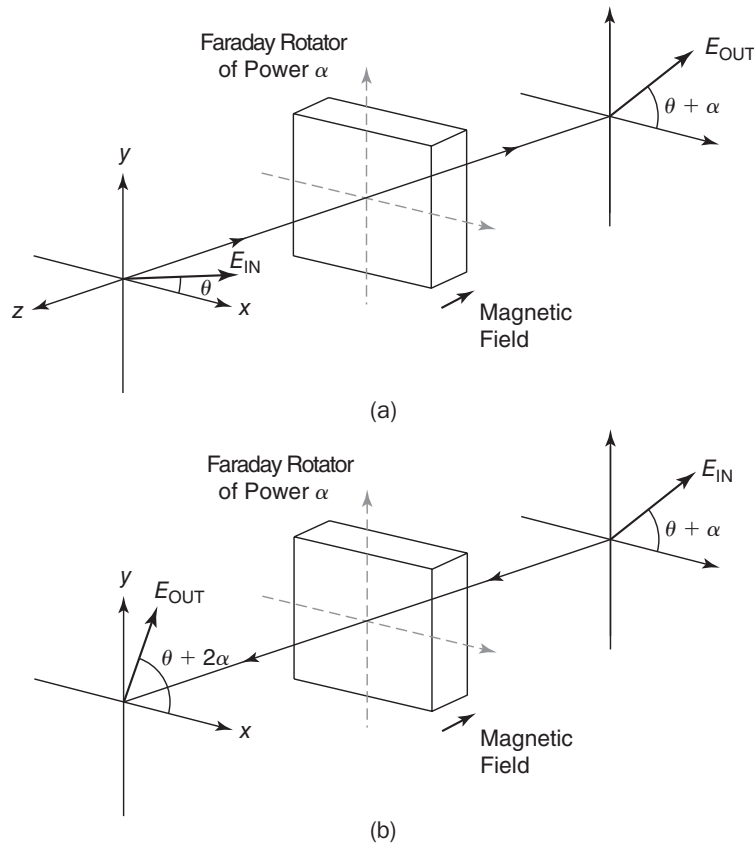


FIGURE 5.32 Shown is the nonreciprocal nature of the Faraday rotator (FR) device with (a) showing first passage of light through device and (b) showing returning light going right to left through the same FR. Note that the returning light does not come back to its original input state of polarization.

As shown in Figure 5.33, one such module is the fiber-optic isolator that has two SMF ports connected to fibers labeled as SMF1 and SMF2. The objective of the isolator is to allow light flow from say SMF1 port to SMF2 port, but prevent light flow in the reverse direction, in other words, SMF2 port to SMF1; hence this provides isolation between the ports for reverse-direction (or reflected) light flow. For example, when designing fiber lasers and fiber-optical amplifiers, certain light flow back into the module can increase noise levels and must be isolated from the desired signal light. In these cases, the fiber isolator is a critical component that can provide back-reflected isolations reaching 40 dB (i.e., a 10,000:1 optical irradiance suppression of the potential back-reflected noise light). As shown in Figure 5.33, a fiber-optic isolator is designed using two SMFs, two FLs, two BDPs, one HWP, and one FR with a 45° rotation power. The HWP SA makes a 45° angle with the input linear-polarization light coming from the FR when traveling left to right in shown in Figure 5.33.

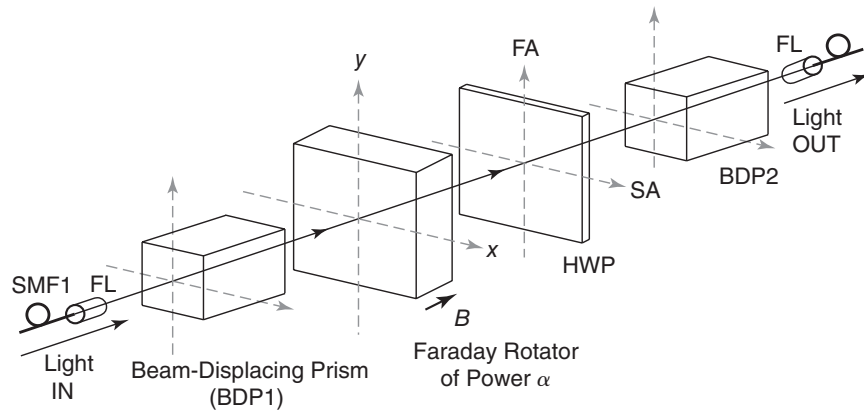


FIGURE 5.33 Fiber-optic isolator design using reciprocal and nonreciprocal polarization-control devices such as BDPs, HWP, and FR.

Figure 5.34 shows the light beam polarizations as the light passes from (a) left to right and then (b) right to left in the isolator module. The light traveling from SMF2 toward SMF1 does not enter the fiber lens of SMF1; hence, forming a barrier to light entry into the SMF1.

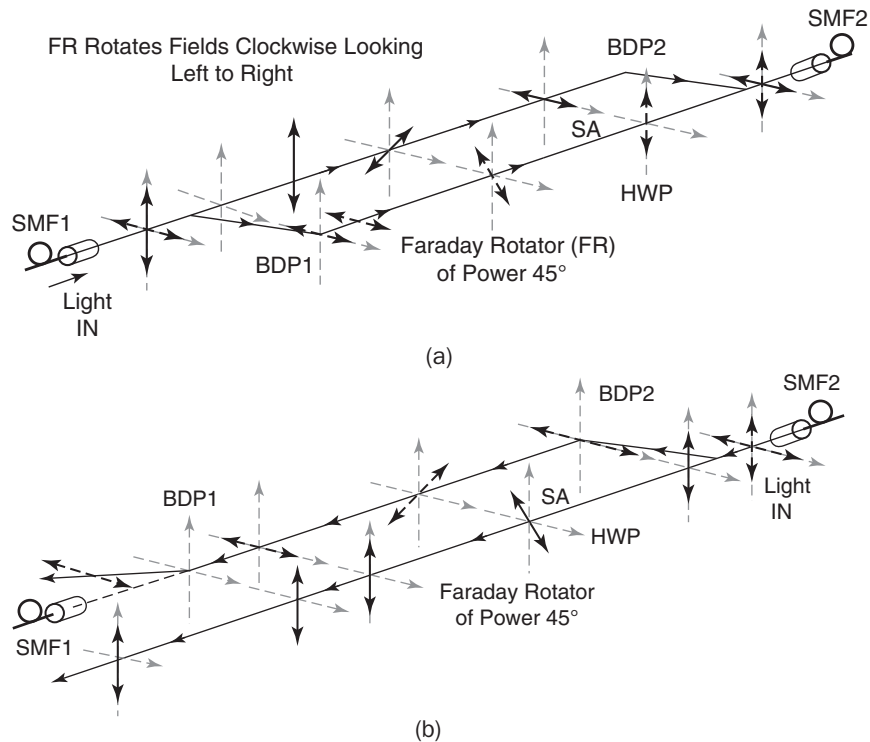
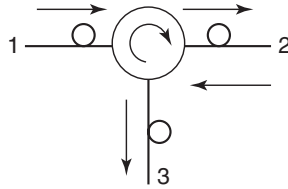


FIGURE 5.34 Light-beam linear polarization states as the light passes both ways through the Figure 5.33 fiber-isolator module. In (a), light travels from SMF1 to SMF2 while in (b) input light travels from SMF2 to SMF1.

FIGURE 5.35
A three-port fiber-optic circulator.



On the other hand, light input into SMF1 travels through the isolator optics to fully enter the fiber lens with SMF2. Hence, the reciprocity properties of the various polarization components comes into play to form the desired isolator function with a two-port fiber module. In a similar fashion, other fiber-optic modules can be designed, such as fiber-optic circulators, switches, and wavelength division multiplexed (WDM) interleavers.

Figure 5.35 shows a three-port fiber-optic circulator that is a three-port optical component shown in with the following light-flow directions as follows: Port 1 to Port 2 and Port 2 to Port 3. Each port is connected to a SMF. We can form a basic circulator with four independent ports using three BDPs, two HWPs (45° SA with input linear polarizations), and two FRs with 45° powers. The sequence of components in the stack can be BDP (x), HWP, FR, BDP (y), FR, HWP, and BDP (x).

Figure 5.36 shows the block diagram of the fiber-optic interleaver (I) device that can also be designed using a cascade of bulk micro-optical components, including wavelength-sensitive optics. The interleaver is commonplace in WDM fiber-optic communication and signal-processing systems where wavelengths need control via parallel-processing optical channels.

The Bragg diffraction process was described when the AO device or Bragg cell was discussed. In a similar way, Figure 5.37 shows the fiber Bragg grating (FBG) device that has an in-fiber grating that forms a sinusoidal refractive index variation in the core of the fiber along the optical axis of the SMF. For classic Bragg diffraction in a material of index n_f , we can write

$$2\Lambda_G \sin \theta_B = m\lambda_f$$

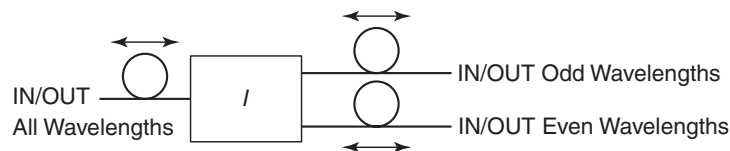


FIGURE 5.36 The fiber-optic interleaver device that separates the odd and even wavelength channels in a wavelength grid such as used in WDM communications.

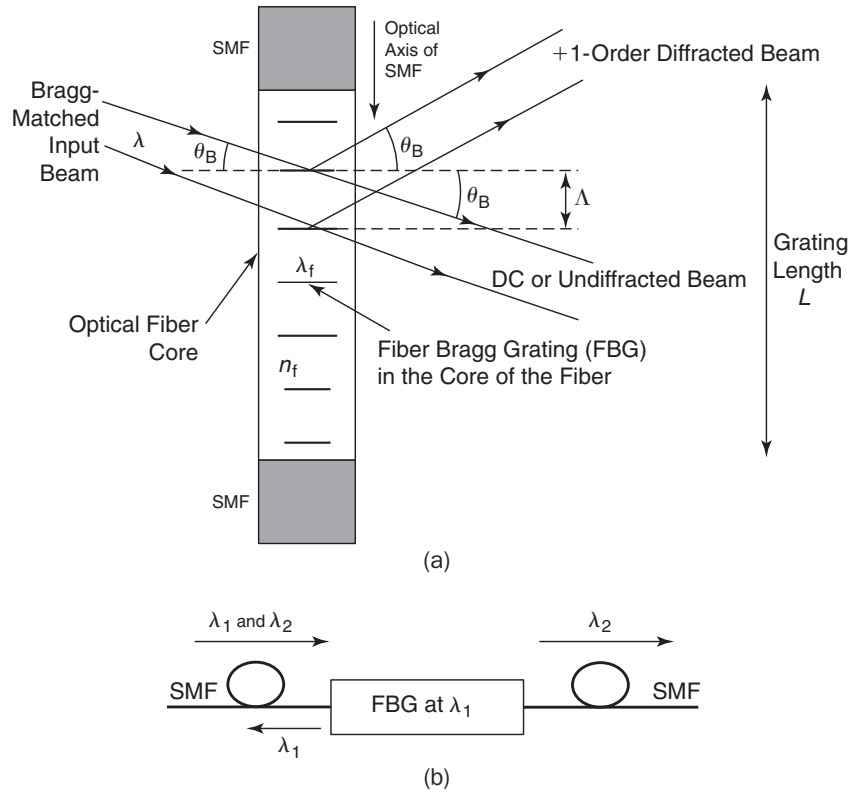


FIGURE 5.37 The Fiber-Bragg Grating (FBG) device. (a) Bragg diffraction principle shown using angled light for clarity of the in-fiber Bragg diffraction operation. (b) FBG device response when light of two different wavelengths is input to the device designed for Bragg reflection from one of these wavelengths.

where Λ_G is the grating period in the SMF, m is the diffraction order number, and λ_f is the light wavelength in the SMF core. For in-line geometry diffraction (also called blazed condition), make the Bragg angle $\theta_B = 90^\circ$ and the diffraction order $m = 1$, giving the condition for FBG design to be

$$2\Lambda_G = \lambda_f = \frac{\lambda}{n_f}$$

$$\text{or } \lambda = 2n_f\Lambda_G$$

Here λ is the wavelength of light that was input into the SMF that would suffer Bragg diffraction. Hence, FBGs can be designed using various fiber-core index-writing techniques (such as by grating patterned UV light exposure) to enable light diffraction of a specific chosen wavelengths band, making an excellent in-fiber light conditioning and control device that is highly useful in sensing,

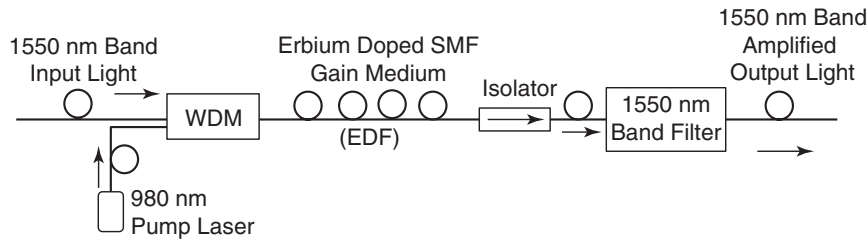


FIGURE 5.38 Fiber-optical amplifier basic design using an erbium-doped fiber (EDF) as the gain medium.

communications, and signal processing functions of a photonic system. The length, L , of the FBG can be controlled along with the grating index materials and 3D grating structure within the core of the SMF to produce near 100 percent diffraction of the chosen design wavelengths leading to low-loss processing. Note that the Bragg diffracted light is retro-reflected in the fiber while the non-Bragg-matched light passes straight through the fiber, forming an optical notch filter.

The erbium-doped fiber amplifier (EDFA) is the backbone of the long-distance fiber-optic network system. Because propagation of light through the SMF over long distances (e.g., > 50 km) suffers significant loss that affects the data BER, EDFAs must be deployed for amplification (> 35 dB per repeater stage) of the optical signal without conversion to the electrical domain. The rare-earth material erbium when optically stimulated at the correct wavelength produces amplified photons at the input wavelength. This goal is achieved using a basic EDFA design such as shown in Figure 5.38. Devices used to assemble the system are isolator (I), 2:1 WDM, erbium-doped SMF or EDF, optical filter (F), and a pump laser (e.g., 980-nm laser diode).

Planar-Optics and Integrated-Optic (Waveguide) Devices

Apart from fiber devices, planar optics and integrated-optic devices are greatly deployed in photonics design. A classic large-scale planar-optic device is the freespace diffraction-grating used to disperse or combine wavelengths. The device can be designed to operate in reflection mode or transmission mode. There are various technologies used to fabricate large (e.g., 1-cm diameter zone) planar-optic diffraction gratings such as diffractive optics (Figure 5.39a) and volume Bragg gratings (Figure 5.39b) in holographic materials. Using SMFs and FLs, we can use freespace optics and grating optics to design a fiber-optic WDM device that is common place in fiber-optic communication networks. WDM devices can operating over various optical bands, for example, over 32 nm with various inter-wavelength spacings (e.g., 0.25 nm) making high-channel (e.g., 128) count devices.

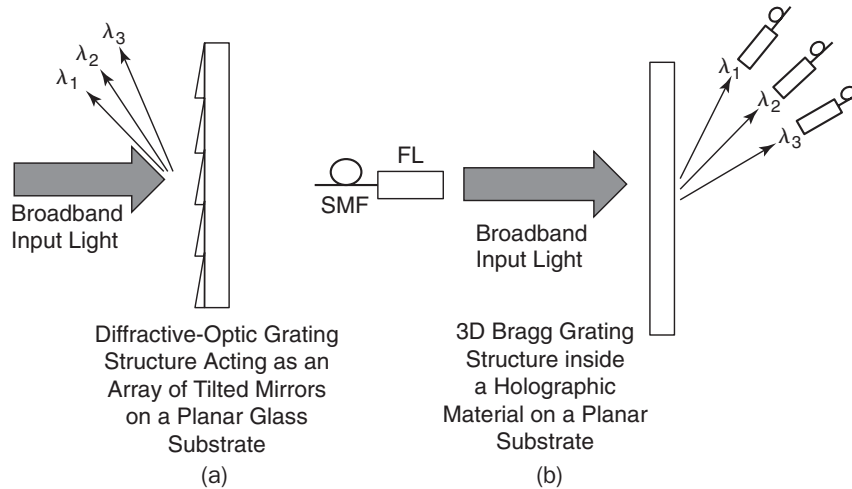
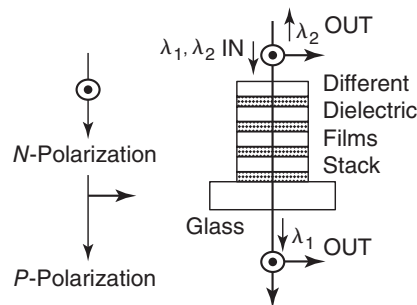


FIGURE 5.39 Planar optic-diffraction gratings used as WDM devices for wavelength combining or separating functions.

Another optical fabrication technology called thin films (TF) can be stacked together in a planar fashion to provide very specific wavelength reflection and transmission properties by controlling the refractive index and thickness of the dielectric thin-film layers deposited on a given substrate such as glass. Each dielectric-layer boundary acts as a partially reflecting mirror and a stack of such mirrors form wavelength-coded interferometric cavities (called Fabry-Perot interferometers), producing a desired wavelength response for the cumulative reflected and transmitted light from the device structure. At a two-materials boundary, such as the interface between the two dielectric films, the ratio of the reflected and transmitted optical fields versus the incident optical field are called *Fresnel* amplitude reflection and transmission coefficients, respectively. Fresnel coefficients are sensitive to various optical factors, such as boundary material indices and light polarization, and angle of incidence of the incident beam. In the often-common case shown in Figure 5.40 of normal-incidence optical beam (angle

FIGURE 5.40 Stack of dielectric thin-films forming an in-line on-axis WDM filter.



of incidence is zero), the Fresnel amplitude coefficients for light traveling from a material with a refractive index n_1 to a material with refractive index n_2 can be written as simple expressions given by

$$r_N = \frac{E_{N_r}}{E_{N_i}} = \frac{n_1 - n_2}{n_1 + n_2} \quad r_P = \frac{E_{P_r}}{E_{P_i}} = \frac{-(n_1 - n_2)}{n_1 + n_2}$$

$$t_N = \frac{E_{N_t}}{E_{N_i}} = \frac{2n_1}{n_1 + n_2} \quad t_P = \frac{E_{P_t}}{E_{P_i}} = \frac{2n_1}{n_1 + n_2}$$

r_N and r_P are the Fresnel amplitude reflection coefficients for light-normal (out of paper) and parallel (in paper plane) polarizations, respectively. t_N and t_P are the Fresnel amplitude-transmission coefficients for light normal (out of paper) and parallel (in paper plane) polarizations, respectively. The notation style E_{N_i} refers to the optical field amplitude for the normal or N -polarization component of the incident or i -beam. The minus-sign difference with the two reflection coefficients indicates a 180° relative phase-shift picked up for one of the reflected polarizations. Optical power is proportional to optical irradiance, which is proportional to the square of the optical field amplitude. Using the principles of conservation of energy, $T + R = 1$ where T and R are the Fresnel power transmittance and reflectance coefficients, respectively. Thus, for the two polarizations components, we can write Fresnel power/irradiance coefficients as

$$R_N = \left| \frac{E_{N_r}}{E_{N_i}} \right|^2 = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \quad R_P = \left| \frac{E_{P_r}}{E_{P_i}} \right|^2 = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

$$T_N = \left| \frac{E_{N_t}}{E_{N_i}} \right|^2 = \left(\frac{2n_1}{n_1 + n_2} \right)^2 \quad T_P = \left| \frac{E_{P_t}}{E_{P_i}} \right|^2 = \left(\frac{2n_1}{n_1 + n_2} \right)^2$$

At normal incidence, proper choice of the stack material indices (e.g., n_1, n_2, n_1 for a three-layer stack) can control the n_2 material cavity mirror reflectivities, add to this aspect, the thickness, d , of the n_2 material, and as a minimum a two-beam interferometer is formed where the interferometric term in the output beam irradiance is $\cos [(2\pi/\lambda)n_2d]$. Fundamentally, a multibeam interferometer is formed as light beams have partial reflections and transmissions, so light of general wavelength, λ , returns back into the cavity for further interference effects. A WDM device can be designed using such methods, for example, displaying constructive interference for one wavelength (e.g., λ_1) and passing through the device and displaying destructive interference for another wavelength (e.g., λ_2) and being retro-reflected by the device (see Figure 5.40). For a very common

air-glass interface, such as in windows and spectacles operating in the visible band, $R = 0.04$ and $T = 0.96$ with (air) $n_1 = 1$ and (glass) $n_2 = 1.5$, indicating 4 percent of light gets reflected from an air-glass interface. Hence, antireflection coatings in the form of dielectric coatings on the glass are used to bring the unwanted reflections to under 1 percent.

Analysis of general Fresnel coefficients can show that reflected light from an interface can be completely linearly polarized for a given incidence angle called the θ_{BR} , Brewster or polarizing angle. Specifically, the Brewster angle is given by

$$\theta_{BR} = \tan^{-1} \left(\frac{n_i}{n_t} \right)$$

where n_i and n_t are the refractive indices of the incident and transmission mediums, respectively. Consider the question: At what angle will light internally reflected from a silicon-air interface be completely linearly polarized? The silicon refractive index is $n = 3.5$. In this case, for internal reflection, $n_i = 3.5$ for silicon and $n_t = 1$ for air. Then internally reflected light will be completely linearly polarized at the Brewster's angle given by

$$\theta_B = \tan^{-1} \left(\frac{n_i}{n_t} \right) = \tan^{-1} \left(\frac{3.5}{1} \right) = 15.95^\circ$$

Figure 5.41 shows the design of an integrated-optic (IO) 2×2 3-dB coupler device using silicon-on-insulator (SOI) fabrication technology. A 3-dB coupler splits the irradiance of the input port light 50:50 between the two output ports. SOI technology uses silicon to fabricate the optical waveguides on a silica/glass planar substrate. Because the refractive-index difference at the telecom IR bands for silicon (3.5) and silica (1.5) is so high, at about 2.0, the waveguide can be formed by

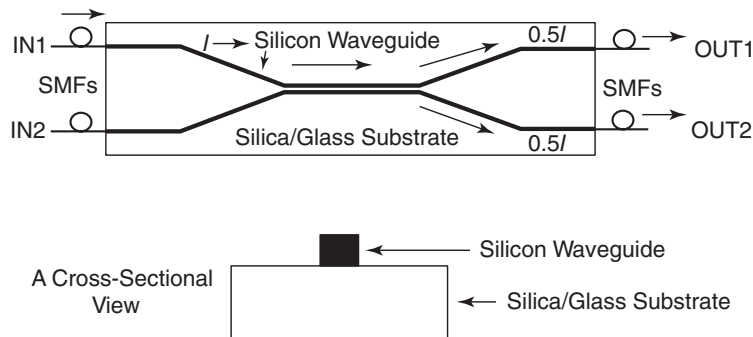


FIGURE 5.41 Integrated-optic 2×2 3-dB coupler using silicon-on-insulator (SOI) fabrication technology.

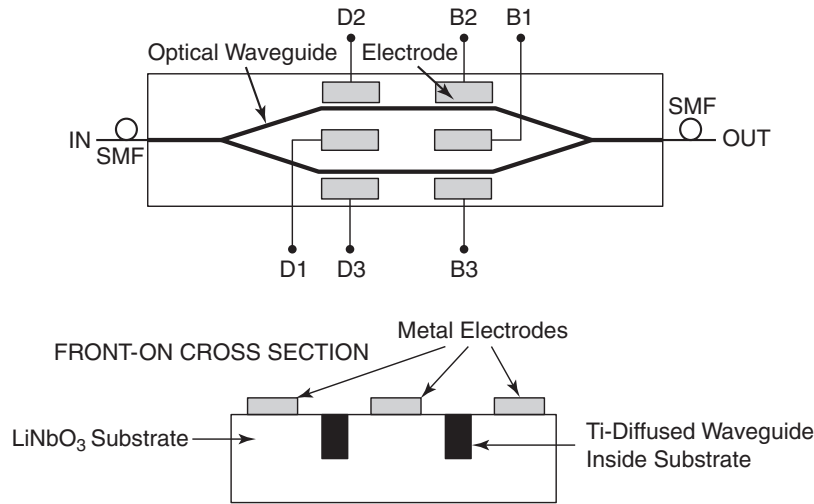


FIGURE 5.42 Integrated-optic electrical-to-optical (E-to-O) high-speed Mach-Zehnder modulator using lithium niobate electro-optic waveguide-fabrication technology for digital and analog signals' E-to-O conversion.

a thin layer (e.g., $1\ \mu\text{m}$) versus all-silica waveguides devices with for example $10\text{-}\mu\text{m}$ layers. SOI technology is attractive, being compatible with CMOS Si-electronics. The 3-dB coupler device is extensively used in fiber-optic photonic systems. Figure 5.42 shows only the IN1 port lit, but both ports can also be lit. Note that there is a region in the central part of the device where the two optical waveguides are in close proximity. This region is called the coupling region and here evanescent wave coupling takes place between the two waveguides to result in some power transfer to the adjacent waveguide, hence implementing a power splitting function. The gap between the waveguide and the length of the coupling region is designed to give the desired optical power split ratio (e.g., 50:50; 70:30, etc).

Note that IO waveguides can be made in other fabrication materials including electro-optic materials, such as lithium niobate (LiNbO_3) and indium phosphide (InP) that can be designed to form high-speed electrical-to-optical modulators commonly used in digital and analog high-speed fiber-optic systems. For example, in LiNbO_3 , the optical single mode waveguide can be formed by titanium (Ti) in-diffused into the LiNbO_3 substrate. Electrodes can apply a voltage across the optical waveguide to induce a refractive-index change via the electro-optic effect leading to optical phase-control for the light traveling in the waveguide.

The DC bias voltage applied to the DC terminal of the modulator selects the operating point in the device input (voltage)/output (Irradiance) transfer function about which the modulation takes place for desired input, such as a RF or analog signal or a digital 1/0 state signal. The bias voltage can also be used to offset an optical phase imbalance between the two arms of the waveguide Mach-Zehnder

interferometer or any phase drifts that can happen as the modulator operates over time. In Figure 5.42, B1, B2, B3 and D1, D2, D3 are the bias and data input electrodes, respectively. B2, B3, D2 and D3 are connected to ground. B2 and D2 are connected to the device bias and data voltages, respectively. The applied electric fields are normal to the waveguide directions. The presence of the electric field alters the refractive index in the two paths of the interferometer. The electrode-induced field directions for the two waveguides is opposite because of the placements of the electrodes. As the electro-optic effect depends on the direction of the applied electric field with respect to the waveguide propagation axes, one waveguide experiences an increase in index whereas the other gets an equivalent decrease in refractive index. The net result is doubling of the refractive index effect and a net phase-shift for light passing via the two arms of the interferometer.

For the Figure 5.42 modulator, the output irradiance I_0 from the SMF output can be written as a standard two-beam interferometer expression given by

$$I_0 = T_d I_i \left[1 + \cos \left\{ \pi \frac{V_d(t)}{V_\pi} + \phi(V_{BD}) \right\} \right]$$

I_i is the input irradiance, and T_d is the input/output optical-power transmission factor (≤ 1) due to device parameters such as fiber-to-waveguide coupling loss. $\phi(V_{BD})$ is the optical phase induced by the digital bias-voltage, V_{BD} , to select where in the cosinusoidal output irradiance versus drive-voltage transfer function does the input data signal, $V_d(t)$, want its optical irradiance modulation swing. When $\phi(V_{BD})$ is zero or a multiple of 2π , one can say the modulator operates in-phase and the modulator output can be written as

$$I_0 = T_d I_i \left[1 + \cos \left\{ \pi \frac{V_d(t)}{V_\pi} \right\} \right]$$

Figure 5.43 shows a plot of the modulator-output irradiance versus the data-drive voltage signal, $V_d(t)$. One can see that when $V_d(t) = mV_\pi$ with $m = 0, 1, 2, 3, \dots$, the output irradiance is a maximum of $I_0 = 2I_i T_d$. On the other hand, when $V_d(t) = (2n + 1)V_\pi$ with $n = 0, 1, 2, 3, \dots$, the output irradiance is a minimum of $I_0 = 0$. Hence, there are several sections along the drive data signal voltage axis where one can get the desired output irradiance levels. In the very basic digital 1/0 or on-off light modulation case, one can toggle the data signal drive voltage between zero volts to represent a data 1-bit (or on-light level) to a V_π voltage to represent the 0 bit (or no-light level).

In the case of an analog data signal, we must choose a central-modulation voltage about which the analog signal can oscillate. Typically, the most linear region for this mapping is the indicated quadrature points Q1 and Q2 in Figure 5.43. Each point is located

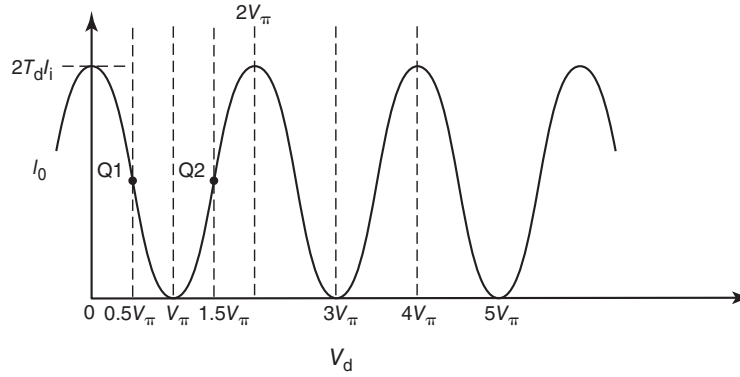


FIGURE 5.43 Plot of the integrated-optic balanced Mach-Zehnder (MZ) E-to-O modulator output irradiance versus the data-drive voltage signal, $V_d(t)$.

halfway between the output irradiance levels. The first quadrature point, Q1, is on a negative slope of the transfer function at $0.5 V_\pi$ volts while the second quadrature point, Q2, is on a positive slope of the transfer function at $1.5 V_\pi$ volts. Note that data modulated about these two points will also have a relative- π phase-shift between them and this feature can be useful in designing photonic signal processors for RF signals. Specifically, negative value signal representations are not possible with intensity modulated light as irradiance is always positive. Nevertheless, independent irradiances produced by intensity modulation via two MZ-modulators with the same small-signal input-drive signal can be made to be 180° out-of-phase using one modulator at Q1 bias point and the other modulator at the Q2 bias point. On photodetection by a single detector, the original-input RF signal subtracts from itself, implementing the minus operation in the optical domain.

The analog data signal can be written as $V_d(t) = V_B + V_{SS}(t)$ where V_B is the modulator analog modulation-bias signal. Consider that the analog modulated signal is biased on its negative-slope quadrature point (see Figure 5.43), where $V_B = 0.5 V_\pi$ giving $V_d(t) = 0.5 V_\pi + V_{SS}(t)$. When $V_{SS}(t) \ll V_\pi$, the modulation is considered small-signal (SS) modulation that allows the cosine term to be first written as a sine term that under the SS condition approximates to give

$$I_0 \approx T_d I_i \left[1 - \pi \frac{V_{SS}(t)}{V_\pi} \right]$$

Hence for the SS condition, the output irradiance is linearly proportional to the input small signal and hence acts as a high speed analog signal modulator.

The modulator performances described used a balanced modulator setting via the bias voltage set for $\phi(V_B)$ of zero or a multiple of 2π , but another **other** bias-voltage setting simply translates the transfer-function curve along the modulator signal-voltage axis and we can

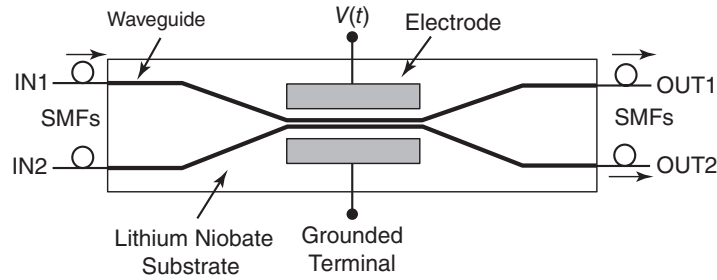


FIGURE 5.44 Integrated-optic electrical-to-optical (E-to-O) high-speed directional coupler modulator using Lithium Niobate electro-optic waveguide fabrication technology for digital and analog signals E-to-O conversion.

again choose the right data-signal voltage levels to get the desired output response. The modulator described is often called an external modulator and is a vital component for both analog and digital signals with bandwidths reaching 40 GHz and 40 Gbps, respectively.

Figure 5.44 shows an integrated-optic electrical-to-optical (E-to-O) high-speed directional coupler design-based modulator using lithium niobate electro-optic waveguide-fabrication technology for digital and analog signals E-to-O conversion. The coupling region is designed such that with zero applied voltage, all input light transfers power to the adjacent waveguide, so all IN1 light goes to OUT2 and all IN2 light goes to OUT1. When a voltage is applied, the refractive index in the dual-waveguides coupling region changes the effective coupling length and some of the input power in a waveguide remains in the waveguide. If a high enough voltage is applied, in theory, all the light in the waveguide stays in the waveguide and, hence, a digital 1×2 optical switch is formed. This effect can be used to form either a digital- or analog-signal modulator by applying the data signal to the $V(t)$ terminal in the device. The coupler modulator does not show a repetitive sinusoidal transfer function response like the MZ-modulator. In fact, the output irradiance from this coupler modulator shows a sinc function squared dependence on the applied voltage, $V(t)$, as depicted in Figure 5.45.

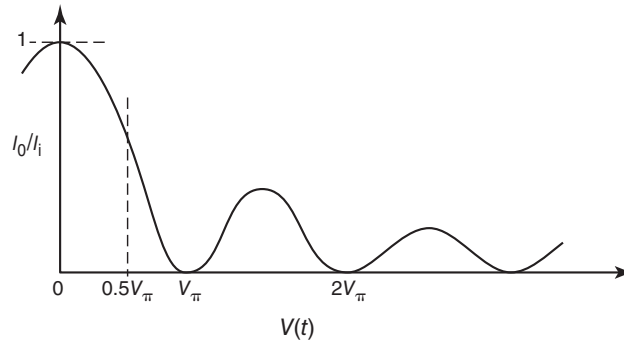


FIGURE 5.45 Plot of the integrated-optic Y-coupler integrated-optic E-to-O modulator output irradiance versus the data drive voltage signal, $V(t)$.

We can also directly modulate a light source with an electrical signal. For example, a laser diode drive current can be electrically modulated with an RF signal on a bias current to produce a linearly intensity modulated light beam. This method is called *direct or internal modulation* versus external modulation using the MZ modulator. The current produced by the high speed photodetector (PD) is proportional to the incident irradiance (or intensity), hence a linear mapping between the laser diode modulation RF signal and the PD-detected electrical signal is achieved. In a similar way, digital modulation of a laser diode can produce a communication link when detected by a PD that produces the digital modulation electrical signal.

Problems

1 Using Figure 5.46 shown, prove the input-beam Bragg-angle diffraction condition for maximum diffraction efficiency of output +1-order diffraction beam is $\sin\theta_B = (1/n)\Lambda_a$. Here Λ_a is the acoustic-signal wavelength in the AO device.

Hint: For optical high-diffraction efficiency-beam generation, the extreme two rays consisting of the +1-order Bragg diffraction should have travelled equal optical path lengths within a multiple of optical wavelengths.

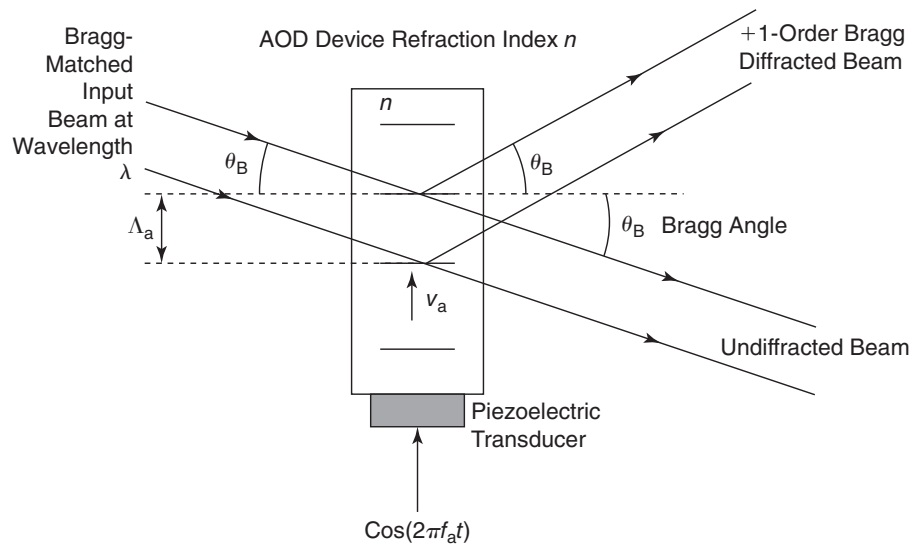


FIGURE 5.46 Bragg-matched operation of an AO device.

2 Given a glass AO Bragg cell with $n = 1.5$, acoustic velocity $3.9 \text{ mm}/\mu\text{s}$, and drive frequency of 100 MHz , calculate the Bragg angle in the device in degrees for optimal Bragg diffraction operation of a red 633-nm input wavelength coming from a collimated helium-neon laser.

3 For the Bragg cell shown in Figure 5.1 with the Bragg angle in the small-angle approximation and using the full-transducer electrical-bandwidth, B , show that the electrically tuned small angular spread of the +1-order-diffracted beam in freespace medium is approximately given by $\Delta\theta \sim (\lambda B)/v_a$.

Hint: Also use Snell's law of refraction.

4 Given a tellurium dioxide Bragg cell with acoustic velocity of $0.67 \text{ mm}/\mu\text{s}$, 60-MHz center frequency, 40-MHz 3-dB bandwidth, and 5-cm device length, find the following parameters when using a 514-nm green laser beam.

- The total laser beam deflection range
- The time aperture of the Bragg cell
- The fastest-possible response time of the Bragg cell
- The fastest possible response time of the Bragg cell or deflector random-switching speed given the optical beam size $d = 1 \text{ mm}$
- The maximum number of deflected beams
- The maximum storage capacity of the AO device

5 Given the relationship $\frac{E_d(V)}{E_i(V)} = -j \frac{cV}{|cV|} \sin(|CV|L)$ between the incident and diffracted optical field amplitudes for an isotropic Bragg cell, derive the optical phase-shift between the two beams.

6 Show that for small diffraction efficiency changes, in other words, $V_s \ll V_B$, the diffracted power P_d is proportional to V_s . The Bragg cell is illuminated by a fixed-power laser beam and operates in its linear intensity-modulation mode biased at its 0.5 diffraction-efficiency point using the correct V_B . The AO drive AC-modulation signal is V_s .

Hint: use the trigonometric expressions $\sin^2\theta = 0.5\{1 - \cos\theta\}$; $\cos|\theta| = \cos\theta$; $\cos(A+B) = \cos A \cos B - \sin A \sin B$; and $\sin\theta \sim \theta$ for small θ .

7 Given the AO Bragg-cell interaction geometries shown in Figure 5.47, complete the expected optical beam paths and Doppler-shift values. Also draw the photon-phonon particle-momentum matching condition using the propagation $\mathbf{k}$ -vectors.

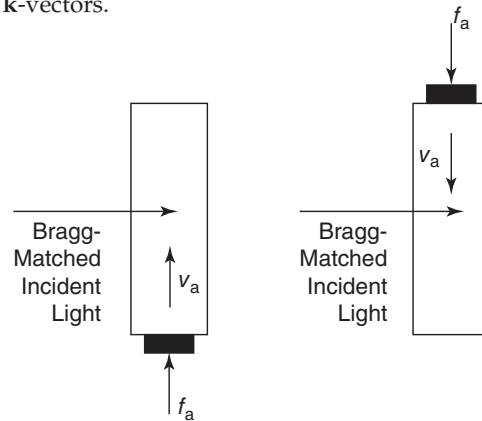


FIGURE 5.47 Different optical geometries for Bragg-matched interactions with an AO device.

8 For small (e.g., < 10 percent) diffraction efficiencies with AO-device driving signal, $s(t)$, derive the AO cell spatial-light modulation transmittance function:

$$\begin{aligned} t(x, t) &= \exp[jm_a s(x, t)] \\ &= \exp[jm_a s(t - x/v_a)] \text{rect}\left[\frac{x - X/2}{X}\right] \\ &\approx [1 + jm_a s(t - x/v_a)] \text{rect}\left[\frac{x - X/2}{X}\right] \end{aligned}$$

Here m_a is an index-modulation term, x is the direction of the acoustic signal in the AO device, and v_a is the acoustic signal velocity.

Hint: Use the following mathematical formulas:

Euler's formula: $\exp(j\theta) = \sin\theta + j\cos\theta$.

Trigonometric formulas: For all real values of θ , one can write

$$\sin\theta = \theta - \theta^3/3! + \theta^5/5! - \theta^7/7! + \dots$$

$$\cos\theta = 1 - \theta^2/2! + \theta^4/4! - \theta^6/6! + \dots$$

9 Given the Bragg cell in Figure 5.48 with drive signal $s(t)$ of amplitude, A , and at the transducer mid-band frequency f_0 , in other words, $s(t) = A\cos(2\pi f_0 t)$, show the demonstration of a negative-Doppler shift to the input beam given -1 -order diffraction. Also show that the -1 -order diffracted field strength is proportional to the drive signal voltage, A .

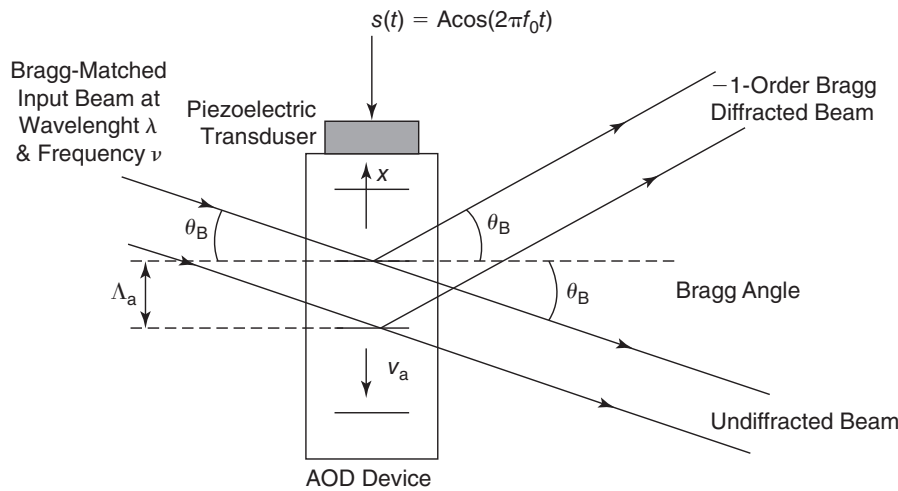


FIGURE 5.48 Negative Doppler shift operation of an AO device.

10 Given a Bragg cell (like Problem 9) with drive signal, $s(t)$, of amplitude, A , and at the transducer mid-band frequency, f_0 , and a scan-angle frequency, f_s , in other words, $s(t) = A \cos[2\pi(f_0 + f_s)t]$, show the demonstration of a frequency-controlled scan-angle beam steerer for the -1 -order diffracted beam.

11 Using Figure 5.49, and given the incident optical-beam geometry with the AO cell, show the AO small-diffraction-efficiency Bragg-cell operation acting simultaneously as a Doppler shifter and beam deflector. Show all mathematical

and graphical steps, including type of Doppler and diffraction order. Drive signal $s(t) = A \cos [2\pi(f_0 + f_s)t]$, AO cell-length X , velocity v_a , bandwidth B , center frequency f_0 , scan frequency f_s , Bragg angle θ_B at center frequency.

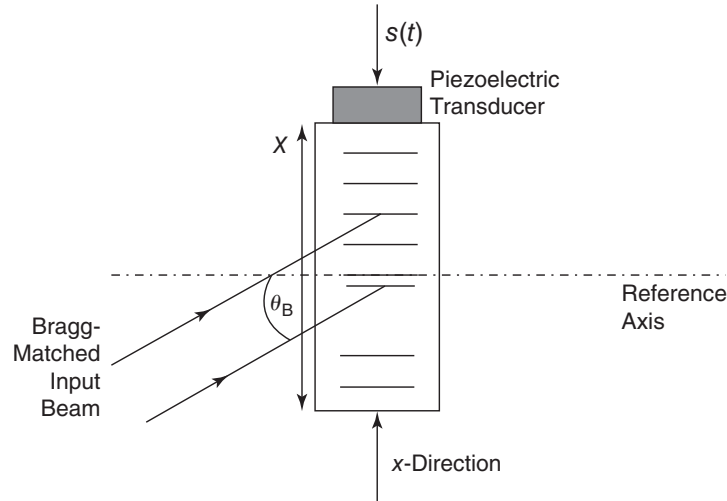


FIGURE 5.49 AO device operations as a Doppler shifter and beam deflector.

12 Given an AO Bragg-cell operation shown in Figure 5.8 with drive signal $s(t)$ representing a standard video signal with a line rate of 15.75 kHz and a total signal duration of 1/30 s, give the requirements for the AO time-space mapper such as

- Minimum aperture time of Bragg cell
- Number of 1D spatial samples (i.e., video image lines) in the folded 2D space-time signal output
- Pulse period of the laser and the integrating time of a detector processing the space-time signal

13 Design an optical system using a collinear AOTF device and another optical component to form a wavelength-selective polarization-based switch used to route optical signals of the electronically chosen wavelengths. Assume all input light is linear horizontally polarized. Assume the diffraction process per wavelength is 100 percent efficient.

14 Given a BM-NLC device design as shown in Figure 5.50, with $n_e = 1.630$ and $n_o = 1.505$, and $n(V) = 1.565$ for $V = 3$ V with a 1-kHz square-wave. The input laser beam has a given linear polarization and a green wavelength of 532 nm.

- The incident light polarization is vertical (along y -direction) and device-voltage $V = 1$ V. What refractive index does the exiting light beam experience?
- The incident light polarization is horizontal (along x -direction) and device-voltage $V = 1$ V. What refractive index does the exiting light beam experience?
- The incident light polarization is vertical (along y -direction) and device-voltage $V = 3$ V. What refractive index does the exiting light beam experience?

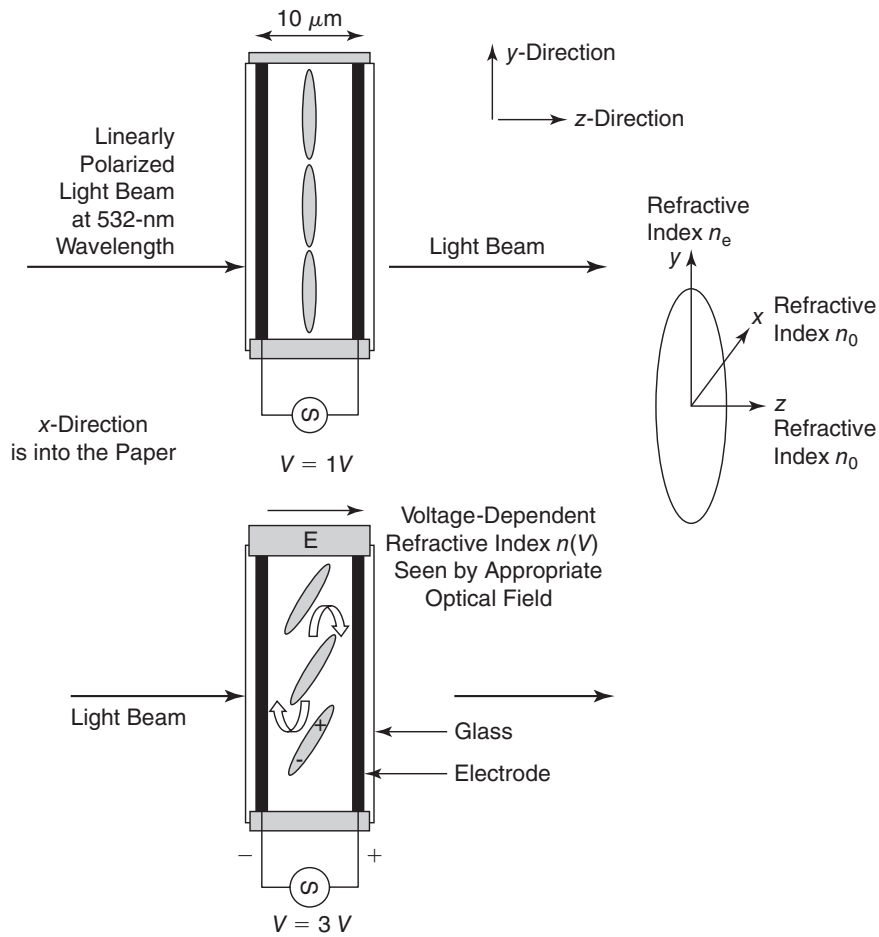


FIGURE 5.50 Interaction of polarized light with an electrically controlled BM-NLC device.

- (d) The incident light polarization is horizontal (along x -direction) and device-voltage $V = 3\text{ V}$. What refractive index does the exiting light beam experience?
- (e) At $V = 5\text{ V}$, the long axis of the molecules get aligned along with z -direction. The incident light polarization is horizontal (along x -direction) and device voltage $V = 5\text{ V}$. What refractive index does the exiting light beam experience?
- (f) At $V = 5\text{ V}$, the long axis of the molecules get aligned along with z -direction. The incident light polarization is vertical (along y -direction) and device voltage $V = 5\text{ V}$. What refractive index does the exiting light beam experience?
- (g) Between 0- and 1-V drive, the molecules stay mainly anchored to the device glass. At 1 V, the molecules begin to tilt along with applied electric field direction. What is a suitable name for the device applied voltage of 1 V?

- (h) The incident light polarization is vertical (along y -direction) and device-voltage $V = 3$ V. What optical path length does the exiting light beam experience?
- (i) The incident light polarization is horizontal (along x -direction) and device-voltage $V = 3$ V. What optical phase shift in radian does the exiting light beam experience?
- (j) The incident light polarization is at 45° to the x -direction and device-voltage $V = 3$ V. What is the relative optical-phase shift in radians between the vertical and horizontal components of the exiting light beam?

15 Using polarizers and an LC device, design an electronically variable optical attenuator for a linearly polarized input laser beam for the (a) and (b) cases. In both cases, be specific to what electrical drive conditions should one meet to achieve the variable optical attenuation. Describe the optical module design when using

- (a) A 90° twisted NLC device with LC molecular rotation start voltage of 1 V and molecular twist elimination of 5 V.
- (b) A BM-NLC device with a molecular rotation start voltage of 1 V. The device provides 90° , 180° , 270° , and 360° optical phase-shifts (for the deployed laser wavelength) at 1.25 V, 1.5 V, 1.75 V, and 2.0 V, respectively. This phase-shift is the relative-optical phase-shift ϕ between the n_e and n_o refractive-index directions of the molecules in the NLC BM-mode cell (as in Figure 5.16). Assume an input optical-field amplitude of E0. Provide optical-irradiance analysis for the output irradiance of the light from the proposed attenuator module in terms of the relative phase-shift and input-field amplitude.

16 Given a MMF, suggest two methods to increase the data rate for optical data communications.

17 Given is a 50-km optical fiber with core and cladding refractive indices of 1.46 and 1.44, respectively. Compute the maximum possible data-rate transfer possible with the given fiber considering worst-case spatial-mode dispersion within fiber guide.

18 Given is an optical fiber with core and cladding refractive indices of 1.50 and 1.49, respectively. Compute the maximum possible fiber length for a $B_T = 1$ -Mbps data-rate transfer with the given fiber considering worst-case spatial-mode dispersion within fiber guide.

19 For a commercial single-mode optical fiber, material dispersion $D_M \simeq 122 (1 - \lambda_{zd}/\lambda)$, where $\lambda_{zd} = 1.3 \mu\text{m}$ and D_M is in ps/km-nm. Find D_M at $\lambda = 1.55 \mu\text{m}$, the typical wavelength used for digital-signal transmission.

20 An optical pulse with a group velocity $v_g = 1.5 \times 10^8$ m/s travels through an optical-fiber length of 200 km. How long a time delay does the signal suffer?

21 Prove that fiber material dispersion for an SMF can be written as

$$D_M = \frac{d}{d\lambda} \left(\frac{1}{v_g} \right) = \beta_2 \left(-\frac{2\pi c}{\lambda^2} \right).$$

- 22** Given a maximum bit rate of 10 Gbps for a 5-km SMF with a 2.0-nm laser-spectral width, what is the fiber dispersion D_M ?
- 23** Given a maximum bit rate of 40 Gbps for a 30-km fiber with a 0.2-nm laser-spectral width, what is the fiber dispersion?
- 24** Complete the optical beam paths' picture (Figure 5.51) in (b) given the BDP behavior shown in (a).

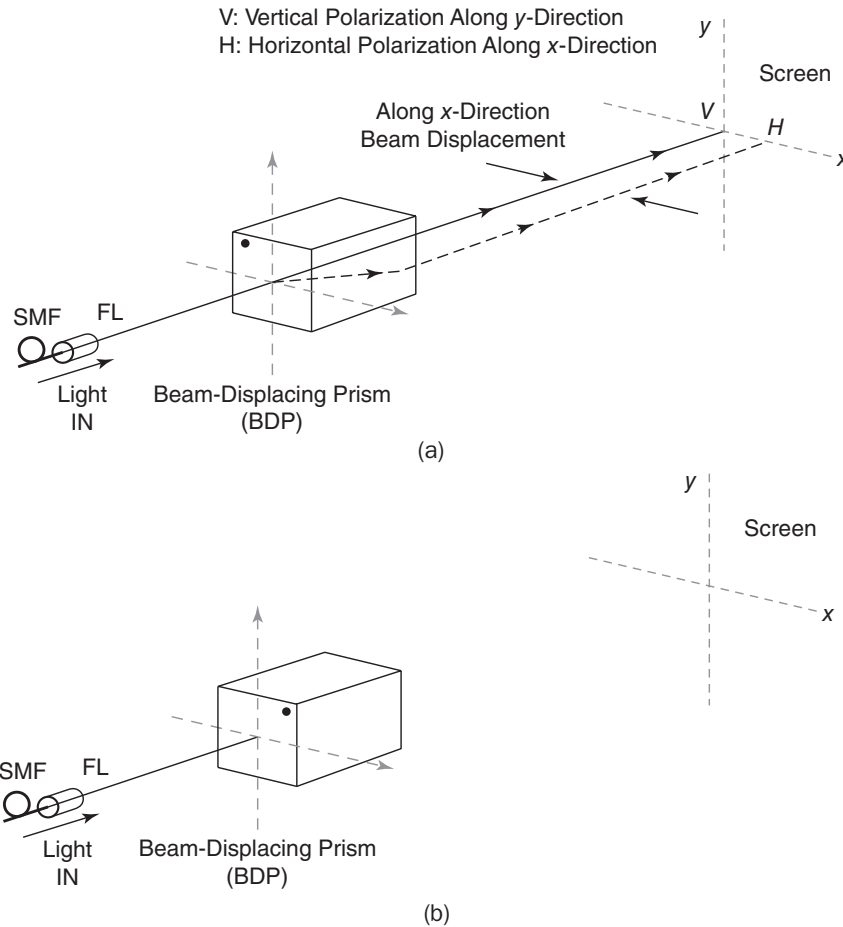


FIGURE 5.51 Interaction of polarized light with BDPs.

- 25** Given the FBG device in Figure 5.52, show how you can use another fiber-coupled optical component to separate the two wavelengths.

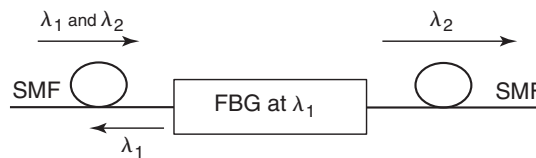


FIGURE 5.52 Interaction of multi-wavelength light with a FBG for a given wavelength.

26 Given a Figure 5.53 shown integrated-optic 2×2 3-dB coupler operations with an IN1 port fed by light of irradiance A and an IN2 port fed by light

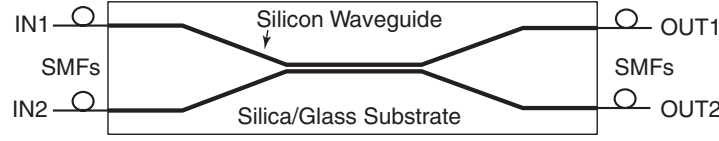


FIGURE 5.53 Shown is a fiber-coupled 2×2 3-dB waveguide coupler.

of irradiance B, write the expressions of the irradiances out of the two independent-output ports OUT1 and OUT2.

27 For an external-balanced MZ modulator shown in Figure 5.42 the data signal is given as $V_d(t) = V_B + V_{ss}(t)$ where V_B is the modulator bias signal. The modulator is biased on its negative-slope quadrature point where $V_B = 0.5 V_\pi$. For the SS condition of $V_{ss}(t) \ll V_\pi$, show that the modulator output approximates

$$I_0 \approx T_d I_i \left[1 - \pi \frac{V_{ss}(t)}{V_\pi} \right]$$

28 For an external-balanced MZ modulator shown in Figure 5.42 the data signal is given as $V_d(t) = V_B + V_{ss}(t)$ where V_B is the modulator bias signal. The modulator is biased on its positive-slope quadrature point (see modulator response shown in Figure 5.43) where $V_B = 1.5 V_\pi$. For the SS condition of $V_{ss}(t) \ll V_\pi$, show that the modulator output approximates

$$I_0 \approx T_d I_i \left[1 + \pi \frac{V_{ss}(t)}{V_\pi} \right]$$

29 Keep in mind the two cases described in Problems 27 and 28. Assume that two separate MZ modulators are deployed with the same RF signal, $V_{ss}(t)$, as the drive signal. One modulator is biased at Q1 point, and the other one is biased at Q2. Each modulator is fed by its own laser. Both lasers are at the same wavelength. The Q1-bias modulator is fed by a laser of irradiance I_1 . The Q2-bias modulator is fed by a laser of irradiance I_2 . The outputs from the two modulators is combined by a single 3-dB coupler, and the combined two output irradiances are detected by a single PD. Write an expression for the photodetected RF signal.

30 Problem 29 showed that two independently driven MZ modulators, each with its own laser, can be used to realize an RF-signal subtraction circuit in the optical domain. Design an optical-subtraction circuit for the RF-signal $V_{ss}(t)$ using a single MZ modulator, thus saving design costs. In addition, make the design with minimal components. At a given wavelength, the MZ modulator has Q1 and Q2 bias points with transfer-function negative and positive slopes, respectively.

CHAPTER 6

Photonic Systems Using Optical Micro- Electro-Mechanical Systems Devices

Optical micro-electro-mechanical systems (MEMS) devices can be used to design a host of photonic modules for a variety of applications. The simple placement of optical components within the right 3D layout framework in an optical design can surprisingly achieve challenging system functions via an elegant design. Hence, this chapter describes how optical MEMS devices can be deployed within an intelligent optical components visual and physical framework to perform desired system specific functions.

Design Problem 6.1: Digital Micromirror Device-Based All-Digital-Mode Laser-Beam-Profiler

Lasers are used in a host of applications ranging from surgery, projection displays, fiber communications, machining, wireless, and temperature sensors. The optical-power profile of the laser beam across the beam cross section is a critical parameter that requires reliable and precise measurement. The CCD chip that is a pixelated array of point photodetectors is, in many ways, an ideal light-imaging device. For example, CCD chips cover the visible-light wavelengths with low-cost silicon photosensors with small pixel size (e.g., 10 μm) and large pixel-array count (e.g., >1 million pixels). The issue with CCDs is that they easily saturate with moderate laser powers (e.g., >100 μW) and optical attenuators must be used to reduce the laser power. Attenuators can spoil the original power profile of the beam, such as by thermal lensing. To cover common IR-laser wavelengths, CCDs use phosphor films that lead

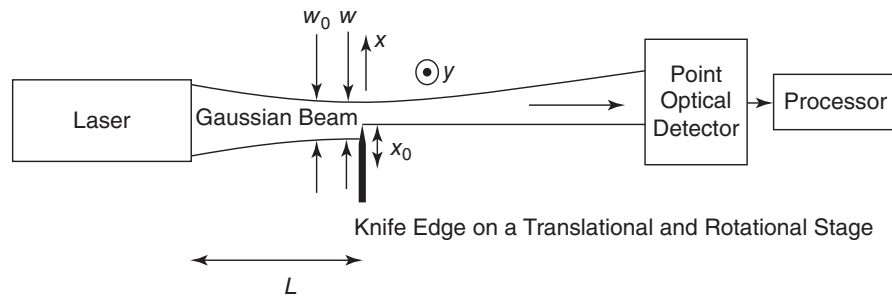


FIGURE 6.1 The classic mechanically moving knife-edge method to power-profile a Gaussian laser beam.

to additional nonlinearity and hysteresis in the detector optical response, apart from causing increased interpixel flooding and spill effects.

Hence, to measure beam profiles without these CCD effects, mechanical methods have evolved, the key method (see Figure 6.1) using a moving knife-edge across the beam with the through-beam power measured by single-point photodetector (PD). This method applies to Gaussian single-mode beams that are typical for many lasers. The normalized power, $P(x_0)$, measured by the PD shown in Figure 6.1 is given by

$$P(x_0) = \left[1 - \operatorname{erf} \left(\frac{\sqrt{2}x_0}{w} \right) \right]$$

where $\operatorname{erf}(q)$ is the error function of q of sigmoid shape with values ranging from 1 to -1 as q varies from near 3 to -3 , respectively. The $\operatorname{erf}(q)$ is given by

$$\operatorname{erf}(q) = \frac{2}{\sqrt{\pi}} \int_0^q \exp(-p^2) dp$$

with $\operatorname{erf}(0) = 0$. P_0 is the total optical power in the laser-beam profile-zone detected by the PD, x_0 is the position of the knife-edge along the x -direction with $x_0 = 0$ giving $P(0) = 1$, and w is the $1/e^2$ laser beam-width radius at the measurement distance, L . $P(x_0) = P_m/P_0$, where P_m is the power reading of the PD. The procedure to measure the Gaussian-beam waist w involves taking many PD readings for different x_0 knife-edge positions along the x -direction to curve fit the error function to produce a curve-fit estimate of w . Smaller the knife-edge steps, better the curve fit to provide the desired beam-waist test measurement. To determine the

Gaussian-minimum beam-waist radius, w_0 , we use the Gaussian-beam propagation equation given by

$$w(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2}$$

where $w(z)$ is the optical-beam radius at location z measured via the instrument, and λ is the wavelength of the laser. At $z = 0$, the reference marker, $w(z) = w_0$, the minimum-beam waist. A single-mode Gaussian beam can be fully characterized by its minimum-beam waist size and location that can both be measured using the knife-edge beam-profiler instrument.

Note that so far all the laser-beam measurements are directed along the x -direction of the beam cross section. To complete the beam 2D power map, the knife-edge of the profiler instrument is rotated by 90° and the whole beam-profiling process is repeated for the y -direction axis (into the paper). As the Gaussian-beam profiles along the x - and y -directions are represented by separable variable Gaussian functions in x and y , the 2D beam profile is obtained by multiplying the two different x -direction and y -direction beam profiles obtained via the instrument. A key benefit of mechanical knife-edge profilers is that we simply change the PD to match the laser wavelength versus changing the entire CCD optical chip. Hence, the mechanical profiler is indeed a powerful instrument that is commonly used to profile laser beams.

Nevertheless, ultimately mechanical-motion profilers rely on repeated positioning of the knife-edge at a predefined 2D sampling grid. The issue is mechanical positioners have accuracy and placement errors, which means the process of locating the knife-edge on the grid suffers from positional errors that, in turn, give beam-measurement errors. Reliability of any instrument is a key performance factor and motion-based errors from mechanical-motion profilers should be removed. In addition, the problem is exacerbated as the knife-edge might cover 1 million positions in the x - y grid with a very small $1\text{-}\mu\text{m}$ step. In addition, if the beam profile area is large (e.g., $>3\text{-mm}$ diameter), the problems mentioned are even worse.

Design a beam-profiler that has the best attributes of both CCD and mechanical knife-edge profilers and without their limitations.

Solution

Figure 6.2 shows the photonic system that indeed answers the presented question. The systems in Figure 6.1 and Figure 6.2 are operationally similar, except the Figure 6.2 system (a) operates with a reflected-laser beam versus the transmitted-through-laser beam onto the PD, and (b) the mechanical actuator-based analog translation and rotation-motion knife-edge is replaced by a stationary 2D DMD chip operating as a software-programmable moving knife-edge. The $+\theta$

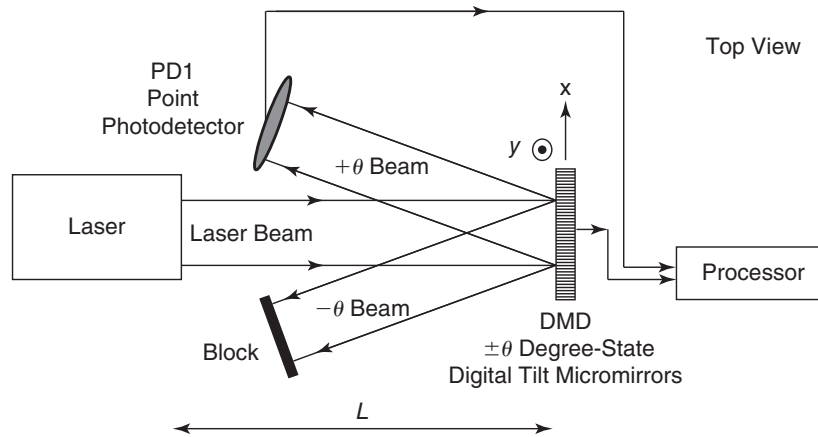


FIGURE 6.2 The all-digital laser-beam profiler using the 2D DMD.

and $-\theta$ beams of light are produced for the $+\theta$ and $-\theta$ micromirror tilt settings, respectively. PD1 measures the optical power for the different DMD settings representing each knife-edge location, and the processor normalizes the power and computes the error function once all knife-edge locations have been scanned.

Specifically, Figure 6.3 shows the operation of the DMD as a moving knife-edge along the x -direction of the beam-profiling plane. The DMD is a two-tilt state-micromirror-array device. Each micromirror in the DMD is programmed such that a $+\theta$ (black-color micromirror) and $-\theta$ state (white-color micromirror) vertical boundary exists that forms the knife-edge location that moves along the x -direction for x -direction profiling. Similarly, each micromirror in the DMD is

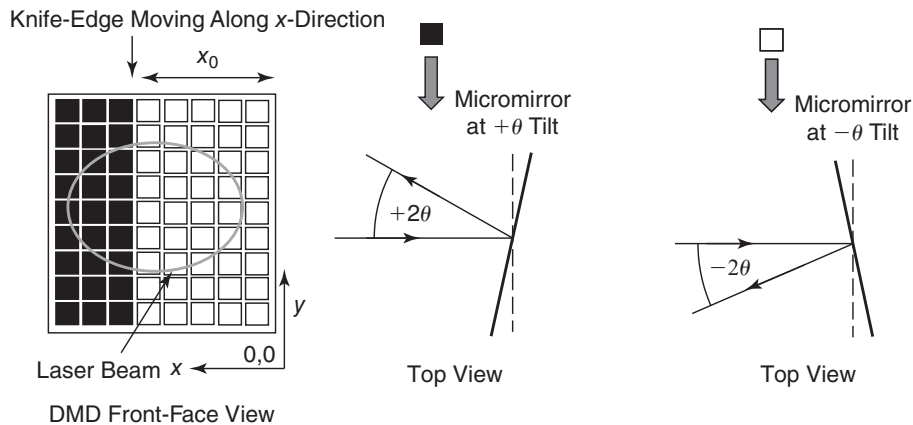


FIGURE 6.3 Views of the 2D DMD operating as a moving knife-edge and in its digital two-tilt modes. An example θ is a 10° angle relative to the shown dashed vertical line in the chip-substrate plane.

programmed such that a $+\theta$ (black-color micromirror) and $-\theta$ -state (white-color micromirror) horizontal boundary exists that forms the knife-edge location that moves along the y -direction for y -direction profiling.

To start the profiling, all micromirrors are set to the $+\theta$ -state to record P_0 at $x_0 = 0$ and then the number of $-\theta$ -state micromirrors along the x -direction is increased to cover the desired beam-zone range with increasing x_0 . The DMD-scan process is repeated for knife-edge scans along the y -direction with the changing y_0 .

When we look at the DMD, we realize its similarity with a CCD-pixel-array layout format with a fixed-spatial grid that gives 100 percent reliability in the positioning of the moving DMD-based knife-edge. Unlike the analog motion and rotation mechanical knife-edge, the DMD knife-edge has digital-operation reliability that via software can be placed along the desired moving edges. Unlike the CCD, the DMD-profiler operates with an indirect illumination single-PD and not an array of PDs that are directly illuminated. This means that, if needed, an optical attenuator can be placed between the DMD and PD1 without affecting the beam quality of the DMD-profiling plane. In addition, the single PD1 can be designed for high-dynamic-range operations versus a saturated operation with CCD pixels.

Engineering-Design Issues and Trade-Offs

Engineers always face system trade-offs and design limitations because of the components and design-layout of the system. Here are some questions and answers for the Figure 6.2 DMD-based laser-beam imager.

1. What is the laser-beam profiling area? The active area of the DMD chip, for example, $1\text{ cm} \times 2\text{ cm}$.
2. What is the smallest step of the DMD knife-edge motion? 1 micromirror pitch, for example, $10\text{ }\mu\text{m}$.
3. How many knife-edges can the DMD generate? The pixel count along the x - and y -directions, for example, 2000 along x -direction and 1000 along y -direction.
4. How long does it take to complete the knife-edge scanning operation? This depends on the profiling zone chosen and the knife-edge scan step-size as the PD is generally high-speed and not the bottleneck in data processing. For example, 23,000 knife-edge patterns can be scanned in the DMD in 1 s. Using this DMD image-update rate, we can compute the DMD-profiler scan times.
5. What is the wavelength of operation of the system? The DMD, for example, has aluminum-alloy mirrors that allow operation from around 400 to 2500 nm with an optical reflectivity from the DMD (i.e., mirror + two-passes in cover

glass) ranging nonuniformly between 50 and 95 percent. We choose the desired PD1 to detect the chosen wavelength band and calibrate the instrument for a specific wavelength range.

6. What is the optical loss in the system? The DMD is a pixelated device like a CCD; hence, it has a 2D grating structure that causes a diffraction-based loss. Specifically, we catch the zero-order or nondiffracted (deflected) beam at PD1. For example, for visible light, 70 percent of the light from the laser stays within the zero-order. A benefit of using a diffraction-based chip is that the PD1 does not get all the laser light as some light is lost in the off-axis orders that can be separately blocked. In effect, the PD will saturate at a higher laser-power level, allowing profiling of higher-power laser beams.
7. What active-area size of PD1 should be used? The PD1 size depends on the wavelength of the laser, its beam-propagation/expansion rate based on diffraction, and the distance between laser and PD1. The size should be big enough such that the PD catches all the $+\theta$ beam coming from the DMD off the DC or undiffracted light, while not catching any of the diffracted orders. We can also place a spatial filter (an iris) between the PD and the DMD to block diffracted orders. It is also possible to use a chosen diffracted order for optical-power detection as diffracted orders away from the undiffracted beam have lower power levels that will not easily saturate a PD.
8. The DMD, like a CCD, is pixelated and so one cannot escape diffraction effects when using highly coherent radiation, such as a laser input. See Figure 6.4.

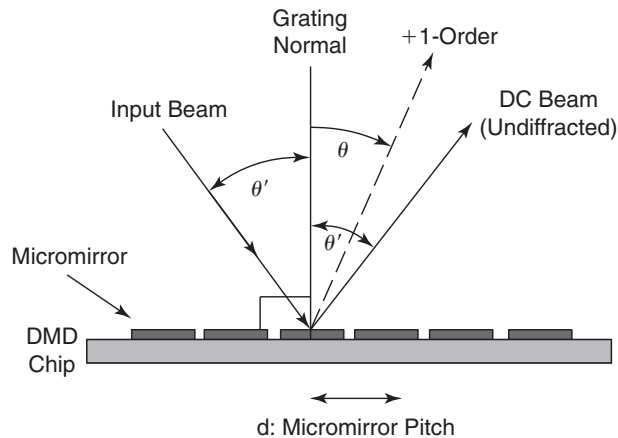


FIGURE 6.4 Shown is the DMD illuminated by a laser beam. A ray represents the beam, but in reality, a wide beam illuminating much of the chip area is present to engage the wavefront diffraction process. A side view of the chip is shown that displays the grating nature of the micromirror grid on the chip.

The pixelation represents a repetitive optical structure made of micromirrors placed with a pitch of $d \mu\text{m}$, for example, $d = 13.84 \mu\text{m}$. The interference condition for a 1D grating structure to produce the diffracted beams is given by $\sin \theta' - \sin \theta = m(\lambda/d)$ where θ' is the incident-beam angle with the grating normal and θ is the diffracted-beam angle with the grating normal (shown for only the +1 order when $m = +1$) where m is the order number. For a red $0.633 \mu\text{m}$ laser and a DMD chip $d = 13.68 \mu\text{m}$, the diffraction angle for the first-order beam relative to the DC beam, in other words, $\theta' - \theta$ is 0.046 rad or 2.636° .

Design Problem 6.2: Input-Power Fluctuations Insensitive DMD-Based Profiler

Imagine that the light-source incident of the DMD-based profiler fluctuates in power level (the profile stays the same) during the instrument-profiler operation. In this case, the profiler will produce an erroneous Gaussian beam laser-power profile as P_0 keeps changing, and the measured power $P_m(x_0)$ is normalized using only one of these values. Design a modified DMD-based profiler system to solve this problem.

Solution

Figure 6.5 shows a modified design that solves the system problem by making note that the DMD operates naturally as a two-port device, where previously the $-\theta$ -beam port was not used. At this port, PD2 is placed to record optical power, P_2 , that did not go to the $+\theta$ -beam port where PD1 measured P_1 power. Note that previously the PD1 power data $P_1 = P_m(x_0)$ was normalized using P_0 that was measured at the

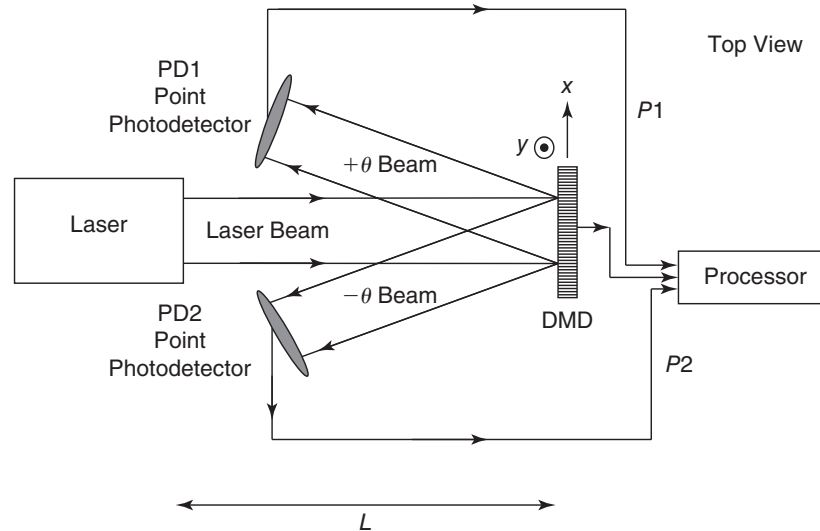


FIGURE 6.5 Input-power independent DMD-based beam-profiler.

beginning of the profiling-time sequence and assumed P_0 did not change during the profiling operation. In the new design, the $P_1 = P_m(x_0)$ power data will be normalized by $P_1 + P_2$ power data that is instantaneously measured for each DMD knife-edge-setting leading to correct normalization of the measured optical power data. In other words, $P(x_0) = P_m/(P_1 + P_2)$ and so as the laser power $P_0(t)$ changes from one DMD knife-edge reading to the next knife-edge reading, $P_1 + P_2$ changes in time as $P_0(t) = k[P_1(t) + P_2(t)]$, where k is a fixed-loss factor connected with freespace propagation and diffraction loss. In summary, each $P_1 = P_m$ power reading is correctly normalized by the scaled total-laser power at that instant. Hence, the modified-profiler design will provide the true laser-beam profile. It is assumed that the laser power does not fluctuate during the PD integration time. Generally, PDs are fast devices so this error can also be minimized depending on PD sensitivity and laser-power levels. Higher-power lasers means shorter PD integration times, indeed a plus for this DMD-profiler design suited for higher-power lasers. Recall that DMDs are used in movie projectors using many watts of light illumination.

Design Problem 6.3: DMD-Based Profiler Non-Gaussian Laser-Beam Profiling

Not all laser beams have single-mode Gaussian spatial profiles. This means that classic knife-edge profiling does not work for non-Gaussian beams. Design a DMD-based beam-profiler that can profile non-Gaussian beams.

Solution

Figure 6.6 is the profiler design that can profile non-Gaussian beams. The system is exactly the same as the classic DMD-based profiler. The key difference is that the DMD is programmed to generate a moving

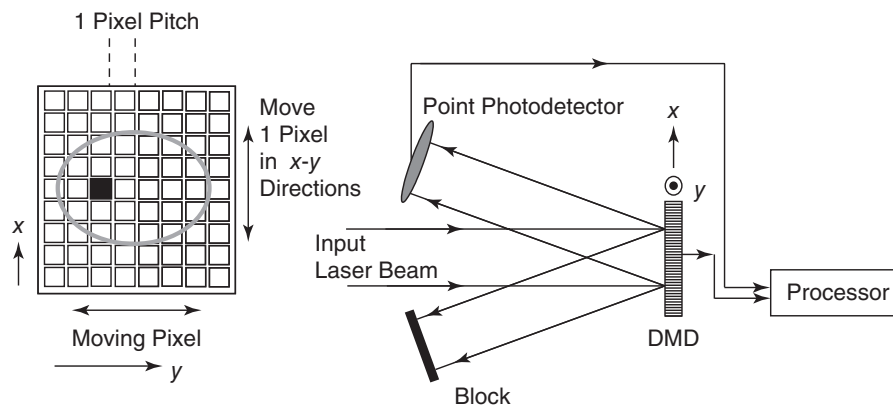


FIGURE 6.6 DMD-based beam-profiler operation for non-Gaussian beams.

Design Problem 6.4: DMD-Based Profiler Incoherent-Light 2D Imaging

Solution

The diagram illustrates a 2D optical Fourier transform setup. Light from a far-field object is imaged by lens S1 onto a DMD. The DMD is tilted at an angle θ relative to the optical axis. The light is then focused by lens S2 onto a photodetector (PD1) and lens S3 onto a photodetector (PD2). The DMD is controlled by a processor (P) which receives signals from PD1 and PD2. A coordinate system (x, y) is shown for the DMD. A 'Moving Pixel' is shown in a grid of pixels, with its position (x, y) being scanned. The light from the far-field object is labeled 'Light from Far-Field Object Imaged by Lens S1'.

FIGURE 6.7 DMD-based robust 2D irradiance imager.

reconstruction of the object. Hence, a two-point photodetector camera is formed. Another benefit of this imager via its point-sampling dual-detector approach is that light-saturated bright objects in darker backgrounds that are not seen using classic CCD-type imaging optics can be observed using this high-dynamic-range point-calibrated camera allowing super-vision capabilities. The $+\theta$ and $-\theta$ light-collection ports are multiplied into multipurpose ports using beam-splitters, attenuators, wavelength-sensitive optics (filters, dispersion optics), polarizers, etc., giving tremendous power to the image-sensing capabilities of the DMD imager. Because these components are added after the DMD plane-sampling zone, the incident-true image data is not spoiled, a key feature of this photonic-system design.

Design Problem 6.5: DMD-Based Profiler Incoherent-Light 3D Imaging

Design a DMD-based beam-profiler that can capture the 3D image irradiance of a 3D object.

Solution

To accomplish 3D imaging, we can capture the 2D slices of the 3D object along the optical axis. In fact, confocal microscopy does so in the object plane by classically moving the object in the direction of the optical axis in the focal plane of the microscope objective and using a pinhole at the detection plane to block out-of-focus plane light. The DMD-profiler system in Figure 6.8 functions as a 3D imager by using

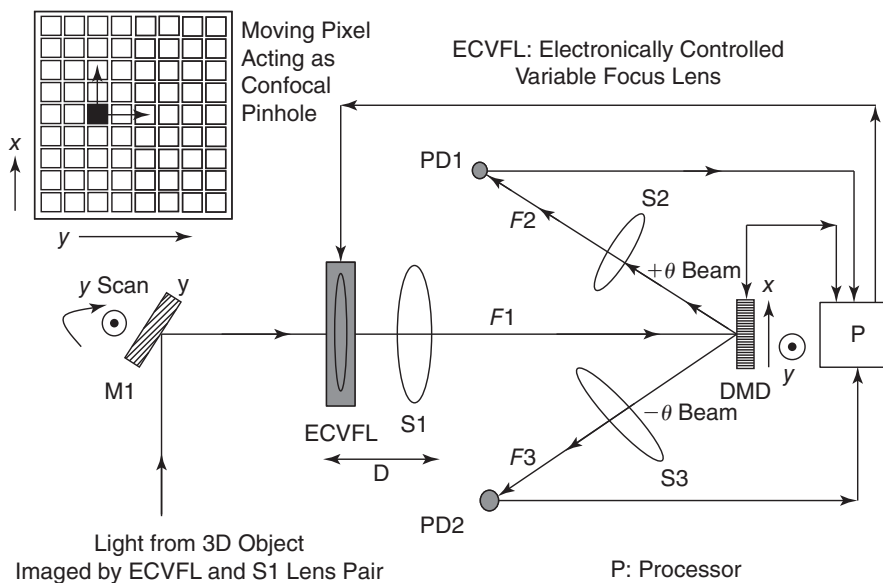


FIGURE 6.8 DMD-based 3D irradiance imager.

an electronically controlled variable-focus lens (ECVFL) to change the object image-plane along the optical axis that falls on the DMD plane. The micromirror naturally acts as a pinhole to reject out-of-plane light. S1 and ECVFL act together as an imaging-lens pair, where S1 is a bias fixed F_1 focal-length lens and ECVFL F_E focal length changes with voltage to change the combined focal length of the imaging pair separated by a distance, D . The combined focal length F_c of the lens pair can be obtained from $1/F_c = 1/F_c + 1/F_1 - [D/(F_1 F_c)]$. ECVFL technologies are diverse, such as via a fluid/liquid lens using electrowetting technology.

Design Problem 6.6: M^2 Measurement Method to Characterize Non-Gaussian Beams

As shown in Figure 6.9, characterization of non-Gaussian beams is done by measurement of the M^2 beam-propagation parameter by taking beam profile and position measurements on either side of the minimum-beam waist. In general, multimode beam radii at the beam waist can be written as $W(z) = Mw(z)$, where $w(z)$ is the embedded fundamental Gaussian mode second-moment radius definition of the beam irradiance and M is a number, for example, 1.2. When access to the minimum-beam waist, W_{01} , is not possible (such as when the waist is inside the laser-cavity box shown in the figure), an external lens, L , is placed to create an external secondary minimum-beam waist, W_{02} , around which several (e.g., four) beam-waist measurements are taken using a moving pinhole mechanical scan beam-profiler at positions z_1, z_2, z_3 , and z_4 . This means many optical-power readings for pinhole positions along the x - y and z -axes of pinhole motion. In other words, a massive amount of pinhole motion is involved, leading to positional reliability issues. An alternate design keeps the pinhole profiler on-axis location fixed but moves the lens,

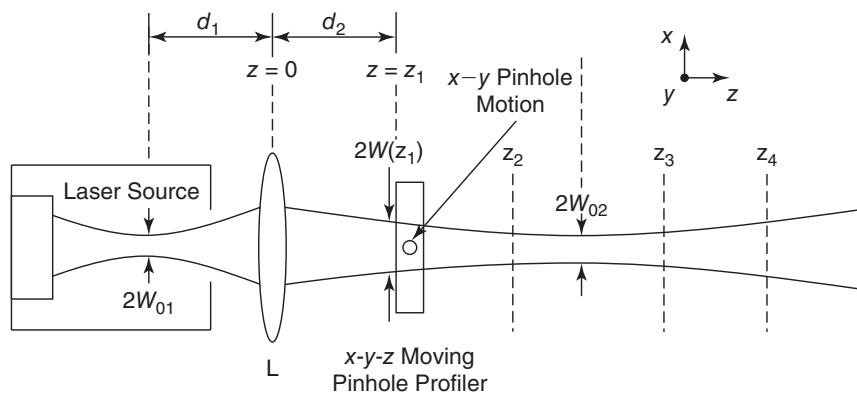


FIGURE 6.9 Non-Gaussian beam measurement by on-axis motion of pinhole profiler.

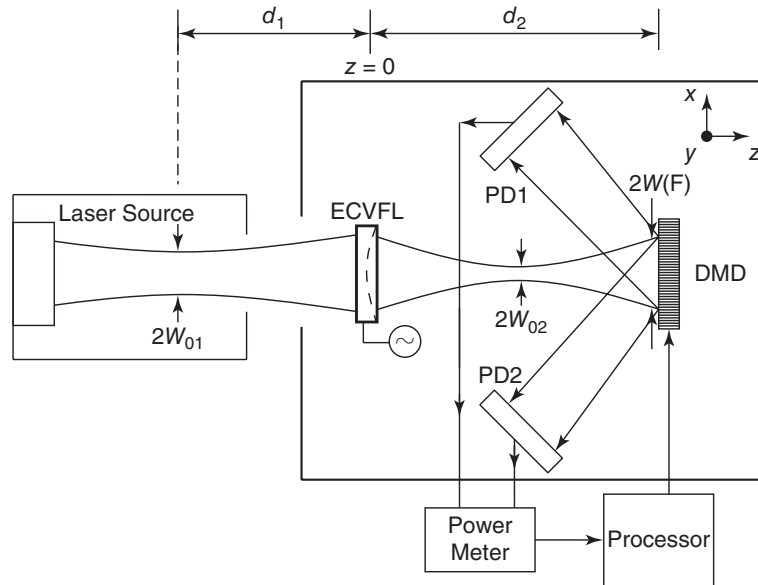


FIGURE 6.10 Non-Gaussian beam measurement by on-axis motion-free pinhole profiler.

L, along the optical axis to a minimum of four z -axis locations. Design a beam analyzer that eliminates the mechanical actuator-based pinhole (or lens, L) motion that leads to instrument-reliability issues.

Solution

Figure 6.10 is the design that eliminates the lens, L, and pinhole motion problem. Specifically, we use the DMD-based profiler operating in pinhole-mode to provide 100 percent positional reliability beam-waist measurement data. Second, the fixed focal-length lens, L, is replaced by an ECVFL that controls the location of the formed secondary minimum-beam waist, W_{02} . In effect, instead of moving the profiling plane or the lens position, the ECVFL focal-length F is electronically changed to produce at least four different $W(F)$ beam-waist conditions as required for M^2 measurements. Thus, no large-scale macro-motion of optical components is needed and a highly reliable beam-analyzer is realized.

Design Problem 6.7: High-Dynamic-Range Broadband Fiber-Optic Variable Optical Attenuator

A high-dynamic-range polarization-insensitive broadband fiber-optic variable optical attenuator (VOA) is a highly desired component for many fiber-based applications. Typical numbers can be optical attenuation over a 50-dB dynamic range, uniform spectral operations over 40 nm centered around 1550 nm, and a 1-ms response. The VOA

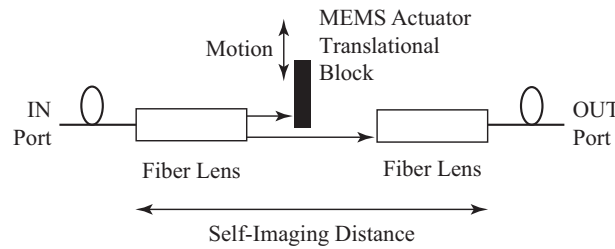


FIGURE 6.11 SMF broadband high-dynamic-range VOA design using micromechanics.

operations must not be dependent on any light polarization state, given light from SMFs can have varying polarizations. Design a compact VOA with the mentioned features.

Solution

Figure 6.11 shows a design of the desired VOA using micromechanics. Specifically, two SMFs with the self-imaging lenses (also called focusers) are placed a distance apart to satisfy self-imaging between the two SMFs. A small micromechanical block acting as a moving knife-edge is placed midway between the SMFs. Analog smooth translational motion of the block across the light beam path creates beam blockage, thus reducing the light coupled to the output-SMF. Because the beam block can completely stop all light (apart from some scattered light) from reaching the output-SMF, a high-dynamic range VOA is realized. The beam-spot size is typically under 1 mm in diameter, so a MEMS actuator can drive the knife-edge to produce variable attenuation at low electrical-drive powers.

Design Problem 6.8: High-Dynamic-Range Broadband Fiber-Optic VOA with Graceful Beam Control

A 1D direction translation of micromechanics, such as a moving knife-edge to block a very small (under 1-mm diameter) beam from a SMF-coupling lens, requires a super-precise and reliable MEMS actuator. Design a micromechanics-based fiber-optic high-dynamic-range polarization-insensitive broadband fiber-optic VOA that reduces the demands on the MEMS-actuator precision controls.

Solution

Figure 6.12 shows the desired VOA design that uses the concept of 3D beam spoiling of the entire wave front versus 1D-tilt control of the beam. A deformable mirror (DM) MEMS device is used to introduce phase perturbations on the entire wave front such as by using an array of actuators behind the mirror membrane. Using multiple control signals/actuating sites across the beam aperture gives more

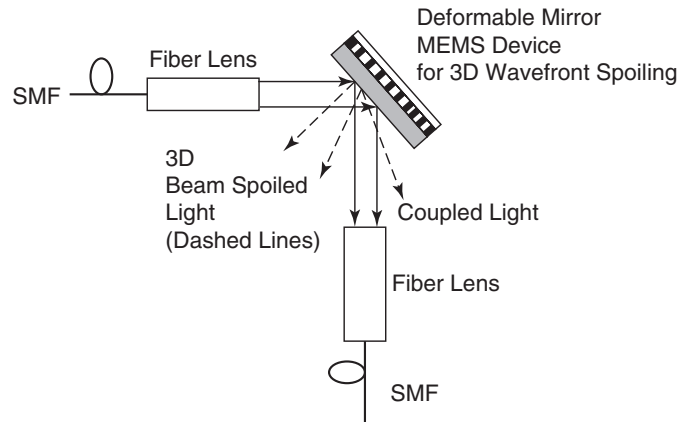


FIGURE 6.12 Graceful beam control VOA with a less-demanding MEMS-actuator control.

degrees of wavefront control using the MEMS device. This multi-zone actuation produces less demands on the VOA attenuation-control mechanisms versus a single degree of freedom optical-beam control method such as via single mirror tilt control. Here the DM device also provides focus/defocus control apart from 2D-tilt controls and beam 2D translational controls. Any reflective optical-phase modulating device can be used to impart optical-phase perturbations on the beam incident on the device. In addition, a VOA design can be realized using a single-fiber lens to form a more compact VOA.

Design Problem 6.9: Fault-Tolerant 100-Percent-Reliable Broadband Fiber-Optic VOA

VOA designs that use gradual motion of a micro-optic, such as a translating mirror or beam block require actuators that are precise and repeatable over their operational lifetimes. The higher the attenuation resolution required from the VOA, the more challenging are the requirements on the MEMS actuation. The analog-mode VOAs also rely on a single micro-optic and, hence, suffer in a way to catastrophic failure. In other words, if the micromirror malfunctions, the whole VOA malfunctions. Analog-mode VOAs require full-range motion of the micro-optics to achieve full dynamic-range operation to cover the entire beam zone. This leads to slower VOA response in time. Design a fiber-optic VOA that is high-speed, fault-tolerant, and 100-percent repeatable in settings.

Solution

Figure 6.13 shows the desired VOA that achieves its powers by simply using an optical MEMS chip that contains an array of digital tilt-state ($\pm\theta$) small micromirrors versus using a multi-tilt-positions state in one

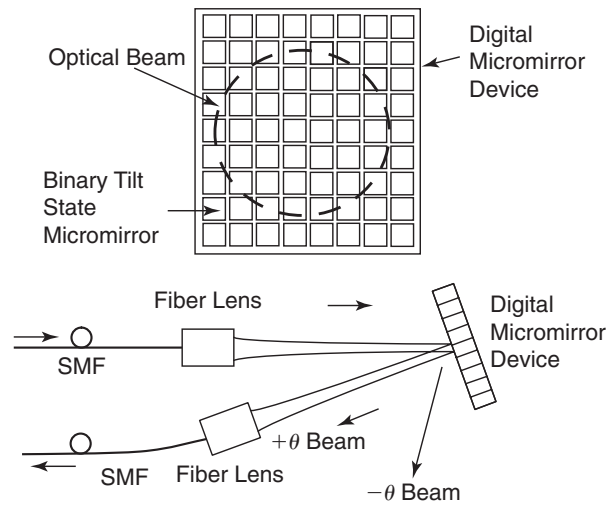


FIGURE 6.13 Fault-tolerant all-digital fiber-optic VOA.

large micromirror. The digital-state chip can be a DMD. Use of many micromirrors adds VOA fault-tolerance to single micromirror failure. Because the micromirrors are smaller in size and use two-tilt states versus a single larger micromirror, the switching speed of the VOA is faster, for example, $16 \mu\text{s}$ versus 1 ms for a 1-mm diameter optical-beam incident on the chip. The incident irradiance on the mirror chip is fixed and the micromirrors control a specific power of the incident beam. Because the micromirrors have only two states, they act as on/off shutters for the incident-light beam. Controlling the on/off states of these micromirrors using digital-state signals leads to a 100-percent reliable optical attenuation-control state for the VOA. As an example, if the beam zone covers 1024 equal-size micromirrors, a 10-bit equivalence VOA is realized assuming each micromirror represents $1/1024$ of the optical power in the incident beam.

Design Problem 6.10: Fault-Tolerant High-Dynamic-Range Fiber-Optic VOA

Given interpixel beam isolation limitations for a typical multi-pixel SLM, a 35-dB optical isolation is expected between micromirror beam directional states, and this leads to a typical 35-dB dynamic range for DMD-based VOAs. Design a high-attenuation dynamic-range VOA using the DMD to preserve fault-tolerant operations.

Solution

Recall that analog-mode VOAs can provide high-attenuation dynamic ranges. Shown in Figure 6.14 is a hybrid analog–digital-mode design VOA using a DMD. Analog motion of the receive fiber lens (translation

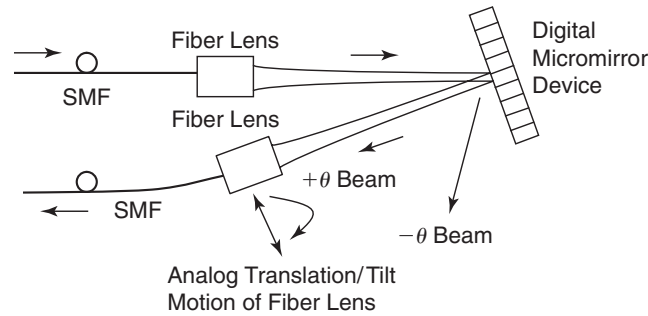


FIGURE 6.14 Hybrid analog-digital-mode fiber-optic VOA.

and tilt) can provide a bias attenuation level while the DMD operations can provide high-resolution attenuations for that bias setting. Hence, both high-resolution and high-dynamic range is achievable using all-digital DMD controls and analog-mode MEMS motion-actuator controls for the receive fiber lens.

Design Problem 6.11: Fault-Tolerant Fiber-Optic Multiwavelength Equalizer

Design a fault-tolerant fiber-optic multi-wavelength equalizer to control the spectrum of input light fed from an SMF.

Solution

Figure 6.15 is the desired fault-tolerant fiber-optic multi-wavelength equalizer, where each optical wavelength is attenuated using an array of pixels in a reflective SLM. The pixels can be of the digital tilt-mode type like DMD micromirrors or of the piston-type for optical-phase steered-beam control. The WDM device spatially separates the input light into its multiple wavelengths for independent spectral processing.

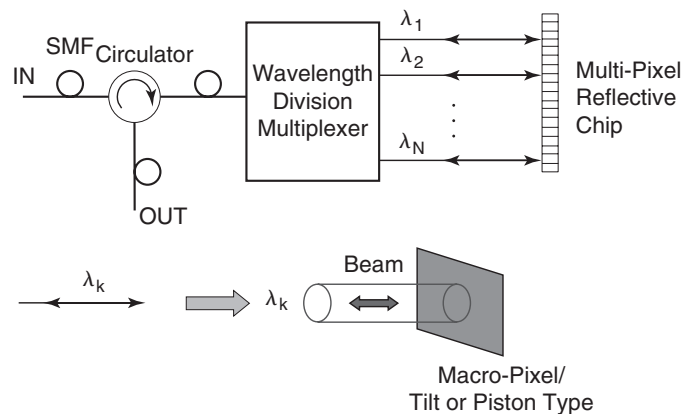


FIGURE 6.15 Fault-tolerant fiber-optic multi-wavelength equalizer.

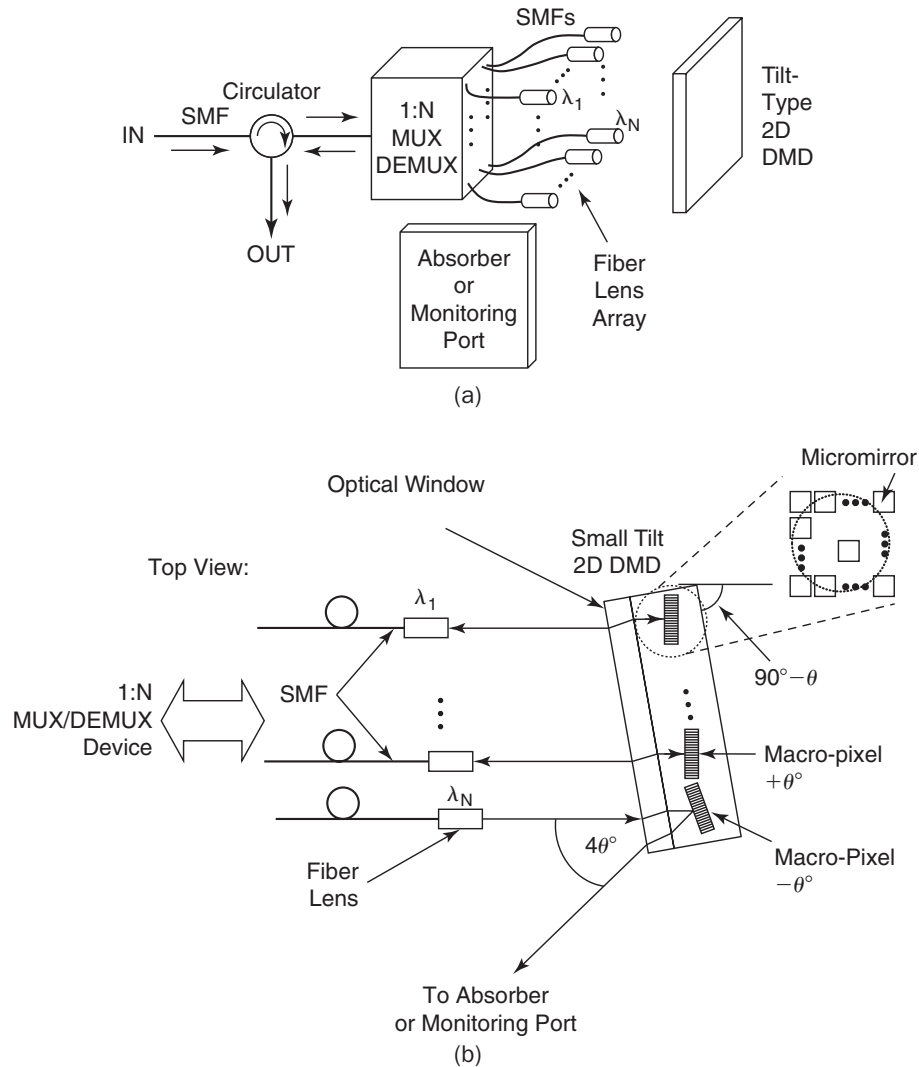


FIGURE 6.16 WDM equalizer using DMD for discrete spectrum processing. (a) The equalizer components layout. (b) The light interaction from each fiber lens with its specific mirror-based macro-pixel.

WDM devices include SMF-connected designs such as when using fiber Bragg-grating (FBG), interference thin-film filters, and arrayed waveguide-gratings (AWGs). Such WDM devices provide discrete wavelength spectra and can be used in the Figure 6.15 design to realize the Figure 6.16 design using a fiber-lens array freespace interconnected to a 2D DMD to implement discrete spectrum processing, such as for WDM fiber communications where discrete wavelength channels are allocated in the optical communications spectrum to represent discrete communication channels, for example, 1545.1 and 1545.5 nm processed in the equalizer via separate WDM fiber-fed channels.

Design Problem 6.12: Continuous-Spectrum DMD-Based Equalizer

Design a fault-tolerant fiber-optic multi-wavelength equalizer to control the continuous spectrum of input light fed from a SMF.

Solution

Figure 6.17 is the desired design of a fault-tolerant fiber-optic multi-wavelength equalizer to control the continuous spectrum of input light fed from a SMF. The WDM device chosen is a bulk optical grating labeled as G with a center-frequency Bragg angle θ_c that matches the central wavelength, λ_c , of the spectrum-processing band from $\lambda_{\min}$ to $\lambda_{\max}$. The bulk grating G is used as it produces the desired continuous distribution of the input spectrum in space (along x -direction) versus a fiber-interconnected WDM device. Focus lens optics C_x of focal length F is used to separate the colors and form a collimated beam input onto the DMD. C_s are cylindrical lenses to implement imaging along the y -direction and focusing/Fourier transforming along the x -direction which is also the direction of the wavelength spatial dispersion. FL is the fiber lens and C is the three-port fiber-optic circulator. Use of the circulator C can be avoided, for example, by tilting (on y -direction axis) the DMD chip and using separate SMF-FL assemblies for input and output ports. The DMD chip is shown at a 45° angle to the x/y axis because the micromirrors

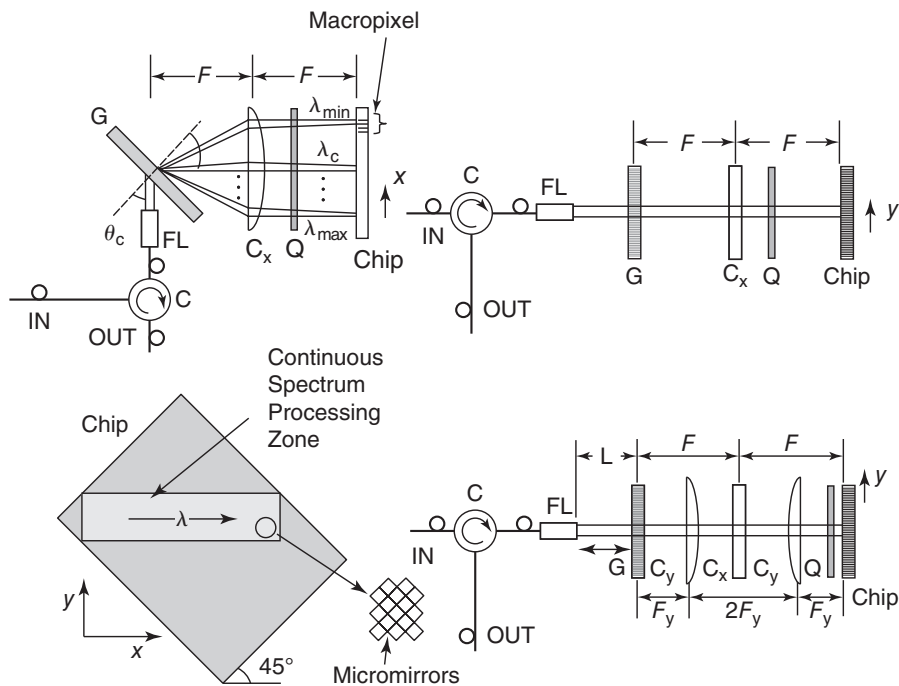


FIGURE 6.17 Continuous-spectrum DMD-based equalizer.

rotate about this 45° axis. The quarter-wave-plate, Q , when used with the reflective SLM reduces polarization dependence in the system.

Design Problem 6.13: Digital Micromirror Device-Based Multi-Wavelength Add-Drop Routing Module

In WDM communications using N -wavelengths to represent N different communication channels, there is a need sometimes to drop a particular wavelength or wavelengths in the main-input signal channel and replace these dropped wavelengths with new signals at the same wavelengths. This operation can be accomplished by a fiber-optic multi-wavelength add-drop routing module. Design such a module using a DMD.

Solution

Figure 6.18 shows the desired module design. Again, gratings are used to spatially separate and gather multiple wavelengths. In the

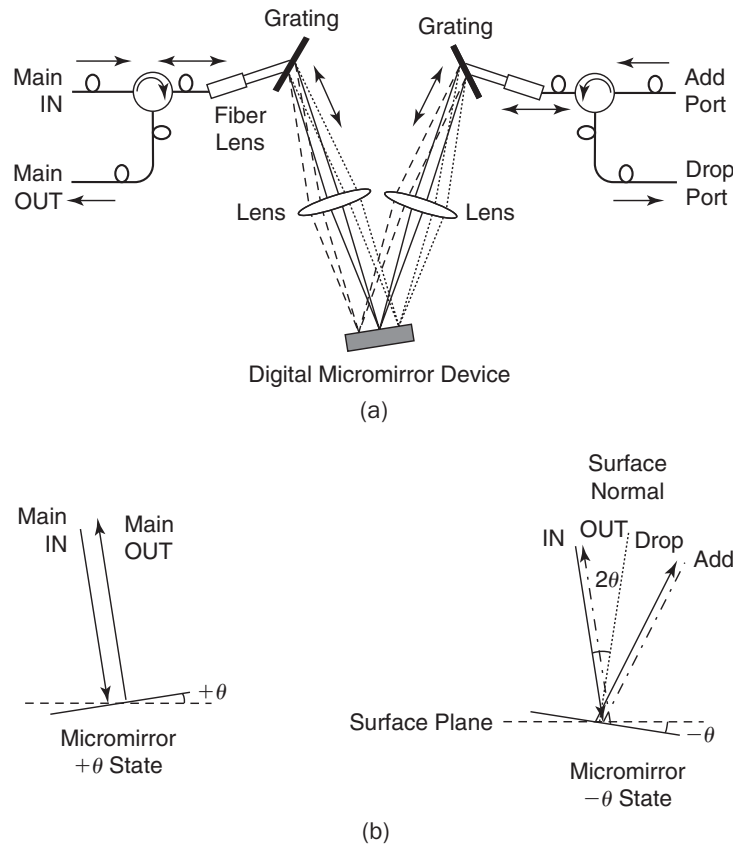


FIGURE 6.18 Digital micromirror device-based multi-wavelength add-drop routing module. (a) The routing module components layout. (b) The two states of the micromirror for operating the two states of the module.

DMD $+\theta$ -micromirror state, light from the main in port flows right back to the main out-port. In the DMD $-\theta$ -micromirror state, light from the main in port flows to the drop port and light from the drop port flows to the main out-port. The binary tilt states of the DMD micromirrors can control which wavelengths are selected for add-drop operations and which ones are selected for main in-main out operations in the WDM SMF communications channel where this multi-wavelength add-drop module is added.

Design Problem 6.14: Array of One-by-Two Fiber-Optic Switches and VOAs

Many electrical (RF, digital, and mixed-signal format) and optical signals require signal processing that involves signal time-delay and weight control. Figure 6.19 shows a universal-type photonic signal-processing module that can time-delay and weight control the optical signal using an array of 1×2 fiber-optic switches that are interconnected to produce a variable time-delay unit (TDU) and a variable gain (G) or VOA module. The TDU uses externally connected SMFs of different lengths to provide variable time delays using the digital switched structure. A variety of fiber types can be used include high-optical dispersion fibers. The 1×2 fiber-optic switches not only provide 1×2 digital path switching but also optical attenuation control. Design a 1×2 fiber-optic switch array that can be used to form the Figure 6.19 universal signal-processing module.

Solution

Figure 6.20 shows the construction of the desired universal module using one DMD chip and linear arrays of fiber-lens coupling optics where the distances between input and the two output ports per light-processing site are designed to obey the low coupling loss

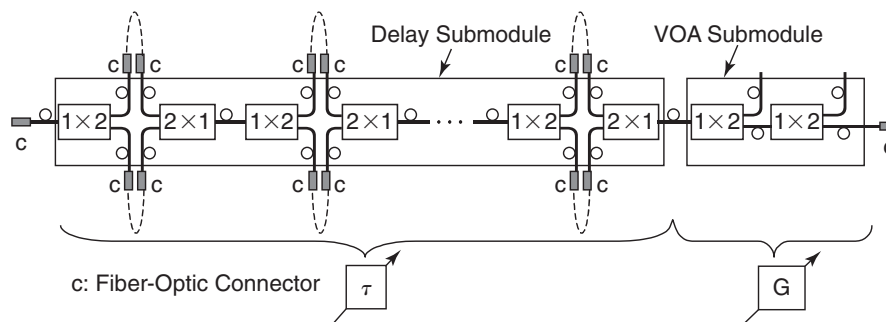


FIGURE 6.19 Universal processor module for optical-domain time-delay and weight controls.

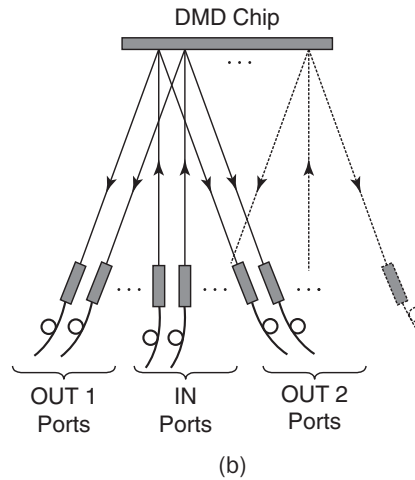
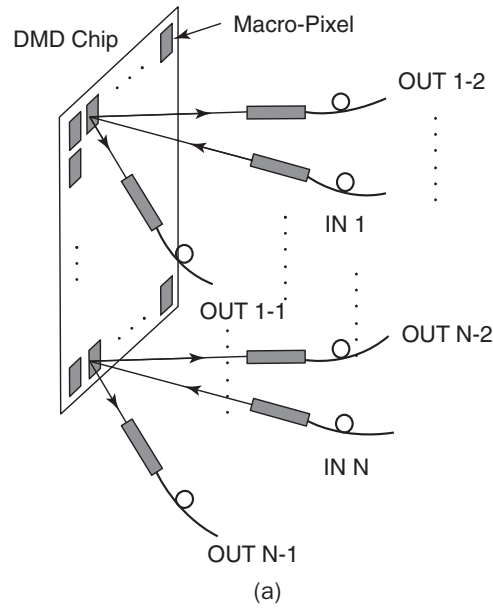


FIGURE 6.20 (a) 3D and (b) top views of the universal signal-processing module design using single DMD.

self-imaging effect. In a 1×2 digital switch mode, IN1 light can be directed either to OUT1-1 port or the OUT1-2 port by turning the $\pm\theta$ -digital state of all the micromirrors in the macro-pixel to a $+\theta$ -state and the $-\theta$ -state, respectively. In a VOA mode, IN1 light can be directed both to OUT1-1 port and the OUT1-2 port by turning the $\pm\theta$ -digital state of some of the micromirrors in the macro-pixel to a $+\theta$ -state and some to the $-\theta$ -state, respectively. Such

a dual-switch-VOA-mode operation is possible by the macro-pixel beam control operation on light coming from an input fiber port. Because the DMD has many macro-pixels, an array of fiber-lens-SMF ports can be engaged to form a compact universal processor module. For example, such a module can be used to provide RF phased-array antenna (PAA) beam-forming using photonics where time-delay control provides wideband RF antenna beam-steering and RF attenuation-control shapes the RF antenna-radiation pattern.

Design Problem 6.15: Long Time Delay and High-Resolution Photonic-Delay Line

Many applications require long time delays (e.g., tens of nanoseconds) with extreme precision time-delay setting control (e.g., picoseconds). For example, long-range microwave PAA radar systems, such as operating at 3 GHz with several-meter-diameter antenna faces require long RF time delays with precise time-delay control for accurate RF beam-pointing over many scan beams. Design such an RF TDU implemented using photonics.

Solution

Figure 6.21 is the desired variable-optical-delay line for RF signals. This required signal-control module design is possible by simultaneously using both analog and digital optics that lead to both a high time-delay dynamic range and high time-delay resolution. The analog optics consists of laser-wavelength tuning and chirped-fiber Bragg-grating (CFBG) usage for wavelength-coded optical delay T with fine precision. For example, a $T = 805$ ps analog-delay range is

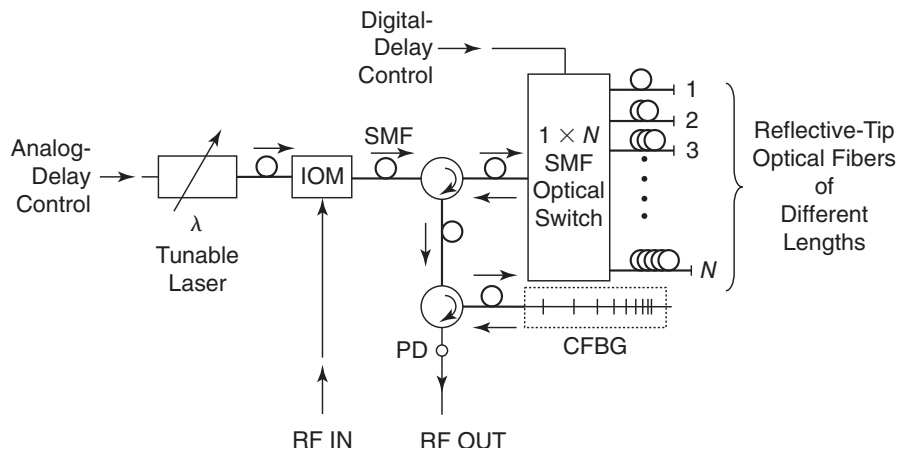


FIGURE 6.21 Hybrid analog-digital control variable-optical-delay line for RF signals.

generated using a CFBG dispersion, D , of 35 ps/nm and a wavelength tuning range of 23 nm. With a 0.01-nm laser-tuning precision, a 0.35-ps time-delay resolution is possible. Note that the tunable laser can be replaced by a broadband optical source and a wavelength selective filter to accomplish the desired analog time-delay control. Digital optics in the form of a digital optical switch and pre-cut optical fibers are used to form a digitally controlled long time delays TDU. For the example mentioned, one can design the time-delay increment between adjacent fibers to be $T = 800$ ps so that using 32 fibers and the analog-delay TDU, a maximum $32T$ time delay is possible. The first fiber delay connected to switch port 1 provides a reference delay setting via a fixed-fiber length, for example, 40 cm. At this switch setting, the analog TDU covers the T delay range. To access the T to $2T$ delay range, the digital switch port is set to port 2 that has a fiber length of 40 cm + 8 cm where the 8 cm provides the T delay and analog TDU provides the variable delay with a T range. Thus, by controlling the $1 \times N$ switch setting and the tunable-laser wavelength, we can cover the full range of time delays (e.g., 25.6 ns) from 0 to $32T$ with extremely small (e.g., 0.35 ps) time-delay steps. Hence, a powerful photonic signal-processing module is realized. The reset time of such a module will depend on the tuning speed of the laser and the switching time of the optical switch.

Design Problem 6.16: Switchless Long Time Delay and High-Resolution Photonic-Delay Line

The hybrid analog–digital variable photonic-delay line shown in Figure 6.21 requires the use of fiber-optical switches, such as optical MEMS or electro-optic waveguide technology-based switches. Switch technologies have limitations, such as switching speed, optical loss, and wavelength dependence. A variable-delay line that is switchless can provide certain performance benefits. Design a switchless long time delay high-resolution delay line for RF signals that can reset at high speeds, for example, nanoseconds.

Solution

Figure 6.22 shows the desired switchless-variable photonic-delay line for RF signals that uses the concept of cascading a coarse WDM device with another wavelength-sensitive device such as a high-dispersion optic. The coarse WDM device has a flat-top passband spectrum as indicated in Figure 6.22 so it forms a wavelength-based $1:N$ SMF-based routing device with fiber channels centered at $\lambda_1, \lambda_2, \lambda_3, \dots, \lambda_N$, where each SMF channel has a $\Delta\lambda$ bandwidth. The coarse WDM device output fiber channel is connected to a custom length SMFs such that the n th fiber channel provides a time delay of $(n - 1)\tau + T_n$, where τ is the digital step in delay as the wavelength changes from the center

wavelengths λ_1 to λ_N . A second coarse WDM device combines the N separate SMF channels into one SMF channel that connects to a high-dispersion fiber (HDF) with a negative-dispersion D_f (e.g., -600 ps/nm-km) and fiber length L . Tuning the coarse wavelength over a $\Delta\lambda$ bandwidth over its center wavelength λ_n ($n = 1, 2, 3, \dots, N$) sets the fine delay via analog control within a τ range of the RF signal. Each SMF segment in the digital delay structure has a bias delay T_n . For the n th fiber channel of the coarse WDM, $T_n = T_0 + n(\lambda_n - \lambda_{n-1})D_f L$ that counters the relative-delay shift produced between the different coarse central wavelengths λ_n when passing through the HDF. T_0 is a fixed-fiber time delay that occurs between the two WDMs as the two WDMs need some small fiber length for a connection. Tunable lasers can be reset at fast speeds, for example, 10 ns, so a fast reset speed variable optical delay line is possible. For $n = 1$, the first coarse WDM fiber port is selected and with the wavelength tuned from $-0.5\Delta\lambda + \lambda_1$ to $+0.5\Delta\lambda + \lambda_1$, an analog tuned delay over a τ range is possible via the HDF optic. For $n = 2$, the second coarse WDM fiber port is selected and with the

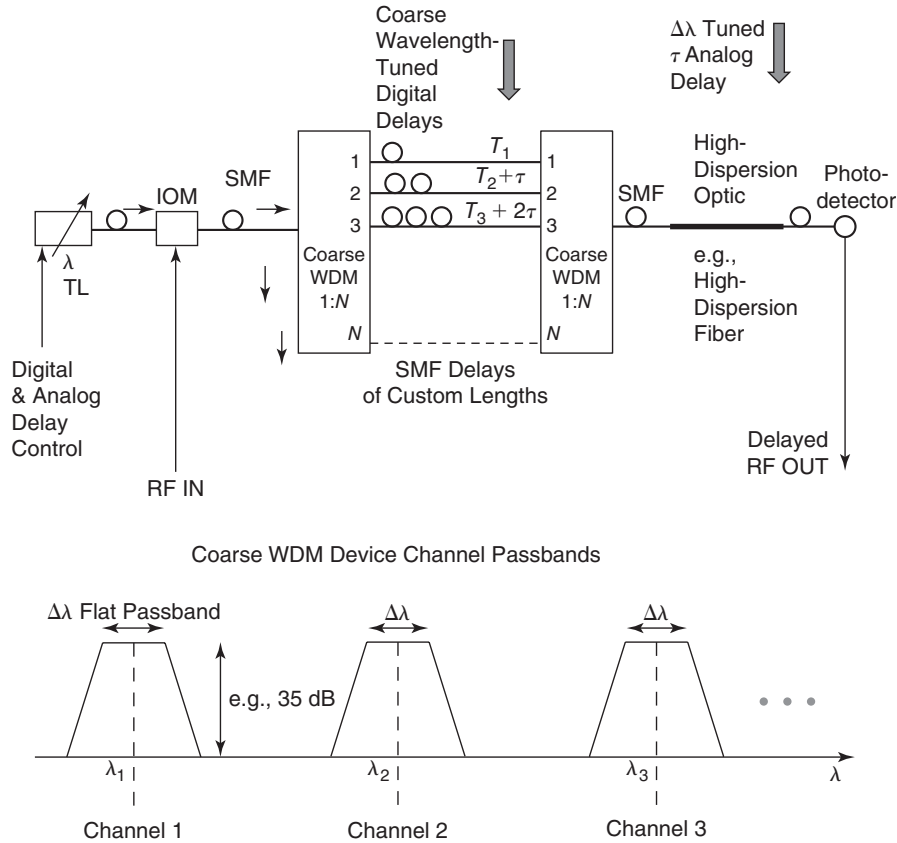


FIGURE 6.22 The desired switchless long time delay high-resolution variable-photonic delay line for RF signals with $\lambda_n < \lambda_{n+1}$ wavelength, for example, $\lambda_1 = 1500$ nm, $\lambda_2 = 1503$ nm, and $\lambda_3 = 1506$ nm.

wavelength tuned from $-0.5\Delta\lambda + \lambda_2$ to $+0.5\Delta\lambda + \lambda_2$, and again an analog tuned delay over a t range is possible via the HDF optic but over a τ to 2τ range. Using both coarse WDM port selection and fine-wavelength selection, a wide $N\tau$ time-delay range high-resolution time delay line is formed. The fine-wavelength-sensitive optic can also be a WDM device that has a modulo- $\Delta\lambda$ bandwidth such as a grating-optic or arrayed waveguide-grating (AWG) optic.

Design Problem 6.17: All-Optical Coder/Decoder Using Wavelengths and DMD

Secure Optical-Code Division Multiple-Access (O-CDMA) fiber networks can be realized using Figure 6.23 shown multidimensional codes using wavelength, time, and amplitude coding of optical

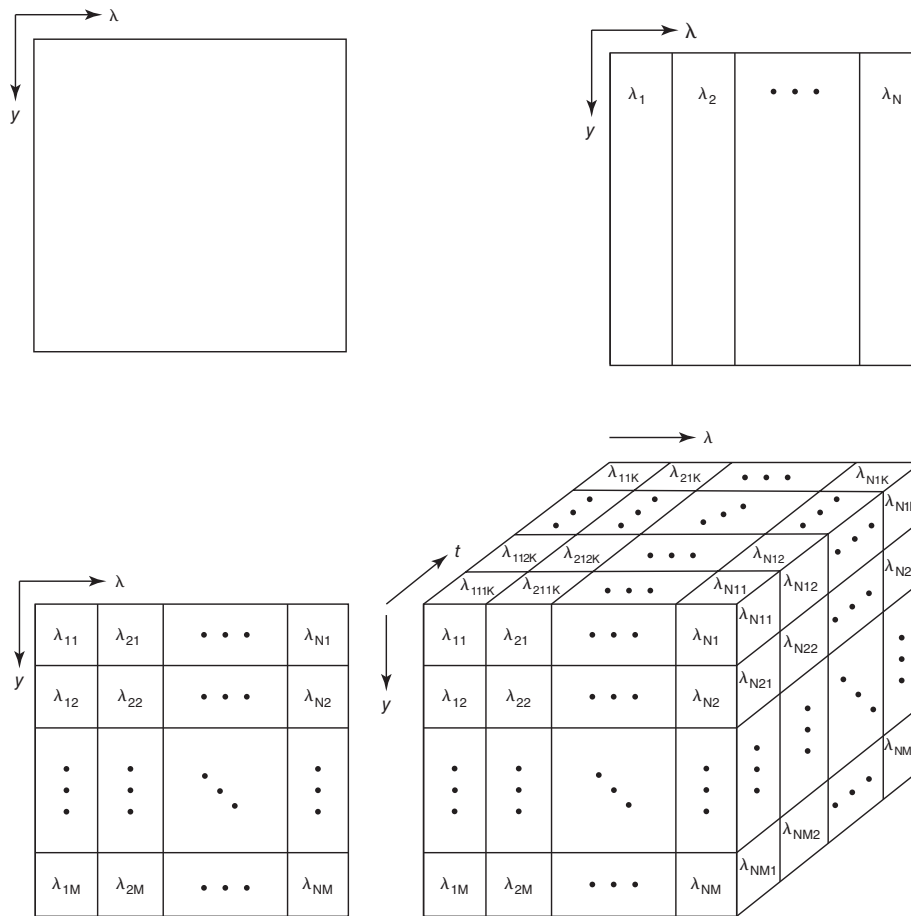


FIGURE 6.23 Multidimensional optical codes using wavelength, time, and amplitude coding.

signals. As shown before, gratings in freespace configuration engaged with macro-pixel DMD optics can achieve wavelength-selection amplitude and time-delay control. For Figure 6.23, the input optical signal is sliced into N -independent wavelengths. Each wavelength is then spatially spread over the y -direction so the wavelength can be attenuated over M -settings. Each wavelength for any given attenuation setting can also receive its own time-delay value selected over K different delays. Design a digital MEMS device-based SMF interconnected optical coder/decoder module for multidimensional optical CDMA fiber-optic communications.

Solution

Figure 6.24 is a digital MEMS-based high time-delay dynamic-range O-CDMA encoder/decoder module for O-CDMA. Components used are: S: spherical lens; C: cylindrical lens; G: freespace bulk grating. The SMF-S-G-C combination makes an optical wavelength-to-space mapper with the output/input interface plane called I whose orthogonal axes represent the wavelength axis and the y -direction space axis. The high signal-conditioning time-delay dynamic range is achieved through the use of an N -bit variable-delay line that gives $K = 2^N - 1$ delays that can be long-duration delays depending on the delay media used in the TDU module. The module as described earlier (Figure 6.17 and Figure 6.19) showed a typical DMD-based TDU via the macro-pixel approach for beam control that also acts as a VOA for specific wavelengths.

If short delays (e.g., <100 ps) are acceptable, Figure 6.25 shows an alternate coder/decoder design where a single $\pm\theta$ -state DMD chip is engaged with the fixed mirror to provide variable time delays.

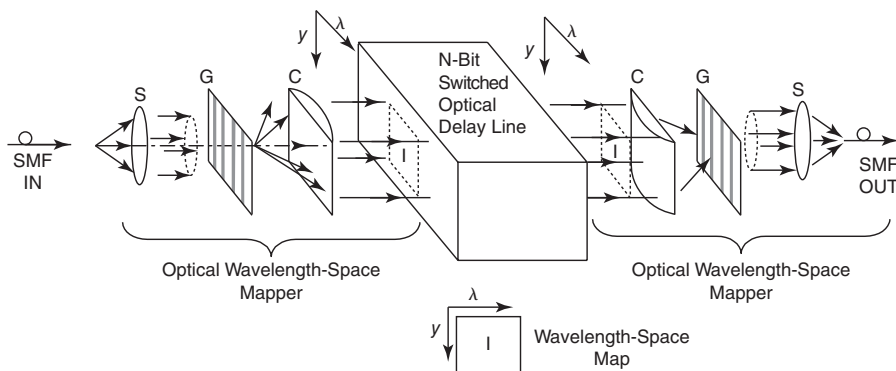


FIGURE 6.24 DMD-based coder/decoder module for multidimensional optical CDMA.

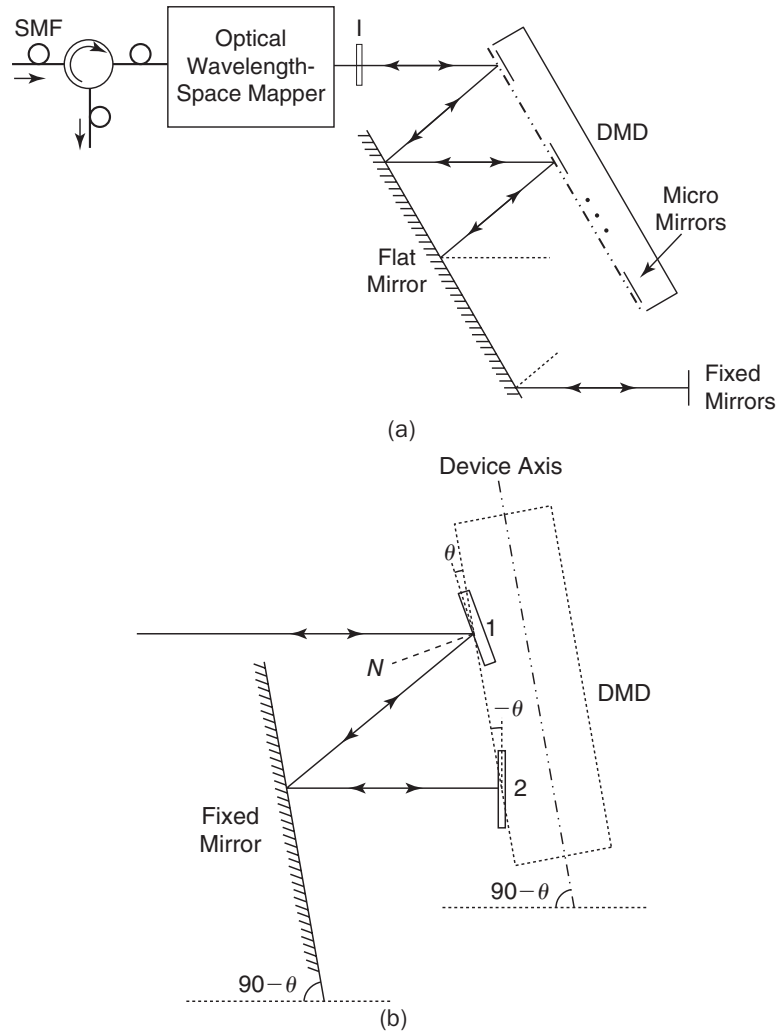


FIGURE 6.25 Short variable-delay optical encoder/decoder design using single DMD. Subpart (a) shows how the DMD micromirrors are set for a short time delay while subpart (b) shows the DMD micromirror settings for maximum time delay.

Design Problem 6.18: Large-Scale Low-Loss Fiber-Optic Switch (Cross-Connect)

Optical routing of high-data signals traveling in different SMFs is required for fiber-based communication systems. Such all-optical circuit switching can have a very large number of input-SMF and out SMF ports. Figure 6.26 shows a classic design of a large all-optical switch using $2N$ rotating mirrors that route beams between N -input SMFs and N -output-SMFs. Both the SMFs and mirrors can be placed in a 2D array and the mirrors can rotate in 2D-tilt mode (i.e., rotation

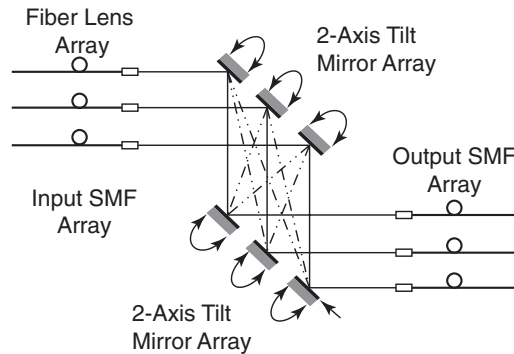


FIGURE 6.26 Classic $N \times N$ switch design using $2N$ tilting mirrors for moderate N values. Shown is a design where $N = 3$.

about two orthogonal axes). The rotating mirrors can be made by various means including optical MEMS fabrication technologies. As N gets large, the Figure 6.26 cross-connect design suffers key limitations. First, there are different path lengths for different switch input-output connections and as N gets large, these path length variations get larger leading to different and higher optical loss and inter-SMF/channel crosstalk values. For $N \times N$ switch approaching $N = 1000$, SMF-to-SMF optical loss can become large and the variations for the 1 million switch settings can also become large as optical path lengths become large. Design an $N \times N$ SMF cross-connect that eliminates the mentioned problems when N is large.

Solution

Figure 6.27 shows the desired $N \times N$ low-loss optical cross-connect for N large using 3D beam conditioning. Depending on the beam

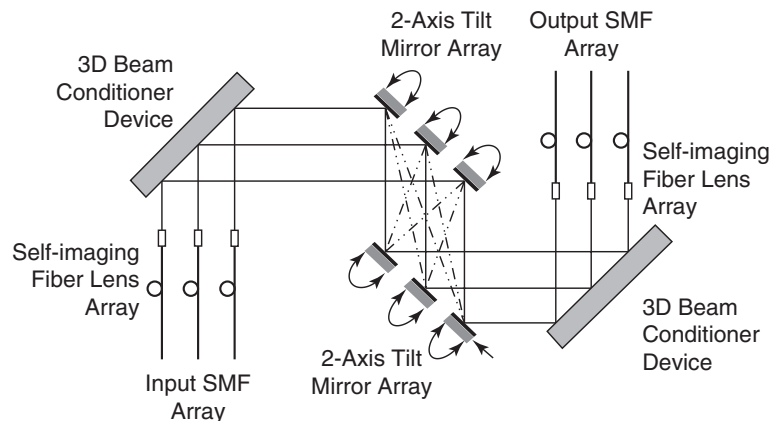


FIGURE 6.27 3D beam conditioning-based $N \times N$ low-loss optical cross-connect design suited for large N values.

routing path selected, the 3D beam-conditioning optics adjusts the focus/defocus of the beam such that in theory, a zero optical interconnection loss between input and output-SMFs is achieved using the fiber-lens-assisted self-imaging effect. Given N interconnection beams, a 3D beam-conditioner device can be made of N independently controlled deformable mirrors. Reflective phase-modulating liquid crystal devices can also be deployed as the 3D beam conditioner. $N = 10,000$ is achievable with optimal design of 3D switch freespace optics, fiber optics, and spatial modulation optical devices.

Problems

- 1 The DMD-based profiler described assumed a CW laser-beam operation during the profiling operation. How can we implement profiling for a pulsed-laser beam with a pulse-repetition frequency of f_L ?
- 2 The spatial-sampling resolution of the DMD-based profiler is limited to the micromirror pixel pitch, for example to $10\text{ }\mu\text{m}$. Is it possible to improve this spatial-sampling resolution?
- 3 The DMD-based profiler requires reflection off the DMD plane to produce the desired optical beam for power measurements. The distance between the DMD and the PD must be long enough to separate the reflected beam from the incident beam. This, in turn, leads to a physical size-layout limitation of the profiler. Is it possible to design the profiler with a smaller layout size? Provide a new design and discuss the engineering trade-offs.
Hint: Can other SLM types be used?
- 4 Using the design of a DMD-based 3D imager, design a 3D image-irradiance capture system of a 3D object using a LC SLM?
- 5 The dual-detector DMD-based imager for incoherent-light imaging is a powerful instrument to implement smart optical sampling of a far-field imaged optical-irradiance distribution. Many image data contain nonuseful background information that is captured by classic CCD-type imagers for data transmission. For example, if the image of interest is an aircraft in the sky, then image data of the sky is unwanted information. It is highly useful to not capture unwanted information and then transmit and process it as this act involves poor use of channel bandwidth and system processing power. Design a DMD-based imager that produces smart image data when looking for objects in a scene.
- 6 Pixelated beam-profilers like the ones using a CCD, DMD, and LC SLM produce diffraction effects as the pixel array in the optical device structure causes diffraction orders. In some applications, diffracted light can interfere with the optical system whose laser beam is under test. Can we design a beam-profiler that eliminates diffraction effects from the profiler instrument?
Hint: Think of a different type of pixel diffraction-free SLM.

- 7** Design a micromechanics-based fiber-optic high-dynamic-range polarization-insensitive broadband fiber-optic VOA using a single-fiber lens.
- 8** A high-precision polarization-insensitive broadband fiber-optic variable ratio 1×2 splitter (also called a valued-added module or VAM) is a highly desired component for many fiber-based applications. Typical split ratios are 99:1, 95:1, 90:10, and 50:50. Design a micromechanics-based fiber-optic broadband fiber-optic 1×2 splitter.
- 9** Design an all-digital fault-tolerant fiber-optic VOA using a single-fiber lens. Furthermore, achieve an N -bit VOA operation using only N micromirrors.
- 10** Design an all-digital fiber-optic variable optical splitter (1×2 type) using a single-fiber lens. This splitter should give tap ratios of 5:95 and 10:90.
- 11** Photonics can be deployed to implement RF filtering for wideband RF signals such as in RF radar and RF wireless applications. A classic RF filter is the transversal filter where the output of the filter $f(t)$ be written as

$$f(t) = \sum_{n=0}^{N-1} A_n s(t - n\tau)$$

where $s(t)$ is the input signal, A_n is the weight of the n th filter coefficient and τ is the time delay between adjacent filter-weighted input-signal components. The RF signal $s(t)$ can be used to intensity modulate laser light, and this laser light can be processed via photonic components to implement the Transversal filter signal processing. Design such as transversal filter using a DMD to produce the weight and time-delay selection. Explain how the photonic transversal filter-output optical spectrum can be used to obtain the time-domain impulse-response $h(t)$ of the filter and the frequency response $H(f)$ of the filter. Explain how we can experimentally verify if the computed response $H(f)$ is indeed the experimentally measured RF filter frequency response. Furthermore, explain how the photonic processor can determine the input RF spectrum without using an RF spectrum analyzer that requires very high-speed RF electronics.

- 12** Many applications, such as microwave radar tests and antenna-array control systems, require long time delays (e.g., >20 ns) simultaneously with extreme precision time-delay setting controls, e.g., >16-bit equivalent variable delay. Design such a photonics-based RF TDU implemented using a broadband laser (BL) and minimal-count optical fibers.
- 13** Using digital-state mirrors, design a 4-input port 4-output port nonblocking SMF-based optical switch, also called a 4×4 crossbar switch. The time delay in going from any input-SMF to any output-SMF should be the same.
- 14** Design a 1×2 SMF-based optical switch using a SMF optical circulator and mirror-optics.
- 15** Design a 2×2 SMF-based optical switch using SMF optical circulators and mirror-optics. Explain how one can extend this switch design to form a N -wavelength 2×2 routing module such as for applications like wavelength add-drop filtering.

16 Design a 2×2 SMF-based multi-wavelength routing optical switch using SMF optical circulators, a digital micromirror device, and other optics.

Hint: Modify the Figure 6.18 multi-wavelength add-drop module design so that in one switch state, main in-light goes to main out-light and add-port in-light goes to the drop-port out-light. In the other switch state, the main in-light should go to the drop port and drop Port in-light should go to the main out-port.

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CHAPTER 7

Photonic Systems Using Acousto-Optic Devices

Acousto-optic (AO) devices can be used to design a host of photonic modules for a variety of applications. The simple placement of optical components within the right 3D layout framework in an optical design can surprisingly achieve challenging system functions via an elegant design. Hence this chapter describes how AO devices can be deployed within an intelligent optical components visual and physical framework to perform desired system specific functions.

Design Problem 7.1: High-Stability AO Interferometer for Test and Measurement

Laser interferometers are powerful tools for test and measurement, particularly for nanoscale (subwavelength) changes in optical path lengths, in other words, nd , where n is the refractive index and d is the physical length of the optical path. For example, highly sensitive two-beam interferometers can be used in DNA sequencing via detection of the different optical-path lengths for the different molecules. Interferometers are notoriously sensitive to vibrations, air currents, and other environmental effects (e.g., air temperature). In addition, noise in electronics can be an additional factor, such as the $1/\text{frequency}$ or $1/f$ noise in electronics. The higher the photodetected electrical-signal frequency f , the lower the $1/f$ noise. Design an environmentally robust heterodyne interferometer using acousto-optic devices (AODs).

Solution

Figure 7.1 shows a high environmental robustness AO heterodyne two-beam interferometer. The system uses two AO Bragg cells interconnected with S1/S2 and S3/S4 spherical lens-imaging systems. AOD1 functions as a beam-splitter (BS) and AOD2





the +1-order beam (from AOD1) and the −1-order beam from AOD2 can be written as

$$\begin{aligned}
 i(t) &= KI_0 \left| t_a A_1 \sqrt{1 - A_2^2} \exp(-j[2\pi f_c t - \phi]) + A_2 \right. \\
 &\quad \left. \sqrt{1 - A_1^2} \exp(+j[2\pi f_c t]) \right|^2 \\
 &= KI_0 \left[t_a^2 A_1^2 (1 - A_2^2) + A_2^2 (1 - A_1^2) + 2 t_a A_1 A_2 \right. \\
 &\quad \left. \sqrt{1 - A_1^2} \sqrt{1 - A_2^2} \cos(2\pi 2 f_c t - \phi) \right]
 \end{aligned}$$

The first optical field in the summation is the +1-order beam while the second term represents the −1-order field. K is a constant factor that includes the AOD diffraction constants, optical component losses, photodetector light-to-electricity conversion factors, etc. As the AODs are operating in their small-signal low-diffraction efficiency (e.g., < 5 percent) modulation modes, $A_1^2 \ll 1$ and $A_2^2 \ll 1$, and the photodetected RF signal at $2f_c$ carrier from the interferometer can be written as

$$i(t) \approx KI_0 [t_a^2 A_1^2 + A_2^2 + 2 t_a A_1 A_2 \cos(2\pi 2 f_c t - \phi)]$$

The first two terms are bias/DC signals and can be electronically filtered out giving an RF signal whose amplitude and phase provide the desired measured parameters of the test sample. This RF signal is compared in phase to an RF-reference signal locked-in phase to the RF signal generator that provided the AOD drive signals.

The unique photonic design of this interferometer provides the basis for its strong optical/RF-phase stability. Note that both beams between AOD1 and AOD2 stay near each other with the **separate** controlled by the AOD Bragg angle value and the focal length of S1/S2 with S1 and S2 implementing 1:1 imaging between AOD1 and AOD2. Typically Bragg angles can range from subdegrees to several degrees and so appropriate focal lengths for S1 and S2 can be picked depending on photonic-system application and deployment conditions. In addition, both beams (i.e., DC beam and +1 beam from AOD1) pass through the same optical components. In effect, any optical-phase noise in the components or environments affects both beams and then cancels out on heterodyne detection. The only optical phase not common between both interfering beams is the phase picked up by the +1-order test beam via the test sample, as intended. Note that the position of the test object can be switched to the AOD1 DC beam S1 focal plane. Hence, the desired environmentally robust interferometer is formed.

Design Problem 7.2: High-Stability 1D Spatial-Scanning AO Interferometer

In many cases, different zones of a test sample require optical sampling to read the test object phase and amplitude transmittance information. For example, a security 1D bar code can have both optical-phase and amplitude information. Another example is a medical-sample optical-array chip. Design an environmentally robust heterodyne AO interferometer with fast 1D-sample scan capabilities of an array of fine-point locations in a line.

Solution

Figure 7.2 shows a high environmental robustness AO 1D-scanning heterodyne two-beam interferometer. An expanded collimated beam view is shown so the focus effect of the lenses can be shown in the test object and detector planes. The AOD drive frequency is changed to move the location of the scan spot on the test object. f_s is the scan frequency. S1 and S2 conduct 1:1 imaging between the two AODs. S3 acts as a focus lens. When f_s is changed, the focused beams on the block B1 move; hence, B1 is not a good spot to locate the point detector D. On the other hand, when f_s is changed, the focused beams on detector D do not move; hence, a good spot to locate the point detector D. Note that imaging holds between the test object plane and the detector/block plane. The two beams at D are the original DC beam from AOD1 and a $+1 \times +1$ double diffracted beam produced by AOD1 and AOD2. The double diffraction process eliminates the relative beam motion between the AOD1 diffracted beam and AOD2 diffracted beam (from the AOD1 $+1$ order), so the double diffracted beam after AOD2 is collinear with the original DC beam from AOD1. So regardless of the scan frequency/position, the two interfering beams on D remain fixed. To get a small scan spot size, one should use the full aperture of the AODs for light interaction. A small scan

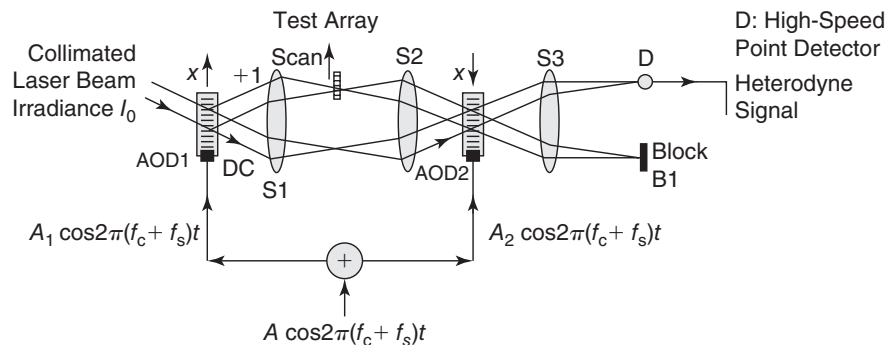


FIGURE 7.2 High environmental robustness AO 1D scanning heterodyne interferometer.

spot also means using a small D that is typical for a high-speed photodiode. The photodetected RF signal from the interferometer can be written as

$$\begin{aligned} i(t, f_s) &= KI_0 \left| t_a A_1 A_2 \exp(-j[2\pi 2(f_c + f_s)t - \phi]) + \sqrt{1 - A_1^2} \sqrt{1 - A_2^2} \right|^2 \\ &\approx KI_0 \left| t_a A_1 A_2 \exp(-j[2\pi 2(f_c + f_s)t - \phi]) + 1 \right|^2 \\ &= KI_0 \left[t_a^2 A_1^2 A_2^2 + 1 + 2t_a A_1 A_2 \cos(2\pi 2[f_c + f_s]t - \phi) \right] \end{aligned}$$

Design Problem 7.3: Frequency-Coded RF Phased-Array Antenna Beam Steering

RF phased-array antennas can electronically steer RF beams in space by providing phase-shifted RF signals to the antenna elements in the array. By changing the relative RF phase-shift between two adjacent antenna elements, the RF beam in space can be steered. Design an environmentally robust heterodyne AO interferometer to implement RF frequency coded fast 1D steering of a linear format RF antenna array.

Solution

The photonic system design shown in Figure 7.3 provides the desired RF system solution using the specific AOD drive signals, $s_1(t)$ and $s_2(t)$. The system is designed around the two-AOD in-line interferometer introduced earlier in the Chapter. S1/S2 lens pair forms a 1:1 imaging system between the two AOD planes. S3/S4 form a 1:M imaging plane between the AOD2 plane and the output phase sampling plane where a linear array of optical point samplers (e.g., optical fibers) are placed. Here M is a magnification factor that is picked based on RF phase error tolerance requirements based on optical sampler pitch, d , and number, N , of point samplers, for

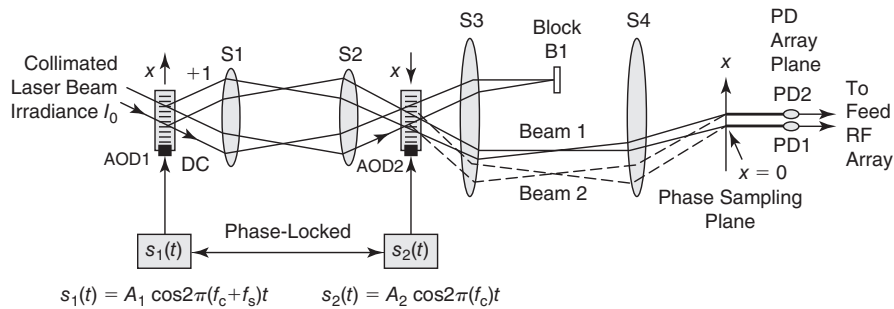


FIGURE 7.3 Frequency-coded RF phased-array antenna beam-former.

example, each point sampler/optical fiber is placed $d = 200 \mu\text{m}$ apart and there are $N = 100$ samplers placed in a linear array to drive a 100-element antenna array. As an example, two samplers are shown on the output phase sampling plane that are connected to two high-speed point detectors PD1 and PD2. PD1 is placed at the $x = 0$ location and forms a fixed RF phase reference while PD2 is placed at a distance x from the $x = 0$ location and forms the RF phase shifted signal that drives an antenna element in the array. AOD1 produces a +1-order beam that shows up as Beam 1 at the output sampling plane while AOD2 produces a -1-order beam that shows up as Beam 2 at the output sampling plane. Because AOD1 and AOD2 have a difference of f_s between the drive frequencies, Beam 1 and Beam 2 have a relative angle when they arrive at the sampling plane. Because of this angular difference, the two beams have a relative spatial frequency between them and it is sampling this relative spatial frequency that shows up as a relative RF phase shift between PD1 and PD2 signals. To change this relative phase shift to steer an RF antenna array, the spatial frequency between Beam 1 and Beam 2 must be changed by changing the scan frequency f_s . Block B1 is used to stop the unwanted beams from reaching the phase-sampling plane.

Using AOD notation introduced in Chapter 5, expressions for Beam 1 and Beam 2 can be obtained as given next. For simplicity, $M = 1$ is assumed, which means that the laser-beam incident width D across AOD1 is imaged to a width D on the output plane. The +1-diffracted optical field representing Beam 1 at the output-phase sampling plane is given by

$$\begin{aligned} E_{+1}(x, t) &\propto \exp\left\{-j2\pi \frac{\sin \theta_B}{\lambda} x\right\} \tilde{s}_1\left(t - \frac{x}{v_a}\right) = \exp\left\{-j2\pi \frac{f_c}{2v_a} x\right\} \tilde{s}_1\left(t - \frac{x}{v_a}\right) \\ &= 0.5A_1 \exp\left\{-j2\pi \frac{f_c}{2v_a} x\right\} \exp\left\{-j2\pi [(f_c + f_s)]\left[t - \frac{x}{v_a}\right]\right\} \\ &= 0.5A_1 \exp\{-j2\pi (f_c + f_s)t\} \exp\left\{j2\pi \frac{f_c}{2v_a} x\right\} \exp\left\{j2\pi \frac{f_s}{v_a} x\right\} \end{aligned}$$

and the -1-diffracted optical field representing Beam 2 at the output-phase sampling plane is given by

$$\begin{aligned} E_{-1}(x, t) &\propto \exp\left\{-j2\pi \frac{\sin \theta_B}{\lambda} x\right\} \tilde{s}_2^*\left(t + \frac{x}{v_a}\right) = \exp\left\{-j2\pi \frac{f_c}{2v_a} x\right\} \tilde{s}_2^*\left(t + \frac{x}{v_a}\right) \\ &= 0.5A_2 \exp\left\{-j2\pi \frac{f_c}{2v_a} x\right\} \exp\left\{j2\pi f_c \left[t + \frac{x}{v_a}\right]\right\} \\ &= 0.5A_2 \exp\{j2\pi f_c t\} \exp\left\{j2\pi \frac{f_c}{2v_a} x\right\} \end{aligned}$$

The photodetected current after heterodyne detection by a photodetector located at the sampler location x distance away, such as PD2 from the $x = 0$ point can be written as

$$\begin{aligned} i(x, t) &\propto |E_{+1} + E_{-1}|^2 = |E_{+1}|^2 + |E_{-1}|^2 + 2 \operatorname{Re}[E_{+1}^* E_{-1}] \\ &= K \left[A_1^2 + A_2^2 + 2A_1 A_2 \cos \left\{ 2\pi(2f_c + f_s)t - 2\pi \frac{f_s}{v_a} x \right\} \right] \end{aligned}$$

K is a constant that includes photodetector response plus other fixed photonic system parameters. Given there are a discrete number of N -point samplers at the system output plane with a distance d between the samplers, $x = nd$ where $n = 0, 1, 2, 3, \dots, N-1$. For the $n = 0$ location that corresponds to $x = 0$ position that is the PD1 reference sampler location, the photodetected current can be written as

$$i(x = 0, t) = K(A_1^2 + A_2^2 + 2A_1 A_2 \cos\{2\pi(2f_c + f_s)t\})$$

For the generation location of the n th photodetector that corresponds to $x = nd$ position that is shown as the PD2 sampler location, the photodetected current can be written as

$$\begin{aligned} i(n, t) &= K \left(A_1^2 + A_2^2 + 2A_1 A_2 \cos \left\{ 2\pi(2f_c + f_s)t - n 2\pi \frac{f_s}{v_a} d \right\} \right) \\ &= K(A_1^2 + A_2^2 + 2A_1 A_2 \cos\{2\pi(2f_c + f_s)t - n\phi\}) \end{aligned}$$

Here the inter-sampler optical or inter-antenna RF phase shift is written as $\phi = (2\pi f_s d)/v_a$. Note that the RF phase shift of the current increases linearly with distance x along the sampling plane to provide the required linear-phase ramp required for steering a plane wave transmitted by the linear phased-array antenna (PAA) consisting of N antenna elements spaced equally along a linear geometry. Hence, to steer the PAA, f_s is changed to change the inter-element phase difference ϕ . Note that the carrier of the RF signals produced by the photonic system is beam scan position coded, in other words, each phase shift set by adjusting f_s produces a specific RF beam in scan-angle space with a specific carrier frequency $2f_c + f_s$. In effect, a frequency-swept scanning PAA control system is realized to produce a frequency-scanned antenna platform. From a technology point-of-view, AODs can have center carriers from 50 MHz to 3 GHz, hence a wide range of antenna carriers can be generated from 100 MHz to 6 GHz.

Design Problem 7.4: Full Calibration RF Phased-Array Antenna Beam Steering

Practical RF phased-array antennas have element-level RF phase and amplitude errors across the array aperture that requires individual RF phase and amplitude calibration. Design a photonic control system that can not only provide RF beam-forming capabilities but also element-level RF phase and amplitude calibration of the signal set that drives the PAA.

Solution

The system shown in Figure 7.4 controls an $N \times M$ element PAA using two $N \times M$ pixel NLC devices called LC1 and LC2, where LC1 is a parallel-rub BM-NLC device that provides $N \times M$ RF phase shifts for the PAA beam steering control. LC2 is either a parallel-rub BM-NLC device or a TN-NLC device that provides $N \times M$ RF amplitude control values for the PAA radiation pattern control. Because each pixel in the NLC devices can be individually controlled, individual antenna elements RF phase- and amplitude-signal calibration and control is possible. This photonic system takes advantage of the polarization properties of light and NLC devices to deliver the system solution using the mentioned 2 AOD heterodyne interferometer. Specifically, the input light has a linear horizontal or p -state polarization. The Half-Wave Plate (HWP) converts the AOD1 produced $+1$ -order beam p -state to the vertically polarized s -state. The -1 -order beam produced by AOD2 has a horizontal or p -polarization. Both the $+1$ (s) and -1 (p) beams becomes collinear after AOD2 and are beam expanded using the S4/S5 lens pair. LC1 has its NLC director oriented along the s -direction so the $+1$ beam picks up a voltage-dependent optical phase shift $\phi_m(V_1) = (2\pi/\lambda)n(V_1)d$ at the m -th pixel location in the NLC device where $n(V_1)$ is the LC refractive index for voltage V_1 and d is the thickness of the LC1 device. The -1 (p) beam picks up a fixed-phase shift $\phi_0 = (2\pi/\lambda)n_0d$ independent of voltage to LC1, where n_0 is

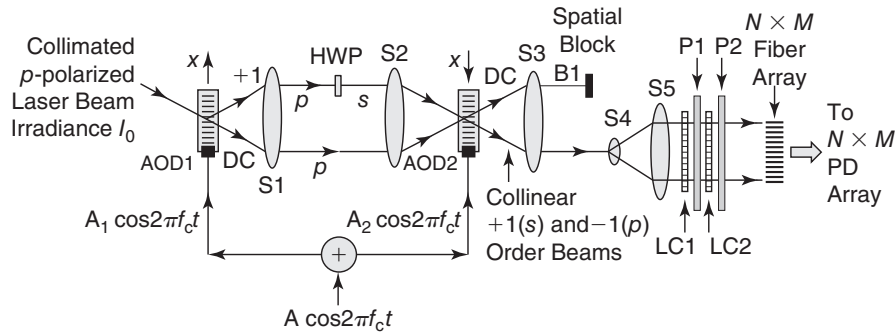


FIGURE 7.4 Full-calibration RF phased-array antenna beam-former.

the ordinary refractive index of the LC material. So only the vertical s -polarized light sees the voltage changing optical phase while the horizontal or p -polarized light keeps seeing the fixed optical phase-shift provided by the ordinary NLC material index. Polarizer P1 is oriented at 45° to p and s directions so the in-line components of the +1- and -1-order beam can pass through to the LC2 device that for instance is a 90° twist TNLC device used to act as a variable light shutter to provide RF amplitude control on a pixel/antenna element level. P2 polarizer is cross-aligned with the P1 polarizer so with no voltage applied to LC2 pixels, all light coming from P1 passes through P2 to the 2D $N \times M$ fiber array connected to an $N \times M$ high speed Photodetector (PD) array. When voltage V_2 is applied to the m -th pixel of the LC2 device, not all input light has its polarization rotated by 90 degrees and so less light passes through P2 giving RF amplitude control to the signal via the gain factor $G_m(V_2)$. Hence, by controlling V_1 and V_2 on the m -th pixels of the LC1 and LC2 devices, one can set the RF phase and amplitude of the RF signal generated by the photonic system.

The photodetected current after heterodyne detection by a photodetector connected to the m -th pixel sampler location can be written as

$$\begin{aligned} i(m, t) &\propto |E_{+1} + E_{-1}|^2 = |E_{+1}|^2 + |E_{-1}|^2 + 2 \operatorname{Re}[E_{+1}^* E_{-1}] \\ &= KG_m(V_2) [A_1^2 + A_2^2 + 2A_1A_2 \cos\{2\pi(2f_c)t - (\phi_m[V_1] - \phi_0)\}] \end{aligned}$$

K is a constant that includes photodetector response plus other fixed photonic system parameters. Note that one has solved the RF-array problem using optical array devices, a natural fit in many ways.

Design Problem 7.5: Instantaneous Operation Wideband RF-Spectrum Analyzer

In certain scenarios, near-instantaneous wideband RF-spectrum information is required. In other words, there is no time for implementing RF-signal sampling and then electronic post-processing to determine the received RF-signal spectrum. Design a photonic system that can provide a near-instantaneous RF spectrum with the best possible dynamic range via optical detection.

Solution

Figure 7.5 is the photonic system that solves the desired system problem. In the earlier Chapter 5 dealing with AODs, it was mentioned that an AOD such as the shown AOD1 can be used as a frequency-controlled laser-beam steerer as the diffracted beam (shown as Beam 1) has an angle relative to the DC beam that is

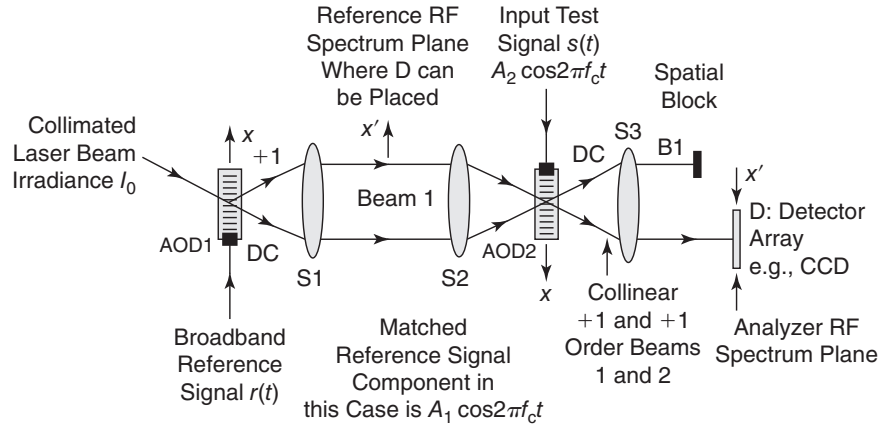


FIGURE 7.5 Instantaneous operation wideband RF-spectrum analyzer.

proportional to the input AOD1 RF frequency and hence shows up at a different spatial location on the RF spectrum detection plane along the x' direction shown as the back focal plane of lens S1 of focal length, F_1 . Such a system (AOD1 working with S1) forms an RF power-spectrum analyzer as the detector current at the $x' = (\lambda F_s)/v_a$ is proportional to signal AOD1 Bragg angle carrier offset frequency f_s where $x' = 0$ marks the f_c carrier location on the spectrum plane. Here the AOD1 drive signal is given by $A_1 \cos[2\pi(f_c + f_s)t]$. The photodetector array (e.g., CCD) time-integrated current distribution for the RF spectrum plane at the back focal plane of S1 is given by

$$i(x' = \{f_s \lambda F_1 / v_a\}) = KI_0 \int_T |E_1|^2 dt = KI_0 T A_1^2$$

This relation indicates that the photodetector array provides the RF power spectrum of the input RF signal and not the RF amplitude spectrum. Ideally, it would be best to have the detector output proportional to the test RF amplitude and not the square of the amplitude. This can indeed be achieved using optical interferometric detection. To achieve this goal, the system shown using AOD1 and AOD2 is used. In this case, AOD2 is used to enter the test RF signal and with lens S3 of focal length F_3 form the earlier mentioned RF power spectrum analyzer. S1 and S2 provide 1:1 imaging between AOD1 and AOD2, so have same focal lengths. To form an interferometer, AOD1 is now driven by a reference RF signal $r(t)$ that is a broad instantaneous bandwidth signal (e.g., a linear frequency modulation (LFM) or chirp RF signal that contains all the RF frequencies that are expected in a test signal under study). For example, if AOD2 is driven by test signal $A_1 \cos[2\pi(f_c + f_s)t + \phi]$ where ϕ is a relative phase, then $r(t) = A_2 \cos[2\pi(f_c + f_s)t]$. Reference signal

AOD1 and test signal AOD2 both operate in the +1 order linear amplitude modulation mode. The time integrated photodetected signal produced by the detector D is given by

$$i\left(x' = \frac{\lambda F_3 f_s}{v_a}\right) = KI_0 T[A_1^2 + A_2^2 + 2A_1 A_2 \cos(\phi)]$$

The +1-order beam, s , from the two AODs are collinear between AOD2 and D and hence, RF frequency contents of both test and reference RF signals match spatially on the output detector plane. One can introduce a very slight (e.g., $f_0 = 10$ kHz) (spatially unresolvable at the detector plane) frequency spectrum offset between the two spectra by introducing a relative beam tilt between the +1-order beam and DC beam from AOD1. By doing so, the time integrated photodetected signal produced by the detector, D, can be rewritten as

$$i\left(x' = \frac{\lambda F_3 f_s}{v_a}\right) = KI_0 T[A_1^2 + A_2^2 + 2A_1 A_2 \cos(2\pi f_0 t + \phi)]$$

Note that the RF-spectrum amplitude information, A_1 , is modulated by a slow temporal carrier I_0 ; hence, the bias terms $(A_1)^2$ and $(A_2)^2$ can be electronically filtered out. As the reference signal amplitude A_2 is fixed, the photodetected current is proportional to the RF-spectral amplitude A_1 , the desired result for the shown RF spectrum analyzer using AODs. The operation of the shown spectrum analyzer requires that the reference signal be a periodic chirp (LFM) signal where the signal chirp duration is no longer than the full aperture time of the AOD1 and the repetition period is no shorter than the AOD1 aperture time. The instant the test signal enters the AOD2, it engages the light from AOD1 and produces interferometric detection on the detector to indicate the test signal spectral content. Given AODs can have 1-GHz instantaneous bandwidths with high 3-GHz carrier center frequencies, a 1-GHz instantaneous bandwidth RF-spectrum analyzer over a 3-GHz center frequency is possible, highly useful in electronic warfare systems.

Design Problem 7.6: Efficient Free-Space to Single-Mode Fiber (SMF) Light Coupling

Many photonic systems require the use of both SMFs and bulk or micro-optical components that requires light to exit the SMF for a while and then re-enter the SMF. As shown in Figure 7.6, use of traditional collimating lens optics leads to loss of light that can be very severe

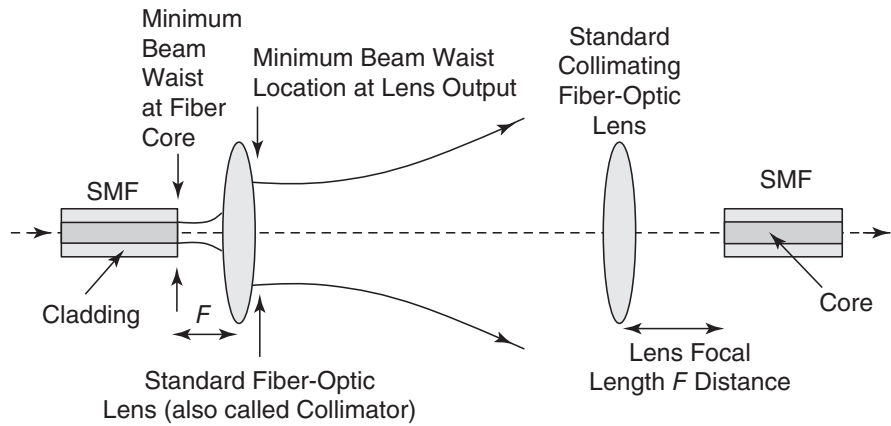


FIGURE 7.6 Classic light-beam behavior from a SMF and collimating lens.

depending on the distance between the transmit and receive SMFs. Thus, all efforts are made to reduce the freespace distance between the transmit and receive SMFs. Figure 7.6 shows how the Gaussian beam launched from the SMF core propagates through the collimating lens that is placed a focal-length distance from the collimating lens. The receive port is identical to the transmit port as in many cases, the photonic systems have ports that are reversible input-output ports. Design a SMF-free-space-SMF interconnection that has 100 percent coupling of light between two SMFs placed a fixed distance apart.

Solution

The interconnection shown in Figure 7.7 meets the requested photonic system requirement of 100 percent coupling efficiency between **to** SMFs separated in freespace by a given fixed distance. The key aspect of the innovation is the use of a specially designed fiber-optic lens called a self-imaging lens or a focuser lens that produces a Gaussian minimum beam-waist midway between the SMFs. Such a beam-forming optic can be constructed by controlling the distance between the SMF core aperture and the spherical lens called the focuser. Using

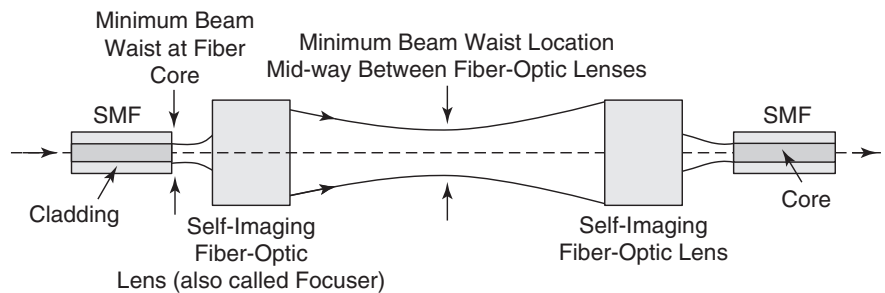


FIGURE 7.7 One hundred percent coupling-efficiency link between SMFs using the self-imaging fiber lenses.

such fiber-optic lens optics for the SMFs, the minimum beam-waist location of the transmit fiber core is imaged onto the minimum beam-waist location of the receive fiber core, hence a self-imaging system is formed with 100 percent light transfer between the two SMFs. This is an excellent optical design feature for SMF-freespace photonic systems as there will be adequate physical space to place optical components in the system between SMFs and still achieve very low SMF-to-SMF optical loss in the system.

Design Problem 7.7: Fiber-Optic Variable Optical Attenuator (VOA) Using Single AOD

Fiber-optic (FO) systems use VOAs to control the light level passing through SMFs to specific components, modules, and systems such as gain fibers, amplifiers, and switching systems, respectively. The optical power-level handling, dynamic range, static insertion loss, and reset speed of the VOA is application-dependent. The bulk material-based AOD is fundamentally a fast microseconds speed, high-watt-level power handling, polarization insensitive (e.g., for flint glass AO material) light modulation device. Design a FO VOA using a single AOD. Write an expression for the VOA dynamic range.

Solution

The shown Figure 7.8 system forms the desired VOA by placing an AOD between two self-imaging mode SMF lens-optics. The light attenuation is controlled by changing the drive power of the AOD

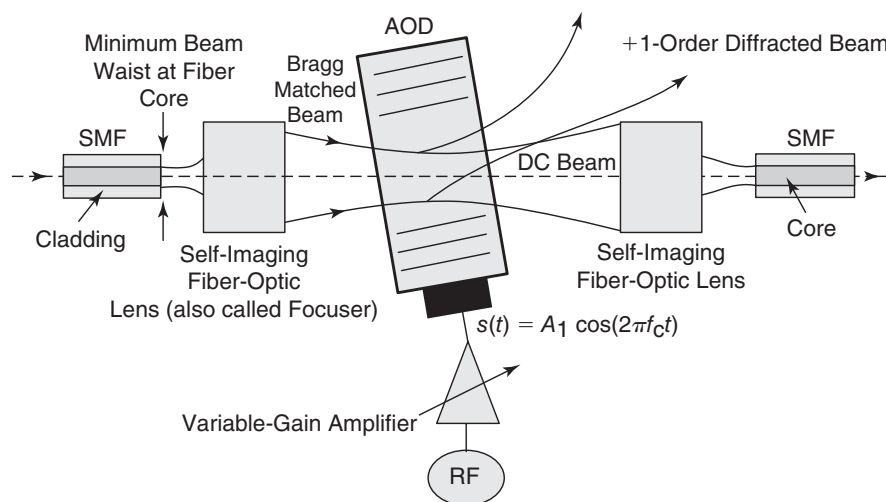


FIGURE 7.8 Fiber-optic VOA design using single AOD and VGA control.

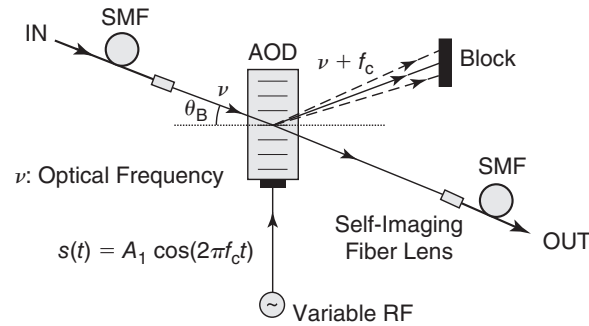


FIGURE 7.9 Fiber-optic VOA design using single AOD and drive-frequency control.

using the variable-gain amplifier (VGA). The beam from the input SMF is Bragg-matched to the carrier frequency f_c of the AOD to enable a +1-diffracted beam that sucks out light power from the DC beam that enters the output SMF. The maximum diffraction efficiency (DE) of the AOD is η_m where $0 < \eta_m < 1$ and is proportional to the RF drive power into the AOD, so DE is proportional to the square of the drive voltage, A_1 . The higher the η_m , the higher the VOA attenuation dynamic range (DR) that is given in decibel (dB) units by $-10 \log(1 - \eta_m)$. For example, if $\eta_m = 0.99$ or a 99 percent diffraction efficiency, then 1 percent of the input light stays in the output light and the VOA DR = $-10 \log(1 - 0.99) = -10 \log(0.01) = 20$ dB. Note that a 20-dB attenuation DR for a VOA can be adequate for many applications. The switching time of the VOA is the time the acoustic wave takes to cross the optical beam and can be computed as equal to (beam size in AOD/AOD acoustic velocity). Note that if the input optical wavelength changes, one can change the f_c value to maintain the AOD Bragg-angle diffraction condition for the new wavelength.

As shown in the Figure 7.9 without the VGA, another way to produce attenuation via this VOA design is to change the AOD drive frequency so the input beam Bragg matching condition is spoiled as the physical location of the optics is unchanged, but the AOD drive frequency is changed from the original Bragg-matched f_c value.

Design Problem 7.8: High-Dynamic-Range Fiber-Optic Variable Optical Attenuator (VOA) Using an AOD

Some photonics applications such as optical radar require a high dynamic range high speed high power handling VOA. Design a high dynamic range (> 20-dB variable attenuation) FO VOA using a single AOD. Write an expression for the VOA dynamic range.

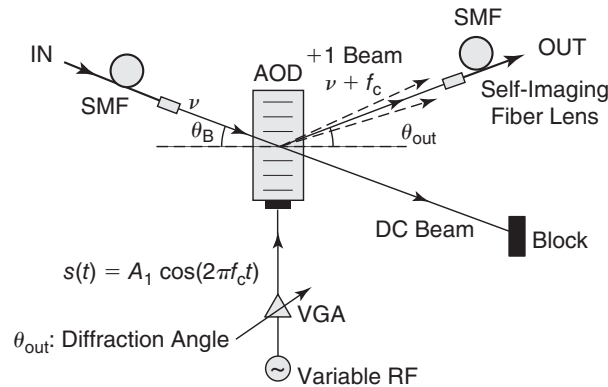


FIGURE 7.10 High dynamic-range fiber-optic VOA using an AOD.

Solution

The shown VOA in Figure 7.10 achieves the design goal by using the +1-order beam as the output beam from the attenuator. To get the maximum light through the VOA, one must operate the AOD at its highest diffraction efficiency of η_m so the light irradiance through the VOA is $I_0\eta_m$, where I_0 is the input irradiance of the light entering the VOA. Ideally, with no RF signal applied to the AOD, no light reaches the output SMF giving the VOA an infinite optical attenuation dynamic range. In reality, some scattered light of irradiance I_N from the optics enters the output SMF. Thus, the DR of the VOA in decibels is given by asking a base-10 logarithm written as $10 \log[(I_0\eta_m)/I_N]$. From a practical point of view, such VOAs can reach over 60 dB in attenuation range. Note that the +1 order has a Doppler shift of f_c . In certain applications, any Doppler shift to the attenuated light is undesirable and the appropriate zero Doppler shift VOA should be deployed.

Design Problem 7.9: High-Dynamic-Range Fiber-Optic Variable Optical Attenuator (VOA) using AODs

Design a high dynamic-range FO VOA using AODs that does not Doppler shift the attenuated light. Write an expression for the VOA dynamic range.

Solution

Figure 7.11 is the VOA design that forms a zero-Doppler shift attenuator by using one +1-order diffraction from AOD1 and one -1-order diffraction from AOD2 to cancel AOD-based Doppler shifts to the input light beam at optical frequency, ν . Using the same notation as the earlier design problem, the dynamic range for this VOA in decibels can be written as $10 \log[(I_0\eta_m\eta_m)/I_N]$.

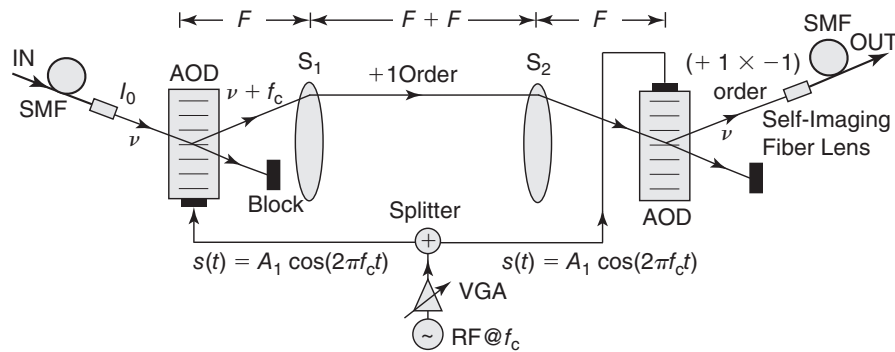


FIGURE 7.11 Zero net-Doppler shift high-dynamic range fiber-optic VOA using AODs.

Design Problem 7.10: Bulk AOTF-Based Multi-Wavelength Variable Optical Attenuator (MVOA)

Many fiber-optic systems use multiple wavelengths than often need optical-power conditioning over the wavelengths band to produce optimal system performances. For example, wavelength division multiplexed (WDM) fiber-optic communication systems deploy multiple wavelengths for transmitting different data channels. These WDM signals pass through other optics that modify optical power levels across the band. In addition, wideband optical amplifiers also require optimal signal spectrum inputs and also change amplified spectra. There is a need to place multi-wavelength optical gain adjusters often called spectrum equalizers to adjust optical power spectra. Design a bulk AOTF-based multi-wavelength variable attenuator (MVOA).

Solution

Shown in Figure 7.12 is a design of a MVOA using a bulk AOTF device. The key design features include the use of a retro-reflective in-line optical geometry that leads to simple self-aligning component placements with AOTF-based double diffraction for enhanced wavelength attenuation control. Shown is the use of a bulk collinear type AOTF such as made of tellurium dioxide or TeO_2 material. A BDP is used to produce two side-by-side linearly polarized p- and s-beams and the HWP converts one linear polarization (the s-state) to its orthogonal state, p, to match the other linear p-polarization beam. This is done so both beams suffer the same diffraction amount and hence both polarizations of the input beam have the equal attenuation effects to eliminate PDL in the MVOA. The two polarization components also trace slightly different separate optical paths causing a slight time difference in the attenuated beams for the p and s polarizations. This time difference is called polarization dependent (temporal) dispersion

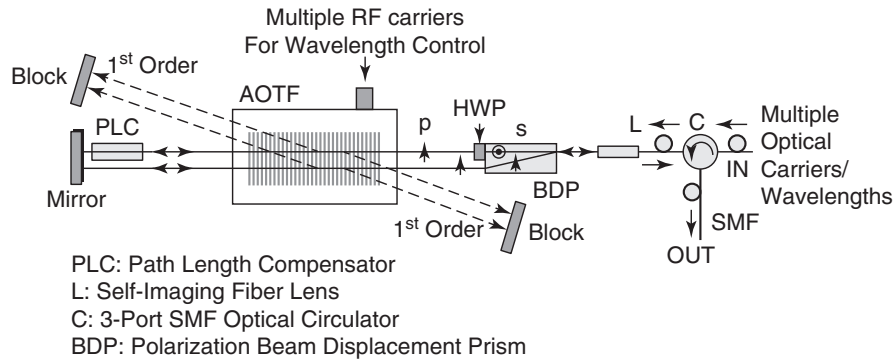


FIGURE 7.12 Bulk AOTF-based multi-wavelength variable attenuator (MVOA).

(PDD) and should be ideally zero. Hence, an optical path compensation plate called PLC is placed in the upper path for the polarized beam pair as the lower path is longer than the upper path. Each RF drive, frequency to the AOTF corresponds to Bragg-matched first-order diffraction (diffracted beam makes an angle with the DC beam) for a given input wavelength. Hence frequency choice and RF power of the RF drive signal to the AOTF controls the attenuation each wavelength suffers via the MVOA, allowing optical spectrum control.

Design Problem 7.11: Analog RF Transversal Filter Design Using AOTF

Photonics can be deployed to implement RF filtering for wideband RF signals, such as in RF radar and RF wireless applications. A classic RF filter is the transversal filter where the output of the filter $f(t)$ would be written as

$$f(t) = \sum_{n=0}^{N-1} A_n s(t - n\tau)$$

$s(t)$ is the input signal, A_n is the weight of the n -th filter coefficient and τ is the time delay between adjacent filter weighted input signal components. The RF signal, $s(t)$, can be used to intensity-modulate laser light, and this laser light can be processed via photonic components to implement the transversal filter signal processing. Design such as transversal filter using an AOTF device to produce the weight and time delay selection.

Solution

Figure 7.13 is a retro-reflective design programmable broadband RF transversal filter using compact chirped-fiber Bragg-grating (CFBG)

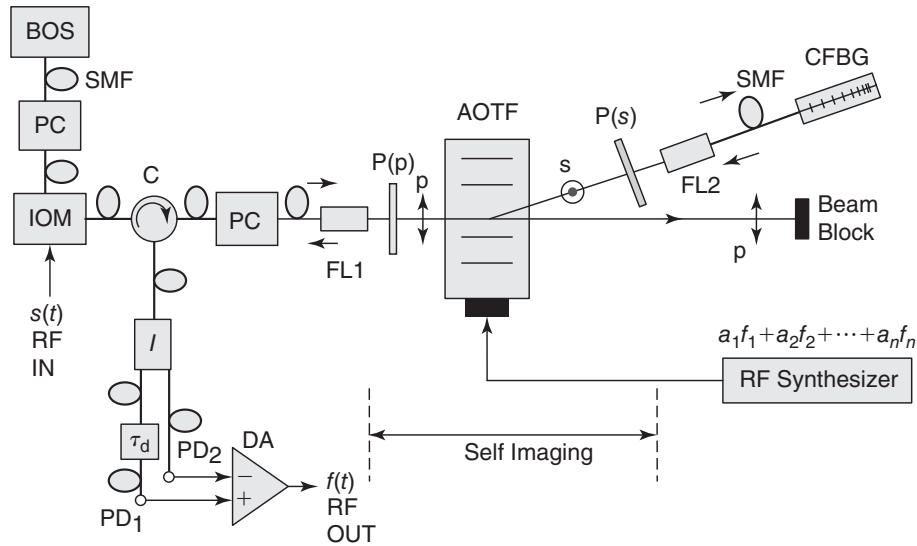


FIGURE 7.13 Analog RF transversal filter design using AOTF.

fiber optics and an AOTF. The other key components are: IOM, high-speed optical-intensity modulator; BOS, broadband optical source containing a continuous or discrete array of optical wavelengths; I, interleaver device that separates light into its odd and even wavelength channels in a predetermined and designed wavelength channel grid; DA, differential amplifier; C, optical circulator; PD1, PD2, high-speed photodetectors; FL1, FL2, self-imaging mode fiber lens; PC, polarization controller. The AOTF is used to select discrete wavelengths and their optical power weighting by using the RF frequency synthesizer signal generator. These positive and negative weights represent A_n in the RF filter function. As optical intensity cannot represent negative numbers, the negative and positive filter taps are assigned to BOS odd wavelengths and even wavelengths, respectively. The CFBG causes the selected wavelengths to acquire a relative time delay needed to produce the multiples of τ delays for the weighted signal taps. Total time delay from the CFBG is equal to bandwidth of the grating ($\lambda_{\max} - \lambda_{\min}$ in nm centered at λ_b) times the dispersion, D , of the CFBG in ps/nm. These parameters should match the AOTF optical spectrum-control device parameters and also the BOS. There is a time delay τ_d between consecutive odd and even wavelengths and this relative delay is cancelled using the τ_d SMF element after the interleaver device. PD2 produces a signal with all the negative weight time delayed taps while PD1 produces a signal with all the positive-weight time-delayed taps. The DA produces the difference signal that gives the RF filter output signal $f(t)$. Note that since the AOTF operates with linearly polarized light, the PC one is optimized to deliver the highest amount of p-polarized light out

of FL1. The simplest form of RF filter is the two-tap filter, or $N = 2$ with equal weight taps represented by

$$f(t) = \sum_{n=0}^1 A_n s(t - n\tau) = A_0 s(t) + A_1 s(t - \tau) = A_0 [s(t) + s(t - \tau)]$$

To form a nulling filter for a RF signal $s(t) = \cos(2\pi f_c t)$, $\tau = 1/(2f_c)$ to produce a 180° phase shifted version of $s(t)$ or $-s(t)$ signal tap that adds with the 1st tap $s(t)$ to produce a zero or a null. To form a tunable nulling 2-tap RF filter, one must be able to pick the right τ and this is done by the AOTF selecting the two wavelengths that have a relative time delay of τ . Using many taps via many wavelengths, the RF filter performance (e.g., depth and shape of null) can be optimized.

Problems

- 1 In some cases, it is desirable to generate the optical interference on a baseband (or DC) signal so a slow high-sensitivity detector such as a CCD can capture the interference signal. Design a high-phase stability AO interferometer that produces a baseband output signal.
- 2 Design a high-phase stability AO 1D-scanning heterodyne interferometer using a single AOD.
Hint: Use a fiber-optic three-port circulator in the photonic system design.
- 3 For the frequency-coded RF phased-array antenna beam-steering photonic system described in Design Problem 7.3, write the expression for the photodetected current for the n -th optical sampler when the optical magnification, M , is not equal to 1. Describe how choice of M can optimize system design.
- 4 Design a scan frequency independent RF PAA beam-steering photonic system using the basic two-AOD-based PAA control system described in Figure 7.3 in the chapter. Write the expression for the photodetected current for the n -th optical sampler when the optical magnification, M , is not equal to 1.
- 5 Design a SMF-free-space-SMF interconnection that has 100 percent coupling of light between two SMFs for varying freespace distances between the SMF ports.
- 6 Design a high-dynamic-range Doppler-free fiber-optic VOA using a single AOD. AODs are known to give some polarization-dependent behavior that can, in turn, produce a VOA with polarization-dependent loss (PDL) that is harmful to some applications. In other words, general polarization state input light has both horizontal (p) and vertical (s) polarizations and these suffer different diffraction efficiencies in the AOD. Design the VOA to eliminate PDL.

7 Design a zero PDL and PDD bulk AOTF-based multi-wavelength variable attenuator (MVOA) without using an optical delay-compensation plate.

8 The AOTF-based RF transversal filter can provide a limited number of tap selections because of limitations on the number of RF frequencies that can be fed into the AOTF device without causing inter-mixing problems. Nevertheless, the AOTF is an analog signal controlled spectrum selection and weight device that gives accurate tap weight selection. Design a transversal filter that keeps the positive features of the AOTF while providing the ability to produce many more taps for the RF filter.

Hint: Deploy an additional SLM device for spectral control.

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CHAPTER 8

Photonic Systems Using Liquid Crystal and Liquid Devices

Liquid crystal (LC) and liquid-based optical devices can be used to design a host of photonic modules for a variety of applications. The simple placement of optical components within the right 3D layout framework in an optical design can surprisingly achieve challenging system functions via an elegant design. Hence, this chapter describes how LC and liquid-based optical devices can be deployed within an intelligent optical components visual and physical framework to perform desired system specific functions.

Design Problem 8.1: Liquid Crystal Analog Fiber-Optic Variable Optical Attenuator (VOA)

Using a voltage-controlled 90° twisted nematic liquid crystal (TN-LC) device, design a fiber-optic variable optical attenuator (VOA).

Solution

Figure 8.1 shows the desired VOA using two self-imaging fiber-optic lenses, a pair of birefringent beam-displacing prisms (BDPs), and one TN-LC cell driven by an analog voltage-control signal to change the polarization control state of the TN-LC cell. Because the TN-LC device requires a linearly polarized input, the BDP is used to generate these spatially separated orthogonal p (horizontal) and s (vertical) components from the input light coming from the input SMF and fiber lens (FL). The degree of input-light linear polarization rotation produced by the TN-LC device is controlled by the device voltage level and with zero voltage applied, all input linear polarized light is rotated in polarization by 90° that are spatially recombined by the output BDP and then sent into the output FL and SMF. The zero-voltage state of the module becomes the zero attenuation state of

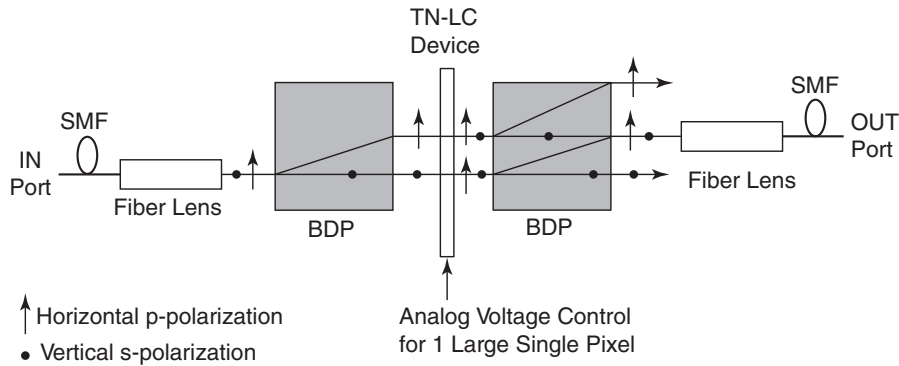


FIGURE 8.1 The liquid crystal analog fiber-optic VOA design.

the VOA. As the voltage to the TN-LC device is increased, the two input linear polarizations directed through the TN-LC device suffer partial 90° linear polarization rotations producing both p- and s-polarizations for each spatially separated beam through the TN-LC device. When these beams pass through the output BDP, only part of these beams that have the correct linear polarizations are recombined by the BDP to be sent through the FL and output SMF. The remaining light using the output BDP is directed away from the FL and output SMF; hence, forming an analog voltage-controlled fiber-optic VOA with a voltage-controlled attenuation setting. To get maximum attenuation from the VOA, a high enough voltage to the TN-LC device (e.g., 5 V) completely stops the 90° polarization rotation of the input light polarization components and this un-rotated light is completely directed away from the FL and SMF. Ideally, zero light reaches the SMF and in effect the VOA has infinite light suppression or infinity attenuation dynamic range control. In reality, this is not so as the TN-LC device even with maximum voltage applied does produce some small fraction of 90° polarization rotation to the input linearly polarized light. For example, 1 in a 1000 s-polarized photons converts to p-polarized photons and 1 in a 1000 p-polarized photons converts to s-polarized photons when the TN-LC device has maximum applied voltage. In effect, the TN-LC device has a 1000:1 or 30-dB optical power-based polarization extinction ratio at its maximum drive state. So if the input light power is 1 watt, then 1 mW (not zero photons) shows up at the output SMF when the VOA is set to its maximum attenuation using the maximum TN-LC device-drive voltage. Now consider the least attenuation state, say when the TN-LC device drive voltage is 0 V. In reality, not all input linearly polarized light is rotated by 90° . For example, 1 in a 1000 s-polarized photons stays as s-polarized photons and 1 in a 1000 p-polarized photons stays as p-polarized photons when the TN-LC device has the minimum applied voltage. In effect, the TN-LC device has a 1000:1 or 30-dB optical power-based polarization extinction ratio at the VOA's least attenuation state.

For input light of say 1 W power level, 999 mW passes through the VOA into the output SMF. Thus, the dynamic range for attenuation of the VOA is $999 \text{ mW} / 1 \text{ mW} = 999:1$ or about 30 dB, consistent with the extinction ratio of the TN-LC device operations. The analysis conducted assumes the BDP operate perfected and the SMF-FL self-imaging coupling between the input and output ports is ideal with zero loss. For variable attenuation, the VOA is calibrated for many voltage-drive conditions between the maximum voltage (maximum attenuation) and minimum voltage (minimum attenuation) to give the desired optical-attenuation levels. Such an analog VOA operation assumes no hysteresis in TN-NLC response with stable polarization control operations between the extreme voltage drive states. In reality, the TN-LC device does not operate hysteresis-free. It would be highly useful to have a TN-LC VOA that does away with this hysteresis problem inherent in multistate optical polarization control devices. (See Problem 1.)

Design Problem 8.2: Liquid-Crystal-Based Polarization Dependent-Loss (PDL) Compensator

Many optical systems suffer from PDL where one linear state of polarization has higher optical loss through the system versus its orthogonal linear component. Design a liquid crystal-based PDL compensator.

Solution

Figure 8.2 shows the desired liquid crystal-based PDL compensator than has the same design as the Figure 8.1 VOA, except the TN-LC

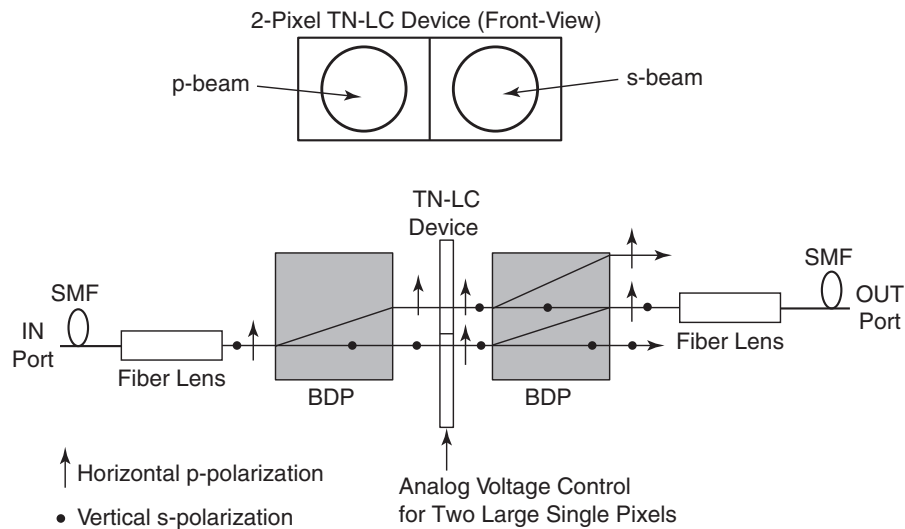


FIGURE 8.2 Liquid crystal-based PDL compensator.

device is a two-pixel device where each large pixel is independently controlled by its voltage drive signal. One pixel attenuates the p-beam while the other pixel in the TN-LC device attenuates the s-beam. The two drive signals can be designed to produce the desired PDL in the output light exiting the output SMF.

Design Problem 8.3: Liquid Crystal Deflector Fiber-Optic VOA

The Figure 8.1 VOA uses BDPs. Design a more compact LC-based VOA without BDPs.

Solution

Shown in Figure 8.3 is the desired VOA. Light from the input SMF has both p and s polarization beams. Because LCs are polarization sensitive devices, two independent birefringent-mode parallel-rub nematic liquid crystal (NLC) 1D beam-deflector devices are deployed, one to deflect the p-beam and one to deflect the s-beam. The distance between the output FL-SMF and input FL-SMF is designed such that the NLC deflectors can produce adequate beam deflection to achieve no light coupling at the output SMF. The nematic director of the p-beam deflector is along the p-direction and the nematic director of the s-beam deflector is along the s-direction. The NLC deflectors act as voltage programmed optical wedges to steer the input plane wave in one dimension. The p-beam deflector moves the beam in the x -direction while the s-beam deflector moves the beam in the y -direction. Because the SMF core is small (e.g., $9\ \mu\text{m}$ at $1550\ \text{nm}$), only small angle ($<2^\circ$) beam deflection is typically required from the NLC deflectors to produce limited light coupling to SMF and, hence,

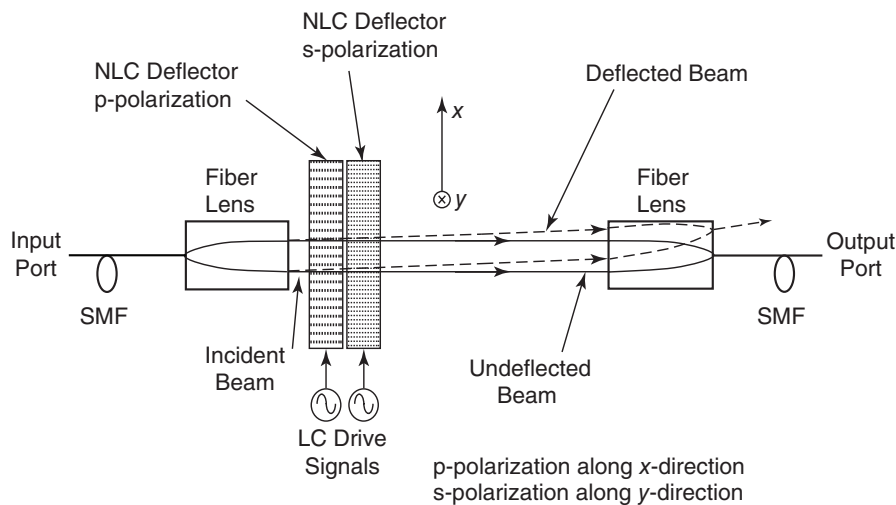


FIGURE 8.3 Liquid crystal deflector fiber optic VOA.

VOA-based attenuation. Because two separate drive signals control the VOA, a PDL compensator can also be realized.

Design Problem 8.4: Wavelength-Tunable Fiber-Optic VOA Using Liquid Crystal Controls

Certain applications require not only wavelength selection or filtering, but also amplitude control for the selected wavelength. For example, RF signal processing in wavelength-sensitive optics and WDM fiber communications benefit from such a module. Design a wavelength tunable fiber-optic VOA using LC controls.

Solution

Figure 8.4 shows the desired wavelength-sensitive VOA. The grating angularly separates the different wavelengths that make up the input optical beam. The mirror tilt about the x -direction axis controls, which Bragg grating-dispersed wavelength in the collection of wavelengths is Bragg-matched to the grating so on return back via the grating gets redirected into the fiber lens and SMF. The NLC beam-deflector tilt along the y -direction keeps the selected wavelength Bragg-matching, but steers the returning beam off the fiber lens to introduce attenuation. Hence, using independent x - y direction beam controls, a chosen wavelength and its power level can be selected as output for the filter-VOA module. Shown is the case of input wavelengths λ_1 , λ_2 , λ_3 and the

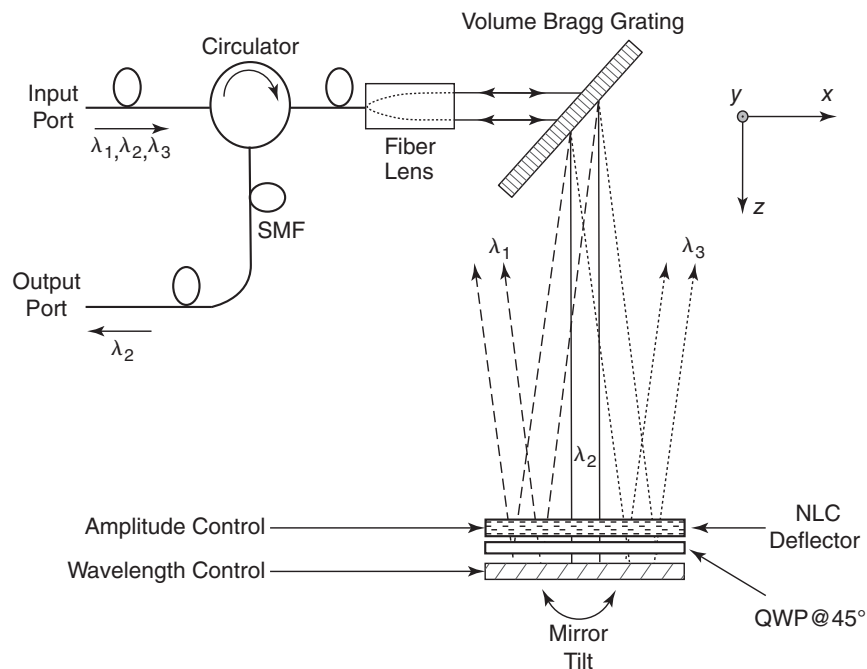


FIGURE 8.4 Wavelength-tunable fiber-optic VOA using LC controls.

mirror aligned for retroreflection of the λ_2 -wavelength while λ_1 and λ_3 return un-Bragg-matched to the grating. Note that the mirror y -tilt can be replaced by NLC device based y -tilt. In fact, a 2D NLC pixelated device can accomplish both independent functions of beam x - and y -tilt controls without requiring mirror motion where NLC-based beam x -tilt is for wavelength selection and y -tilt is for attenuation controls.

Design Problem 8.5: Multi-Wavelength Wavelength Fiber-Optic VOA Using Liquid Crystal Controls

The module shown in Figure 8.4 can only select and attenuate one chosen wavelength. Applications like WDM communications operate with many wavelengths and these wavelengths require independent and simultaneous amplitude control. Design a module using NLCs to achieve this goal.

Solution

Figure 8.5 is the desired module. The system design is similar to the Figure 8.4 design except a cylindrical lens, L , is used to focus the different wavelength beams generated from the grating such that each wavelength shows up as a vertical line (along y -direction) on the NLC SLM plane. Here, the wavelengths occupy spatially separate zones on the 2D NLC SLM and the distance between L and

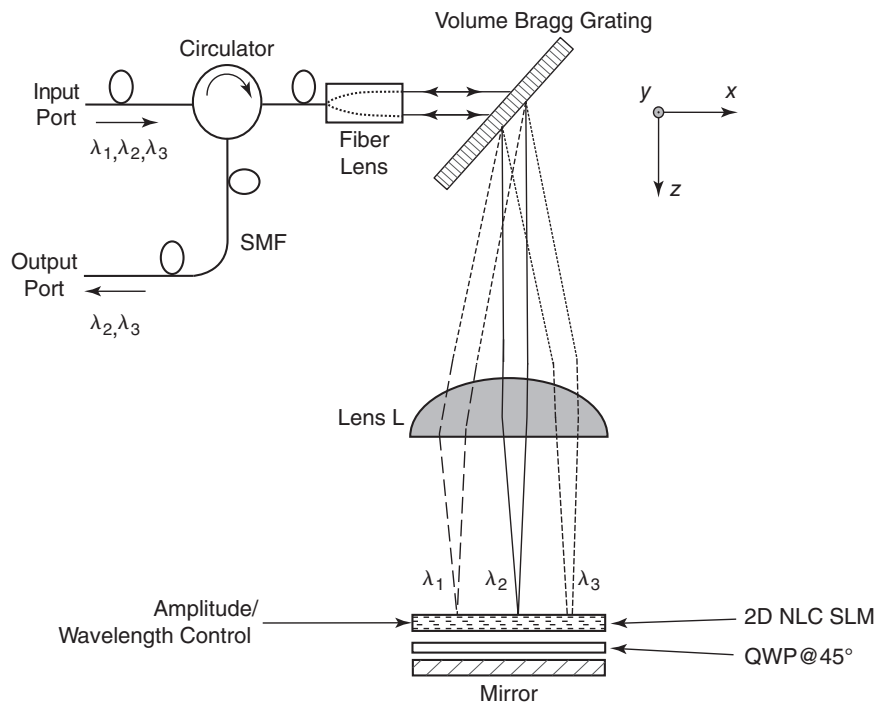


FIGURE 8.5 Multi-wavelength wavelength fiber-optic VOA using LC controls.

the SLM is the focal length of L. To attenuate a wavelength, an optical wedge along the y -direction is created on the NLC SLM to steer the beam and, hence, cause reduced coupling at the fiber lens. This operation can be done independently for all wavelengths. Shown is the case of input wavelengths $\lambda_1, \lambda_2, \lambda_3$ and phase in the NLC SLM is set such that the λ_1 wavelength beam on the return path is completely decoupled from the fiber lens to produce wavelength blocking while λ_1 and λ_3 return fully Bragg-matched to the grating but with some attenuation based to the y -direction tilts received independently on the λ_2 and λ_3 beams on return to the fiber lens.

Design Problem 8.6: Liquid Crystal Freespace 1×2 Switch Using Cube PBS

Figure 8.6 shows a classic cube polarization beam-splitter (PBS) that operates on the principle of linearly polarized light generation by Fresnel reflections off a multilayer dielectric film stack on the diagonal interface face of two sandwiched TIR prisms. Input any state polarized light is split into two orthogonal linear polarizations called s- (vertical) and p- (horizontal) polarizations produced at two

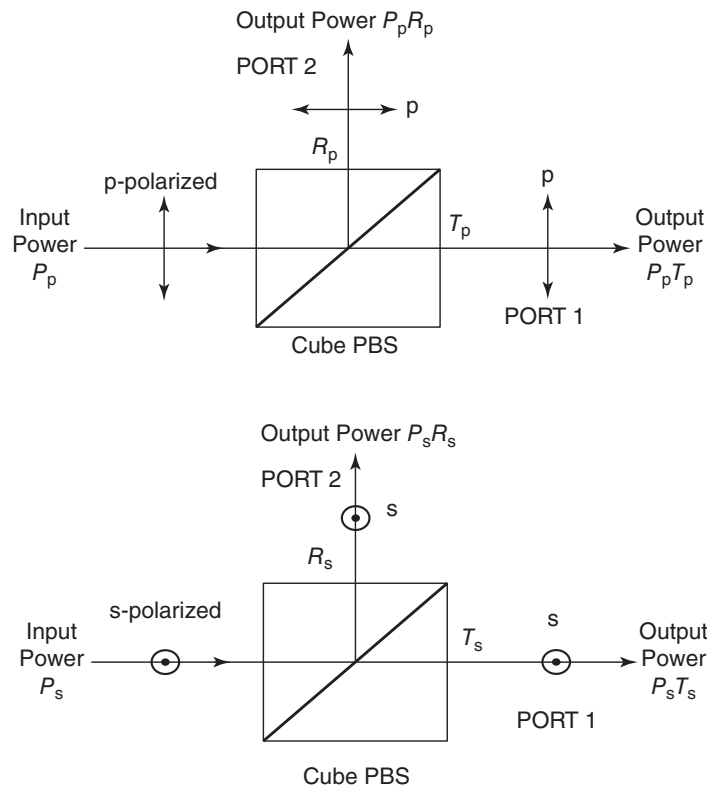


FIGURE 8.6 Operation of a classic cube polarization beam-splitter (PBS).

spatially independent output ports (Port 1 and Port 2) of the PBS. The PBS Fresnel irradiance reflection coefficients for p and s polarized light is given by R_p and R_s notations, respectively. These R_p and R_s reflection coefficients indicate what fraction of the input p and s light irradiance (or power) is directed to the PBS reflection port called Port 2 in Figure 8.6. In a similar way, the PBS Fresnel irradiance transmission coefficients for p and s polarized light is given by T_p and T_s notations, respectively. These T_p and T_s transmission coefficients indicate what fraction of the input p and s light irradiance (or power) is directed to the PBS transmission port called Port 1 in Figure 8.6. In theory, Port 2 has zero p-light and 100 percent s-light so ideally $R_p = 0$ and $R_s = 1$ and Port 1 has zero s-light and 100 percent p-light so ideally $T_s = 0$ and $T_p = 1$. From a practical point of view, a typical cube PBS Fresnel irradiance coefficient numbers would be $R_p = 0.05$ (or a 5 percent reflection of input p-light) and $R_s = 0.999$ (or a 99.9 percent reflection for s-light), $T_s = 0.001$ (or 0.1 percent transmission of input s-light) and $T_p = 0.95$ (or 95 percent transmission of input p-light). Clearly such a cube PBS has an asymmetric performance across the two output ports and in many photonic system design cases, this aspect would be detrimental to overall system performance.

We can define the polarization extinction ratios at the shown PBS output ports to be Port 2 Polarization Extinction Ratio = (s-light power at Port 2)/(p-light power at Port 2) = $(P_s R_s)/(P_p R_p)$ where the PBS input port P_s and P_p are the s-light power and p-light input power, respectively. In a similar way, we can define the shown PBS Port 1 Polarization Extinction Ratio = (p-light power at Port 1)/(s-light power at Port 1) = $(P_p T_p)/(P_s T_s)$.

The cube PBS is a powerful polarization based optical component. Using a 90° TN-LC device, design a freespace linearly polarized input laser beam 1 × 2 optical switch using a cube PBS. For each port, write expressions for the on/off optical power ratios. Using the typical cube PBS performance numbers stated earlier and a TN-LC device with a typical 999/1 polarization extinction ratio performance for both on and off TN-LC device states, compute the proposed switch port on/off numbers and comment of this performance.

Solution

Figure 8.7 and Figure 8.8 show the design and operations of the desired 1 × 2 TN-LC device and cube PBS-based 1 × 2 freespace switch for a linear input polarization beam. The switch on/off power ratios for the two ports can be written as

$$\begin{aligned} \text{on/off Ratio Port 1} &= \frac{\text{Switch on – State Light in Port 1}}{\text{Switch off – State in Port 1}} \\ &= \frac{P_p(\text{on})T_p + P_s(\text{on})T_s}{P_p(\text{off})T_p + P_s(\text{off})T_s} \end{aligned}$$

$$\begin{aligned} \text{on/off Ratio Port 2} &= \frac{\text{Switch on - State Light in Port 2}}{\text{Switch off - State in Port 2}} \\ &= \frac{P_p(\text{on})R_p + P_s(\text{on})R_s}{P_p(\text{off})R_p + P_s(\text{off})R_s} \end{aligned}$$

The cube PBS parameters are $R_p = 0.05$, $R_s = 0.999$, $T_s = 0.001$, and $T_p = 0.95$. For on/off ratio Port 1 calculation, $P_p(\text{on}) = 999$ and $P_s(\text{on}) = 1$ and $P_p(\text{off}) = 1$ and $P_s(\text{off}) = 999$. Using these numbers, one computes

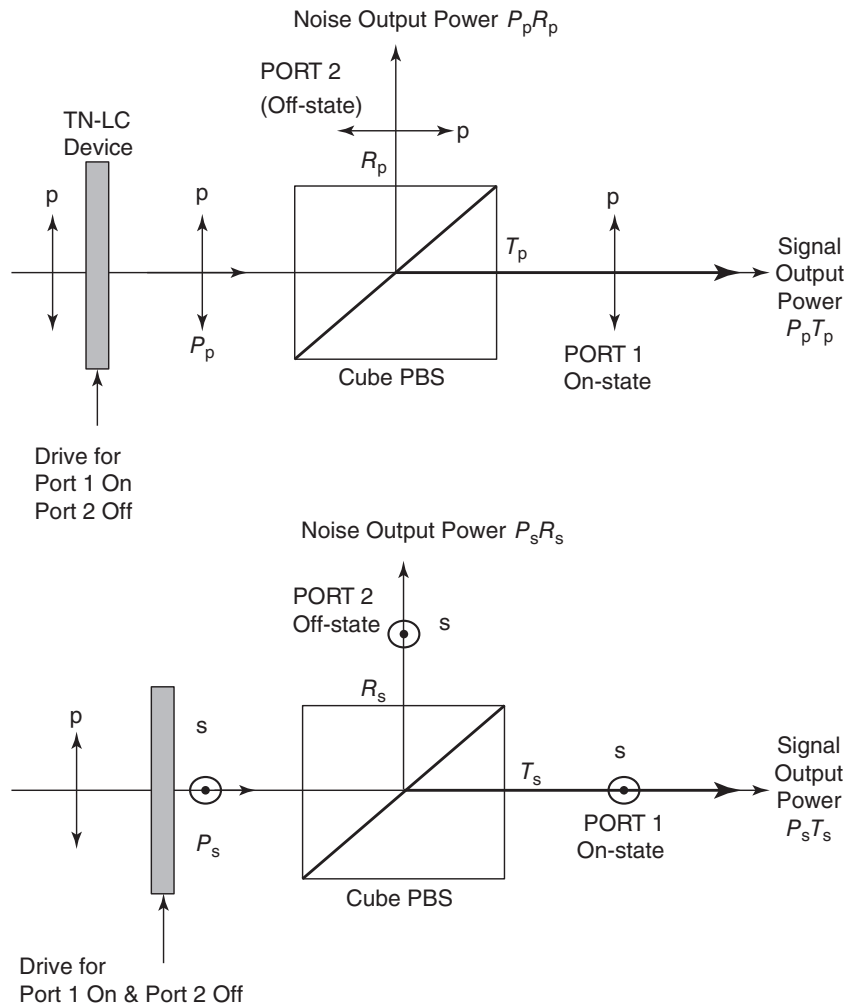


FIGURE 8.7 1×2 TN-LC device and cube PBS-based 1×2 freespace switch for a linear input polarization beam shown with input p-light being directed to Port 1 of switch. As the TN-LC device is not a perfect 90° polarization rotator and the cube PBS is also not a perfect polarization splitter, unwanted light shows up at both switch-output ports.

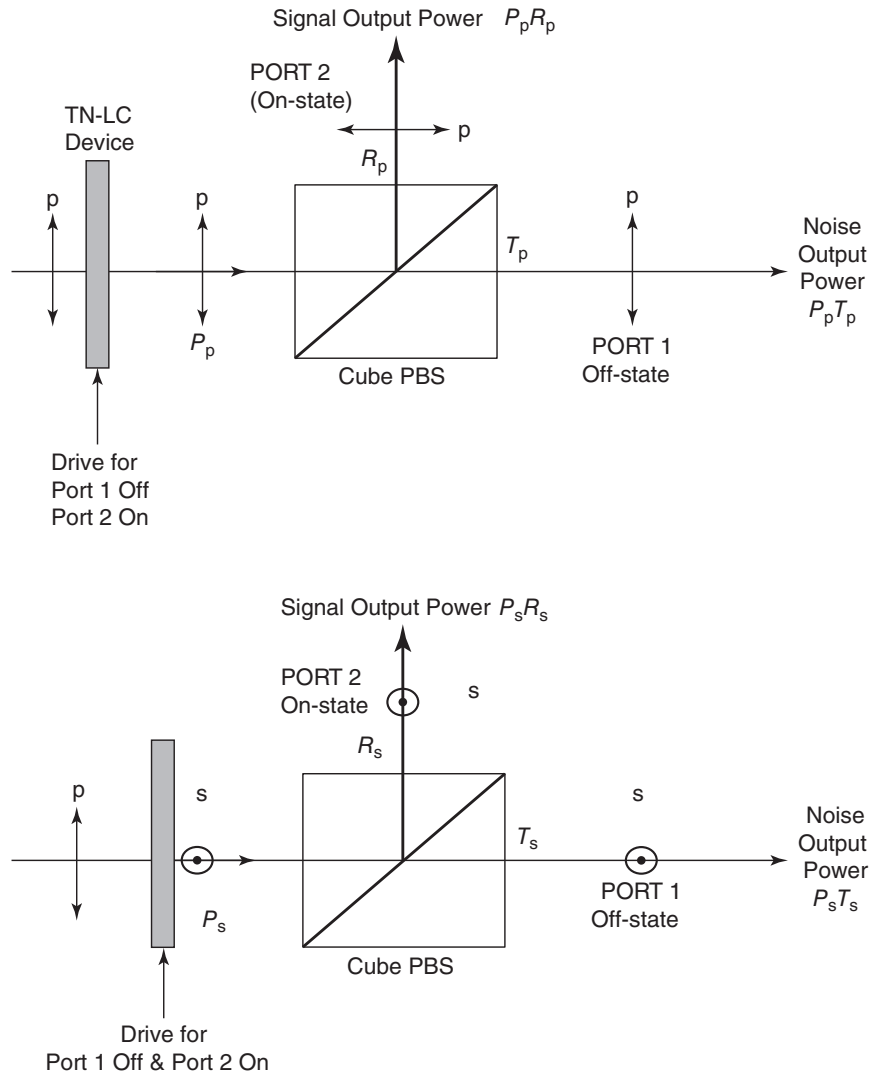


FIGURE 8.8 1×2 TN-LC device and cube PBS-based 1×2 freespace switch for a linear input polarization beam shown with input p-light being directed to Port 2 of switch. As the TN-LC device is not a perfect 90° polarization rotator and the cube PBS is also not a perfect polarization splitter, unwanted light shows up at both switch-output ports.

Port 1 Crosstalk Ratio = 486/1. For on/off ratio Port 2 calculation, $P_p(\text{on}) = 1$ and $P_s(\text{on}) = 999$ and $P_p(\text{off}) = 999$ and $P_s(\text{off}) = 1$. Using these numbers, we compute Port 2 on/off ratio ratio = 20/1. The optical on/off ratio levels can be expressed in the standard dB notation by using optical on/off ratio in dB = $10 \log (\text{Optical Crosstalk Ratio})$. For the current example, the Port 1 and Port 2 optical on/off ratio comes to be 13 dB and 27 dB, respectively. Clearly, the shown classic 1×2 freespace switch using a cube PBS has very limited on/off ratio

performance for Port 2 and a good on/off ratio performance for Port 1. The situation for Port 2 can be even worse if the TN-LC device does not operate with equal polarization-switching quality for both its device-on and device-off states. The current example assumes that both for the device-on and -off state operations, the polarization extinction ratios stay 999:1 (about 30 dB) and hence, both, Port 1 and Port 2 computations used the 999:1 optical power ratios between the orthogonal linear polarizations entering the cube PBS for both states of switch operations.

Another useful switch parameter is the optical isolation level between the output ports (Port 1 and Port 2) for the two states of the switch. Interport isolation is also called crosstalk levels. The interport optical isolation for the two switch settings (i.e., Port 1 active or Port 2 active) can be written as

$$\begin{aligned} \text{Isolation Ratio (Port 1 Active)} &= \frac{\text{Switch on} - \text{Light in Port 1}}{\text{Switch on} - \text{Light in Port 2}} \\ &= \frac{P_p(\text{on})T_p + P_s(\text{on})T_s}{P_p(\text{on})R_p + P_s(\text{on})R_s} \end{aligned}$$

$$\begin{aligned} \text{Isolation Ratio (Port 2 Active)} &= \frac{\text{Switch off} - \text{Light in Port 2}}{\text{Switch off} - \text{Light in Port 1}} \\ &= \frac{P_p(\text{off})R_p + P_s(\text{off})R_s}{P_p(\text{off})T_p + P_s(\text{off})T_s} \end{aligned}$$

For Port 1 active calculation, $P_p(\text{on}) = 999$ and $P_s(\text{on}) = 1$ and for Port 2 active calculation $P_p(\text{off}) = 1$ and $P_s(\text{off}) = 999$. Using the mentioned cube PBS Fresnel coefficient, one computes the isolation ratios as 20:1 and 512:1 for active Port 1 and Port 2, respectively. Clearly the switch interport isolation level is weak when the switch is in its Port 1 active state when the input light is directed to Port 1, but a significant fraction (1 in 20) also shows up at Port 2. Hence, port on/off ratios and interport isolations are intimately connected switch parameters.

Design Problem 8.7: Higher-Performance LC Freespace 1×2 Switch Using Cube PBS

The Figure 8.7 and Figure 8.8 cube PBS TN-LC device 1×2 switch has limited performances in port on/off ratio and interport crosstalk ratio. Design a new higher performance 1×2 switch using the same basic optics plus any other optics deemed useful.

Solution

Figure 8.9 shows the desired higher-performance 1×2 switch. The key innovation is the use of two polarizers of the correct orientation at the two output ports. This innovation is possible when one realizes that the noise in the output ports has a polarization direction that is orthogonal to the signal polarization and, hence, placement of a polarizer with Fresnel transmission coefficients T_p' and T_s' can greatly suppress the noise and drastically improve switch port on/off ratio and interport crosstalk performances. The switch port on/off ratio and crosstalk ratio expressions can be rewritten as

$$\begin{aligned} \text{on/off Ratio Port 1} &= \frac{\text{Switch on} - \text{State Light in Port 1}}{\text{Switch off} - \text{State Light in Port 1}} \\ &= \frac{P_p(\text{on})T_p T_p^1 + P_s(\text{on})T_s T_s^1}{P_p(\text{off})T_p T_p^1 + P_s(\text{off})T_s T_s^1} \end{aligned}$$

$$\begin{aligned} \text{on/off Ratio Port 2} &= \frac{\text{Switch on} - \text{State Light in Port 2}}{\text{Switch off} - \text{State Light in Port 2}} \\ &= \frac{P_p(\text{on})R_p T_p^2 + P_s(\text{on})R_s T_s^2}{P_p(\text{off})R_p T_p^2 + P_s(\text{off})R_s T_s^2} \end{aligned}$$

$$\begin{aligned} \text{Isolation Ratio Port 1 Active} &= \frac{\text{Switch on} - \text{Light in Port 1}}{\text{Switch on} - \text{Light in Port 2}} \\ &= \frac{P_p(\text{on})T_p T_p^1 + P_s(\text{on})T_s T_s^1}{P_p(\text{on})R_p T_p^2 + P_s(\text{on})R_s T_s^2} \end{aligned}$$

$$\begin{aligned} \text{Isolation Ratio Port 2 Active} &= \frac{\text{Switch off} - \text{Light in Port 2}}{\text{Switch off} - \text{Light in Port 1}} \\ &= \frac{P_p(\text{off})R_p T_p^2 + P_s(\text{off})R_s T_s^2}{P_p(\text{off})T_p T_p^1 + P_s(\text{off})T_s T_s^1} \end{aligned}$$

Using typical earlier mentioned cube PBS parameters and a good noise reduction polarizer with transmission coefficients for Port 1 polarizer P1 as $T_p^1 = 0.999$ and $T_s^1 = 0.001$ and Port 2 polarizer P2 as $T_p^2 = 0.001$ and $T_s^2 = 0.999$, one can compute the on/off ratios for Port 1 and Port 2 to be 1008:1 and 951:1, respectively. In addition, one computes the optical isolation ratios of 9500:1 and 999:1 for Active Port 1 and Active Port 2, respectively. Note the drastic improvement of Port 2 on/off ratio from 13 to 29.8 dB using a simple yet powerful photonic design innovation within the switch structure with polarizer P2

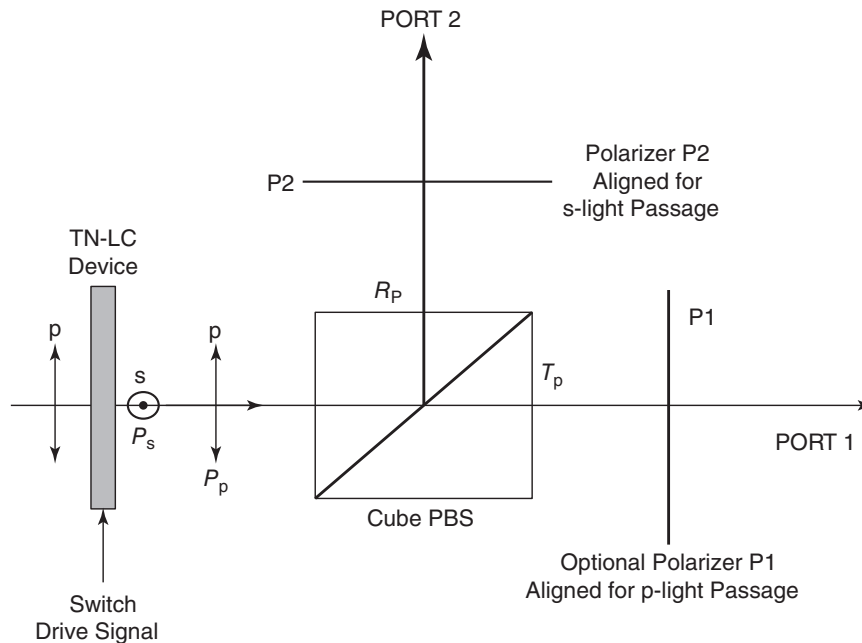


FIGURE 8.9 The desired higher-performance 1×2 switch.

making the major impact compared to polarizer P1. In addition, note the drastic improvement in Active Port 1 isolation ratio from 20:1 to 9500:1 caused using the placement of P2 at the Port 2. The improvement in Active Port 2 isolation ratio from 512:1 to 999:1 caused using the placement of P1 at the Port 1 is not so drastic and depending of system design costs and requirements can be removed from the switch.

Design Problem 8.8: Low-Noise LC 1-Bit Freespace TDU Using PBSs

Time-delay units (TDUs) are needed in many photonic signal processing applications such as RF and laser radar, short-pulse optical signal-timing control, and high data-rate communication systems. Using TN-LCs, cube PBSs, and other basic optics, design a low-noise two-state TDU.

Solution

Figure 8.10 shows the desired low-noise performance 1-bit optical TDU. The first part of the TDU is the Figure 8.9 low noise 1×2 optical switch. The second part of the TDU is the beam path recombination optics using cube PBS2 whose direct output depending on the TN-LC device 1 digital drive state is a straight path p-polarized beam or a delayed path (beam goes into the delay loop) s-polarized beam.

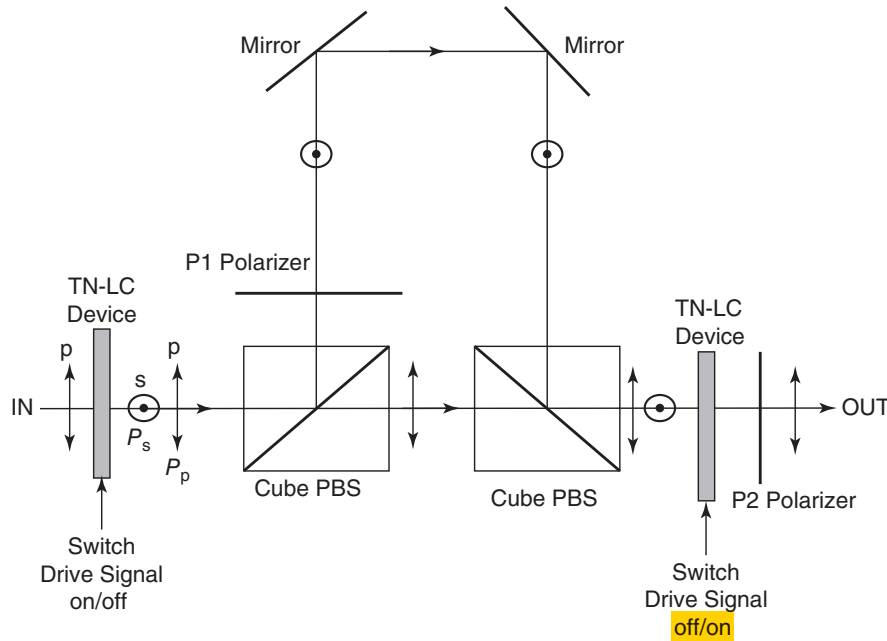


FIGURE 8.10 The desired low-noise performance 1-bit optical TDU.

Hence, the polarization state of the output of the TDU changes depending on the TDU delay/non-delay setting. This aspect of the TDU is not ideal for cascading with other photonic signal processing building block that maybe polarization sensitive. Ideally, the TDU output should maintain the polarization of the TDU input beam. The more serious issue due to the cube PBS2 is its asymmetric polarization extinction ratio response depending on which of the two input ports of the cube is engaged. In effect, the light output from cube PBS2 suffers from non-optimal on/off ratio and crosstalk problems. These problems are immediately solved by placing TN-LC device 2 and polarizer P2 at the output of the cube PBS2. The two TN-LC devices operate such that when the input p-light to the TDU is nonrotated in polarization by 90° by TN-LC device 1 for TDU reference delay operation, then TN-LC device 2 also does not rotate the p-light polarization and, hence, the p-light passes through polarizer P2 to the TDU output port. In a similar way, the two TN-LC devices operate such that when the input p-light to the TDU is rotated in polarization by 90° by TN-LC device 1 to produce s-light for TDU loop-delay operation, then TN-LC device 2 also rotated the s-light polarization output from cube PBS2 and hence produces p-light that then passes through polarizer P2 to the TDU output port. The combination of TN-LC device 2 and polarizer P2 forms an active optical noise-reduction filter and can be used in any polarization-based switching optics including fiber-connected modules to improve overall system performance.

Design 8.9: SMF Optical TDU Using LC Polarization Control

SMFs are excellent for implementing long (>1 ns) optical delays, but do not preserve the polarization of the light input to the fiber. Hence, the Figure 8.10 freespace delay-looped path cannot be simply replaced by a SMF. Only a polarization-maintaining SMF or PMF can be used in the delay loop with proper PMF core alignments with the freespace light s-polarization directions to get proper beam directing via the cube PBSs. Any physical pressure or temperature variations on the PMF can alter its high extinction ratio polarization maintaining property causing noise and optical loss in the Figure 8.10 TDU. Design a SMF-based optical TDU using TN-LC polarization switching that is insensitive to light polarization changes due to travel in the regular non-polarization maintaining SMF, thus making a cost-effective and environmentally robust optical TDU.

Solution

Figure 8.11 shows the desired SMF optical TDU using LC polarization control via TN-LC devices, a Faraday rotator (FR) of power θ° , a quarter-wave plate (QWP), mirrors (Ms), a cube PBS, and polarizer P1.

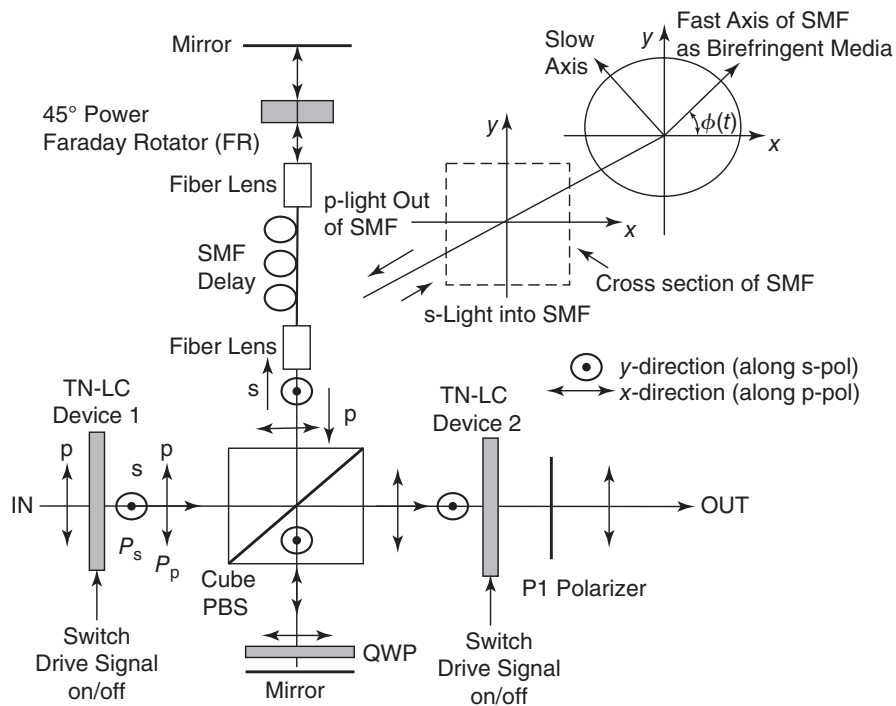


FIGURE 8.11 SMF optical TDU using LC polarization control.

The SMF can be considered to act as a variable-optical retardation plate (a birefringent material) with its fast and slow axes aligned at a time varying angle $\phi(t)$ with the light-polarization p-direction (or x-direction) as shown in Figure 8.11. Depending on the SMF environments conditions (e.g., stresses and strains along the SMF), this phase retardation, Γ in radians, can be time-varying, hence linearly polarized input s-polarized light exits the SMF as a general time varying elliptically polarized light that enters the $\theta = 45^\circ$ polarization rotation power Faraday rotator. Retro-reflective light passage through this Faraday rotator-mirror combination and the SMF that causes a 90° flipping of the SMF input light s polarization component to a SMF output p-polarization component. In effect, passage of the light in the SMF conditioned by FR-M-FR cancels the relative phase retardation originally imparted on first passage through the SMF. The net result is that the light exiting the SMF is purely p-polarized and, hence, passes through the PBS to enter a QWP-mirror assembly to retroreflect and return to the PBS as s-polarized light for passage via the non-delay path of the TDU. Active noise reduction using TN-LC device 2 and polarizer P1 is used to reduce noise in the module. By controlling the on/off states of the two TN-LC devices, either the fiber-delay path or the no-delay straight path of the TDU can be selected. Many such TDUs can be cascaded together to form an N-bit optical TDU module useful in photonic signal processing where long (>1 ns) delays are required. The mathematical polarization analysis for the SMF-FR-mirror-FR-SMF light passage can be conducted as follows using Jones vector and matrix analysis.

The FR Jones matrix for light coming from the PBS into the FR (called forward light) can be written as

$$[\text{FR}^F] = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}$$

while the Jones matrix for light coming from the mirror into the FR (backlight) can be written as

$$[\text{FR}^B] = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}$$

The Jones matrix for a mirror given light coming from the PBS direction is

$$[M] = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$$

Using the $\theta = 45^\circ$ value for the FR power, the Jones matrix for the FR^F -mirror- FR^B assembly can be computed by multiplying the matrices for the three optical interactions via the components and written as

$$[FMF] = [FR^B][M][FR^F] = \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix}$$

The Jones matrix for a general phase-retarder with a retardation of Γ in radians can be written as

$$[R(\Gamma)] = \begin{bmatrix} \exp(j0.5\Gamma) & 0 \\ 0 & \exp(-j0.5\Gamma) \end{bmatrix}$$

The SMF retarder's fast axis makes an angle, ϕ , with the defined x -axis, hence the polarization rotation matrix must be used to put the SMF retardation in the correct frame of reference. The Jones matrix for coordinate frame rotation by ϕ is given by

$$[R^\phi] = \begin{bmatrix} \cos \phi & \sin \phi \\ \sin \phi & \cos \phi \end{bmatrix}$$

Note that the rotation matrix is the same as that for the Faraday rotator of power, ϕ .

For the SMF birefringent material with fast axis making an ϕ angle with the x -direction, the Jones matrix for the SMF can be written as

$$\begin{aligned} [SMF(\phi)] &= [R^\phi][R(\Gamma)][R^{-\phi}] = \begin{bmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{bmatrix} \begin{bmatrix} e^{j0.5\Gamma} & 0 \\ 0 & e^{-j0.5\Gamma} \end{bmatrix} \\ &= \begin{bmatrix} \cos \phi & -\sin \phi \\ -\sin \phi & \cos \phi \end{bmatrix} \\ &= \begin{bmatrix} e^{j0.5\Gamma} \cos^2 \phi + e^{-j0.5\Gamma} \sin^2 \phi & j \sin 2\phi \sin(0.5\Gamma) \\ j \sin 2\phi \sin(0.5\Gamma) & e^{j0.5\Gamma} \sin^2 \phi + e^{-j0.5\Gamma} \cos^2 \phi \end{bmatrix} \end{aligned}$$

Next we compute the Jones matrix for the system that involves a first passage of light through the SMF retarder, then through the FR-mirror-FR assembly, and then back through the SMF retarder with

the light propagation direction reversed to get the SMF delay-system matrix expressed as

$$[S] = [SMF(-\phi)][FMF][SMF(-\phi)] = \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix}$$

The Jones matrix for the delay system is independent of the phase-retardation parameters of the SMF. In addition, it is independent of time. The assumption is that the SMF phase retardation is the same during the round-trip travel of the photon in the SMF, a good assumption considering the SMF environmental perturbations effecting retardation happen at slow time scales compared to the SMF provided optical time delay. For a given optical polarization Jones vector input (e.g., s-polarized or vertically polarized light) into the SMF-based shown delay system, the output light Jones vector can be written as

$$[J_{OUT}] = [S][J_{IN}] = \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = - \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad \text{or} \quad \text{p-polarization}$$

Indeed, the shown SMF-based delay preserves the linear polarization state (although in 90° rotated state) of the input light when it exits the SMF after delay, and hence can be used with other polarization optics such as LC devices to form a switched optical TDU. The conducted polarization analysis shows how elegant R. C. Jones-proposed polarization methods representing optical fields and components can help photonic design engineers in optimal system invention and design.

Design Problem 8.10: 2 × 2 Fiber-Optic Switch Using LC Devices and Cube PBSs

Now we examine 2 × 2 fiber-optic switches, which are highly useful modules in applications ranging from optics-based RF signal processing to WDM switching and filtering applications. Design a 2 × 2 low-noise fiber-optic switch using TN-LC devices and cube PBSs that can be packaged into a compact assembly.

Solution

Figure 8.12 shows the desired 2 × 2 fiber-optic switch using LC devices and cube PBSs. The beam retro-reflection principle is used in the design. Each TN-LC device has two side-by-side independently controllable pixels. TN-LC pixel on means light suffers a 90° rotation

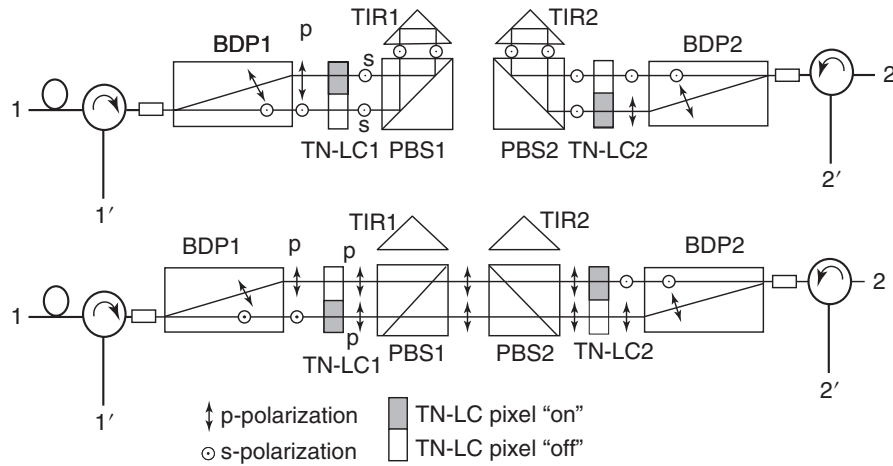


FIGURE 8.12 2×2 fiber-optic switch using LC devices and cube PBSs.

while TN-LC pixel off means no polarization rotation to the input light. The top figure shows how light from Port 1 and Port 2 go to Port 1' and Port 2', respectively. The lower figure shows how light from Port 1 and Port 2 go to Port 2' and Port 1', respectively. Hence, by controlling the two TN-LC devices, a 2×2 fiber-optic routing switch is formed. An array of such switches can be formed if additional pairs of TN-LC pixels are added to the devices in the direction of the s or vertical polarization and fiber-lens arrays and circulator arrays are deployed at the input/output ports. Because all optics has flat surfaces, they can be stacked together for tight packaging.

Design Problem 8.11: Fast Reset-Speed Variable Focal-Length Lens Using LCs

An electronically controlled variable focal length lens (ECVFL) can be designed using parallel-rub birefringent-mode NLCs. Birefringence Δn of NLCs and the thickness d of the NLC layer in devices is limited. For example, $\Delta n = n_e - n_o < 0.2$ and $d < 10 \mu\text{m}$, for a voltage (e.g., $< 20 \text{ V}$) limited performance leads to thin refractive weak lensing (e.g., focal lengths 1 m to infinity). For stronger lensing, pixelated NLC device design with small pixel pitch (e.g., $< 10 \mu\text{m}$) are individually programmed with optical-phase shifts to produce a diffractive-optical lens. Depending on the wavelength, NLCs operate in the milliseconds reset range and hence result in moderate speed ECVFLs. Ferroelectric LCs (or FLCs) can be used to realize much faster microseconds domain binary state linear polarization rotators, much like 90° TN-LC devices. Both FLC and NLC devices are planar devices that can be fabricated as large area (e.g., $> 2 \text{ cm}$ diameter) thin

(<3 mm thickness per device) devices. Using both FLC linear polarization rotators and NLC ECVFLs, design a fast reset time ECVFL.

Solution

Figure 8.13 show the desired fast reset time ECVFL using fast FLC device 90° polarization digital switching so that light can be switched between p- and s-polarizations. Between the FLC devices are NLC lenses that are programmed for a given lensing Dioptric power D for one input linear polarization (e.g., s-polarization) while appear like a clear piece of non-focusing optic for the orthogonal linear polarization (e.g., p-polarization). Lens power in D diopters is equal to inverse of the lens focal length, F , in meters or $D = 1/F$ in inverse meters units. Hence a NLC lens electronically set for $F = 2$ m gives a NLC lens dioptric power of 0.5. Figure 8.13 uses 4 NLC lenses to form a $2^4 = 16$ state digital lens using a binary-switching structure with NLC lens powers set to D , $2D$, $4D$, and $8D$, where D is the smallest dioptric power required from the fast ECVFL module. D is also the digital step in the changing ECVFL power as FLC devices switch states to have the module provide $0, D, 2D, 3D, 4D, 5D, \dots, 15D$ power settings.

The last FLC device in the sequence works with the final polarizer to form an active noise filter. In addition, the active noise filter in combination with the first polarizer makes sure the input and output light is p-polarized. This ECVFL design can work in an all-digital fast lens setting mode or a hybrid slower speed digital-analog mode for fully continuously focal length control. Specifically, digital control of the FLC devices sets the coarse focal length of the ECVFL module

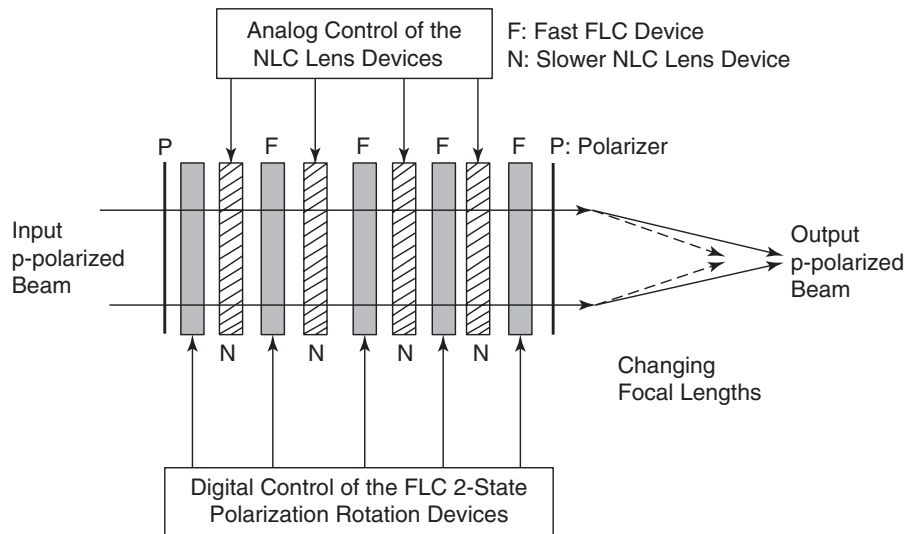


FIGURE 8.13 Fast reset-speed variable focal-length lens using LCs.

while analog voltage control of the non-engaged NLC lens (or multiple NLC lenses) in the coarse digital focal length control is now engaged and used to finely adjust the module overall focal length over a D Dioptic power step. Hence, a high resolution (fine Dioptic power) and high dynamic range (large Dioptic power) ECVFL is formed. Note that one can also add fixed birefringent lensing optics (e.g., custom material-fabricated optics) between FLC devices to provide a desired bias point for the Dioptic powers of the ECVFL module. The shown ECVFL module can be used in all photonic-system applications that require a changing focal length to implement a system function such as 3D optical imaging and sensing and low-loss freespace optical interconnects.

Design Problem 8.12: Zero Propagation-Loss Variable-Link Distance Optical Wireless Communications

Many scenarios can benefit from zero propagation loss freespace optical (FSO) wireless communications where link distances can change such as indoor wireless communications, intersatellite communications, indoor data center wireless communications, interprocessor communications, multisensor body area networks, and indoor medical multisensor links. Design a variable link-distance zero propagation-loss FSO link between two optical transmit/receive modules.

Solution

Figure 8.14 is the desired variable link-distance zero propagation-loss FSO link design that implements the self-imaging effect using a pair of ECVFLs. The self-imaging effect was mentioned in Chapter 6 when describing SMF-fiber-lens pair freespace coupling. The same concept

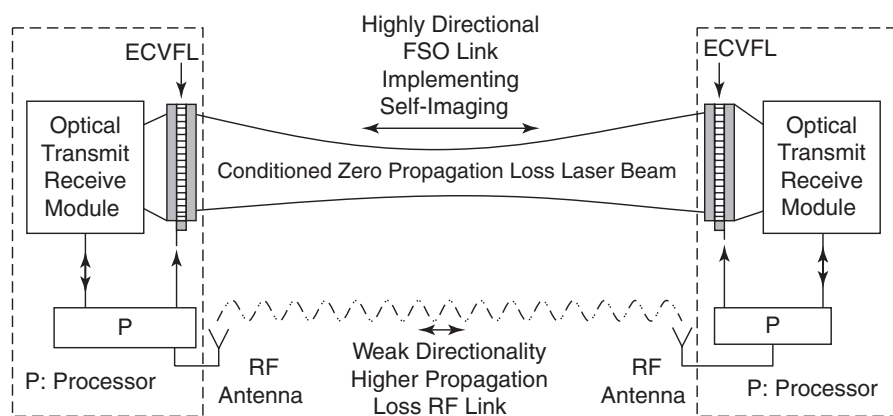


FIGURE 8.14 Variable link-distance zero propagation-loss FSO link design.

for SMF-to-SMF coupling via Gaussian beam propagation applies here where the ECVFL in a transmit/receive (T/R) module is adjusted in focal length to maintain the Gaussian beam minimum beam-waist at the halfway distance between the T/R modules. Figure 8.14 shows a dual-mode hybrid link that uses RF and optical carriers for the data communications. An RF carrier is effective under adverse weather conditions but is loss-heavy as the RF radiation is highly diffracting with a wide-coverage RF antenna pattern. In addition, RF radiation affects other electronic systems via interference and also uses precious electromagnetic spectrum bands. On the contrary, the optical link shown is perfectly directional and in theory sends no photons away from the receiver ECVFL aperture. In addition, the optical carrier produces no RF electromagnetic interference (EMI) and air waves have open optical spectrum usage options. From the FSO link operations point of view, the ECVFL can also be operated in a wide search mode using the ECVFL as a concave or diverging lens versus a focus mode convex lens. The ECVFL device can be replaced by a general 3D beam-former device that can produce x - y beam scans as well as multiple beams along with beam focus/defocus controls. Such capabilities via a 3D beam-former device are possible using an electronically programmed multipixel NLC phase-modulating aperture.

Design Problem 8.13: Fast 3D Optical Sensing and Imaging

Three-dimensional information capture and sensing is a highly desired task in many applications ranging from 3D object shape measurement, 3D laser machining, and 3D optical imaging. Achieving fast 360° optical scanning of a 3D object is highly desirable. Design a photonic system to achieve this task.

Solution

It has been known that EM radiation when coupled with periodic structures can produce frequency-steered radiation in 3D space. A classic frequency-scanned RF phased-array radar scanning and the wavelength-swept optical radar beam scanning using an optical wavelength dispersing element. Advances in lasers and fiber-optic devices have led to fast-tunable lasers and SMF-coupled many channel (e.g., 512) WDM devices. Figure 8.15 shows how a fast tunable laser coupled with a 1:N wavelength SMF-coupled WDM device and additional BFE devices can lead to a 360° coverage optical scanner and sensing system. Here, the tip of each SMF is coupled to a fiber lens and an additional BFE that can be an optical MEMS beam steering chip, a LC beam-former chip, or a non-programmable optic such as a diffractive optical element (DOE) that produces a desired optical beam that interrogates the 3D object under observation.

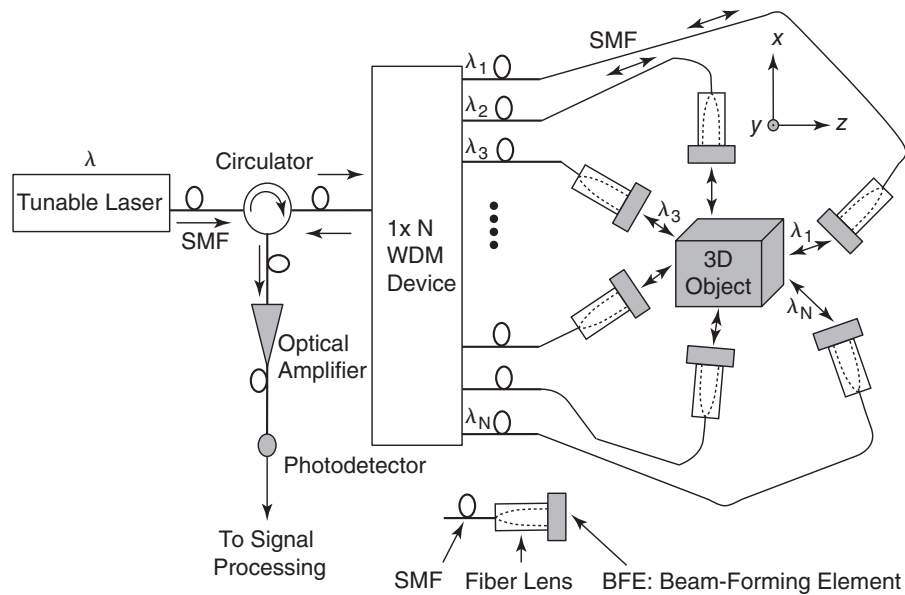


FIGURE 8.15 Fast 3D optical-sensing and -imaging system using wavelength selection and 3D distributed beam-forming elements (BFEs) such as LC 3D beam-forming devices.

Because the tunable laser can sweep its wavelength rapidly (e.g., nanoseconds), fast 3D object data acquisition is possible. The flexibility of the SMF allows conformal placement of the BFE imaging heads. In a transmit-only mode, the system functions as a fast 3D scanner. The optical spatial mapping in the system follows the single point (laser source) to multiple scan points (via WDM and BFE devices) to single point (at point photodetector) system.

Design Problem 8.14: Fast 1D Optical Sensing and Imaging Using Multiple Wavelengths

Many applications require fast optical scanning and imaging along one dimension or 1D space. Examples include fluid-flow measurements, bar-code reading, and laser cutting. Using the frequency scanning-array concept, design a simple 1D optical scanning and imaging system that is readily adaptable to both a large (>2 cm diameter) and small (e.g., intracavity <1 mm diameter) optical aperture design.

Solution

Figure 8.16 shows the desired W-MOS for 1D scans that uses a large area (or small area depending on application) Volume Bragg grating (VBG) dispersive-optical element. For example a Dickson grating can be deployed where the holographic grating is sandwiched between

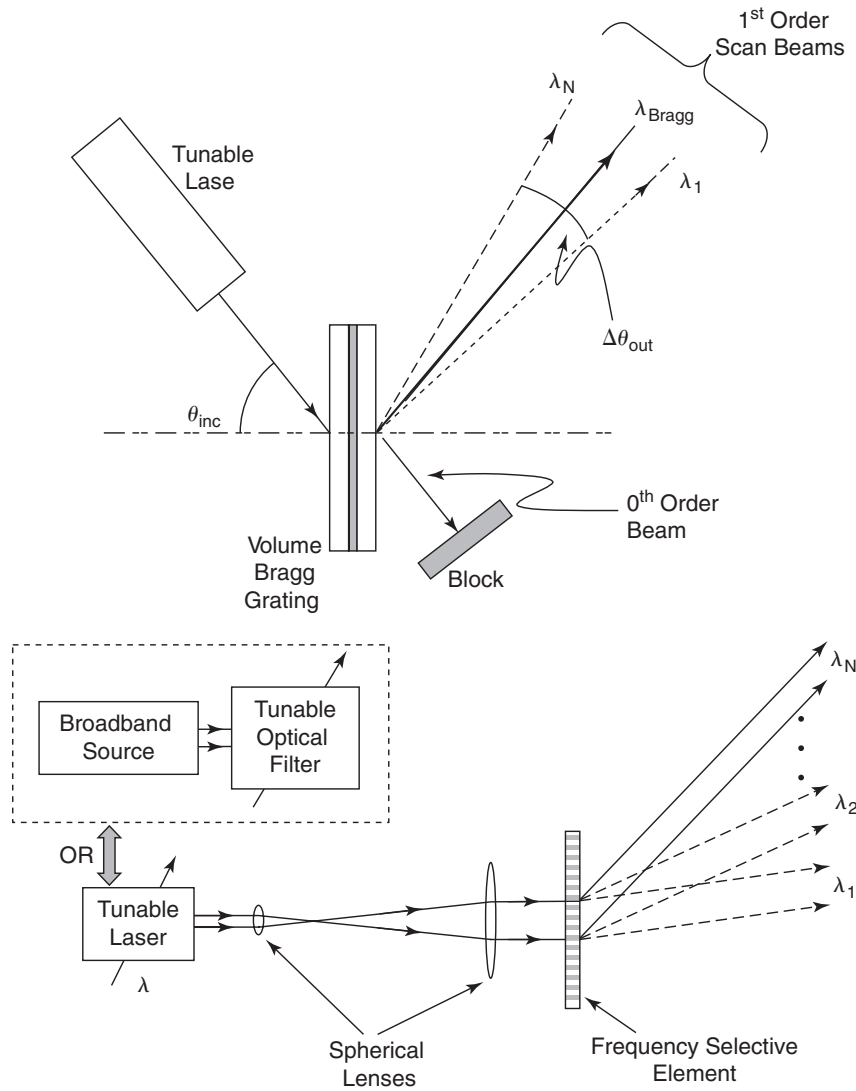


FIGURE 8.16 Wavelength-multiplexed optical scanner (W-MOS) for 1D scans.

two glass plates. The scan angle range for the 1D scan W-MOS can be written using the classic grating equation as

$$\Delta\theta_{\text{out}} = \sin^{-1} \left\{ \frac{\lambda_N}{d} - \sin \theta_{\text{inc}} \right\} - \sin^{-1} \left\{ \frac{\lambda_1}{d} - \sin \theta_{\text{inc}} \right\}$$

Here d is the grating spatial-period distance. For a Dickson grating, a typical incidence Bragg angle can be 47° and scan zones of 7° is possible with 1520- to 1600-nm wavelength scans. Both single-beam and multiple-beam scanning options are possible using the Figure 8.16 system.

Design Problem 8.15: Fast 1D Interferometric Optical Sensing and Imaging Using Multiple Wavelengths

Many applications require fast interferometric optical scanning and imaging along one dimension or 1D space. Design an interferometric W-MOS or I-WMOS to achieve optical phase-sensitive optical sensing.

Solution

Much like the traveling wave bulk acousto-optic grating in an AOD, the Bragg-matched incident beam on the stationary volume Bragg grating (VBG), such as in the holographic plate shown in Figure 8.17, produces both an undeflected nondiffracted or DC beam and a deflected +1 order beam. Recall that an in-line AO scanning interferometer can be designed using the two output beams from AO diffraction in an AOD. The same architecture is applied in Figure 8.17 to design an I-WMOS. In an AOD, the RF-drive frequency is tuned to change the deflection angle of the diffracted beam. In the I-WMOS, the laser frequency (wavelength) is tuned to change the scan angle of the +1-order diffracted beam, thus forming a 1D fast-scanning optical interferometer. To enable a heterodyne interferometric sensor, the reference beam mirror can be mechanically dithered to produce a Doppler shift on the reference beam. Another option is to introduce a NLC phase-modulator in the reference beam path to introduce a reference beam temporal modulation.

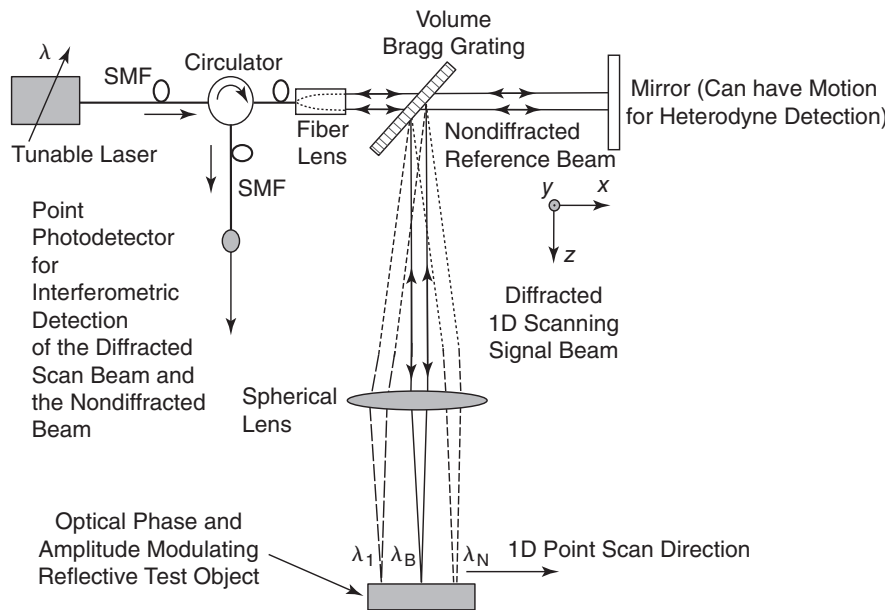


FIGURE 8.17 Fast 1D interferometric optical-sensing and -imaging system using multiple wavelengths.

Design Problem 8.16: Intracavity Sensing and Imaging Using Multiple Wavelengths

Some applications require intracavity imaging such as in biomedical endoscopic imaging scenarios where tiny (<2 mm diameter) cross-section probes are needed. Design intracavity imaging probes using features of SMFs and active and passive micro-optic devices. Design the probe such that it can be modified for use with a variety of waves such as mechanical and electromagnetic.

Solution

Figure 8.18 shows the design of an all-passive imaging probe that can implement transmit-mode ultrasonic and RF beam steering or T/R mode optical imaging. The probe design relies on the W-MOS concept using a broadband optical source (BOS) coupled with a SMF and tiny WDM optics like holographic plates with grating structures. Depending on the WDM optics, the wavelengths can be spatially mapped in space at the probe output end in a 1D, 2D, or 3D optical sampling array. For 3D light motion, one can deploy a broadband high chromatic dispersion lens whose focal length is dependent on the wavelength. When a photoacoustic material is placed at the multiwavelength sampling array plane and the different optical

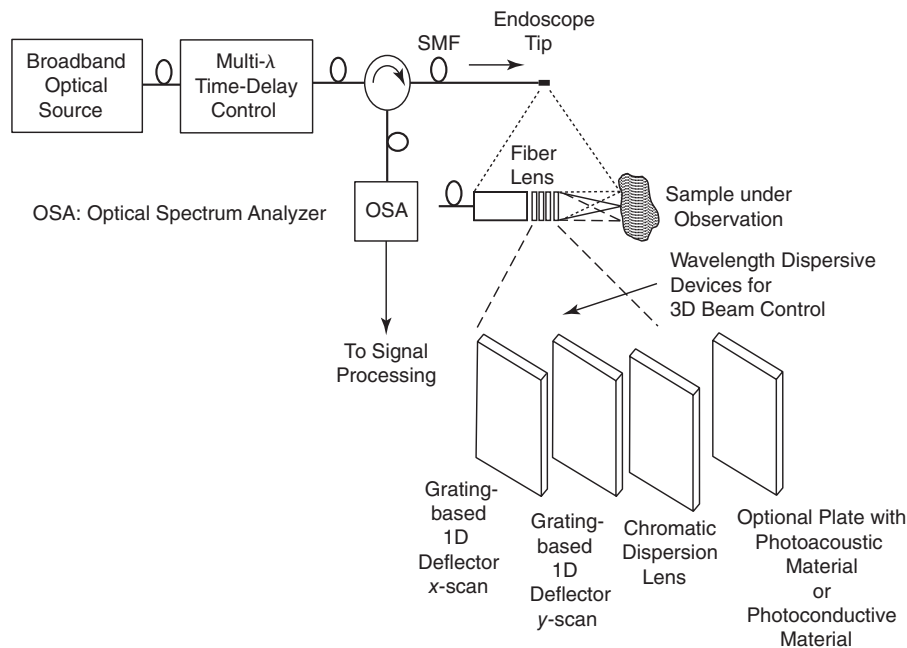


FIGURE 8.18 Design of an all-passive imaging probe that can implement ultrasonic and RF transmit beam-steering or T/R optical imaging.

wavelengths have different delay optical pulses via a multiwavelength coded time-delay photonic beam-former, a steered transmit ultrasonic beam can be generated in the intracavity medium. Similarly, when a photoconductive material (interconnected with RF-antenna array patches) is placed at the multiwavelength sampling-array plane and the different optical wavelengths have different delay optical pulses via a multi-wavelength coded time delay photonic beam-former, a steered transmit RF (e.g., mm-wave and THz bands) beam can be generated in the intracavity medium. When operating in the all-optical mode and mechanical wave mode, a fully passive intracavity-imaging probe is realized that does not require an electrical connections or wires at the cavity end of the probe. Hence, an ultracompact and electrically safe optical-imaging probe can be realized.

Figure 8.19 shows an alternate intracavity probe design using three NLC chips for optical beam pointing, one for x -scan, one for y -scan, and one for focus/defocus control. These tiny NLC chips require very little operation power and can have RF wireless-scan controls via on-chip RF T/R circuits.

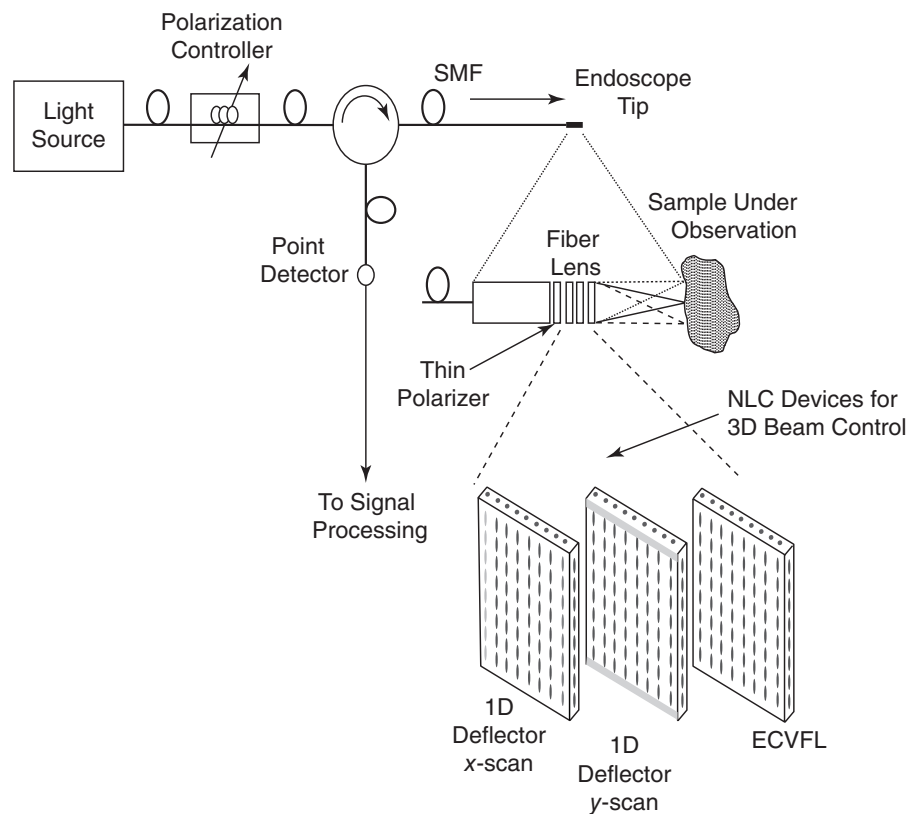


FIGURE 8.19 Intracavity optical-imaging probe using three NLC optical-scanning chips.

Design Problem 8.17: Smart High-Resolution Laser-Scanning Display

Laser-scanning display (LSD) is a powerful display technology based on rapidly scanning a point of light on a screen to form a time-integrated color image in the human eye system. LSD technology unlike other dominant display technologies like LCDs, plasma TV, and DMD and LC projectors does not require hardwired multi-pixel chips to form the image. The size of the image depends on the scan zone on the screen and the resolution of the image depends on the laser beam spot size on the screen. As the screen distance gets bigger, the image resolution gets poorer, an intrinsic limitation of LSDs. Design a smart LCD that can provide the highest resolution images at the screen given the screen can be moved over a range of distances.

Solution

Figure 8.20 shows the desired photonic system where an ECVFL is used to produce the tightest focused spot on the display screen for a given screen distance. As the screen is moved between its screen

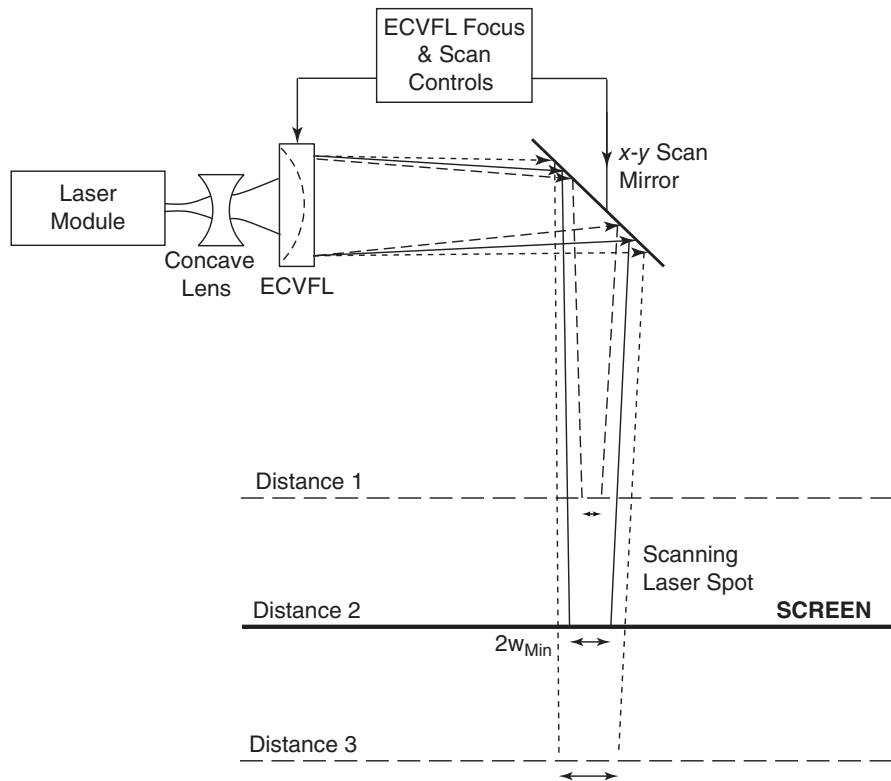


FIGURE 8.20 Smart high-resolution laser-scanning display.

positioning distance range zone, the ECVFL focal length is adjusted to condition the laser Gaussian beam to form a minimum beam waist at the screen. The scan-mirror tilt angles are also adjusted to keep the same image aspect ratio. This ECVFL should work with the primary red, green, and blue colors needed for color image formation. In addition, the ECVFL should preferably be polarization insensitive. An ideal lens for this smart display application is a liquid lens such as one based on electrowetting technology. As lasers provide output beams under 3 mm in diameter, a miniature liquid lens can be used for this system application.

Design Problem 8.18: Optical Distance Sensor Without Time Processing

Noncontact distance sensing is required in many industrial and scientific applications including shape sensing and extreme environments' liquid-level measurement. Time-of-flight laser radar methods are common place for distance sensor as well as optical triangulation methods. Time-of-flight methods require wideband RF signal generation and processing while triangulation methods are highly dependent on having adequate on-axis apertures for return light capture. Design an optical-distance sensor that does not have the mentioned limitations and requirements.

Solution

Figure 8.21 shows the desired optical distance sensor that does not use time-based processing but instead uses spatial processing using

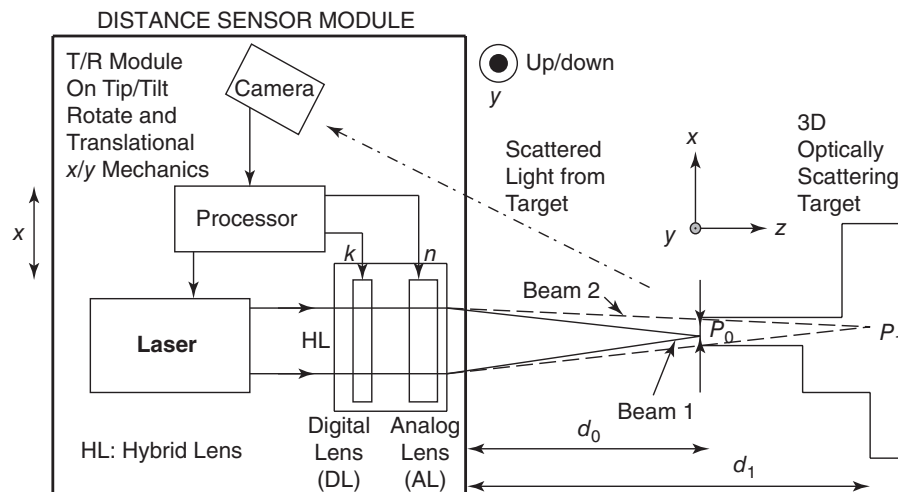


FIGURE 8.21 Optical distance sensor based on spatial processing using an ECVFL.

an ECVFL formed via a digital lens (DL) and an analog lens (AL). Distance is measured by targeting the test object and sweeping the ECVFL focal length over a calibrated range and observing when a minimum spot size is observed either by direct retro-reflective capture of the target reflected laser beam or slightly off-axis viewing of the spot on the target using a camera. Because the sensor is previously calibrated for distance versus ECVFL focal-length values, noting the focal length for the observed minimum spot size gives the target distance. The lens used can be a hybrid analog-digital ECVFL to produce a desired distance measurement range with the desired accuracy. Figure 8.21 shows the optimum minimum focus Beam 1 formed for the target surface at P_0 and distance d_0 . Figure 21 also shows as a dotted line, the optimum minimum focus Beam 2 formed for the target surface at P_1 and distance d_1 . A liquid lens can be used to form the AL in the ECVFL module.

Problems

- 1 Design a hysteresis-free TN-LC device based fiber-optic VOA that is highly suited for test and instrumentation applications.
- 2 Design an analog voltage-controlled liquid crystal deflector-based fiber-optic VOA using a single fiber lens.
- 3 Design a liquid crystal deflector-based fiber-optic 1×2 switch using a single-fiber lens.
- 4 Design a liquid crystal deflector-based fiber-optic 1×2 variable tap-coupler using a single fiber lens.
- 5 A coherent optical pulse contains many wavelengths. We can shape the pulse by modifying its spectrum. One approach to modify the pulse's optical spectrum is to modify the amplitude and phase of the optical spectral components. Design a photonic system using NLCs to accomplish this goal.
- 6 Design an RF transversal filter using the Figure 8.5 multiwavelength fiber-optic attenuator.
- 7 Unlike the cube PBS, the Thompson Prism PBS (T-PBS) shown in Figure 8.22 operations is made by cementing prisms of a birefringent crystal (e.g., calcite) and has symmetric excellent polarization extinction ratios (e.g., $>10,000:1$) for both its output ports. The T-PBS can be used with TN-LC devices to design polarization based high performance optical beam switching and routing units. Using T-PBSs and TN-LC devices plus other optics, design a freespace linear polarization input laser beam 1-bit optical TDU (i.e., a photonic module that has two different optical beam travel-time delay states). Show how the module design can be modified to work with light input from a SMF so a SMF input/output module is realized.

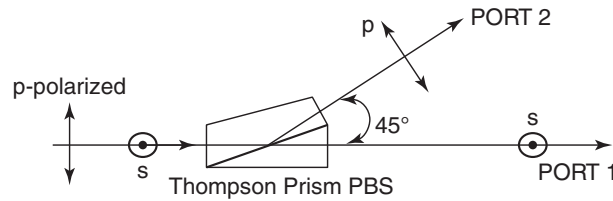


FIGURE 8.22

8 Using optical TDU such as shown in Figure 8.10 and also implemented in Problem 7, design an RF transversal filter to process RF signals, such as for signal nulling.

9 As shown in Figure 8.23, birefringent materials such as calcite can be shaped like a wedge to form birefringent beam deflecting plates for input linearly polarized light aligned with the plate beam deflection axis. Using birefringent material wedges and fast switching FLC 90° polarization rotators, design a fast x - y beam-deflector module that can produce four deflected beam spots in a 2×2 geometry in x - y output space.

10 The Figure 8.15 multipoint 3D optical-imaging and -sensing system acquires object-scan data in a time-sequential method based on the scan sequence of the laser wavelength. Design a 3D optical-scanning and -sensing system that can have a choice to instantaneously see and gather all the multipoint data or part of the multipoint data.

11 The Figure 8.15 multipoint 3D optical-imaging and -sensing system acquires object-scan data in a time-sequential method based on the scan sequence of the laser wavelength. Design a 3D optical-scanning and -sensing system that does not require the use of multiple wavelengths to implement the 3D scan.

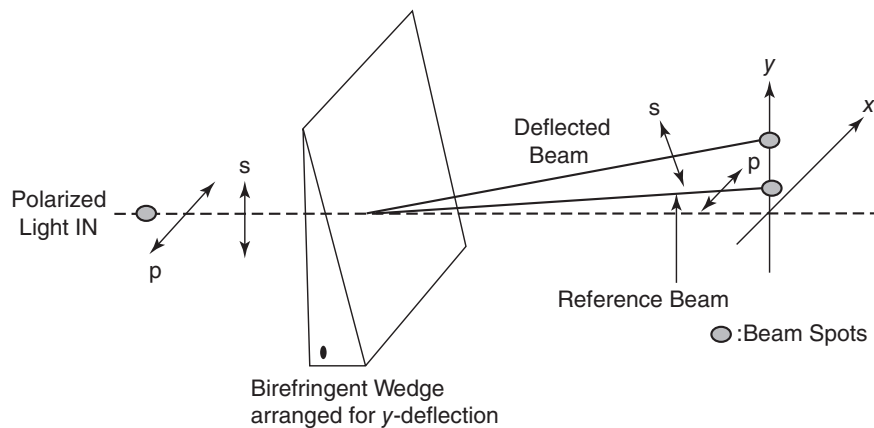


FIGURE 8.23

- 12** Design a wavelength multiplexed optical scanner (W-MOS) for 2D scanning.
- 13** Design a large-aperture compact-design optical scanner for 3D scanning.
- 14** Design a passive optics no-moving parts W-MOS based 1D barcode scan reader. Assume the bar codes are made using black-and-white bars.
- 15** Confocal microscopy is a powerful imaging tool, in particular for biological samples. Traditional confocal microscopes use motion of the objective lens or the test sample along the optical beam direction to image sample slices at different depths of the sample. Because the objective lens and test sample in biological conditions are tightly coupled via fluids (e.g., oil-immersion lens used with a biological specimen slide), microscopic sample content can experience mechanical forces that can change the nature of the test sample under study. Design a confocal microscope that eliminates this sample/objective motion problem.
- 16** Design a 2×2 SMF-based optical switch using liquid-lens technology-based ECVFLs.
- 17** SMF-coupled variable optical delay lines for broadband operations are highly desirable modules, particularly for photonic sensing and signal processing applications. An approach often applied is broadband freespace variable optical delays via mirror motion along a freespace beam path. Although the approach is effective for a moderate range of time delay, mirror motion over a freespace path causes the delay line to become lossy via poor coupling with the output SMF. Design a variable optical delay line for broadband light using mirror motion that does away with the large-loss penalty.

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CHAPTER 9

Optical Experiments

This chapter provides basic guidelines for a reader to conduct ten experiments covering some fundamentals and applications of photonics. Each experiment's description includes a basic list of equipment that guides the reader to assemble the laboratory set-up. A reader can modify and build on the described experiments to experience additional photonics fundamentals and applications covered in the book. Each experimental description also includes a relevant foundational photonics section to provide the reader some optics theory guidance for the experiment. The topics covered by the experiments are:

- Laser beams
- Incoherent-light imaging
- Coherent-light focusing
- Coherent-light imaging
- Coherent-light fourier transforms
- Optical-phase retardation
- Free-space optical switching using polarization
- Acousto-optical modulation of laser beams
- Acousto-optical interferometry of laser beams
- Optical fibers and fiber lenses and mirrors

Experiment 9.1: Laser Beams

Equipment

- 1 optical bench
- 1 linearly polarized helium- neon-gas laser with a 633-nm wavelength
- 1 laser holder
- 1 optical polarizer

- 3 iris mounts
- 1 measurement microscope view finder (or a CCD camera with PC interface)
- 3 visible-light mirrors with mount and tilt control
- 1 ruler for measurements
- 25- μm pinhole

Foundational Photonics

From study in the fundamentals of photonics, the following aspects of laser beams should be familiar, such as those coming from a He-Ne gas laser.

1. The fundamental spatial mode of a laser-beam cavity, such as from a gas laser, has a Gaussian optical irradiance beam profile (circularly symmetric) that can be written as

$$I(r) = I_0 \exp\left(-\frac{2r^2}{w^2}\right)$$

$I(r)$ is the irradiance at a distance r from the center of the beam; w is the $1/e^2$ power-beam radius; and I_0 is the peak irradiance in the beam.

2. The beam waist in a Gaussian beam travels along the beam-propagation direction, z , as

$$w(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2}$$

w_0 is the minimum beam-waist radius of the beam.

3. The Rayleigh or collimation range of the laser beam is given by

$$z_R = \frac{\pi w_0^2}{\lambda}$$

4. The half-angle beam divergence of the laser beam can be approximated as

$$\theta = \frac{\lambda}{\pi w_0}$$

Conduct Experiments to Show and/or Determine the Following

1. Use the polarizer and relevant mechanical and optical power detection components to estimate the polarization direction of the laser beam.
2. Use the polarizer and relevant mechanical component to make a variable optical attenuator for the laser beam.
3. The laser beam travels in a straight line.
Hint: Use the laser-holder tilt stages with the iris holders to make the beam travel parallel to the table. This experimental accomplishment indicates the straight-line travel. Measure the height of the laser beam above the table surface.
4. The laser-beam profile is Gaussian.
Hint: Use a combination of the CCD, measurement microscope viewer, and the pinhole on a motion stage to measure the intensity profile of the laser-beam cross section.
5. The laser-beam profile stays Gaussian as the beam continues to travel away from the laser cavity.
Hint: Repeat the procedure in the hint for experimental step 4 using multiple z distances. Then plot the approximate beam-profile behavior along the propagation direction.
6. Find the laser-beam divergence using the experimental data in experimental step 5.
7. Calculate the minimum beam-waist value using prior experimental data.
8. Compute the full-width half-max (FWHM) beam waist where the optical power drops to half its on-axis power.
9. Compute the beam Raleigh range using earlier measured data. Next measure the Raleigh range knowing that it is the distance of beam travel when the beam-waist radius is $1.4 w_0$.

Experiment 9.2: Incoherent-Light Imaging**Equipment**

- 1 optical bench
- 1 flashlight
- 1 flashlight holder
- 1 optical polarizer in mount and holder
- 1 CCD camera with PC interface

- 1 10-cm focal-length lens in holder
- 1 20-cm focal-length lens in holder
- 1 Air Force measurement slide (or general slide with measured shapes)
- 1 measurement viewfinder

Foundational Photonics

From study in the fundamentals of photonics, the following aspects of incoherent light, such as from a flashlight and its interaction with lenses, should be familiar.

1. Poorly collimated light, such as from a flashlight beam, cannot be tightly (or point) focused using a lens, unlike a highly collimated laser beam.
2. A single lens can be used to form an imaging system with non-magnification/demagnification where the single-lens imaging equation is

$$\frac{1}{F} = \frac{1}{d_i} + \frac{1}{d_o}$$

F is the focal length of the lens, and d_i and d_o are the lens-to-image and lens-to-object distances, respectively.

Conduct Experiments to Show and/or Determine the Following

1. Prove the statement in (1, above) using a given 10-cm focal length lens. Using the measurement ruler or measurement viewfinder, measure the smallest spot you can form with this single-lens arrangement. Measure the distances of the spot and flashlight from the lens, and explain why these distances are chosen.
2. Repeat 1, but using a CCD camera to measure the spot size. Given the flashlight has high irradiance, the spot on the CCD is non-optimal. Can you explain why? Next use the polarizer provided to solve the just-mentioned problem and explain how the problem is solved. Use the CCD to snap a photo of this smallest-spot size and compare with what you visually measured.
3. Place the Air Force object slide at a close distance from the flashlight. Using a single lens provided, design an imaging system with a factor of 1 magnification. Use the CCD to snapshot this image for comparison purposes. Measure the distances you used for the AF chart and CCD from the lens.

- Using the two lenses provided, design imaging systems with a factor of 2 magnification and a factor of 2 demagnification. What is this arrangement called? Use the CCD to take a snapshot of these images. Prove that you reached these desired imaging numbers using data from previous step 3. Compared to the step 3 image, is there anything different about the images in step 4? Explain why.

Experiment 9.3: Coherent-Light Focusing

Equipment

- 1 optical bench
- 1 red 633-nm He-Ne laser
- 1 laser holder
- 1 10× microscope objective
- 1 optical polarizer in mount and holder
- 1 CCD camera with PC interface
- 1 10-cm focal-length lens in holder
- 1 20-cm focal-length lens in holder
- 1 5-cm focal-length lens in holder
- 1 measurement viewfinder
- 1 optical flat to check beam collimation

Foundational Photonics

From study in the fundamentals of photonics, the following aspects of coherent light, such as that from a laser and its interaction with lenses, should be familiar.

- Highly collimated light, such as that directly coming from a laser, can be tightly focused to small point using a lens assembly, such as a microscope objective. Also an objective lens can be used to expand the original laser beam to a desired size using a properly placed collimation lens.
- The focused point due to a beam-lens interaction in reality is not a spatial delta function but a 2D point-like diffraction pattern based on the type of aperture spatially restricting the laser light. Using a pinhole at the focused-light position, we can clean the final-beam spatial characteristics by blocking the unwanted diffraction orders, an operation called spatial filtering. Since the pinhole is a circular aperture, we can see light in the far-field that is the known diffraction pattern caused by a circular aperture.

Conduct Experiments to Show and/or Determine the Following

1. Prove the statements in (1 above) using a given 10× microscope objective and 10-cm focal-length lens. Decide where to place the 10-cm lens to get the desired beam collimation result. Using the measurement ruler or measurement viewfinder, measure the collimated beam-spot size and predict the diameter of the beam coming from the laser.
2. Using the appropriate bulk lens experimentally produce a final-output laser beam that is bigger than one provided in step 1. Measure the final beam size and compare the size with step 1. Via geometrical optics, show that the expected beam expansion compared to step 1 is valid.
3. Using the marked polarizer, determine the linear polarization direction of the light coming out of the provided laser.
4. Using the marked polarizer, attenuate the final output light beam until you can photograph it without saturating the CCD. Take the photo. And also indicate what is the polarization direction of the output light hitting the CCD. Also indicate how much power of the original-output laser beam has been lost and explain the result using Malus's law.
5. Using the step 2 set-up, place the provided 25- μm pinhole aperture at the tightly focused spot produced by the objective. Adjust all translational knobs on the pinhole spatial filter assembly to produce an output beam with minimal diffraction rings. When you have done so, store a photo of this beam using the CCD. What is this beam pattern expected to look like based on diffraction theory? State the expected mathematical function and its key features.
6. The degree of collimation of the final output laser beam can be determined by viewing the reflection off an optic called a FLAT. A flat is a wedge that produces two reflections: one off the front-face and one off-the-back face. When the two reflected beams meet, they produce an interference pattern. For a beam to be highly collimated, the interference pattern looks like an onion with a uniform central region and onion-like lines around the central region. The best collimation assumes the central region to be the biggest and most symmetrical. Using the motion of the collimation lens while viewing the onion on a sheet of paper, achieve the best collimation you can and then take the onion photo using the CCD. Also measure the distance of the collimation lens from the pinhole and state it. Using geometrical optics, does this measured distance make sense and why.

Experiment 9.4: Coherent-Light Imaging

Equipment

- 1 optical bench
- 1 red 633-nm He-Ne laser
- 1 laser holder
- 1 10× microscope objective
- 1 optical polarizer in mount and holder
- 1 CCD camera with PC interface
- 1 10-cm focal-length lens in holder
- 1 20-cm focal-length lens in holder
- 1 5-cm focal-length lens in holder
- 1 measurement viewfinder
- 1 optical flat to check beam collimation
- 1 Air Force chart slide
- 4 slides, each with two dots of different separations
- 1 slide with an amplitude-chirped grating

Foundational Photonics

From study in the fundamentals of photonics, the following aspects of coherent light, such as that from a laser and its interaction with lenses, should be familiar.

1. Highly collimated laser light can be used to form imaging systems with different magnifications based on positions and number of lenses.
2. Imaging systems have limited spatial resolution based on diffraction theory.

Conduct Experiments to Show and/or Determine the Following

1. Using methods described in earlier experiments, produce a collimated beam of laser light. Use the 10-cm focal-length lens for beam collimation. Using the provided Air Force slide as object and the provided lenses, form the following types of object imaging systems. Use a single lens to form a 1:1 imaging system. Take a photo of the AF chart produced in the image plane to confirm the 1:1 scaling for the image. The image will have some grain-like texture. Can you explain why this grainy texture appears?
2. Using two lenses, form a 4:1 demagnification system. Take a CCD snapshot of the AF chart and show the 4× image size reduction.

3. Form a 1:1 imaging system using a single lens. Place the two-dot (or two-pin-hole slide) in the object space and snap the image seen by the CCD. Use the four different two-dot slides provided and observe via the CCD if you can always clearly see the two dots separated. Explain via diffraction theory what is limiting the seeing resolution of the imaging system.
4. Form a 1:1 imaging system using a single lens. Place the changing grating-frequency slide in the object space and snap the image seen by the CCD. Observe via the CCD what you can always clearly see in the grating pattern. Explain via spatial-frequency limits of an imaging system what is limiting the seeing resolution of the imaging system.

Experiment 9.5: Coherent-Light Fourier Transforms

Equipment

- 1 optical bench
- 1 red 633-nm He-Ne laser
- 1 laser holder
- 1 10× microscope objective
- 1 optical polarizer in mount and holder
- 1 CCD camera with PC interface
- 1 10-cm focal-length lens in holder
- 1 20-cm focal-length lens in holder
- 1 5-cm focal-length lens in holder
- 1 measurement viewfinder
- 1 optical flat to check beam collimation
- 1 Air Force chart slide
- 4 slides with two dots of different separations
- 3 slides with an amplitude gratings of different pitch
- 1 slide with an amplitude-chirped grating

Foundational Photonics

From study in the fundamentals of photonics, the following aspects of coherent light, such as that from a laser and its interaction with a single lens, should be familiar.

1. Highly collimated laser light can be used to form a spatial Fourier transforming system.
2. Image spectrum analysis is possible using a lens and laser light.

Conduct Experiments to Show and/or Determine the Following

1. Using methods described in earlier experiments, produce a collimated beam of laser light. Use the 10-cm focal-length lens for beam collimation. Using the provided 20-cm lens, form a spatial optical Fourier transformer. Decide where to place the object slide, 20-cm lens, and CCD. Explain why you have chosen these distances and the diffraction-based optics theory indicating the Fourier transform mapping.
2. Place the two-dot slides and CCD view and photograph the outputs. Explain why you see a specific pattern. Also explain why the changing inter-spot distances on the object slides produce the same pattern but with different repeat rates.
3. Place the grating slides in the Fourier transformer and snap the CCD images and explain the results via Fourier transform optics. Use the CCD images to predict the spatial frequencies of the gratings on the slides.
4. Place the chirped-grating slide in the Fourier transformer and snap the CCD image and explain the results via Fourier transform optics. Use the CCD images to predict the spatial bandwidth of the chirp grating on the slide.
5. Place a slide with a grating in the Fourier transformer such that one can rotate the grating in the object space coordinates. Given the rotation angle is 30° with respect to the original horizontal direction grating axis, snap the CCD image. Explain the results via Fourier transform optics. Quantify your results based on the known grating frequency and grating rotation angle. Repeat the experiment for a 60° rotation angle.

Experiment 9.6: Optical-Phase Retardation**Equipment**

- 1 optical bench
- 1 red 633-nm He-Ne laser
- 1 laser holder
- 1 10× microscope objective
- 3 optical polarizers in mount and holder
- 1 CCD camera with PC interface
- 1 10-cm focal length lens in holder
- 1 20-cm focal length lens in holder
- 1 5-cm focal length lens in holder

- 1 measurement viewfinder
- 1 optical flat to check beam collimation
- 1 parallel-alignment (PA) nematic liquid crystal (NLC) cell
- 1 1.0-kHz square-wave variable-amplitude signal generator

Foundational Photonics

From study in the fundamentals of photonics, the following aspects of polarized light, such as that from a laser or a white-light source and its interaction with a variable optical retardation wave-plate, should be familiar.

1. Polarized laser light can suffer optical-phase shifts based on the direction of the E-field with respect to the refractive-index axes of a birefringent optical material such as a PA-NLC cell. This optical-phase shift cannot be detected directly by an optical power meter.
2. Relative optical-phase shift can be introduced between orthogonal components of the incident linear polarized light using a birefringent media such as a PA-NLC cell. The imparted relative-phase shift can be observed indirectly by using an optical power meter.
3. Relative optical phase shift can be introduced between orthogonal components of the incident linear polarized light to produce elliptically polarized light. Using an electrically controlled PA-NLC cell, the relative optical phase shift can be controlled to produce very specific polarization states.

Conduct Experiments to Show and/or Determine the Following

1. Using methods described in earlier experiments, produce a collimated beam of laser light. Use the 10-cm focal-length lens for beam collimation. Place the linear polarizer after the 10-cm lens such that vertically polarized light exits the polarizer. Place the PA-NLC such that its marked refractive-index axis 1 is along the vertical direction. Next, use the photodetector with power meter to measure the power of the light as the voltage of the PA-NLC cell is changed from 0.5 to 5 V. Explain the data you observe. Does it prove point (1, section above) mentioned earlier?
2. Repeat step 1 but with the PA-NLC cell marked index-axis 2 along the vertical axis. Again, explain the data you observe and does it prove point (1, section above) mentioned earlier.
3. Place the PA-NLC cell axis 1 at 45° to the vertical axis. Place a polarizer after the PA-NLC cell such that it is oriented

orthogonal to the first polarizer. Repeat step 1 and explain the results. Provide a mathematical expression for the detected optical irradiance. Explain the result as the PA-NLC cell voltage is changed. Draw a plot of the indirectly detected voltage-dependent optical-phase-shifting power provided by the NLC cell.

4. Repeat step 3 but with the PA-NLC cell axis 2 at 45° to the vertical axis. Explain the results.
5. Using the step 4 experimental set-up with the second polarizer removed, produce horizontally polarized light and vertical polarized light using the change in cell voltage. Indicate the voltages when these two states happen and why.
6. Using the step 4 experimental set-up but with the PA-NLC cell refractive index axis at 30° to the vertical direction, measure the detected optical light power with changing voltage. Provide a mathematical expression for the detected optical irradiance. Explain the result as the PA-NLC cell voltage is changed. Draw a plot of the indirectly detected voltage-dependent optical-phase shifting power provided by the NLC cell. When does the output-detected light become horizontally linear-polarized and compare its strength to step 5 (but with the output polarizer loss taken into account).
7. Comment on how the proposed system can be designed to produce general elliptically polarized light. You have full electrical and mechanical control of the PA-NLC cell.
8. Replace the laser source with the white-light source flashlight. Repeat step 3 with all its details. In optics, what is the observed phenomenon called, and what is a possible use of the system?

Experiment 9.7: Free-Space Optical Switching Using Polarization

Equipment

- 1 optical bench
- 1 red 633-nm He-Ne laser
- 1 laser holder
- 1 10 $\times$ microscope objective to couple laser light into optical fiber
- 2 optical polarizers in mount and holder
- 1 CCD camera with PC interface
- 1 parallel-alignment (PA) nematic liquid crystal (NLC) cell

- 1 twisted nematic (TN) liquid crystal cell
- 1 1.0-kHz square-wave variable-amplitude signal generator
- 3 visible-light optical fibers connected to visible fiber-collimating lens
- 2 half-wave plates (HWP) in rotation holders
- 2 cube polarization beam-splitters (PBS)
- 1 optical power meter with visible photodetector

Foundational Photonics

From study in the fundamentals of photonics, the following aspects of polarized light should be familiar: a laser and its interaction with a fixed-optical retardation wave-plate, a single-mode optical fiber, mirrors, and twisted and birefringent-mode nematic liquid crystals.

Conduct Experiments to Show and/or Determine the Following

1. Using the raw laser beam and the provided polarization optics, design a freespace voltage-controlled variable-optical attenuator module using first a TN-LC cell and then a PA-NLC cell. Optimize your design using polarization optics to get the highest attenuation dynamic range possible with the lowest possible in-out module static optical loss. Make a plot of the variable-attenuation level in decibels versus the LC cell drive peak voltage. Start with the zero-attenuation level corresponding to the static loss of the module. Explain why attenuation is possible using your optical design.
2. Using the raw laser beam and the provided polarization optics, design a freespace voltage controlled 1×2 optical switch module using first a TN-LC cell and then a PA-NLC cell. Optimize your design using polarization optics to get the best switch interchannel crosstalk performance with the lowest-possible in-out module static optical loss. Explain why 1×2 switching is possible using your optical design. Measure the optical loss in-to-out for both output ports. Measure the interchannel crosstalk in the switch for both states of the 1×2 switch operations. Also measure the polarization extinction ratio of the light at both output ports for both states of the switch operations.
3. Using the raw laser as a light source, couple as much as light possible into the provided optical fiber that is connected to a fiber lens. Using the collimated light beam coming out of the fiber lens and the provided polarization optics, design a fiber-based voltage controlled variable optical attenuator module using first a TN-LC cell and then a PA-NLC cell. Optimize your design using polarization optics to get the highest

attenuation dynamic range possible with the lowest possible in-out module static optical loss. Use the second fiber lens to capture the processed light from the module. Make a plot of the variable attenuation level in decibels versus the LC cell drive peak voltage. Start with the zero-attenuation level corresponding to the static loss of the module. Explain why attenuation is possible using your optical design for light passing through fiber optics. Remember, your design should not be affected by light polarization changes inside the optical fibers.

Experiment 9.8: Acousto-Optical Modulation of Laser Beams

Equipment

- 1 optical bench
- 1 red 633-nm He-Ne laser
- 1 laser holder
- 1 60-MHz RF variable-amplitude signal generator
- 1 RF mixer
- 1 100-kHz to 1-MHz RF variable-amplitude signal generator
- 1 optical power meter with visible photodetector
- 1 RF oscilloscope
- 1 visible band 60-MHz center-frequency glass AO device
- 2 20-cm focal-length lenses
- 1 CCD
- 1 knife-edge spatial filter

Foundational Photonics

From study in the fundamentals of photonics, the aspects of light such as that from a laser and its interaction with an acousto-optic device, also known as a Bragg cell, should be familiar. Specifically, readers should be able to recall the relationship between Bragg angles, laser wavelength, RF, acoustic velocity in cells, and beam deflection angles, as well as the relationship with RF drive voltage and diffracted optical field amplitude and its relation to Bragg-cell diffraction efficiency.

Conduct Experiments to Show and/or Determine the Following

1. Using the raw laser beam and the provided AO Bragg cell, design a freespace laser-beam deflector module. Optimize

your design using motion mechanics, electronics, and spatial optics to get the cleanest and highest optical-power deflected beam. Draw a plot of the measured-beam deflection angle versus the module-control parameter. Using the CCD, take data for the scanned beam.

2. Using the setup in 1, design a freespace laser-beam variable optical attenuator module. Draw a plot of the measured beam power versus the module control parameter. Also draw a plot of your module attenuation values in dB versus the control parameter. Indicate the static loss in dB of the module for IN/OUT operations.
3. Using the 1 and 2 setups, design a freespace laser-beam intensity-modulator module in the time domain. Use the RF sources and mixer device to produce the desired RF signal drive to the Bragg cell. Record an oscilloscope trace of the RF modulation produced on the laser beam by the module. Plot the RF bandwidth response of your module given the output detector is fixed and output detector can be moved. Explain the different bandwidth responses based on your specific optical module designs.
4. Given the task to accomplish RF-signal spectrum analysis using the optical module developed in the earlier parts of the lab, explain via a design equation how this goal can be accomplished. Then using the provided RF-signal generator and the appropriate detection optics, produce the calibration data for the module to implement RF spectrum analysis around the 60-MHz center frequency. Measure what 3-dB bandwidth your RF-spectrum analyzer can operate over using the provided hardware.

Experiment 9.9: Acousto-Optical Interferometry of Laser Beams

Equipment

- 1 optical bench
- 1 red 633-nm He-Ne laser
- 1 laser holder
- 2 60-MHz RF variable-amplitude signal generators
- 1 optical power meter with visible photodetector
- 1 RF oscilloscope
- 2 visible-band 60-MHz center-frequency acousto-optic devices
- 4 20-cm focal-length lenses

- 2 mirrors
- 2 flat-glass plates of different thicknesses
- 1 CCD
- 2 knife-edge spatial filters
- 1 high-speed photodetector (150-MHz bandwidth)

Foundational Photonics

From study in the fundamentals of photonics, aspects of light such as laser interferometry using an acousto-optic device, also known as a Bragg cell, should be familiar. Specifically, readers should be able to recall how two Bragg cells can be used to form the in-line interferometer introduced in the book. Readers should also recall the relationship between placements of spherical lenses within the Bragg cells arrangement to produce the desired beams for interferometry, including any needs for spatial filtering of beams.

Conduct Experiments to Show and/or Determine the Following

1. Using the provided optical and electronic hardware, design the in-line Bragg cell homodyne interferometer module introduced in the book. Explain the homodyne-detection operation via optical-field mathematics. Indicate which output beams are being used for the desired homodyne output. Using the provided two glass plates, indicate the interferometer outputs via power-meter readings and CCD images.
2. Using the provided optical and electronic hardware, design the in-line Bragg cell heterodyne interferometer module introduced in the book. Explain the heterodyne detection operation via optical-field mathematics. Indicate which output beams are being used for the desired homodyne output. Using the provided two glass plates, indicate the interferometer outputs via the high-speed detector output and external RF source. Use the oscilloscope traces to show interferometric operations via the two glass plates.
3. Using the designs from 1 or 2, configure a scanning interferometer design where the signal beam can be electronically programmed to scan in 1D space, where a test object such as a glass plate is placed. Implement this design in the lab and show scanned glass plate interferometric data. Explain the scanning operations via the optical field mathematics of Bragg cells. Provide a relation for the scan zone of your interferometer and its electrical control signal parameter.

Experiment 9.10: Optical Fibers and Fiber Lenses and Mirrors

Equipment

- 1 optical bench
- 1 red 633 nm He-Ne laser
- 1 laser holder
- 1 10× microscope objective to couple laser light into optical fiber
- 1 CCD camera with PC interface
- 2 mirrors
- 2 three-port fiber-optic circulators
- 4 visible-light optical fibers connected to visible fiber-collimating lens
- 1 optical power meter with visible photodetector

Foundational Photonics

From study in the fundamentals of photonics, the aspects of light, such as how light flows in a single-mode optical fiber, in a fiber collimator lens, and in freespace when exiting/entering the fiber lens, should be familiar. You should also be familiar with how light flows in a fiber-optic circular device and how freespace light from fiber self-imaging collimators travels in space and interacts with mirrors.

Conduct Experiments to Show and/or Determine the Following

1. Using the raw laser as a light source, couple as much as light possible into the provided optical fiber that is connected to a fiber lens. Using the collimated-light beam coming out of the fiber lens and the provided components, design a fiber-based variable optical attenuator (VOA) module using the minimal components. Optimize your design to get the highest attenuation dynamic range possible with the lowest possible in-out module static optical loss. Make a plot of the variable attenuation level in decibels versus any control parameter you choose for your VOA. Start with the zero-attenuation level corresponding to the static loss of the module. Explain why attenuation is possible using your optical design for light passing through fiber optics. Remember, your design should not be affected by light polarization changes inside the optical fibers.
2. Using the components provided, design a 1×2 fiber-optical switch module using the minimal components. Optimize your design to get the best switch interchannel crosstalk

performance with the lowest possible in-out module static optical loss. Explain why 1×2 switching is possible using your optical design. Measure the optical loss in-to-out for both output ports. Measure the interchannel crosstalk in the switch for both states of the 1×2 switch operations.

3. Using the components provided (except circulators), design a 2×2 fiber-optical switch module using the minimal components. Optimize your design to get the best switch interchannel crosstalk performance with the lowest possible in-out module static optical loss. Explain why 2×2 switching is possible using your optical design. Measure the optical loss in-to-out for both output ports. Measure the interchannel crosstalk in the switch for both states of the 2×2 switch operations.
4. Repeat the 2×2 fiber-optic switch design using circulators and repeat the experimental measurements.
5. Suggest a design to realize a very large switch like a 100×100 fiber-optical switch using minimal components. Assume you are using components like in the experiment.



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Problem Solutions

Chapter 2

1 According to the law of refraction, light from source, S , travels to detection point, D , via interface point, I , via two segments or two lights paths given by SI and ID . The shortest path from S to D is a straight line segment SD shown as a dashed line. Indeed, light does not take this shortest-path length in refraction and takes the longer path that is sum of segments SI and ID . Hence, Hero's shortest-path principle violates the law of refraction. (See Figure PS.1.)

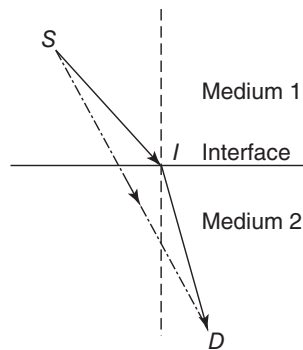


FIGURE PS.1 Possible paths of light travel in refraction. As an example, shown for Medium 1 refractive index lower than Medium 2 refractive index.

2 As shown in Figure PS.2, the shortest path light takes on reflection is given by the sum of the two segments, SI and ID . Hero's principle says $SI + SD$ should be the shortest physical path. Fermat says light travels with the least time from S to D . Time is distance divided by speed of light in medium. Because in reflection light stays in the same medium, both light-path distances are divided by the same speed to calculate the travel time. Thus, finding the least time of travel is equivalent to finding the shortest path multiplied by a number given by the inverse speed of light in the medium.

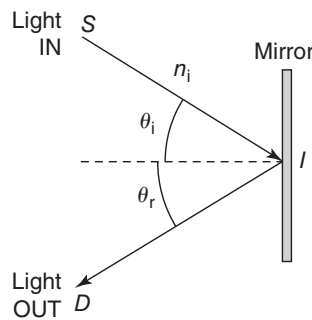


FIGURE PS.2 Paths of light travel in reflection.

3 We need to prove that minimizing the OPL is the same as minimizing the time to travel this OPL. Time to travel $T = \text{OPL}/v$, where v is the speed of light in the medium. OPL is a function of a defined-path distance variable x . Take the derivative of T with respect to x and make this equal to zero to get the condition for the minimum time to travel from Source S to Detector D . Hence, $d/dx[T] = d/dx[\text{OPL}/v] = 1/v[d/dx(\text{OPL})] = 0$. As v is a constant, we can rewrite $d/dx(\text{OPL}) = 0$. Thus, we can conclude that $d/dx[T] = 0$ and $d/dx(\text{OPL}) = 0$ are equivalent conditions relating to the Fermat's principle.

4 Use the expression for Fermat's least-time principle from source, S , to detector, D , position, i.e., $\frac{d}{dx}[T_{S-D}] = 0$.

Then $T = (1/v)[SI + ID]$ where SI is the distance from S to I , and ID is the distance from I to D , with v_1 being the speed of light in the reflection medium. From Figure 2.21, $SI^2 = x^2 + a^2$ and $ID^2 = b^2 + (c - x)^2$. Insert the expressions for SI and ID in terms of x in the equation for T . Take the derivative of T with respect to x and put equal to zero to obtain the expression:

$$\frac{x}{v_1 \sqrt{a^2 + x^2}} = \frac{c - x}{v_1 \sqrt{b^2 + (c - x)^2}}$$

$$\sin \theta_i = \sin \theta_r$$

$$\theta_i = \theta_r$$

Hence, the law of reflection is derived from Fermat's principle of least time.

5 Use the expression for Fermat's least-time principle from source, S , to detector, D , position, i.e., $\frac{d}{dx}[T_{S-D}] = 0$.

Then $T = (1/v)[SI + ID]$ where SI is the distance from S to I and ID is the distance from I to D , with v_1 being the speed of light in the reflection medium and v_2 being the speed of light in the transmission medium.

From the figure: $SI^2 = x^2 + a^2$ and $ID^2 = b^2 + (c - x)^2$. Insert the expressions for SI and ID in terms of x in the equation for T . Take the derivative of T with respect to x and put equal to zero to obtain the expression:

$$\frac{x}{v_1 \sqrt{a^2 + x^2}} = \frac{c - x}{v_2 \sqrt{b^2 + (c - x)^2}}$$

$$\frac{\sin \theta_i}{v_1} = \frac{\sin \theta_t}{v_2}$$

$$\frac{c}{v_1} \sin \theta_i = \frac{c}{v_2} \sin \theta_t$$

$$n_i \sin \theta_i = n_t \sin \theta_t$$

Hence, the law of refraction is derived from Fermat's principle of least time.

6 OPL contains both refractive index and physical path, d . We can also use material refractive-index change by chemical, biological, and temperature changes to make chemical, biological, and physical (temperature) sensors, respectively. Fluid-level sensors can also use change in d . Finally, wavelength changes can also affect index change, so wavelength meters can also be made.

7 Repeatedly apply Snell's law at each boundary. Hence:

$$n_0 \sin \theta_a = n_1 \sin \theta_1 = n_2 \sin \theta_2 = n_3 \sin \theta_3 = n_0 \sin \theta_b,$$

where $\theta_1, \theta_2, \theta_3$ are the refraction angles formed at the $n_0/n_1, n_1/n_2, n_2/n_3$ interfaces, respectively. Hence, $\theta_a = \theta_b$.

8 Follow the ray physically through the paths and components to write the expression:

$$\text{OPL} = n_0 L_0 + 2n_1 L_1 + 2n_0 L_3 + 2n_2 L_2 + n_0 L_4.$$

The mirror plays the role of doubling some of the path lengths.

9 Follow both ray paths physically to note that there are common paths; hence, to find the difference in ray paths, we only consider non-overlapping ray paths to give the Ray A-Ray B OPL difference to be

$$\text{OPL Difference} = 2n_0 L_3 + 2n_2 L_2 - 2n_0 L_5$$

10

- (a) We can write $f \lambda_n = c/n$. Hence, $f = c/(n \lambda_n)$.
- (b) Write the equation $f = c/\lambda$, then take the derivative of f with respect to freespace wavelength to get $df/d\lambda = -c/\lambda^2$.
- (c) Write the equation $f = c/n \lambda_n$, then take the derivative of f with respect to medium wavelength to get $df/d\lambda_n = -c/(n \lambda_n^2)$.
- (d) Optical-light frequency stays constant regardless of medium. The wavelength decreases once the wave enters the medium with a positive real index of refraction.

11 Use a tunable laser to measure the refractive index $n(\lambda)$ per tuned laser wavelength λ . Determine the OPL via intrinsic chip optical interferometry and divide the measured OPL value by d , giving the $n(\lambda)$ value.

12 Start with the definition $n = c/v$. Then $n^2 = c^2/v^2 = (\mu\epsilon)/(\mu_0\epsilon_0) = (\mu/\mu_0) \times (\epsilon/\epsilon_0) = \mu_r \epsilon_r$. Next, taking the square root of n gives $n = \pm \sqrt{\mu_r \epsilon_r}$.

13 Using the modified Snell's law expression $n_i \sin \theta_i = n_t \sin(-\theta_t)$ and $n_i = 1$, $\theta_i = 30^\circ$ and $n_t = 2$, we compute $-\theta_t = 14.5^\circ$, indicating that the transmitted ray is below the interface normal and on the same side as the incident ray.

14 Use Planck's equation $E = hf$ to find f , given the Si and Ge band gaps as E in eV. Convert f 's to wavelengths, and this gives the wavelength limit not to exceed for successful optical detection.

15 Power = Energy/sec. Compute green photon energy in joules using Planck's equation. Divide laser energy in joules in one second by photon energy to get number of photons per second. Each photon produces only one electron, so number of photons per second = number of electrons per second.

16 The work function in joules = $4.7 \times 1.602 \times 10^{-19} = 7.53 \times 10^{-19}$ J. Photon energy in joules = 6.62×10^{-34} J-s $\times 1.5 \times 10^{15}$ Hz = 9.93×10^{-19} J. Max kinetic energy of ejected electrons = Photon Energy - Work Function = 2.4×10^{-19} J = 1.5 eV.

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17 Apply the light-wave formula $c = f \times \lambda$ equation, where λ is the optical wavelength. Use λ as the de Broglie wavelength in the equation to compute the photon frequency. $f = 6 \times 10^{18}$ Hz in the X-ray band.

18 $T = 273 + 27 = 300$ K. Substituting the values of T and k_B into $E = k_B T$ gives $E = 414 \times 10^{-23}$ J. Given $1 \text{ eV} = 1.602 \times 10^{-19}$ J, E in eV for the room temperature electron is $E = (414 \times 10^{-23}) / (1.602 \times 10^{-19}) = 25.84 \times 10^{-3} = 25 \text{ meV}$. The $0.5 \mu\text{m}$ photon has an energy of $1.24/0.5 = 2.48 \text{ eV}$, which is significantly higher by a factor of 99.2 over the electron thermal excitation energy.

19 The photon that exits the laser suffers n reflections from $M1$ and -1 reflections from $M2$, hence the term R_2 with $(n - 1)$ multiplications. Also, this photon must pass only once through $M2$, hence the single use of T_2 .

20 The output mirror $M2$ reflectivity $R_2 = 0.95$ so $T_2 = 0.05$ so 5 percent of light comes out via the output mirror $M2$ to form the output laser beam. Using $G = 2 \text{ cm}^{-1}$, cavity length $L = 1 \text{ cm}$, $n = 2$ for two roundtrips, initial laser intensity $I_0 = 4 \text{ W/cm}^2$, and the laser equation in the chapter, yields:

$$I = [1 \times \exp(2 \times 2 \times 1)]^2 \times 0.95 \times 0.05 \times 0.01 = 1.416 \text{ W/cm}^2.$$

21 Electron is a fundamental particle of nature. A static electron has an electric field. A moving electron in space produces a magnetic field that leads to the existence of a unified field called the electromagnetic field whose existence then manifests itself in the EM-wave, also called a light wave or the photon that is used for photonic engineering.

Chapter 3

1 At time t , the wave is represented by $\psi(z, t) = g(z - vt)$.

At time $t + \Delta t$, replace t by $t + \Delta t$ and z by $z + \Delta z$ to get the wave represented as $\psi(z, t) = g[z + \Delta z - v(t + \Delta t)] = g[z - vt + \Delta z - v\Delta t] = g[z - vt + \Delta z - \Delta z] = g(z - vt)$. Hence, the wave function/shape is the same after a time Δt .

2 Define $u = z \pm vt$. The $du/dz = 1$ and $du/dt = \pm v$.

Find $\frac{\partial \psi}{\partial z} = \frac{\partial g}{\partial u} \frac{\partial u}{\partial z} = \frac{\partial g}{\partial u}$ and $\frac{\partial \psi}{\partial t} = \frac{\partial g}{\partial u} \frac{\partial u}{\partial t} = \pm v \frac{\partial g}{\partial u}$ then find $\frac{\partial^2 \psi}{\partial z^2} = \frac{\partial^2 g}{\partial u^2} \frac{\partial u}{\partial z} = \frac{\partial^2 g}{\partial u^2}$ and $\frac{\partial^2 \psi}{\partial t^2} = \frac{\partial^2 g}{\partial u^2} \frac{\partial u}{\partial t} = v^2 \frac{\partial^2 g}{\partial u^2}$. We can write $\frac{1}{v^2} \frac{\partial^2 \psi}{\partial t^2} = \frac{\partial^2 g}{\partial z^2}$. Then we can write $\frac{1}{v^2} \frac{\partial^2 \psi}{\partial t^2} = \frac{\partial^2 g}{\partial u^2}$, the 1D nondispersive wave equation.

3 $\psi(z, t) = \sin[k(z - vt)] = \sin[k(z + \lambda_m - vt)] = \sin[k(z - vt) + k\lambda_m]$. For this equation to hold, $k\lambda_m = 2\pi$, which implies $k = 2\pi/\lambda_m$.

4 (a) Wave representation argument is of the form $(vt + z)$, which means $v = 5 \text{ m/s}$ and the wave is in $-z$ -direction with amplitude of E_0 .

(b) $E(x, t) = E_0 (3x - t)^2 = 9E_0 (x - t/3)^2 = 9E_0 (t/3 - x)^2$. Hence wave representation argument is of the form $(vt + x)$, which means $v = 1/3$ m/s and wave is in $+x$ -direction with amplitude of $9E_0$.

(c) $E(y, t) = E_0 \cos[2\pi(y/\alpha + t/\beta)^4] = E_0 \cos[(2\pi/\alpha^4)(y + \alpha t/\beta)^4]$. Hence wave representation argument is of the form $(vt + y)$, which means $v = \alpha/\beta$ m/s and wave is in $-y$ -direction with amplitude of E_0 .

5 Wave function argument is of the form $\omega t - kz$. In this case, $\omega = 2\pi\nu = 4 \times 10^{14}$ radians/s so optical frequency is $\nu = 2 \times 10^{14}$ Hz.

Next, $k = 2\pi/\lambda_m = 2\pi \times 10^6$ or $\lambda_m = 10^{-6}$ m. As refractive index $n = \frac{c}{\lambda_m \nu} = \frac{3 \times 10^8 \text{ m/s}}{10^{-6} \text{ m} \times 2 \times 10^{14} \text{ Hz}} = 1.5$.

6 Start with the complex index definition of $\tilde{n} = n(1 - j\chi) = 5.1[1 - j(0.3/5.1)] = 5.1(1 - j0.0588)$. Hence, $\chi = 0.0588$. Skin depth is

$$\delta = \frac{c}{n\chi 2\pi\nu} = \frac{3 \times 10^8 \text{ m/s}}{5.1 \times 0.0588 \times 2\pi \times 4.4 \times 10^{14}} = 3.62 \times 10^{-7} \text{ m} = 362 \text{ nm}.$$

7 Start with the complex index of refraction expression:

$$\begin{aligned} \tilde{n}_c &= \sqrt{\epsilon_r \mu_r - j \frac{\sigma}{\epsilon_0 \omega}} \\ &= \sqrt{\epsilon_r \mu_r} \sqrt{1 - j \frac{\sigma}{\epsilon_0 \omega \epsilon_r \mu_r}} \\ &= n \sqrt{1 - j \frac{\sigma}{\epsilon \omega \mu_r}} \\ &\approx n \left[1 - j \frac{\sigma}{2\epsilon \omega \mu_r} \right] = n[1 - j\chi] \end{aligned}$$

where $\chi = \frac{\sigma}{2\epsilon \omega \mu_r}$ and we have used the binomial theorem:

$(1+x)^p = 1 + px + \frac{p(p-1)}{2!}x^2 + \frac{p(p-1)(p-2)}{3!}x^3 + \dots$ where $|x| < 1$. We have used $x = -\frac{j\sigma}{\epsilon \omega \mu_r}$ and $p = 1/2$.

8 The capacitor contains an insulator and only the time varying aspect of the input current contributes to the displacement current as $D/t = \epsilon E/t$. The constant value A_0 of the current produces a zero displacement current density as $D_0/t = \epsilon E_0/t = 0$ as via Ohm's law for this time-varying current contribution in the transmission line, $E \propto E_0 \propto i_0 \propto A_0$. Hence the conventional current that flows in the circuit is only the time-varying current or $a(t)$. The direct current (DC) value of the current source, i.e., A_0 , is blocked by the capacitor and hence the capacitor connected in series to the source is called an electrical DC block. Only the AC (alternating current) or time oscillating current provided by the current source flows in the circuit.

300 Problem Solutions

9 Use the equation: $\delta = \frac{\lambda_0}{2\pi\sqrt{n_i^2 \sin^2 \theta_i - n_t^2}}$ with $\theta_i = 50^\circ$, $\lambda_0 = 1.55 \mu\text{m}$, $n_i = 2.57$ and $n_t = 1$ and gives skin depth of $0.1455 \mu\text{m}$ or 145.5 nm .

10 The design of the 2×2 freespace optical switch using two TIR prisms. Shown are the two different switching states of the 2×2 optical switch that deploys control of the physical gap between the TIR Prisms to change switch modes.

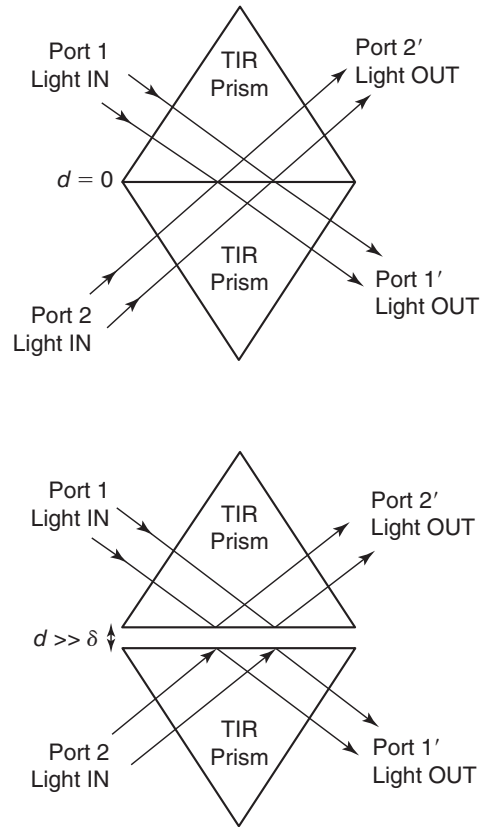


FIGURE PS.3

11

$$\begin{aligned}
 v_g &= \frac{d\omega}{dk} \\
 &= \frac{d}{dk} [vk] \\
 &= v \frac{dk}{dk} + k \frac{dv}{dk} \\
 &= v + k \frac{dv}{dk} \\
 &= v + \frac{2\pi}{\lambda} \frac{dv}{dk}
 \end{aligned}$$

Use the following to complete the derivation:

$$k = \frac{2\pi}{\lambda}$$

$$\frac{dk}{d\lambda} = -\frac{2\pi}{\lambda^2}$$

$$\frac{1}{dk} = -\frac{\lambda^2}{2\pi d\lambda}$$

Insert the value for $1/dk$ to get

$$v_g = v + \frac{2\pi}{\lambda} \frac{dv}{dk}$$

$$= v + \frac{2\pi}{\lambda} \frac{dv}{d\lambda} \left[-\frac{\lambda^2}{2\pi} \right]$$

$$= v - \lambda \frac{dv}{d\lambda}$$

12

$$v_g = \frac{d\omega}{dk} = \frac{c}{n_g}$$

$$n_g = c \frac{dk}{d\omega}$$

Recall $k = \omega/v = (n\omega)/c$. Use the value of k in the derivative to write

$$n_g = c \frac{dk}{d\omega}$$

$$= c \frac{d}{d\omega} \left(\frac{n\omega}{c} \right)$$

$$= \frac{d}{d\omega} (n\omega)$$

$$= n \frac{d\omega}{d\omega} + \omega \frac{dn}{d\omega}$$

$$n_g = n + \omega \frac{dn}{d\omega}$$

13 (a) $E_{0x} = 0$ and $E_{0y} = 5$ V/m gives $\vec{J} = \begin{bmatrix} 0 \\ 5 \end{bmatrix}$

(b) $E_{0x} = 2$ V/m and $E_{0y} = 0$ gives $\vec{J} = \begin{bmatrix} 2 \\ 0 \end{bmatrix}$

(c) $E_{0x} = 2 \cos(\beta)$ V/m and $E_{0y} = 2 \sin(\beta)$ gives $\vec{J} = \begin{bmatrix} 2 \cos \beta \\ 2 \sin \beta \end{bmatrix}$

(d) $E_{0x} = -4 \cos(\beta)$ V/m and $E_{0y} = 4 \sin(\beta)$ gives $\vec{J} = \begin{bmatrix} -4 \cos 30 \\ 4 \sin 30 \end{bmatrix} = \begin{bmatrix} -2\sqrt{3} \\ 2 \end{bmatrix}$

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14 As the beams are considered coherent, the independent optical fields for the two polarizations can be added. One represents the normalized Jones vectors for the given polarizations and then one adds the two vectors as shown next.

$$(a) \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -j \end{bmatrix} + \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ j \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1+1 \\ -j+j \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 2 \\ 0 \end{bmatrix} = 2 \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

LCP light plus RCP light gives linear horizontal polarization light whose amplitude is two times that of the RCP and LCP light beams.

$$(b) \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \sqrt{2} \begin{bmatrix} \cos 45^\circ \\ \sin 45^\circ \end{bmatrix}$$

HLP light plus VLP light gives a linear polarization light at 45° to the horizontal and vertical directions and whose amplitude is $\sqrt{2}$ times that of the HLP and VLP light beams.

15 (a) With input light vertical polarization, we obtain vertical polarization light through the polarizer with TA vertical, thus

$$\begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \text{ so } 0 = T_{12} \text{ and } 1 = T_{22}$$

With input light horizontal polarization, we get no light through the polarizer with TA vertical, thus

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ so } 0 = T_{11} \text{ and } 0 = T_{21}$$

$$\text{Hence, } T_M = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

(b) With input light vertical polarization, we get no light through the polarizer with TA horizontal, thus

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \text{ so } 0 = T_{12} \text{ and } 0 = T_{22}$$

With input light horizontal polarization, we obtain horizontal light through the polarizer with TA horizontal, thus

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ so } 1 = T_{11} \text{ and } 0 = T_{21}$$

$$\text{Hence, } T_M = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$$

(c) With input light linear polarization at angle θ with the horizontal direction, we get polarized linear light at angle θ with the

horizontal direction through the polarizer with TA at angle θ with the horizontal direction, thus:

$$\begin{bmatrix} \cos \theta \\ \sin \theta \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} \cos \theta \\ \sin \theta \end{bmatrix} \text{ so}$$

$$T_{11} \cos \theta + T_{12} \sin \theta = \cos \theta \text{ and } T_{21} \cos \theta + T_{22} \sin \theta = \sin \theta$$

With input light linear polarization at angle θ with the vertical direction, we get no light through the polarizer with TA at angle θ with the horizontal direction, thus

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} -\sin \theta \\ \cos \theta \end{bmatrix} \text{ so}$$

$$-T_{11} \sin \theta + T_{12} \cos \theta = 0 \text{ and } -T_{21} \sin \theta + T_{22} \cos \theta = 0$$

Solving the four equations gives the components of the Jones matrix to be

$$T_M = \begin{bmatrix} \cos^2 \theta & \sin \theta \cos \theta \\ \sin \theta \cos \theta & \sin^2 \theta \end{bmatrix}$$

16 For polarized light passing through the retarder as explained in the book, we can write

$$\begin{bmatrix} E_{0x} e^{j[\phi_x + \beta_x]} \\ E_{0y} e^{j[\phi_y + \beta_y]} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} E_{0x} e^{j\phi_x} \\ E_{0y} e^{j\phi_y} \end{bmatrix}$$

Now using the given Jones matrix for the retarder as given in the question, we can simply prove that left-hand side (LHS) of the equation is equal to right-hand side (RHS) of the equation.

17 Using the Jones vector for the input linear polarized light making an angle $90 - \theta$ with the $-x$ -axis and the Jones matrix for a HWP FA vertical, we can multiply the input vector with the Jones matrix of the component to get the Jones vector of the output light to be:

$$\vec{J} = e^{j\frac{\pi}{2}} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} -E_0 \sin \theta \\ E_0 \cos \theta \end{bmatrix} = -e^{j\frac{\pi}{2}} \begin{bmatrix} E_0 \sin \theta \\ E_0 \cos \theta \end{bmatrix}$$

This output Jones vector is indeed for a linear polarization making an angle $90 - \theta$ with the x -axis.

Chapter 4

- 1 (a) Equal-strength EM waves imply that the EM wave-induced voltages produced by the antenna is $V_{A0} = V_{B0} = V_0$. As power is being amplified, the best condition to achieve this goal is when the two EM waves have met the positive interference condition such as their relative time delay

is zero or integer multiples of 1 ns. This positive interference condition gives the RF signal of $v(t) = 2V_0 \cos[2\pi f_{\text{RF}} t]$. As the received peak voltage has doubled and since RF power is the square of the voltage, the received power has quadrupled.

- (b) The received RF signal will go to zero for the negative or destructive interference condition, namely, when the relative time delay, τ , between the two EM waves is half of the RF period T or an odd multiple of the period, for example, $\tau = n0.5T$ where $T = 1/f_{\text{RF}}$ and $n = 1, 3, 5$, etc. So the values are 0.5 ns, 1.5 ns, 2.5 ns, etc.

2 From geometry, the relative time delay between the radio signals incident on the two radio telescopes separated by 1.5 m is $\tau = \{1.5 \cos 60^\circ\}/c = [0.75 \text{ m}]/c$, where $c = 3 \times 10^8 \text{ m/s}$ is the speed of light in air. This computation gives $\tau = 2.5 \text{ ns}$ which is a $\pi/4$ phase shift as a 2π phase shift for the RF signal from the star is 10 ns.

3 Because of the angle of the jammer signal with respect to the two antennas, the antenna 1 RF signal is produced at a later time of $\tau = [d \cos \alpha]/c$ versus the antenna 2-produced signal. Here c is the speed of the EM wave, i.e., speed of light. To represent this time delay as a β phase-shift value in radians, we can write $\beta = 2\pi[\tau/T_{\text{RF}}] = 2\pi f_{\text{RF}} \tau$. To produce an out-of-phase RF signal from the phase shifter compared to the RF signal coming from antenna element 1, the RF phase-shift phase ϕ should be $\phi = 2\pi f_{\text{RF}} \tau + \pi$.

4 The received signal $r(t)$ can be written as the provided multibeam interference signal:

$$r(t) = \sum_{n=0}^N V \sin[2\pi f_{\text{RF}} t + n\alpha] = \left[\frac{\sin\left(\frac{N+1}{2}\alpha\right)}{\sin\left(\frac{\alpha}{2}\right)} \right] \sin\left[2\pi f_{\text{RF}} t + \frac{N\alpha}{2}\right]$$

In this case, the interbeam RF time delay $\tau = (2L)/(c \cos \theta)$ with $\alpha = 2\pi f_{\text{RF}} \tau$.

5 Start with the expression that the irradiance in freespace for a plane wave with amplitude E_0 can be written as $I = \frac{1}{2c\mu_0} E_0^2$. Substitute the value of c and then we see the freespace impedance in the denominator to get the desired result.

6 (a) The speed of the light beam in the medium $v = c/n$. Hence in the irradiance derivation for freespace, where c is the speed of the wave, we can replace c by v when inserting the expression for the magnetic induction field; this gives n in the numerator in the expression for irradiance.

(b) Rewrite the given equation in (a) for irradiance so Z_0 appears in the equation with refractive index n and then replace both terms by Z_m .

7 By definition, $n = c/v$, $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$, and $n = \sqrt{\epsilon_r \mu_r}$. Using these definitions gives the desired expression for v .

8 Energy Stored per Laser Pulse = Peak Power $\times$ Pulse Time = $1 \text{ kW} \times 10 \text{ ns} = 10 \mu\text{J}$.

9 This is a case of two-beam interference at a single optical frequency. The irradiance bias terms due to the two beams do not contain any optical-phase terms so we can ignore those terms for sensor analysis. Assume first that one beam suffers an optical phase α while the other beam suffers a different optical phase β . In this case, we can write the two-beam interferometric term as

$$\begin{aligned}\langle 2\vec{E}_1\vec{E}_2 \rangle &= \frac{1}{T} \int \{E_{01}E_{02} 2 \cos[2\pi\nu t + \alpha] \cos[2\pi\nu t + \beta]\} dt \\ &= \frac{1}{T} E_{01}E_{02} \left\{ \int \cos[4\pi\nu t + \alpha + \beta] dt + \int \cos(\alpha - \beta) dt \right\} \\ &\approx E_{01}E_{02} \cos(\alpha - \beta)\end{aligned}$$

If $\alpha = \beta$ is the refractive index-based phase term picked up by both beams, we see that $\alpha - \beta = 0$ and $\cos(0) = 1$. Hence, the interferometric term is just a product of the field amplitudes and does not contain the material index-related phase and photodetected irradiance is given by $I = I_1 + I_2 + 2\sqrt{I_1 I_2}$. Hence, the mentioned optical sensor design in the problem statement will not work. For the sensor to work, only one of the laser beams must pick up the phase because of the material refractive index while the other laser beam must have a stable fixed phase.

10 Best interference modulation means $M_F = 1$.

$$\begin{aligned}M_F &= \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} = 1 \\ 2\sqrt{I_1 I_2} &= I_1 + I_2 \\ 4I_1 I_2 &= I_1^2 + I_2^2 + 2I_1 I_2 \\ I_1^2 + I_2^2 - 2I_1 I_2 &= 0 \\ (I_1 - I_2)^2 &= 0 \\ I_1 &= I_2\end{aligned}$$

Hence, to have the maximum modulation from interference, the irradiances of the two beams should be equal. This further implies that the optical field amplitude of the two beams should also be equal or $E_1 = E_2$.

$$\begin{aligned}\mathbf{11} \quad I &= I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \phi \\ &= I_0 + I_0 + 2\sqrt{I_0 I_0} \cos \phi \\ &= 2I_0 [1 + \cos \phi] \\ &= 2I_0 \left[2 \cos^2 \left(\frac{\phi}{2} \right) \right] \\ &= 4I_0 \cos^2 \left(\frac{\phi}{2} \right)\end{aligned}$$

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$$\begin{aligned}
 \mathbf{12} \quad (a) \quad I &= \frac{1}{2c\mu_0} [E_1^2 + E_2^2 + 2E_1E_2 \cos \phi_{12}] \\
 &= \frac{1}{2c\mu_0} \left[4^2 + 3^2 + 2 \times 4 \times 3 \cos \left(\frac{\pi}{2} - \frac{\pi}{6} \right) \right] \\
 &= \frac{1}{2c\mu_0} \left[25 + 24 \cos \left(\frac{\pi}{3} \right) \right] \\
 &= \frac{1}{2c\mu_0} \left[25 + 24 \times \frac{1}{2} \right] \\
 &= \frac{37}{2c\mu_0} \text{ W/m}^2 \\
 (b) \quad I_1 &= \frac{1}{2c\mu_0} E_1^2 \quad \text{and} \quad I_2 = \frac{1}{2c\mu_0} E_2^2 \\
 M_F &= \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} = \frac{2E_1 E_2}{E_1^2 + E_2^2} = \frac{2 \times 4 \times 3}{4^2 + 3^2} = \frac{24}{25} = 0.96
 \end{aligned}$$

- 13** (a) Because the two interfering beams have optical fields that are normal to each other, they have no common direction-field components. Hence, the photo detected irradiance has no interference term and the total irradiance is simply

$$\begin{aligned}
 I &= \frac{1}{2c\mu_0} [E_1^2 + E_2^2] \\
 &= \frac{1}{2c\mu_0} [4^2 + 3^2] \\
 &= \frac{1}{2c\mu_0} [25] \\
 &= \frac{12.5}{c\mu_0} \text{ W/m}^2
 \end{aligned}$$

- (b) The polarizer acts as a common optical field direction combiner for both the optical beams. The E_1 field component that passes through the polarizer is $E_1 \cos \alpha$, where α is the angle the horizontal field direction makes with the polarizer axis. In the same way, the E_2 field component that passes through the polarizer is $E_2 \cos \beta$, where β is the angle the vertical field direction makes with the polarizer axis. In the given case, $\alpha = \beta = 45^\circ$. The irradiance detected by the photodetector using the two beams that pass through the polarizer is

$$\begin{aligned}
 I &= \frac{1}{2c\mu_0} [(E_1 \cos \alpha)^2 + (E_2 \cos \beta)^2 + 2E_1 \cos \alpha E_2 \cos \beta \cos \phi_{12}] \\
 &= \frac{1}{2c\mu_0} \left[4^2 \cos^2 45^\circ + 3^2 \cos^2 45^\circ + 2 \times 4 \times 3 \cos^2 45^\circ \cos \left(\frac{\pi}{2} - \frac{\pi}{6} \right) \right] \\
 &= \frac{1}{2c\mu_0} \left[12.5 + 12 \cos \left(\frac{\pi}{3} \right) \right] \\
 &= \frac{1}{2c\mu_0} \left[12.5 + 12 \times \frac{1}{2} \right] \\
 &= \frac{18.5}{2c\mu_0} \text{ W/m}^2
 \end{aligned}$$

- 14 (a) Recall that the phase of the wave has to be scaled by the wavelength in the travel medium or $\lambda_m = \lambda_0/n$, where n is the index. Hence, the optical fields incident on the photodetector can be written as

$$\begin{aligned}\bar{E}_1 &= \bar{E}_{01} \cos \left[2\pi vt - \frac{2\pi}{\lambda_1} z_1 \right] = \bar{E}_{01} \cos \left[2\pi vt - \frac{2\pi}{\lambda_0} n_1 z_1 \right] \quad \text{and} \\ \bar{E}_2 &= \bar{E}_{02} \cos \left[2\pi vt - \frac{2\pi}{\lambda_2} z_2 \right] = \bar{E}_{02} \cos \left[2\pi vt - \frac{2\pi}{\lambda_0} n_2 z_2 \right]\end{aligned}$$

- (b) The photodetected irradiance is given by

$$\begin{aligned}I &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos \phi_{12}] \\ &= \frac{1}{2c\mu_0} \left[E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos \left\{ \frac{2\pi}{\lambda_0} (n_2 z_2 - n_1 z_1) \right\} \right]\end{aligned}$$

- 15 (a) For the Young's double-slit experiment, the photodetected irradiance is given by

$$\begin{aligned}I &= \frac{1}{2c\mu_0} [E_0^2 + E_0^2 + 2E_0E_0 \cos(k\Delta z)] \\ &= \frac{E_0^2}{c\mu_0} \left[1 + \cos \left(2\pi \frac{d}{\lambda L} x \right) \right]\end{aligned}$$

For the irradiance peak, the cosine should give a 1 and for the null, the irradiance should give a -1. This happens when

$$2\pi \frac{d}{\lambda L} x = m2\pi \quad \text{for peaks} \quad x = \frac{m\lambda L}{d} \quad \text{with } m = 0, \pm 1, \pm 2, \dots$$

$$2\pi \frac{d}{\lambda L} x = \left(m + \frac{1}{2} \right) 2\pi \quad \text{for nulls} \quad x = \left(m + \frac{1}{2} \right) \frac{\lambda L}{d} \quad \text{with } m = 0, \pm 1, \pm 2, \dots$$

- (b) The distance between two consecutive peaks and two consecutive nulls is

$$\text{peaks at } x_0 = 0 \text{ and } x_{+1} = \frac{\lambda L}{d} \quad \text{for } m = 0, 1$$

$$\text{nulls at } x_0 = \left(\frac{1}{2} \right) \frac{\lambda L}{d} \text{ and } x_{+1} = \left(\frac{3}{2} \right) \frac{\lambda L}{d} \quad \text{with } m = 0, 1$$

$$\text{Distance between two nulls is } \Delta x = \frac{\lambda L}{d}$$

- (c) When the source wavelength increases, the peaks and nulls spread out on the x -axis.
- (d) The fringe pattern consists of peaks and nulls that are physically broader compared to the single-wavelength peaks.
- (e) Measure the separation between two consecutive peaks Δx , slit separation d , and the distance between slits and detector, and one can measure the wavelength to be $\lambda = \frac{d \Delta x}{L}$.

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- 16 (a) The two-beam interference based irradiance for equal field strengths of angled plane waves with respect to x -axis is given by

$$\begin{aligned}
 I(x) &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos \phi_{12}] \\
 &= \frac{1}{2c\mu_0} [E_0^2 + E_0^2 + 2E_0E_0 \cos(k\Delta z)] \\
 &= \frac{1}{2c\mu_0} \left[2E_0^2 + 2E_0^2 \cos\left(\frac{2\pi}{\lambda} x \sin \theta_x\right) \right] \\
 &= \frac{2E_0^2}{2c\mu_0} [1 + \cos(2\pi f_x x)]
 \end{aligned}$$

The spatial frequency $f_x = \sin \theta_x / \lambda = \sin(1^\circ) / 514 \text{ nm} = 0.0175 / (514 \times 10^{-6} \text{ mm}) = 33.95 \text{ cycles/mm}$. Spatial period is inverse of spatial frequency so spatial period $p_x = 1 / (33.95 \text{ cycles/mm}) = 0.0295 \text{ mm} = 29.46 \mu\text{m}$.

- (b) The two-beam interference based irradiance for equal field strengths of angled plane waves with respect to y -axis is given by

$$\begin{aligned}
 I(x) &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos \phi_{12}] \\
 &= \frac{1}{2c\mu_0} [E_0^2 + E_0^2 + 2E_0E_0 \cos(k\Delta z)] \\
 &= \frac{1}{2c\mu_0} \left[2E_0^2 + 2E_0^2 \cos\left(\frac{2\pi}{\lambda} y \sin \theta_y\right) \right] \\
 &= \frac{E_0^2}{c\mu_0} [1 + \cos(2\pi f_y y)]
 \end{aligned}$$

The spatial frequency $f_y = \sin \theta_y / \lambda = \sin(2^\circ) / 514 \text{ nm} = 0.0349 / (514 \times 10^{-6} \text{ mm}) = 67.9 \text{ cycles/mm}$. Spatial period $p_y = 1 / (67.9 \text{ cycles/mm}) = 0.0147 \text{ mm} = 14.73 \mu\text{m}$.

- (c) The two-beam interference based irradiance for equal field strengths of angled plane waves with respect to the x - and y -axis because of separation of Cartesian coordinate orthogonal coordinates x and y is given by

$$\begin{aligned}
 I(x) &= \frac{1}{2c\mu_0} [E_{01}^2 + E_{02}^2 + 2E_{01}E_{02} \cos \phi_{12}] \\
 &= \frac{1}{2c\mu_0} [E_0^2 + E_0^2 + 2E_0E_0 \cos(k\Delta z)] \\
 &= \frac{1}{2c\mu_0} \left[2E_0^2 + 2E_0^2 \cos\left(\frac{2\pi}{\lambda} x \sin \theta_x + \frac{2\pi}{\lambda} y \sin \theta_y\right) \right] \\
 &= \frac{E_0^2}{c\mu_0} [1 + \cos(2\pi f_x x + 2\pi f_y y)]
 \end{aligned}$$

The spatial frequencies are: $f_x = \sin \theta_y / \lambda = \sin(1.5^\circ) / 514 \text{ nm} = 0.0262 / (514 \times 10^{-6} \text{ mm}) = 50.93 \text{ cycles/mm}$ and $f_y = \sin \theta_x / \lambda = \sin(5^\circ) / 514 \text{ nm} = 0.0872 / (514 \times 10^{-6} \text{ mm}) = 169.56 \text{ cycles/mm}$. Spatial period along x -direction $p_x = 1 / (50.93 \text{ cycles/mm}) = 0.0196 \text{ mm} = 50.93 \mu\text{m}$. Spatial period along y -direction $p_y = 1 / (169.56 \text{ cycles/mm}) = 0.0059 \text{ mm} = 5.9 \mu\text{m}$.

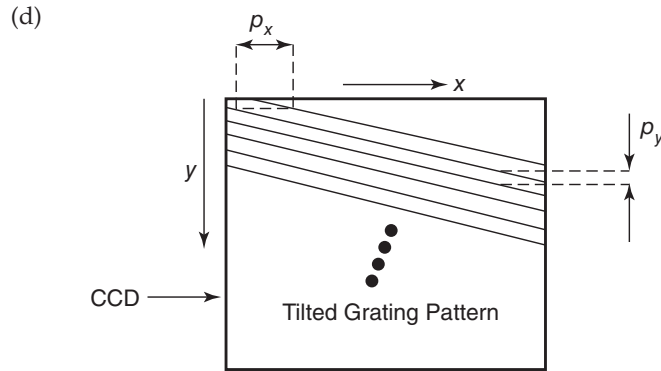


FIGURE PS.4

As shown in the figure, the irradiance pattern produced by the CCD consists of a tilted grating on the x - y axis such that the spatial period along the x -direction comes to be $p_x = 50.93 \mu\text{m}$ and the spatial period along the y -direction to be $p_y = 5.9 \mu\text{m}$.

- (e) In (a), 1 fringe cycle is $29.46 \mu\text{m}$. Given a 10 percent fringe cycle, averaging can be tolerated by the system-output requirements, we can pick a CCD pixel size (along the x -direction) of $10\% \times 29.46 \mu\text{m} = 2.95 \mu\text{m}$. This example gives an idea of the finite size of the delta function sampler in a practical system.

- 17** (a) The RF carrier is produced on the frequency difference between the two interfering beams, namely, $f_{\text{RF}} = 1.001 \times 10^{11} - 1.0 \times 10^{11} \text{ Hz} = 10^{11} [1.001 - 1] = 10^{11} [0.001] = 10^8 \text{ Hz} = 100 \text{ MHz}$.
 (b) The photodetector integration time $T \ll 1/f_{\text{RF}} = 1/(100 \text{ MHz}) = 10 \text{ ns}$.

- 18** First check if the distance satisfies the Fraunhofer regime. We can assume the aperture is a square so the aperture area is $1 \text{ mm} \times 1 \text{ mm}$. To be in the far-field regime, the distance, R , from laser aperture to screen must satisfy $R \gg D^2/(2\lambda)$. $R = 50 \text{ m}$. $D^2/(2\lambda) = 1 \text{ mm}^2 / (2 \times 500 \text{ nm}) = 1 \text{ m}$. As $50 \text{ m} \gg 1 \text{ m}$, one is in the far field. Hence, the far-field laser central-lobe beam size $W = (2\lambda R)/D = (2 \times 500 \text{ nm} \times 50 \text{ m}) / 1 \text{ mm} = 50 \text{ mm}$.

Chapter 5

- 1** As shown from geometry, the physical path-length difference between the two rays that enter the AO device and then get Bragg diffracted is the line segment $BD + DC = 2AD \sin \theta_B = 2\Lambda_a \sin \theta_B$. For in-phase interference

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or diffraction, this path-length difference must be a multiple of the optical wavelength in the AO medium or equal to λ/n . Hence, we obtain $2\Lambda_a \sin \theta_B = \lambda/n$ or $\sin \theta_B = \lambda/(n2\Lambda_a)$, the desired Bragg-angle condition.

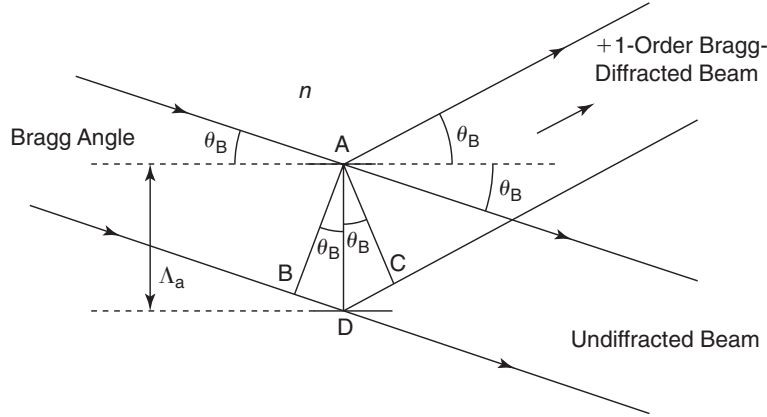


FIGURE PS.5

2 Combine the formulas $\sin \theta_B = \lambda/(n2\Lambda_a)$ and $v_a = \Lambda_a f_a$ to compute θ_B , which comes to be 0.3° .

3 Using Snell's law, $n \sin \theta_d = 1 \times \sin \theta$, where θ_d is the diffracted-beam deflection angle inside the Bragg cell and θ is the diffracted beam deflection angle in freespace. As the angles are small, $\sin \theta \sim \theta$. Given that $\sin \theta_B = (\lambda f_a)/(n2v_a)$ and the deflection angle is defined as $\theta_d = 2\theta_B \sim (2\lambda f_a)/(n2v_a)$, then the deflection-angle sweep $\theta_d \sim (\lambda/nv_a)[(f_c + 0.5B) - (f_c - 0.5B)] = \sim (\lambda B/nv_a)$. Using $n\theta_d \sim \theta$, we obtain $\theta \approx (\lambda B/v_a)$.

4 Deploy the formulas or deduced formulas from the main text.

$$(a) \Delta\theta = \frac{\lambda B}{v_a}$$

$$(b) T_a = \frac{X}{v_a}$$

$$(c) T_F = \frac{1}{f_0 + 0.5B}$$

$$(d) T_F = \frac{d}{v_a}$$

$$(e) N_B = \frac{\Delta\theta}{\Delta\theta_R} = \frac{B}{\delta f} = T_a B = \frac{XB}{v_a}$$

$$(f) 2N_B$$

5 Using Euler's formula and noting that the $-j$ term in the expression contributes to the complex number or optical phase-shift term between the two fields, we obtain the $-j$ term to represent a relative optical phase-shift value of -90° between the incident- and diffracted-beam amplitudes.

$$\begin{aligned}
 6 \quad \eta &= \sin^2(|CV|/L) = 0.5[1 - \cos(2|CV|/L)] = 0.5[1 - \cos(2CVL)] \\
 &= 0.5[1 - \cos\{2CL(V_B + V_S)\}] \\
 &= 0.5[1 - \cos\{2CLV_B + 2CLV_S\}] = 0.5[1 - \cos\{0.5\pi + 2CLV_S\}] \\
 &= 0.5[1 + \sin(2CLV_S)]
 \end{aligned}$$

The bias voltage, V_B , is selected so the DE = 0.5. Using the original DE expression, this happens when $CLV_B = 0.25\pi$. Given small changes in DE that occurs as $V_S \ll V_B$, which implies $\sin(2CLV_B) \sim 2CLV_B$, then one can write DE $\eta \sim 0.5 + CLV_B$ or $P_d \sim 0.5 P_i + P_i CLV_S$. Therefore, the diffracted optical power is proportional to the AO-device drive-modulation AC signal V_S .

7 The Doppler shift absolute value is f_a .

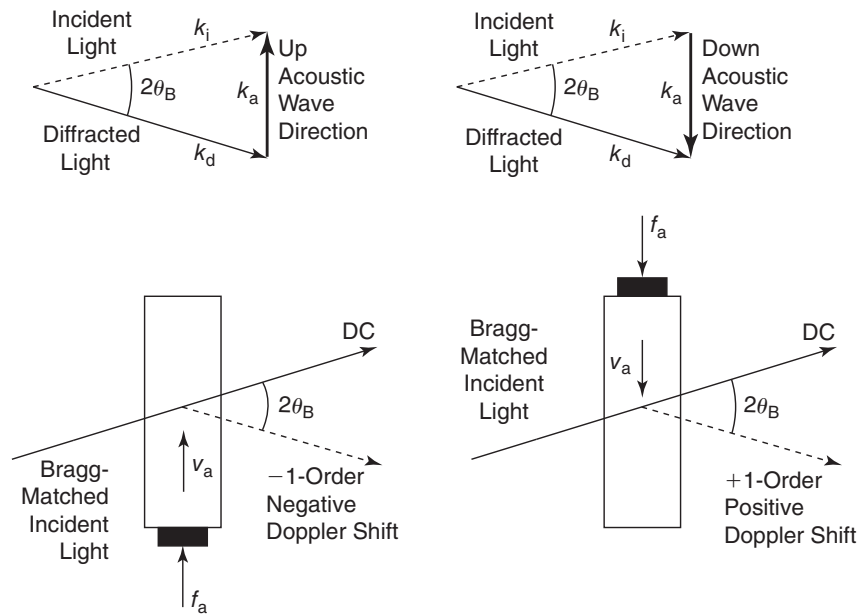


FIGURE PS.6

8 Assume $\theta = m_a s(t - x/v_a)$ and use the Euler and trigonometric formulas for the small diffraction-efficiency case that assumes θ is small so second- and higher-order terms can be dropped in the sine/cosine expansions. This leads to the desired transmittance function model for the AO cell.

9 Express the complex conjugate single sideband signal $\tilde{s}^*(t) = 0.5A \exp(+j2\pi f_0 t)$, then you can insert this value for the -1-diffracted optical field

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with the correct direction of the acoustic signal with respect to x -direction to get

$$\begin{aligned}
 E_{-1}(x, t) &= j0.5m_a \exp\{-j2\pi v \cdot t\} \exp\left\{-2\pi \frac{f_0}{2v_a} x\right\} \tilde{s}^*\left(t + \frac{x}{v_a}\right) \\
 &= j0.5m_a \exp\{-j2\pi v \cdot t\} \exp\left\{-2\pi \frac{f_0}{2v_a} x\right\} A \exp j2\pi f_0 \left\{t + \frac{x}{v_a}\right\} \\
 &= j0.5m_a A \exp\{-j2\pi(v - f_0)t\} \exp\left\{j2\pi \frac{f_0}{2v_a} x\right\} \\
 &= j0.5m_a A \exp\{-j2\pi(v - f_0)t\} \exp\left\{j2\pi \frac{\sin \theta_B}{\lambda} x\right\}
 \end{aligned}$$

10 Express the single-sideband signal $\tilde{s}^*(t) = 0.5A \exp[j2\pi(f_0 + f_s)t]$, then we can insert this value for the -1 -diffracted optical field w.r.t the x -direction to get

$$\begin{aligned}
 E_{+1}(x, t) &= j0.5m_a \exp\{-j2\pi v \cdot t\} \exp\left\{-2\pi \frac{f_0}{2v_a} x\right\} A \exp j2\pi(f_0 + f_s) \left\{t + \frac{x}{v_a}\right\} \\
 &= j0.5m_a A \exp\{-j2\pi(v - f_0 - f_s)t\} \exp\left\{j2\pi \frac{f_0}{2v_a} x\right\} \exp\left\{j2\pi \frac{f_s}{v_a} x\right\} \\
 &= j0.5m_a A \exp\{-j2\pi(v - f_0 - f_s)t\} \exp\left\{j2\pi \frac{\sin \theta_B}{\lambda} x\right\} \exp\left\{j2\pi \frac{f_s}{v_a} x\right\}
 \end{aligned}$$

The last exponential represents the frequency-controlled scan-beam spatial frequency.

11 The configuration is a $+1$ -order diffraction so express the single-sideband signal $\tilde{s}(t) = 0.5A \exp[-j2\pi(f_0 + f_s)t]$, then we can insert this value for the $+1$ -diffracted optical field to get

$$\begin{aligned}
 E_{+1}(x, t) &= j0.5m_a \exp\{-j2\pi v \cdot t\} \exp\left\{2\pi \frac{f_0}{2v_a} x\right\} A \exp -j2\pi(f_0 + f_s) \left\{t + \frac{x}{v_a}\right\} \\
 &= j0.5m_a A \exp\{-j2\pi(v + f_0 + f_s)t\} \exp\left\{-j2\pi \frac{f_0}{2v_a} x\right\} \exp\left\{-j2\pi \frac{f_s}{v_a} x\right\} \\
 &= j0.5m_a A \exp\{-j2\pi(v + f_0 + f_s)t\} \exp\left\{-j2\pi \frac{\sin \theta_B}{\lambda} x\right\} \exp\left\{-j2\pi \frac{f_s}{v_a} x\right\}
 \end{aligned}$$

The last exponential term shows that the $+1$ -order diffracted optical-beam spatial frequency is controlled by the scan-angle frequency, f_s . Specifically, the $+1$ -diffracted beam is positioned at the start angle, θ_B , given by the second

exponential term and the +1 beam scans down in angle for positive values of f_s . This example also shows that the Bragg cell acts as an RF-controlled spatial-frequency generator. If the optical system axis is defined as the negative (angle below z-axis) Bragg-angle direction, we can drop the second exponential term. In addition, if the Doppler shift is not of concern in the photonic-system design, we can also drop the first exponential term and simply write

$$E_{+1}(x, t) \propto A \exp \left\{ -j2\pi \frac{f_s}{v_a} x \right\} = A \exp \left\{ -j2\pi \frac{\sin \theta_s}{\lambda} x \right\}$$

and for small angles, $\theta_s \approx \lambda f_s / v_a$. Hence, a frequency-controlled beam steerer is formed.

- 12** (a) Minimum aperture time of Bragg cell is the inverse of the video-signal line rate or $1/15.75 \text{ KHz} = 63.5 \mu\text{s}$.
 (b) Number of spatial samples in the space-time signal = signal duration / line time = $[1/30 \text{ s}] / [63.5 \mu\text{s}] = 525 \text{ lines}$.
 (c) Laser-pulse period = line period = $63.5 \mu\text{s}$. Detector-integration time is equal to entire signal duration or $1/30 \text{ s}$.

13 As shown in Figure PS.7, place a polarization beam splitter (PBS) after the AOTF to separate the selected wavelengths with vertical polarizations from the other incident horizontal-polarization wavelengths.

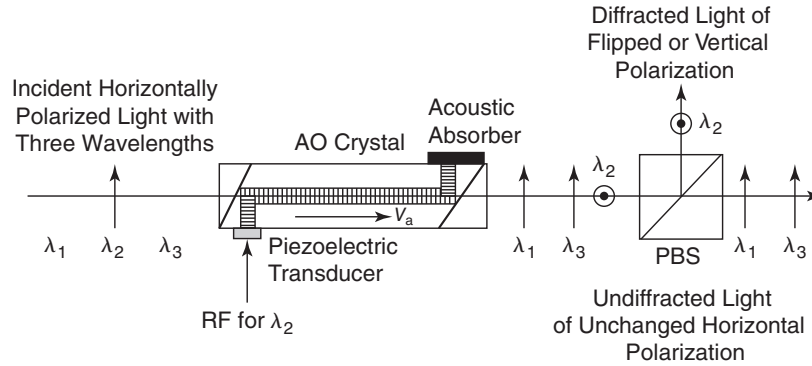


FIGURE PS.7

- 14** (a) $n_e = 1.630$
 (b) $n_o = 1.505$
 (c) $n(V) = 1.565$
 (d) $n_o = 1.505$
 (e) $n_o = 1.505$
 (f) $n_o = 1.505$
 (g) Threshold voltage
 (h) $\text{OPL} = n(V) d = 1.565 \times 10 \mu\text{m} = 15.65 \mu\text{m}$ where d is the thickness of the LC layer

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- (i) Optical-phase shift $= (2\pi/\lambda) \text{OPL} = (2\pi/\lambda) n_0 d = (2\pi/0.532 \mu\text{m}) \times 1.505 \times 10 \mu\text{m} = 56.58\pi \text{ rad}$
- (j) Relative optical-phase-shift $= (2\pi/\lambda) \text{OPL difference} = (2\pi/\lambda)(n_e - n_0)d = (2\pi/0.532 \mu\text{m}) \times (1.630 - 1.505) \times 10 \mu\text{m} = 4.7\pi \text{ rad}$

- 15 (a) Sandwich the TN-LC device between two crossed polarizers (polarization axes at 90° with respect to each other) as shown in Figure PS.8. The input polarizer's polarization axis is vertical (the same as the nematic director axis on the input face of the device) whereas the output-polarizer polarization axis is horizontal (the same as the nematic-director axis on the output face of the device). With $V = 1 \text{ V}$, all input laser-beam light that is vertically polarized gets rotated by 90° by the TN-LC device and exits the output polarizer as horizontally polarized light. As device voltage is varied from 1 to 5 V, the molecular twist in the device weakens. At 5 V, the twist essentially does not exist so the input vertically polarized light stays unchanged at the exit of the device and, hence, is completely blocked by the output polarizer. Hence, a

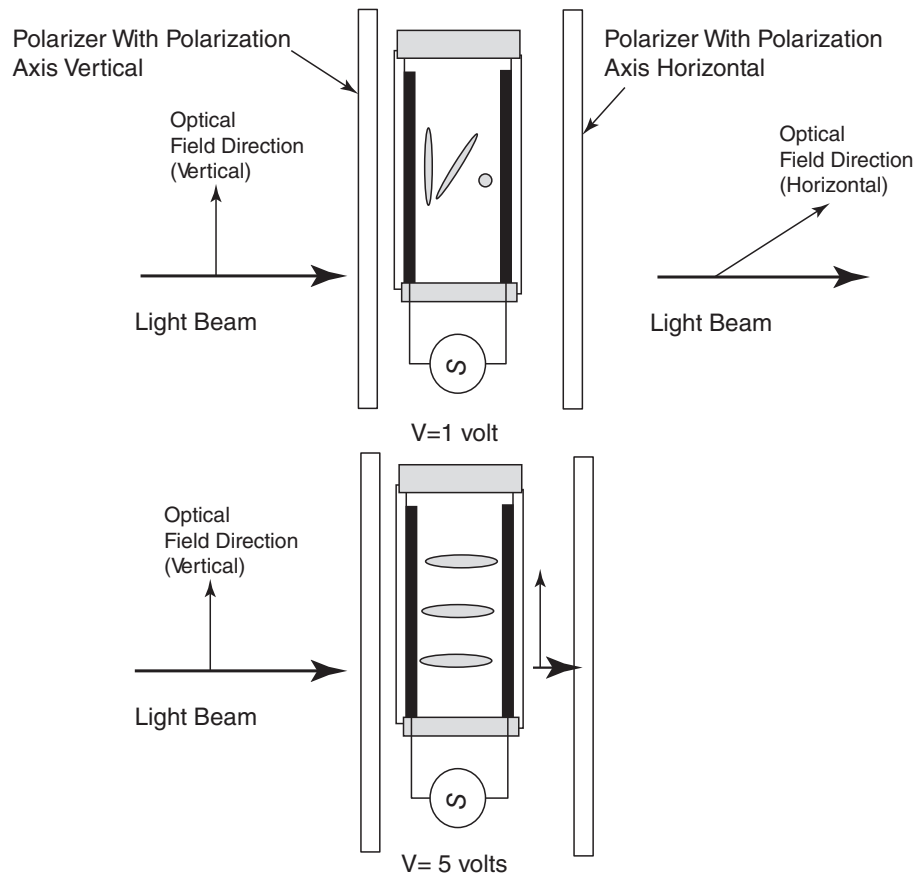


FIGURE PS.8

voltage-controlled laser-beam attenuator is formed by varying the voltage from 1 to 5 V. The laser beam is incident at normal incidence on the device.

- (b) Figure PS.9 shows how the BM-NLC device is sandwiched between two parallel polarizers. The polarizers have their polarization axis at 45° to the vertical direction that is the orientation of the nematic director in the device. The input linearly polarized laser-light of magnitude E_0 strikes at normal incidence and is polarized, such that the polarization is aligned with the input polarizer so all laser-beam light enters the device. The input light can be represented by its equal-weight vertical-V and horizontal-H components given by optical amplitude field strengths of $E_0 \sin 45^\circ = E_0/\sqrt{2}$ and $E_0 \cos 45^\circ = E_0/\sqrt{2}$, respectively. Forty-five degrees is the angle the polarizer axis makes with the nematic director of the device. The V-light sees the changing $n(V)$ index as the device voltage is changed while the H-light sees the ordinary n_0 index regardless of voltage. Hence, a relative optical phase-shift $\phi = [2\pi/\lambda][d(n(V) - n_0)]$ is induced by the device between the V and H components of the input light. Device calibration data given indicates that a 1-V drive and a 2-V drive gives a zero relative phase-shift for the given laser wavelength. This is the condition in which the input light polarization does not change by going through the device, and so all the input light exits the output polarizer. The figure

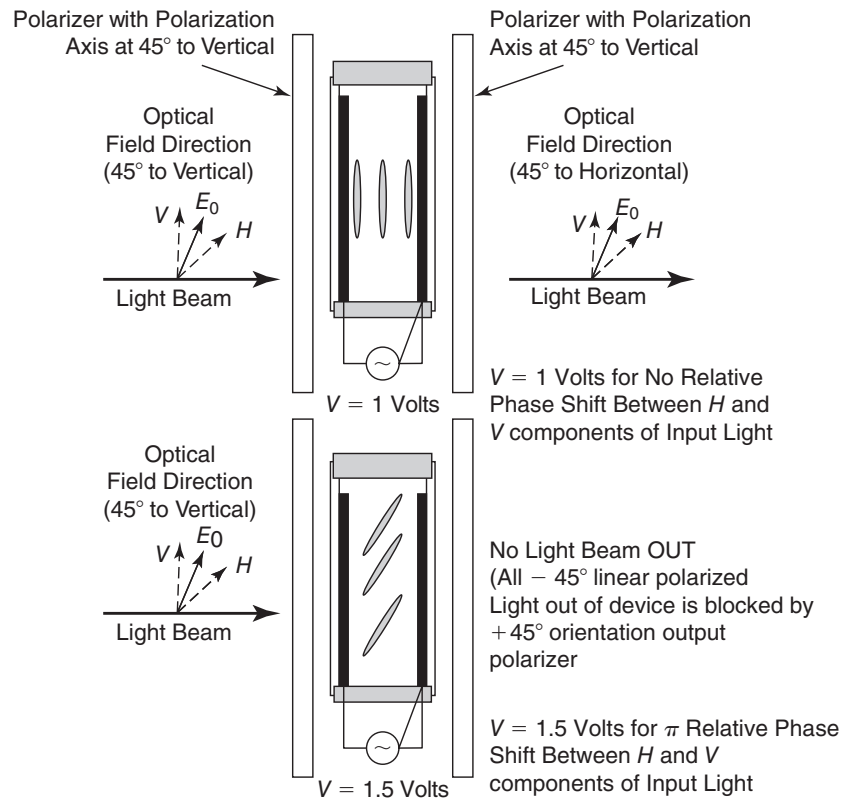


FIGURE PS.9

shows that the 1-V drive is chosen for the zero attenuation operation of the proposed voltage controlled attenuator. On the contrary, to get maximum light attenuation, no light should pass through the output polarizer. This means the light exiting the device should have its linear polarization rotated by 90° with respect to the input polarization. This happens for a V - H relative phase shift of 180° that happens for $V = 1.5$ V. Hence, the input $+45^\circ$ linear polarization light becomes -45° linear polarization light and hence gets fully blocked by the output polarizer. To achieve variable optical attenuation, the device voltage is varied between 1 and 1.5 V. After passing through the BM-NLC device, the V - and H -components can be expressed as $\frac{E_0}{\sqrt{2}}$ and $\frac{E_0}{\sqrt{2}} \exp(j\phi)$, respectively. Given that these components next pass through another polarizer (often called the analyzer) that is in parallel with the input polarizer axis, the V - and H -components in alignment with the output polarizer can be expressed as $\frac{E_0}{\sqrt{2}} \cos 45$ and $\frac{E_0}{\sqrt{2}} \cos 45 \exp(j\phi)$, respectively. Hence, the optical fields exiting the device after the analyzer are given by a sum of the two relative phase-shifted fields and hence the output irradiance I can be written as

$$I \propto \left| \frac{E_0}{2} + \frac{E_0}{2} \exp(j\phi) \right|^2 = \frac{E_0^2}{2} + \frac{E_0^2}{2} \cos \phi = \frac{E_0^2}{2} [1 + \cos \phi] = E_0^2 \left[1 - \sin^2 \frac{\phi}{2} \right]$$

Clearly, when the relative phase shift is 180° , I goes to zero. The required attenuator can also be designed using crossed polarizers versus the shown parallel polarizers. In that case, that the polarizer and analyzer are crossed, and I can be written as

$$I \propto \left| \frac{E_0}{2} - \frac{E_0}{2} \exp(j\phi) \right|^2 = \frac{E_0^2}{2} - \frac{E_0^2}{2} \cos \phi = \frac{E_0^2}{2} [1 - \cos \phi] = E_0^2 \sin^2 \frac{\phi}{2}.$$

Note the sinusoidal nature of the irradiance behavior with changing phase indicating how the attenuator responds to device voltage changes that in turn control the relative optical phase-shift in the BM-NLC device.

16 To increase the data rate we can observe the equations for the fiber NA and the fiber data-rate limit to conclude that we can

- Use a shorter length MMF or
- Reduce the number of spatial modes in the fiber by reducing the refractive index difference between core and cladding.

$$17 \quad \Delta t = \frac{n_g l_0}{c} \left[\frac{n_g}{n_{cl}} - 1 \right] = \frac{1.46(50 \cdot 10^3)}{3 \cdot 10^8} \left[\frac{1.46}{1.44} - 1 \right] = 3.38 \mu s$$

$$\text{Bit rate} = 1/\Delta t = 295.9 \text{ kbps}$$

$$18 \quad l_0 = \frac{c \Delta t}{n_g \left[\frac{n_g}{n_{cl}} - 1 \right]} = \frac{c}{B_T n_g \left[\frac{n_g}{n_{cl}} - 1 \right]} = \frac{3 \times 10^5 \text{ km/s}}{1 \times 10^6 / s \cdot 1.5 \left[\frac{1.5}{1.49} - 1 \right]} = 29.8 \text{ km}$$

19 Using the given expression with the provided wavelengths, $D_M = 19.68$ ps/nm-km.

20 The time delay is the time it takes the pulse to travel the fiber length, L , and is given by $t_d = \frac{L}{v_g} = 1.33$ ms.

21 Start with $D = \frac{d}{d\lambda} \left(\frac{1}{v_g} \right)$. Recall $v_g = \left(\frac{d\beta}{d\omega} \right)^{-1}$, which implies $D = \frac{d}{d\lambda} \left(\frac{d\beta}{d\omega} \right) = \frac{d^2\beta}{d\lambda d\omega}$.

Recall that $d\omega = \left(-\frac{2\pi c}{\lambda^2} \right) d\lambda$ and use the expression for $d\lambda$ in the expression for D . We obtain

$$D = \frac{d^2\beta}{d\lambda d\omega} = \frac{d^2\beta}{d\omega d\omega} \left(\frac{-2\pi c}{\lambda^2} \right) = \frac{d^2\beta}{d\omega^2} \left(\frac{-2\pi c}{\lambda^2} \right) = \beta_2 \left(\frac{-2\pi c}{\lambda^2} \right)$$

which is the defined values of D .

22
$$D_M = \frac{1}{B \times L \times \Delta\lambda} = 10 \frac{\text{ps}}{\text{nm-km}}$$

23
$$\Delta T = LD_M \Delta\lambda$$

$$D_M = \frac{\Delta T}{L \Delta\lambda} = \frac{1}{BL \Delta\lambda}$$

where B is the bit rate. Solving the equation with the given parameters and converting to the standard units for material dispersion answer is $D_M = 4.167$ ps/nm-km.

24

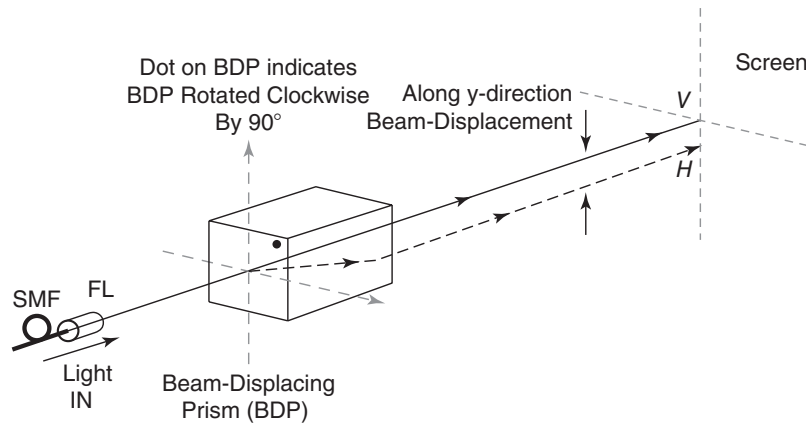


FIGURE PS.10

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25

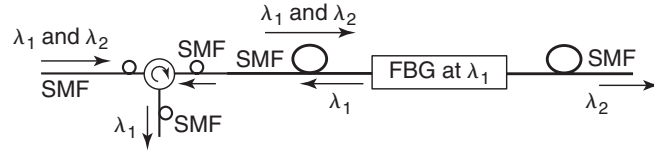


FIGURE PS.11

26 Since the IO device is designed as a 3-dB coupler, input light is split 50:50 between the two output ports. So the port output irradiances I are OUT 1 $I = 0.5A + 0.5B$ and OUT 2 $I = 0.5A + 0.5B$.

27 Start with the expression: $I_0 = T_d I_i \left[1 + \cos \left\{ \pi \frac{V_d(t)}{V_\pi} \right\} \right]$. Insert $V_d(t) = 0.5V_\pi + V_{ss}(t)$ into the expression and use $\cos(A + B) = \cos A \cos B - \sin A \sin B$ with $A = (\pi V_{ss})/V_\pi$ and $B = 0.5\pi$. Then we obtain

$$I_0 = T_d I_i \left[1 - \sin \left\{ \pi \frac{V_{ss}(t)}{V_\pi} \right\} \right]$$

Using the approximation for small-angle A where $\sin A \approx A$, we obtain the desired output irradiance expression of

$$I_0 \approx T_d I_i \left[1 - \pi \frac{V_{ss}(t)}{V_\pi} \right]$$

28 Start with the expression: $I_0 \approx T_d I_i \left[1 + \cos \left\{ \pi \frac{V_d(t)}{V_\pi} \right\} \right]$. Insert $V_d(t) = 1.5 V_\pi + V_{ss}(t)$ into the expression and use $\cos(A + B) = \cos A \cos B - \sin A \sin B$ with $A = (\pi V_{ss})/V_\pi$ and $B = 1.5\pi$. Then we obtain

$$I_0 = T_d I_i \left[1 + \sin \left\{ \pi \frac{V_{ss}(t)}{V_\pi} \right\} \right]$$

Using the approximation for small-angle A , where $\sin A \approx A$, we get the desired output irradiance expression of

$$I_0 \approx T_d I_i \left[1 + \pi \frac{V_{ss}(t)}{V_\pi} \right]$$

29 First note that the lasers are independent light sources, hence when they are optically combined by the 3-dB coupler, their output irradiances I_{01} and I_{02} simply added together and there is no additional interference term. Hence, the photodetected current is proportional to the output irradiance that is given by

$$\begin{aligned} I &= 0.5[I_{01} + I_{02}] \approx 0.5T_d I_1 \left[1 - \pi \frac{V_{ss}(t)}{V_\pi} \right] + 0.5T_d I_2 \left[1 + \pi \frac{V_{ss}(t)}{V_\pi} \right] \\ &= 0.5T_d [I_1 + I_2] + 0.5T_d \frac{\pi}{V_\pi} [I_2 V_{ss}(t) - I_1 V_{ss}(t)] \end{aligned}$$

Hence, the output current is given by a weighted subtraction of the input-RF signal, thus producing the subtraction operation in the optical domain using irradiances.

30 The proposed optical-circuit design is shown in the optical layout. Many times, the MZ modulator uses the same electrode to enter the RF and bias signal, as shown in Figure PS.12. The process to achieve the design solution is as follows. Since we are allowed only one MZ modulator, we have to pick the modulator drive-signal matched to one of the quadrature-bias points. Assume the modulator is fed at the Q1 bias point (at drive voltage of $0.5 V_\pi$ at λ_1) for the input laser of irradiance, I_1 , wavelength λ_1 . So the MZ modulator is fed by the drive signal $V_{ss}(t) + 0.5 V_\pi(\lambda_1)$ to operate RF modulation on the negative slope of the modulator. Now without changing the modulator electrical-drive conditions, a positive-slope modulation transfer-function is also needed for the RF signal. This means a separate MZ modulator transfer-function is needed that is shifted by V_π radians compared to the transfer function at original input laser wavelength of λ_1 . The MZ modulator operates on the principle of optical-phase difference between the two arms of the modulator. Recall that optical-phase term contains the optical wavelength and changing the wavelength produces a phase shift. In effect, we can shift the transfer function of the modulator by simply changing the laser wavelength. Thus, we can use a second laser at wavelength λ_2 of irradiance I_2 that will shift the modulator-transfer function by an equivalent π radians to project the Q2 bias-modulator. The outputs from the two lasers are combined by a 2:1 WDM device to feed the MZ modulator. The MZ modulator processed two output irradiances are simultaneously detected by a single PD. Since the lasers are at different wavelengths, their irradiances are simply added with no interference

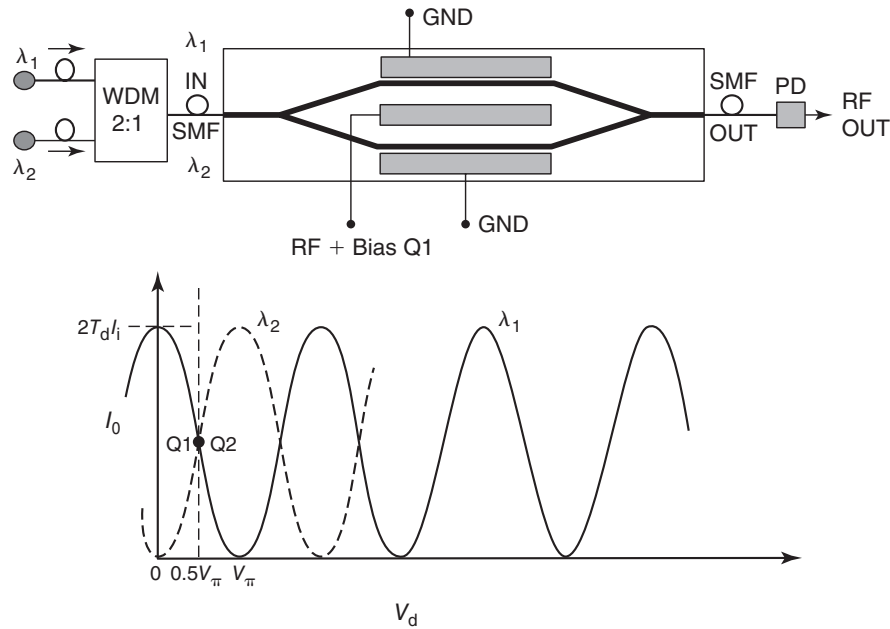


FIGURE PS.12

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effects. No 3-dB coupler is required for adding the laser irradiances. Example wavelengths could be 1550 nm and 1300 nm. The final PD detected irradiance is

$$\begin{aligned} I &= [I_{01} + I_{02}] \approx T_d I_1 \left[1 - \pi \frac{V_{ss}(t)}{V_\pi} \right] + T_d I_2 \left[1 + \pi \frac{V_{ss}(t)}{V_\pi} \right] \\ &= T_d [I_1 + I_2] + T_d \frac{\pi}{V_\pi} [I_2 V_{ss}(t) - I_1 V_{ss}(t)] \end{aligned}$$

Chapter 6

1 The pulsed-laser-beam pulse period is $T_L = 1/f_L$. The pulse width τ of the laser is assumed to be less than T_L and is generally much less than T_L . The image-update time T_D of the DMD, which is the same as the knife-edge position updating time and the PD data update time should be made an integer K multiple of the laser-pulse period, that is, $T_D = KT_L$. The DMD frame rate, PD-update rate, and the laser-pulsing rate should all be time synchronized with each other, that is, the start time of the first laser pulse within the T_D window should correspond to the start time of a new knife-edge on the DMD and the start time of detector integration process. The larger the K , one can improve profiling data given a particular laser-power level.

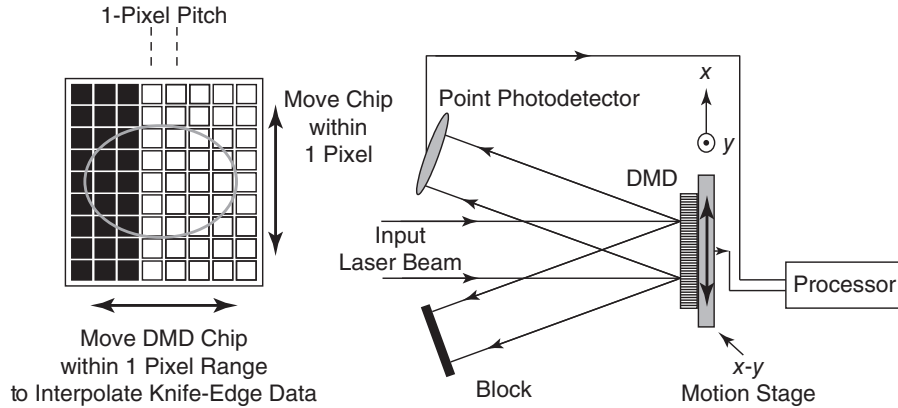


FIGURE PS.13

2 The Figure PS.13 design solves this problem by introducing subpixel motion in x - and y -directions for the DMD chip. In effect, a precision-motion mechanical stage is used to provide the needed subpixel motion. For example, if the micromirror pitch is $d \mu\text{m}$, then we can break the x -direction motion down to $d/N \mu\text{m}$ that improves the sampling resolution by N in the x -direction. The same applies in the y -direction. Note that the DMD needs only motion within one micromirror pitch and not the entire chip size, making the motion transducer requirements stringent over a small motion scale and not over a large range as normally required in classic mechanical beam-profilers. The proposed profiler will take $N \times N$ times more data compared to the all-digital beam-profiler that is then interpolated to map the super-resolution 2D laser-profile map. In effect, a hybrid analog-digital beam-profiler is realized using analog motion via the x - y stage and digital motion via the DMD chip micromirror programming.

3 The DMD-profiler design applies to any binary state 2D spatial-light modulator (SLM). A reflective DMD SLM is used, but any reflective SLM such as a LC on silicon (LCOS) SLM can also be used. As shown in the revised design (Figure PS.14), we can use a transmissive LC SLM like an NLC Display SLM in place of the DMD. Because the shown LC SLM is transmissive, the incident and transmitted beams are on separate sides of the SLM (unlike when the DMD is used), and as such a compact profiler design is possible. In addition, a focus lens and a spatial filter can be placed after the LC SLM to further shorten the output path to the PD. Other benefits of using the LC SLM are that the SLM has intrinsically no microscale moving parts, LC SLMs can have very large sizes to capture big beams, LC SLMs can handle high watts-level optical powers, and LC SLMs can operate over a variety of broad optical bands (visible, near IR, etc.).

Nevertheless, LC SLMs operate with linearly polarized input light and this puts a restriction on the input laser beam type. If the input beam is not linearly polarized, a polarizer will be required before the SLM, which could change the input beam profile. The polarizer after the SLM plane (where the profile is measured) is fine as then the light is in the power-collection mode. The pixels in the LC SLM also can be programmed as on/off shutters using polarizers to stop light from passing through to the PD. For example, the LC pixel can be a 90° TN-LC cell where voltage control either allows no 90° rotation or full 90° rotation of the input-light polarization. Hence, an all-digital LC beam-profiler is realized that is indeed compact in size.

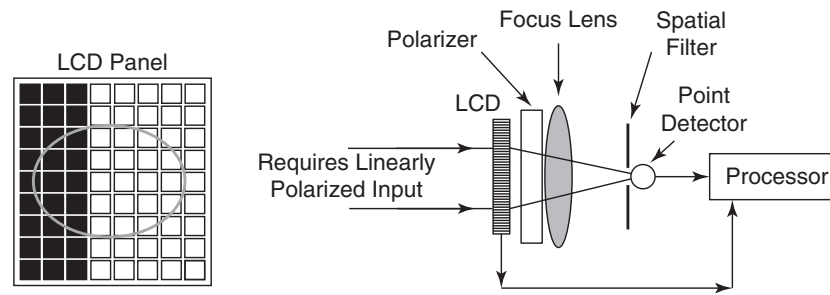
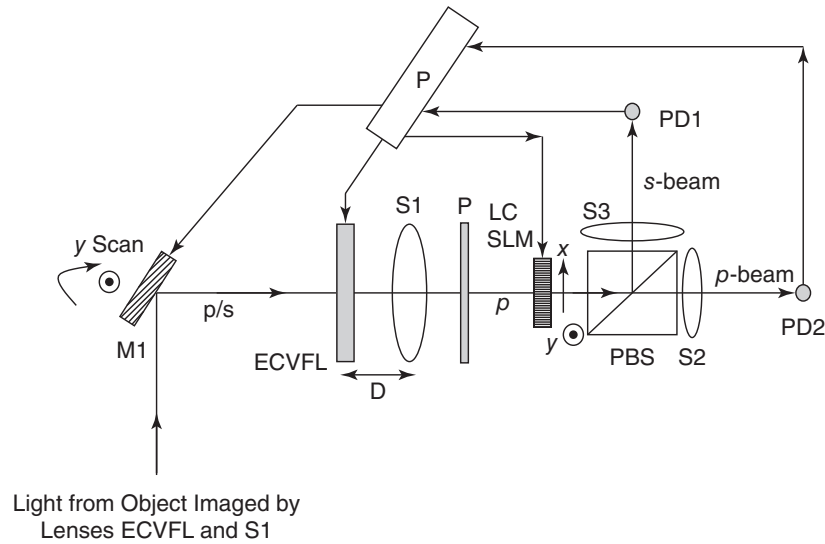


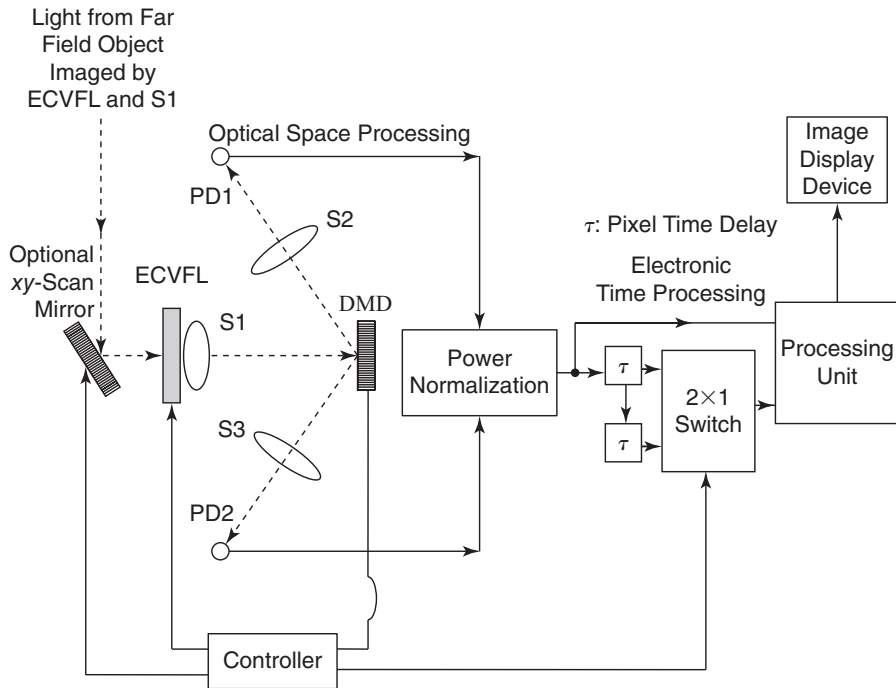
FIGURE PS.14

4 The design in Figure PS.15 uses an LC SLM to produce the desired imager. P is a polarizer as generally LC SLMs require linearly polarized light inputs. P is shown aligned along p (along x) polarization direction. PD1 and PD2 measure light powers that allows power normalization of the pinhole scan-based image irradiance present on the SLM plane.

5 Figure PS.16 shows is the desired imager that uses space-time processing to implement target boundary detection within an incident-image irradiance on the DMD. The DMD operates in a pinhole scan mode in a zig-zag scan pattern and not a classic line-scan pattern so target edges are not missed if they happen to be aligned with the rectangular-grid pixel layout. At each pixel/micromirror location, the imager collects the normalized optical power and provides it to a time-delay processor where the power data is sent via three electronic routes, one direct, one to receive a 1-pixel delay, and another to receive a 2-pixel time delay. A pixel delay is the time it takes to scan and collect a given pixel optical power data.


FIGURE PS.15

Each pixel-power data is compared with its adjacent 2-pixel power data (hence the 2-pixel delay) to conclude if a target edge is present. If the two compared pixel powers differ by a specified amount, an edge location is registered and the power information is saved. If no edge is detected, no power data is saved for


FIGURE PS.16

transmission and the pinhole scan on the DMD plane continues. This process is repeated for the full image-irradiance view and the boundary of the specified target is located without resorting to full pixel data collection. In effect, smart space processing via the DMD and electronic processing via time-delay devices is implemented to achieve the image data compression.

6 Shown in Figure PS.17 (a) is an optical profiler that solves the mentioned problem by using as shown in Figure PS.17 (b), a nonpixelated LC SLM called the optically addressed (OA) parallel-aligned (PA) LC SLM. The test-beam power profile falls on the photoconductive amorphous silicon whose electrical impedance changes depending on the incident-light power level. This change in silicon impedance causes a change in voltage between the PA nematic LC

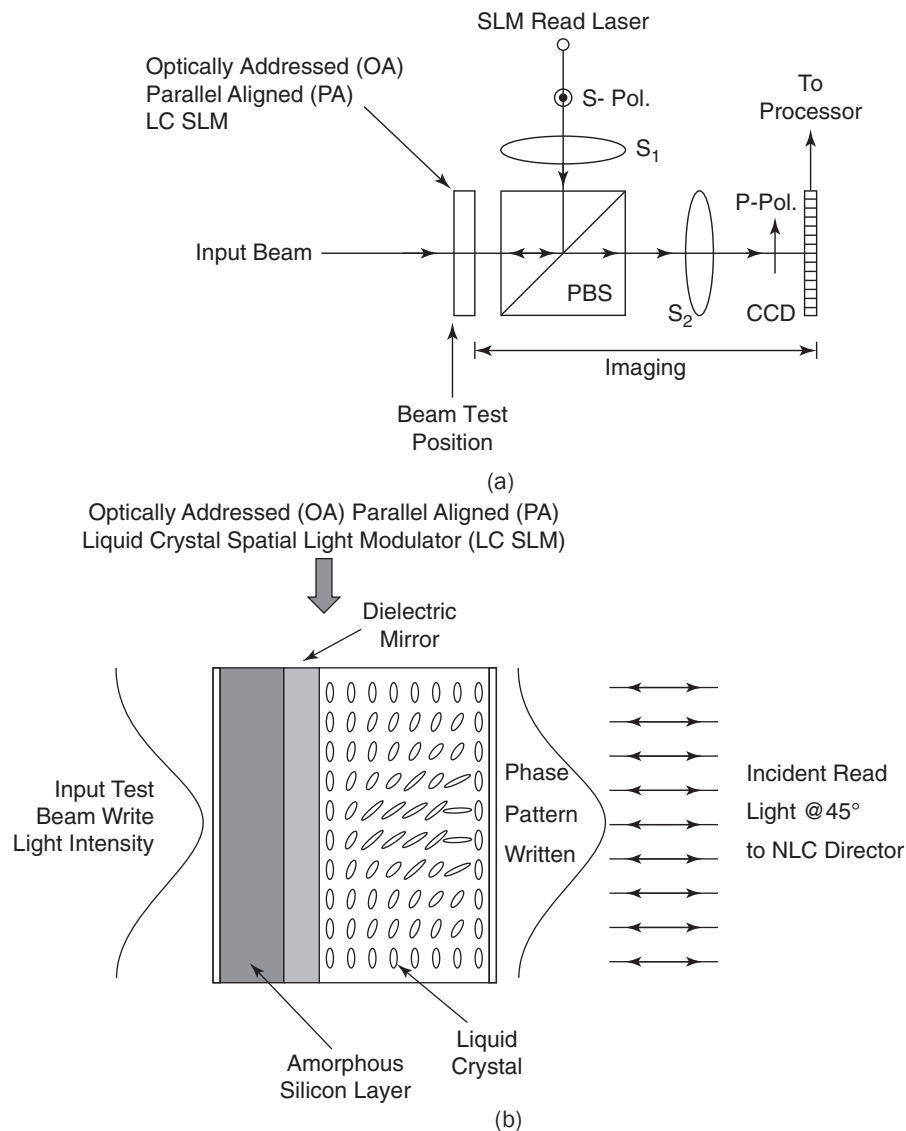


FIGURE PS.17

molecules causing the NLC molecules to rotate different amounts. The read light has both p and s polarizations relative to the NLC nematic director, so one linear polarization picks up an optical-phase-shift versus the other orthogonal linear polarization. The PBS acts as a beam combiner for the p and s 45° components to produce an interference phase-coded map on the CCD. This map using phase-unwrapping methods is used to recover the optical beam power-profile incident on the OALC SLM plane. Because the OASLM has no pixel structure (is smooth), the test beam does not suffer SLM-based diffraction and hence a highly noninvasive beam-profiler has been realized.

7 Figure PS.18 is the desired single-fiber lens based VOA that uses a small tilt micromirror to adjust the level of attenuation via the VOA. The key design feature is the placement of the SMFs alongside the lens to allow light coupling control on reflection angle adjustment via the micromirror tilt angle. Because SMF cores are small (e.g., $10\text{ }\mu\text{m}$ in diameter), very precise 1D-tilt angle control is required via the MEMS actuator.

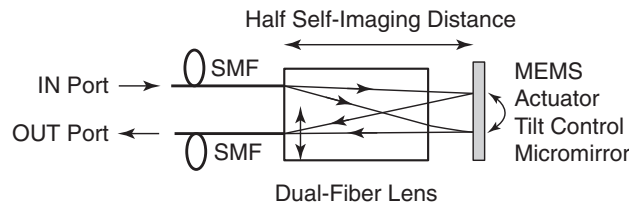


FIGURE PS.18

8 Figure PS.19 is the desired variable splitter, also called variable tap-coupler. The photonic design uses an inclined translating MEMS mirror to slide across the beam from the input-SMF. Part of the beam is reflected to the tapped SMF port while the remaining beam passes straight through to the untapped original light path port. By translating the mirror shown at a 45° angle to the input-light optical axis, a portion of the beam can be split to the tapped port. Thus a variable beam splitter is realized.

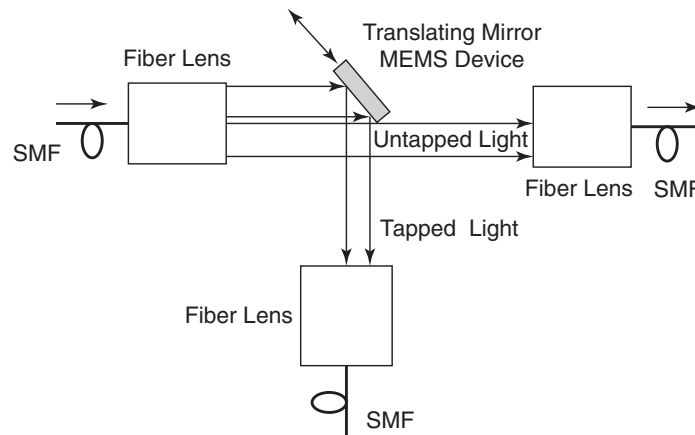


FIGURE PS.19

9 Figure PS.20 is the desired VOA using a dual-collimator fiber lens and an N -micromirror MEMS chip to realize an N -bit VOA. Each micromirror has two-tilt states, one that connects light to the output-SMF and another that reflects light completely away from the output-SMF. The area of each micromirror is designed to cover a binary-weighted optical-power level. If the total power in the incident beam is P_0 and N -bit attenuation control is needed or 2^N levels of power control, then the mirrors are designed as follows: Bit 1 controlled by Mirror M1: $2^0 P_1 = P_1$, the smallest VOA attenuation step possible; Bit 2 controlled by Mirror M2: $2^1 P_1 = 2P_1$; Bit 3 controlled by Mirror M3: $2^2 P_1 = 4P_1$; Bit 4 controlled by Mirror M4: $2^3 P_1 = 8P_1$; and so forth so Bit N controlled by Mirror M- N : $2^{N-1} P_1$. For the shown design with $N = 7$ to form a 7 bit VOA using 7 micromirrors whose reflection areas are fabricated to match reflection power levels as: M1: P_1 ; M2: $2P_1$; M3: $4P_1$; M4: $8P_1$; M5: $16P_1$; M6: $32P_1$; and M7: $64P_1$. In this case, $P_0 = P_1(1 + 2 + 4 + 8 + 16 + 32 + 64) = 127P_1 = (2^N - 1)P_1$ where $N = 7$. When all mirrors are in their for example $+\theta$ -state, in theory, all P_0 light from the input-SMF goes to the output-SMF indicating the VOA no-attenuation state. When the mirrors are independently turned to their $-\theta$ -states, attenuation of light begins. Using any combination of the $+\theta$ -state and $-\theta$ -state of the mirrors produces the 2^{N-1} VOA attenuation digital states via mirror control. Add the no-attenuation state, a total of 2^N VOA attenuation states is achieved.

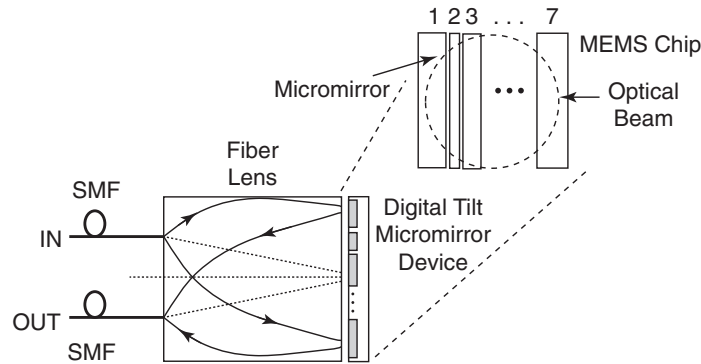


FIGURE PS.20

10 Shown in Figure PS.21 is the desired 1×2 variable splitter. It uses three digital $\pm\theta$ -tilt-state micromirrors with $+\theta$ -state directing light to the OUT SMF and $-\theta$ -state sending light to the TAP output SMF. If the total input optical power is P_0 , the mirror sizes are designed such that mirror M1, mirror M2, and mirror M3 reflect optical powers of $(5/100)P_0$, $(90/100)P_0$, and $(5/100)P_0$, respectively. To get the splitter operating in a 10:90 tap mode with 10 percent light tapped, M1, M2, and M3 are set to $-\theta$ -state, $+\theta$ -state, and $-\theta$ -state, respectively. To get the splitter operating in a 5:95 tap mode with 5 percent light tapped, M1, M2, and M3 are set to $-\theta$ -state, $+\theta$ -state, and $+\theta$ -state, respectively. Another option to get the splitter operating in a 5:95 tap mode with 5 percent light tapped, M1, M2, and M3 are set to $+\theta$ -state, $+\theta$ -state, and $-\theta$ -state, respectively.

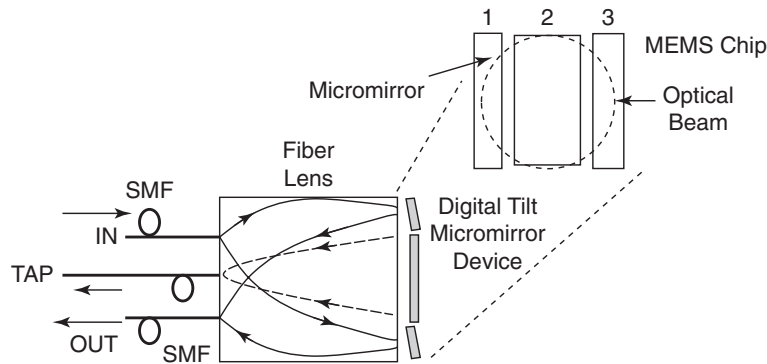


FIGURE PS.21

11 Figure PS.22 is a retro-reflective design programmable broadband RF transversal filter using compact chirped-fiber bragg-grating (CFBG) fiber optics and a DMD-based continuous-spectrum optical equalizer. The other key components are: IOM: high-speed optical intensity modulator; BOS: broadband optical source containing a continuous array of optical wavelengths; I: interleaver device that separates light into its odd- and even-wavelength channels in a predetermined and designed wavelength channel grid; DA: differential amplifier; C1 and C2: optical circulators; PD1, PD2: high-speed photodetectors; FL: self-imaging-mode fiber lens; C: cylindrical lens of focal length F . The DMD is used to select discrete wavelengths and their optical power weighting by using digital control of the two-tilt state micromirrors. These positive and negative weights represent A_n in the RF-filter function. As optical intensity cannot represent negative numbers, the negative and positive filter taps are assigned to BOS odd wavelengths and even wavelengths, respectively. The CFBG causes the

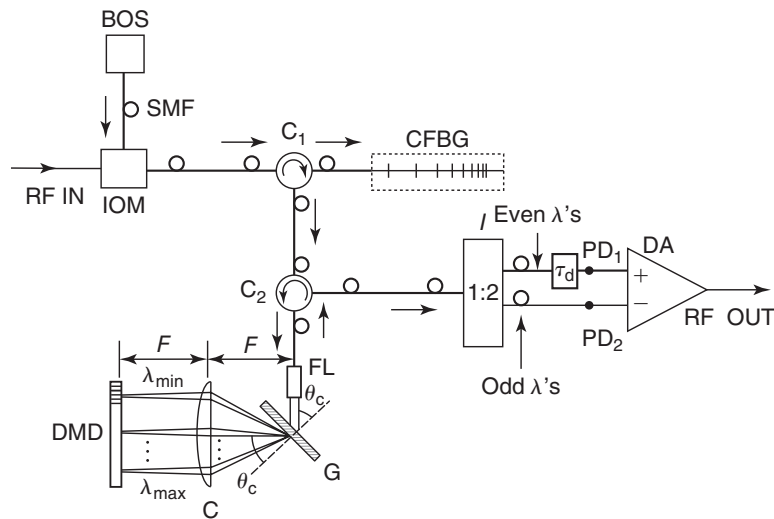


FIGURE PS.22

wavelengths from the BOS to acquire a relative time delay needed to produce the multiples of τ delays for the DMD weighted and selected signal taps. Total time delay from the CFBG is equal to bandwidth of the grating ($\lambda_{\max} - \lambda_{\min}$ in nanometers centered at λ_c) times the dispersion, D , of the CFBG in picoseconds per nanometer. These parameters should match the DMD optical spectrum control equalizer parameters and also the BOS. There is a time delay, τ_d , between consecutive odd and even wavelengths, and this relative delay is canceled using the τ_d SMF element after the interleaver device. PD2 produces a signal with all the negative weight time-delayed taps while PD1 produces a signal with all the positive weight time-delayed taps. The DA produces the difference signal that gives the RF-filter output signal, $f(t)$. The simplest form of RF filter is the two-tap filter, or $N = 2$ with equal weight taps represented by

$$f(t) = \sum_{n=0}^1 A_n s(t - n\tau) = A_0 s(t) + A_1 s(t - \tau) = A_0 [s(t) + s(t - \tau)]$$

To form a nulling filter for a RF signal $s(t) = \cos(2\pi f_c t)$, $\tau = 1/(2f_c)$ to produce a 180° phase-shifted version of $s(t)$ or $-s(t)$ signal tap that adds with the first tap, $s(t)$, to produce a zero or a null. To form a tunable-nulling 2-tap RF filter, we must be able to pick the right τ and this is done by the DMD equalizer selecting the two wavelengths that have a relative time delay of τ . Using many taps via many wavelengths, the RF-filter performance (e.g., depth and shape of null) can be optimized. Any optical beam-forming SLM device can be used in place of the binary amplitude-mode DMD to select and weight the desired wavelengths through a beam spoiling effect via the Grating and FL-SMF freespace optical coupling assemblies.

As shown in Figure PS.23 (left side), the processor optical-output spectrum (just before the interleaver) measured via an optical spectrum analyzer (OSA) instrument has a one-to-one mapping with the RF-filter time-domain impulse-response, $h(t)$. Here the optical wavelength axis maps to the time axis and the optical-spectrum power measured on a dBm scale indicates the amplitude of $h(t)$ in dBm. The wavelength-to-time mapping is dictated by the CFBG parameters in the processor. Example numbers are used in the figure. By taking a computer-based fast Fourier transform (FFT) of the $h(t)$ signal trace (exists as a spatial map

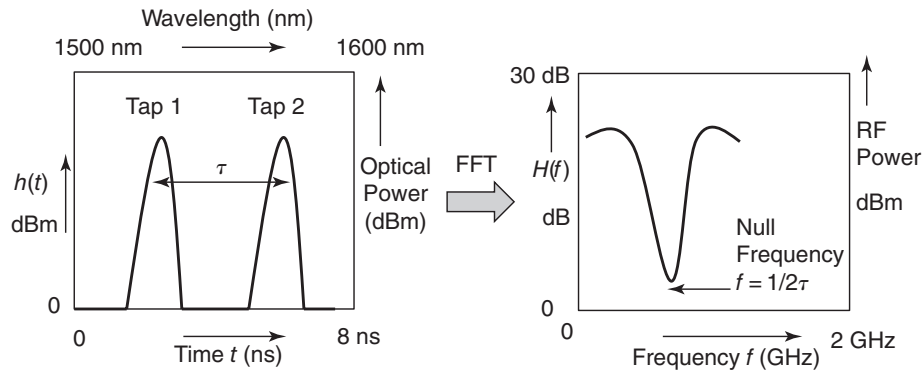


FIGURE PS.23

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read by a CCD and shown on left side of figure) provided by the OSA instrument, the RF transversal-filter frequency domain response $H(f)$ is computed (shown on the right side of the Figure). To experimentally verify the computed $H(f)$, the input RF signal to the transversal filter is tuned along the RF spectrum and the photodetected optical power is measured to give a plot of RF-output power in dBm versus input-signal frequency (also shown on the right side of the Figure). In effect, the proposed RF transversal-filter architecture with pre-RF signal calibration of the processor also functions as an electrical frequency measurement instrument where one did not use electrical high frequency components to determine the RF spectrum of the input RF signal to the processor. This can be an added benefit of using photonic signal processing for RF signals.

12 Figure PS.24 is the desired module using serial signal processing via a cascade of 1×2 and 2×2 fiber-optic switches that forms an efficient binary digital structure 3-bit variable fiber-optic delay line to give eight delay states of $0, T, 2T, 3T, 4T, 5T, 6T$, and $7T$, where the fiber delays used give relative delays of $T, 2T$, and $4T$. TF is a tunable filter that selects the wavelength that passes through the module and using the CFBG gives an analog delay from 0 to T . Hence, the entire module provides a delay control over 0 to $8T$ with precise analog delays with T increments set by the wavelength chosen. Only three fiber delays are used in the 3-bit switched structure to give seven delays. For a N -bit serial delay line, $2^N - 1$ digital delays are possible using only N fiber delays versus a parallel switch structure that would need a large 2^N fiber delays.

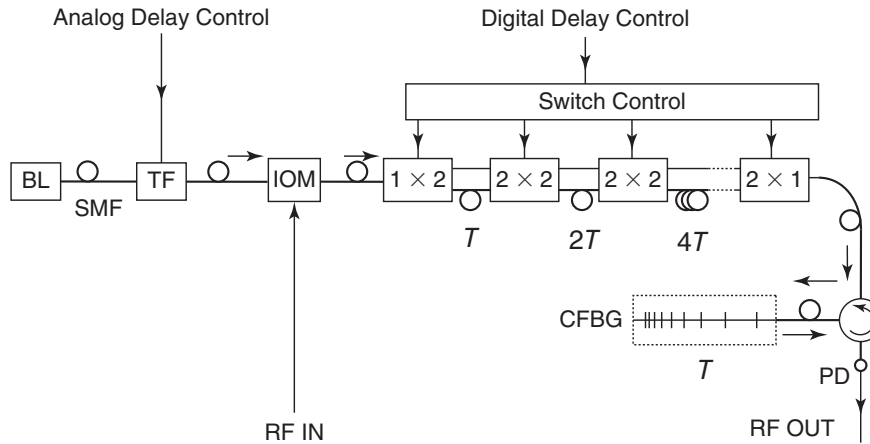


FIGURE PS.24

13 Figure PS.25 is the desired 4×4 switch. It uses 16 mirrors in a digital state that controls the routing path between the input and output SMFs. Each mirror for example can be flat on the mirror mounting platform surface (e.g., a MEMS chip substrate) or sitting vertical/upright on the platform, thus giving its digital states. The input/output SMF arrays are placed in a diagonalized geometry to keep the optical routing signal time delays the same between input and output SMFs. Note that $N \times N$ switch needs N^2 mirrors. When N is large, for example, $N > 10$, the shown design is hardware intensive.

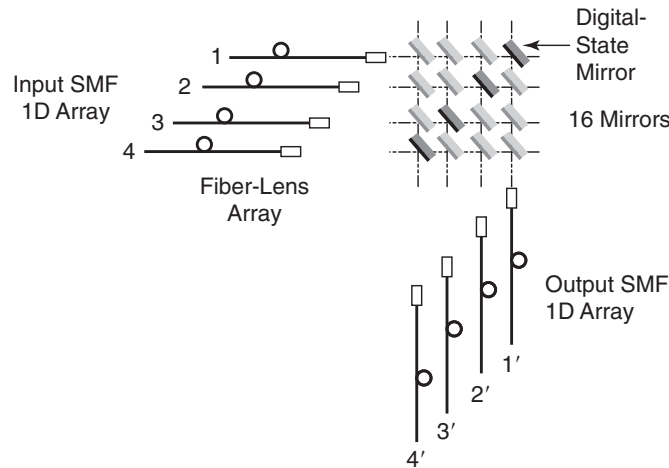


FIGURE PS.25

14 Shown in Figure PS.26 is the desired 1×2 switch. It uses a digital or two-state mirror. The mirror can be a MEMS micromirror on a silicon chip.

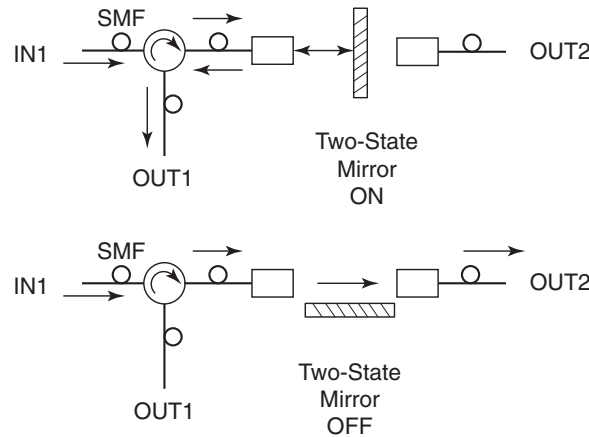


FIGURE PS.26

15 Shown in Figure PS.27 is the desired 2×2 switch that uses two circulators and one digital-state mirror. To form the desired multiwavelength module, between the circulator bi-directional SMF and the fiber lens, add a $1 \times N$ WDM device for both circulators. Use a N mirror array with each mirror in a digital state to individually control the routing of each of the N -wavelengths, thus forming a 2×2 wavelength routing module when using IN1 and IN2 as the input-signal ports and OUT1 and OUT2 as the signal output ports. Use the IN2 port as the main IN line and OUT1 port as the MAIN out fiber line. Use the IN1 port as the add-wavelength port and OUT2 port as the drop-wavelength port.

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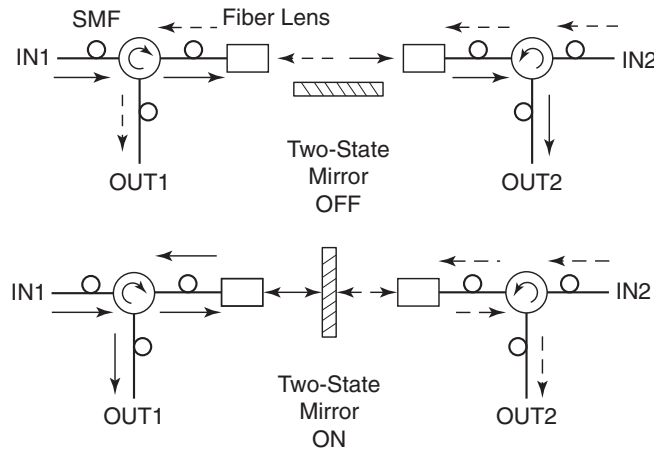


FIGURE PS.27

16 As shown in the Figure PS.28, a mirror is added into the Figure 6.18 multiwavelength add-drop module design. By doing so, the switch state where the DMD is in the $+\theta$ -state, main in-light goes to main out-light and more importantly, add-port in-light goes to the drop-port out-light (which did not happen in the Figure 6.18 design). In the other switch state where the DMD is in the $-\theta$ -state, the main in-light does go to the drop port and the drop-port input light does go to the main out-port as was the case in the Figure 6.18 design.

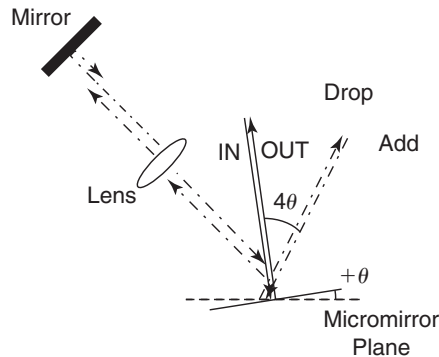


FIGURE PS.28

Chapter 7

1 Shown in Figure PS.29 is the desired AO interferometer that engages the $+1$ order from both AODs to produce the baseband signal. Note that AOD1 and AOD2 have flipped orientations. The photodetected signal is given by

$$i(t) = KI_0 [t_a^2 A_1^2 + A_2^2 + 2t_a A_1 A_2 \cos(\phi)]$$

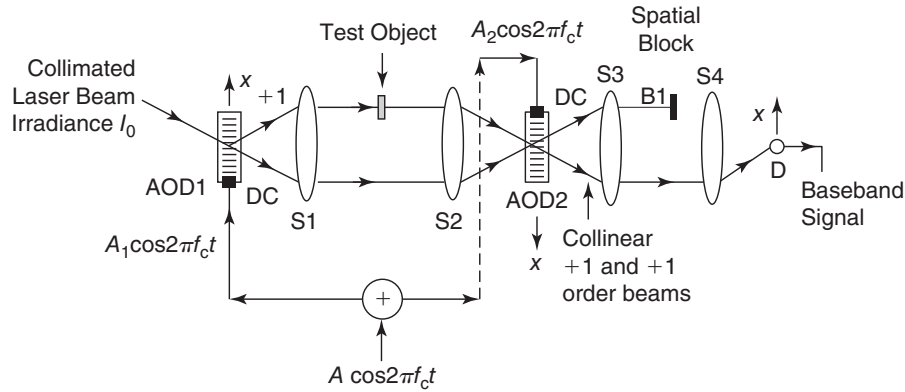


FIGURE PS.29

2 Shown in Figure PS.30 is the desired single AOD-based interferometer that engages a three-port SMF coupled fiber-optic (FO) circulator. The SMF in the bidirectional light path is connected to a fiber lens that collimates the light coming out of the SMF. This collimated light is Bragg-matched to the AOD at its center frequency f_c . The +1 order light from the AOD is focused by the lens S1 and becomes a point on the test array. The DC light from the AOD ends up as a fixed point on a mirror that also is the back-face of the test sample array. The +1-order light returns after reflection from the mirror so it is again Bragg-matched to the AOD to produce a +1-order diffracted beam that heads back into the fiber lens. Hence, this light has suffered two +1 order diffractions and can be written in the notation $+1 \times +1$ indicating a positive- $2f_c$ Doppler shift, with f_c the AOD drive frequency. The straight through DC stays as the original +1 beam that is blocked by the beam block B1. The original DC light from AOD returns from the mirror also to be Bragg matched and produces a DC straight pass beam that enters the fiber lens. In addition, a -1-order diffracted beam is produced that is blocked by B1. Hence the fiber lens receives the test sample signal-coded $+1 \times +1$ beam and the reference DC beam that is carried through the circulator via SMFs to the high speed photodetector. To produce a scanning point on the test sample, the AOD frequency must be shifted from its carrier, hence the AOD drive frequency can

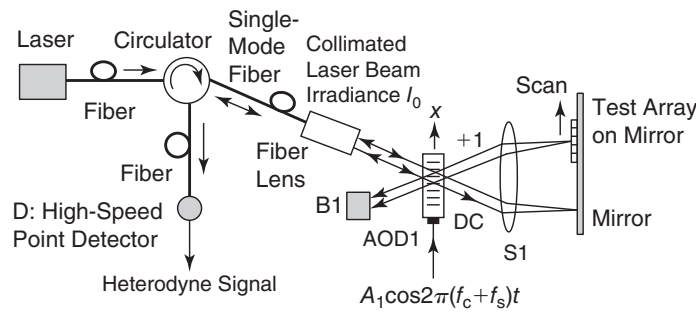


FIGURE PS.30

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be written as $f_c + f_s$ where f_s represents the interferometer scan position control signal. For a positive f_s , the scan spot moves up as shown in the figure. Note that the double +1-order diffraction process in the AOD returns the double diffracted beam along the same path as the original beam output from the fiber lens, a critical feature of this system design as SMF coupling requires perfect on-axis alignment with the SMF core position. For small diffraction-efficiency AOD operation mode, the photodetected signal is given by

$$i(t, f_s) = KI_0 \left[t_a^2 A_1^2 + A_2^2 + 2t_a A_1 A_2 \cos \{ 2\pi 2(f_c + f_s)t - \phi \} \right]$$

The same notation for the test sample optical phase and amplitude is deployed as the chapter.

3 For the generation location of the n -th photodetector that corresponds to $x = nd$ position that is shown as the PD2 sampler location in the chapter, the photodetected current can be written as

$$\begin{aligned} i(n, t) &= k \left(A_1^2 + A_2^2 + 2A_1 A_2 \cos \left\{ 2\pi(2f_c + f_s)t - n 2\pi \frac{f_s}{Mv_a} d \right\} \right) \\ &= K \left(A_1^2 + A_2^2 + 2A_1 A_2 \cos \{ 2\pi(2f_c + f_s)t - n\phi \} \right) \end{aligned}$$

Here the intersampler optical or inter-antenna RF phase shift is written as $\phi = (2\pi f_s d)/(Mv_a)$. By choosing an $M > 1$, the interference zone at the output plane can be made larger that allows more space for placement of the N point samplers/optical fibers at the output plane. In addition, for any given scan frequency f_s , the spatial frequency is lower by a factor of M that implies that for a given point sampler size (e.g., diameter of the fiber) the phase sampling error is a factor of M smaller, hence producing RF phase shifted signals with a smaller RF phase error.

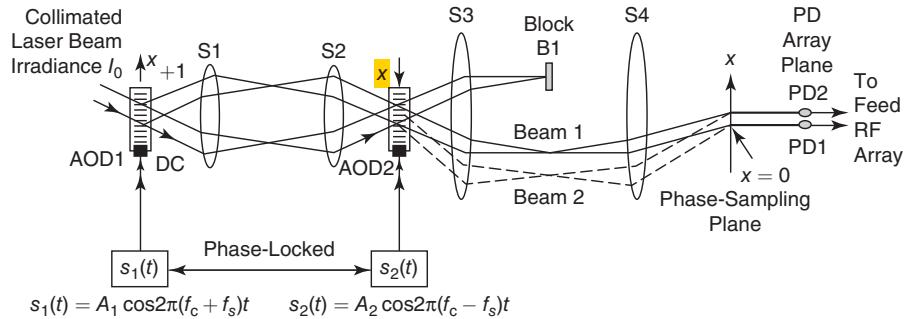


FIGURE PS.31

4 The system shown in Figure PS.31 using upper- and lower-sideband drive signals for the AODs provides the required PAA beam-former where the RF antenna carrier $2f_c$ is independent of the antenna scan angle frequency f_s . The S3/S4 pair provides imaging with magnification M between AOD2 and the output phase sampling plane. The system analysis that shows the desired RF signal output is shown next.

The +1 diffracted optical field representing beam 1 at the output phase sampling plane is given by

$$\begin{aligned} E_{+1}(x, t) &\propto \exp\left\{-j2\pi \frac{\sin \theta_B}{\lambda M} x\right\} s_1\left(t - \frac{x}{Mv_a}\right) = \exp\left\{-j2\pi \frac{f_c}{2Mv_a} x\right\} \tilde{s}_1\left(t - \frac{x}{Mv_a}\right) \\ &= 0.5A_1 \exp\left\{-j2\pi \frac{f_c}{2Mv_a} x\right\} \exp\left\{-j2\pi [(f_c + f_s)] \left[t - \frac{x}{Mv_a}\right]\right\} \\ &= 0.5A_1 \exp\{-j2\pi (f_c + f_s)t\} \exp\left\{j2\pi \frac{f_c}{2Mv_a} x\right\} \exp\left\{j2\pi \frac{f_s}{Mv_a} x\right\} \end{aligned}$$

and the -1 diffracted optical field representing beam 2 at the output phase-sampling plane is given by

$$\begin{aligned} E_{-1}(x, t) &\propto \exp\left\{-j2\pi \frac{\sin \theta_B}{M\lambda} x\right\} \tilde{s}_2^*\left(t + \frac{x}{Mv_a}\right) = \exp\left\{-j2\pi \frac{f_c}{2Mv_a} x\right\} \tilde{s}_2^*\left(t + \frac{x}{Mv_a}\right) \\ &= 0.5A_2 \exp\left\{-j2\pi \frac{f_c}{2Mv_a} x\right\} \exp\left\{j2\pi (f_c - f_s) \left[t + \frac{x}{Mv_a}\right]\right\} \\ &= 0.5A_2 \exp\{j2\pi (f_c - f_s)t\} \exp\left\{j2\pi \frac{f_c}{2Mv_a} x\right\} \exp\left\{-j2\pi \frac{f_s}{Mv_a} x\right\} \end{aligned}$$

The photodetected current after heterodyne detection by a photodetector located at the sampler location x distance away such as PD2 from the $x = 0$ point can be written as

$$\begin{aligned} i(x, t) &\propto |E_{+1} + E_{-1}|^2 = |E_{+1}|^2 + |E_{-1}|^2 + 2\operatorname{Re}[E_{+1}^* E_{-1}] \\ &= K \left[A_1^2 + A_2^2 + 2A_1A_2 \cos\left\{2\pi(2f_c)t - 2\pi \frac{2f_s}{Mv_a} x\right\} \right] \end{aligned}$$

K is a constant that includes photodetector response plus other fixed photonic system parameters. $x = nd$ where $n = 0, 1, 2, 3, \dots, N - 1$. For the $n = 0$ location that corresponds to $x = 0$ position that is the PD1 reference-sampler location, the photodetected current can be written as

$$i(x = 0, t) = K(A_1^2 + A_2^2 + 2A_1A_2 \cos\{2\pi(2f_c)t\})$$

For the generation location of the n -th photodetector that corresponds to $x = nd$ position that is shown as the PD2 sampler location, the photodetected current can be written as

$$\begin{aligned} i(n, t) &= K \left(A_1^2 + A_2^2 + 2A_1A_2 \cos\left\{2\pi(2f_c)t - n2\pi \frac{2f_s}{Mv_a} d\right\} \right) \\ &= K(A_1^2 + A_2^2 + 2A_1A_2 \cos\{2\pi(2f_c)t - n2\phi\}) \end{aligned}$$

Here the inter-sampler optical or inter-antenna RF phase shift is written as $\phi = (2\pi 2f_s d)/(Mv_a)$ and the RF carrier is independent of the scan frequency f_s .

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5 When the distance between the SMFs is variable such as for a variable distance optical wireless data link, the photonic system shown achieves 100 percent inter-fiber coupling by using an electronically controlled variable focal length lens (ECVFL) with the fixed fiber-lens optic to form a distance dependent electronically controllable beam-forming optic so the Gaussian minimum beam waist always falls midway between the two SMFs.

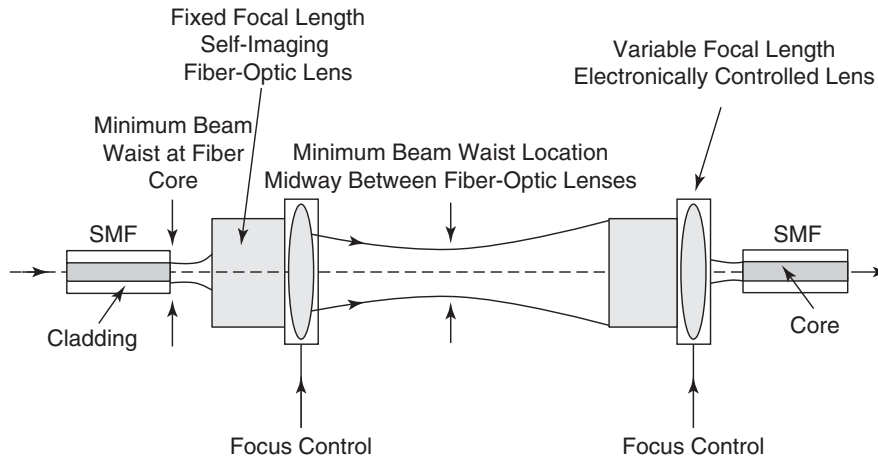


FIGURE PS.32

6 Figure PS.33 shows the desired VOA. Mirrors are used to loop the +1 order diffracted beam back into the AOD to produce a -1-order diffraction, thus cancelling the AOD Doppler shifts. A half-wave plate (HWP) is present in the loop to eliminate PDL effects in the VOA. Assume input light has both p and s components. The AOD diffraction efficiencies for p and s polarizations is η_p and η_s , respectively. Assume that the input irradiances for p and s states are I_p and I_s , respectively. $I_0 = I_p + I_s$. The first +1-order AOD diffraction produces

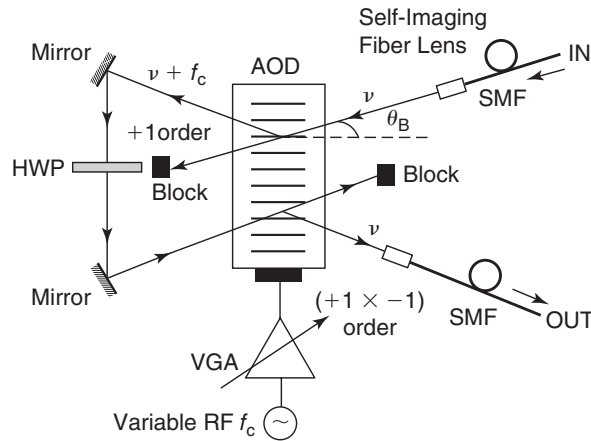


FIGURE PS.33

light with irradiance $\eta_p I_p + \eta_s I_s$. Then the HWP converts p to s and s to p polarizations. Next, these polarization switched optical beams undergo the second AOD diffraction to produce a beam with optical irradiance $\eta_s \eta_p I_p + \eta_p \eta_s I_s = \eta_s \eta_p (I_p + I_s) = \eta_s \eta_p I_0$. Hence regardless of the distribution of the p and s components in the input light, the VOA attenuation operation is PDL independent and simply a product of the total input irradiance and the diffraction efficiencies for both p and s components (i.e., no preferential attenuation for p or s components). The distance between the fiber lenses are design to satisfy self-imaging between the input and output ports. A compact VOA design is realized using the shown design.

7 Shown in Figure PS.34 is the desired MVOA. A TIR prism makes the s and p components of the input light to trace the same folded optical paths, making sure that there is no relative time delay between the two components to produce a zero PDD. In addition, this design preserves the PDL to zero as both components pass through the same optical components that provide attenuation.

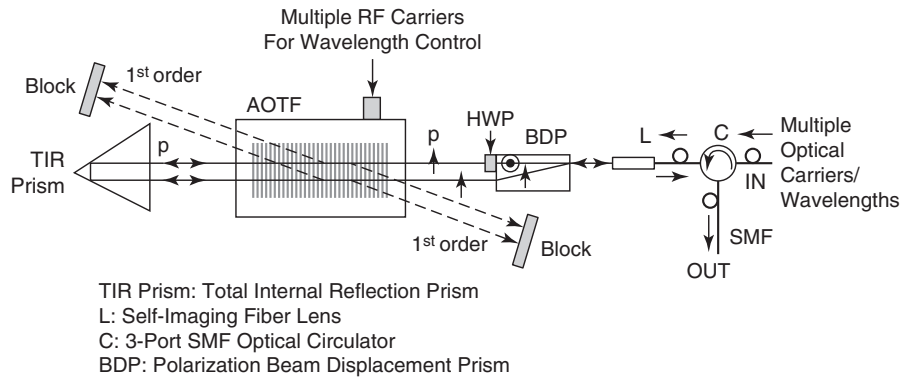


FIGURE PS.34

8 The shown photonic system in Figure PS.35 forms the desired RF filter using both the AOTF and a reflective SLM for spectral control that produces analog and digital controlled RF weight and time delay control for the RF filter taps. L is a spherical lens and C is a cylindrical lens. A transmission grating (such as a holographic thick-volume Bragg grating) is used to disperse the wavelengths provided by the spectrally modified-DC beam from the AOTF to undergo high-resolution spectral selection via the SLM. A variety of reflective SLMs can be used such as a binary state micromirror-based DMD or a liquid crystal-on-silicon (LCOS) phase-only SLM with beam steering control across the wavelength channels. For example, the DMD has typically 1000×1000 micromirrors so 1000 wavelengths can undergo spectral control with each wavelength having 1000:1 or 30-dB optical weight control. The LCOS SLM has similar attributes and can also deliver wavelength sensitive beam-forming to enable beam steered attenuation to the SMF. Hence, a powerful hybrid design RF transversal filter is formed.

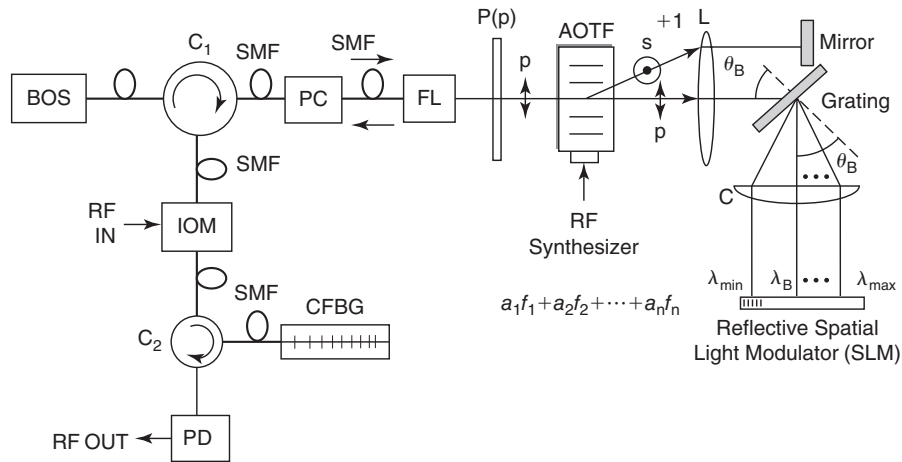


FIGURE PS.35

Chapter 8

1 Shown in Figure PS.36 is the desired VOA that eliminates the use of multistate TN-LC device operation and instead uses the stable two extreme states of the TN-LC device to form an all-digital operation VOA. The attenuation control is achieved using on/off control of pixels within a macro-pixel that controls the light passage for each independent polarized beam coming from the input BDP. The VOA operates in a full-closed fully open small windows mode that provides 100 percent repeatable settings for VOA attenuation.

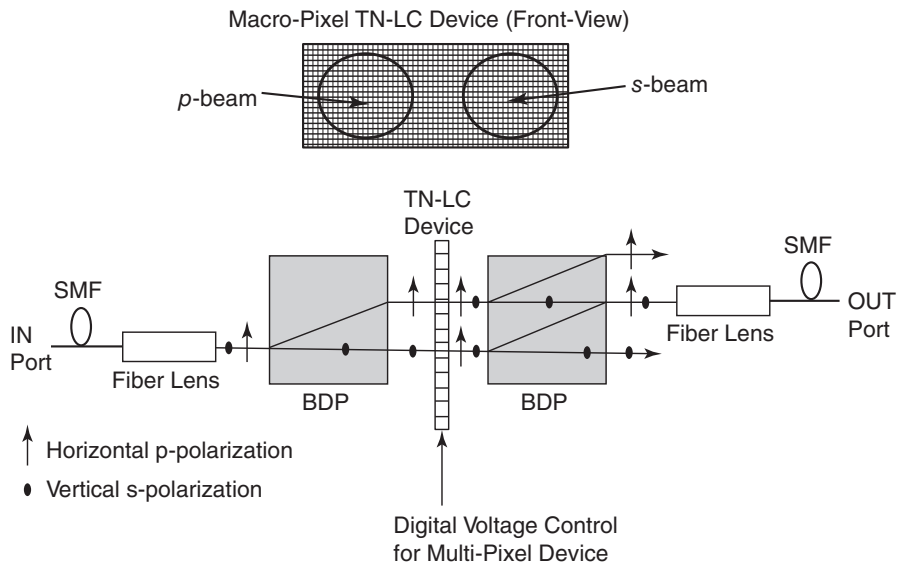


FIGURE PS.36

2 Shown in Figure PS.37 is the desired VOA that uses a single-fiber lens with two SMFs (also called a dual-collimator). The NLC deflector has its Nematic director either along the x -direction (p-polarization) or the y -direction (s-polarization). Assume that the nematic director is along the x -direction. Input p-polarized light when passing through the NLC deflector on its way to the quarter-wave plate (QWP) and mirror will suffer a voltage controlled beam deflection along the x -direction and no deflection on its way back as the QWP converts it to s-polarized light. On the other hand, input s-polarized light when passing through the deflector on its way to the quarter-wave plate (QWP) and mirror will not suffer a voltage-controlled beam deflection along the x -direction and has a deflection on its way back as the QWP converts it to p-polarized light. Hence, input light will undergo beam deflections that will reduce light coupling into the output SMF. Hence, a single lens analog-mode VOA is formed.

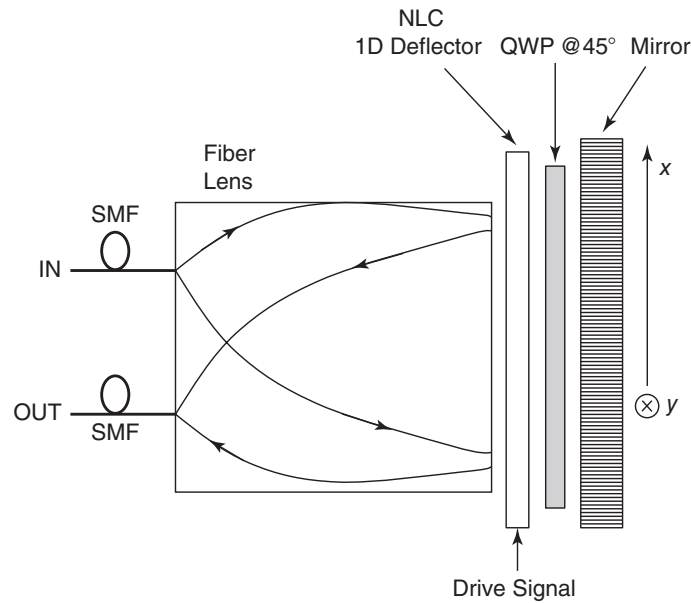


FIGURE PS.37

3 Shown in Figure PS.38 is the desired 1×2 switch where the two state voltage-level driving the NLC deflector controls which output port is the input light directed to for implementing 1×2 switching. The basic operation of the switch is similar to the Problem 2 solution.

4 Shown in Figure PS.39 is the desired 1×2 variable tap coupler. Here, the NLC deflector is a multipixel beam steering device where some pixels in the device operate on a specific part of the beam (e.g., contains 10 percent of the input light power) to deflect it to the chosen output port (the tap port where 10 percent of input is present) while the remaining part of the beam (e.g., contains 90 percent of the light input power) is controlled by the other pixels in the device to send it to the other output port (the main port). The basic operation of the coupler is similar to the Problem 3 solution.

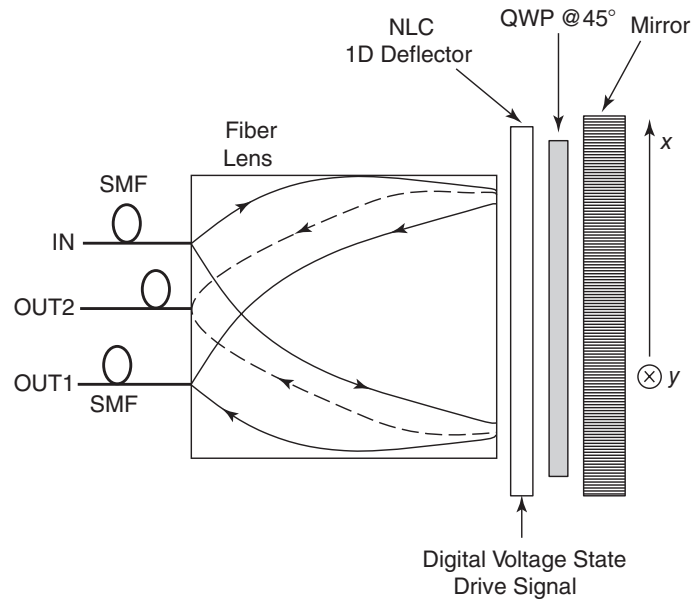


FIGURE PS.38

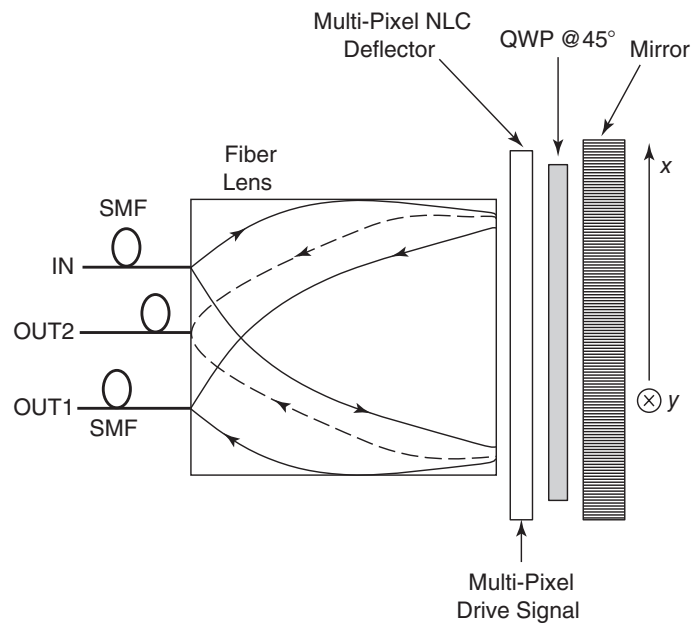


FIGURE PS.39

5 Shown in Figure PS.40 is the desired system that is identical in design to the one in Figure 8.5 in the chapter. Proper optical phase programming of the 2D NLC in the system can lead to optical phase and amplitude conditioning of the spectral optical components. Shown is the case of a pulse containing three wavelengths. The black and white bars show the locations of the three wavelengths spatially on the multipixel NLC phase-only SLM. The bars all have equal heights and widths indicating the spectrum in the pulse is in this case, uniformly distributed. The black bar regions indicate the zones where the NLC SLM is programmed to provide an optical wedge phase ramp to steer the optical beam so it has no optical coupling with the fiber-lens on the lights return path. The white bars indicate the regions where a uniform optical phase is imparted on the different wavelengths. This phase for each white bar can be different. The size of the black bars determines the spectral component attenuation control. The remaining vertical region per wavelength is the light that is returned for pulse recombining with appropriate phase imparted to the beams.

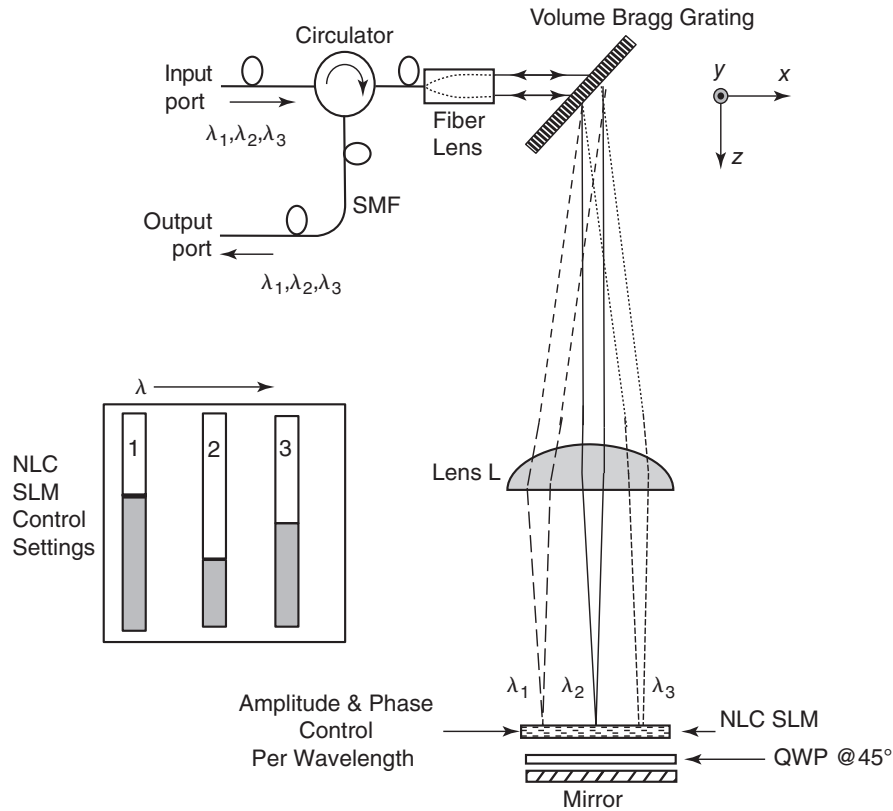


FIGURE PS.40

6 Shown in Figure PS.41 is the desired RF filter system. The notation used is the same as for the optical DMD-based RF filter discussed in Chapter 6. The key point is that a transmissive NLC SLM operating in phase mode is used to select the wavelength hence time delays for the filter taps. In addition, filter tap amplitude weights are also selected via the NLC SLM using its beam

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spoiling optical wedge mode to change the amount of light from a particular wavelength that is coupled back to the fiber lens and SMF. Recall that BOS: Broadband Source; IOM: Integrated-Optic RF-to-Optical Intensity Modulator; L: Cylindrical Lens; CFBG: Chirp Fiber Bragg Grating; I: Interleaver; PD: Photodetector; G: Grating; DA: Differential Amplifier; C: Optical Circulator.

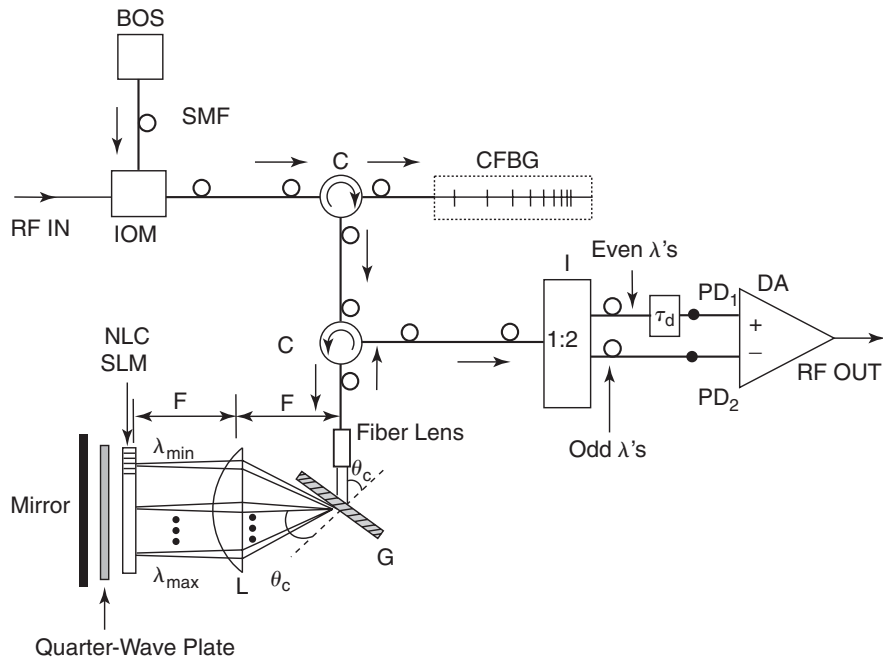


FIGURE PS.41

7 Shown in Figure PS.42 is the desired TDU design. The TN-LC device on/off state controls which path the input light takes to get the desired relative optical delay. Such delays are useful in constructing photonic signal processing

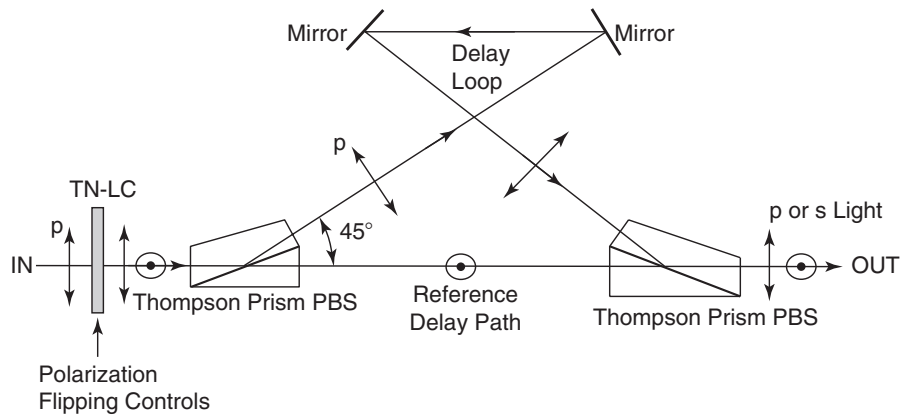


FIGURE PS.42

systems. The mirror distances can be adjusted to control delay length. Solid optics can be placed in the paths to make higher compactness module designs.

In case the module should interconnect with SMFs, the shown connector design in Figure PS.43 will achieve the goal of having p-polarized light at the input to the module. This is done using a fiber lens, a beam-displacing prism (BDP) polarization crystal, and a half-wave plate (HWP) to rotate s- to p-polarization. Hence two parallel adjacent p-polarized beams interface with the freespace-coupled TDU.

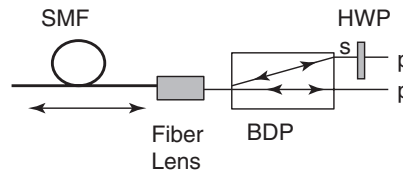


FIGURE PS.43

8 Shown in Figure PS.44 is the design of the desired RF transversal filter using a P-channel N-bit variable Optical TDU built by cascading several 1-bit TDUs such as shown in Figure 8.10. The last LC array device acts as P VOAs to implement weight control for the P optical-taps of the P-tap RF filter. The LC switching devices in the TDUs have p -pixels to route the p -beams that carry P time delayed RF signals. Note that since the P optical beams come from the same laser and incoherent optical summation is required at the photodetector, an optical random phase noise generation device (e.g., a P-pixel optical-phase mode LC device) or an optical light diffuser is used to randomize the relative optical phase between the adding optical beams. The photodetector output produces the sum of the weighted

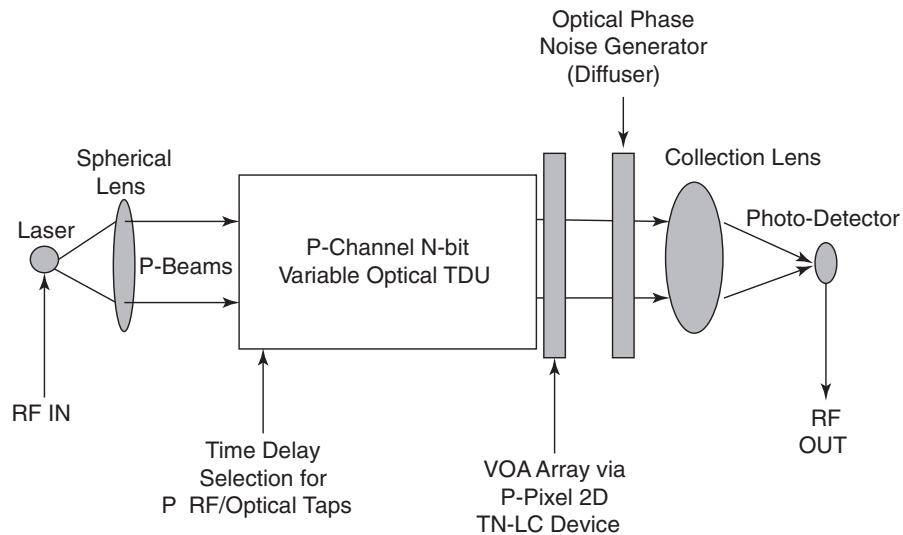


FIGURE PS.44

time delayed tap signals to form the RF transversal filter. Since an LC device can easily have 10,000 pixels, a 10,000 tap-filter is realized. In addition, cascading 10 of the TDUs will provide 10-bits of variable optical/RF time delay to choose from for RF tunability of the filter.

9 The Figure PS.45 shows the desired fast x - y beam deflector using three FLC devices, two fixed power birefringent wedges, and two polarizers. The two birefringent material wedges are placed with their deflection axes orthogonal to each other so deflection are possible for both the x - and y -output beam directions. Both wedges have the same angular beam deflection power and hence an equal spaced four-spot beam deflection is realized. Note that the fixed angular deflection power wedges can be replaced by electronic wedges such as made of NLC devices to form a hybrid analog-digital two-axis-beam deflector.

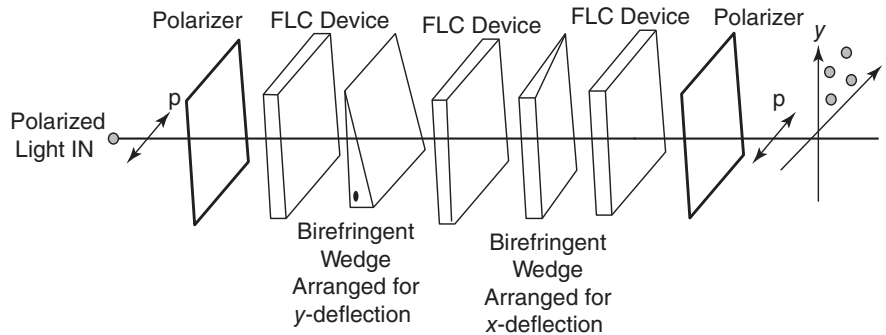


FIGURE PS.45

10 Shown Figure PS.46 is the desired photonic system. A broadband optical source (BOS) is used as an alternative optical source so all wavelengths can be provided instantaneous. If specific choice of instantaneous wavelengths is desired, a tunable optical filter (like a DMD based equalizer) can be used to select the desired wavelengths to produce the desired multiple beams that illuminate the test object. 1×2 optical switches are used to select between the time sequenced scanning mode and instantaneous scan mode. A PD array (e.g., CCD chip with one temporal line scan signal output or a high speed PD array with a parallel independent multiple signals output) coupled with a wavelength dispersive element (e.g., grating) is used to form an instantaneous optical spectrum analyzer (OSA) to read data on all wavelengths at the same time.

11 Shown in Figure PS.47 is the desired solution that uses a single wavelength-laser source and replaces the $1 \times N$ WDM device with a $1 \times N$ SMF optical switch that implements space multiplexed scanning and imaging.

12 Shown in Figure PS.48 is a 2D W-MOS design that uses N tilted 3D holographic gratings to produce N 2D steered beams in space. Each wavelength is Bragg matched to only one grating. Another way to form a 2D W-MOS is to use two cascaded grating devices with the grating axis orthogonal to each other. These gratings are custom design such that one grating is sensitive to small wavelength changes while the other grating is not sensitive to small wavelength changes (in

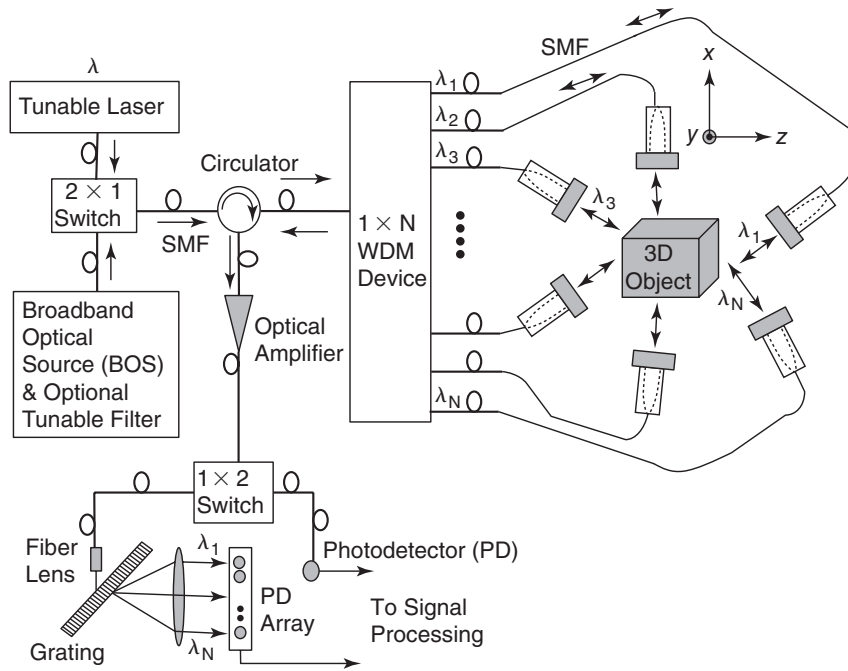


FIGURE PS.46

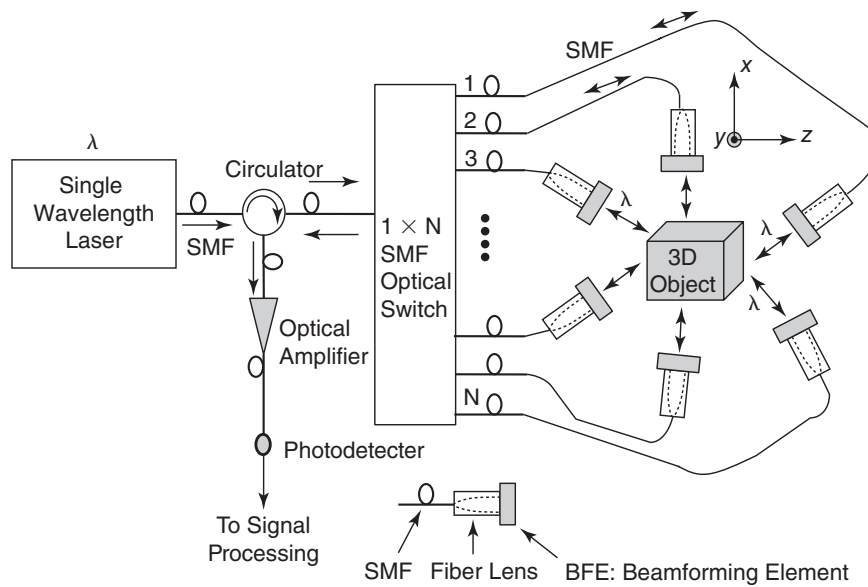


FIGURE PS.47

other words this grating is sensitive to large wavelength changes). Hence, choice of coarse wavelength can set the x -scan direction while choice of the fine wavelength can set the y -scan direction. Recall that gratings because of their periodic structure exhibit a wavelength-based response that is periodic in wavelength.

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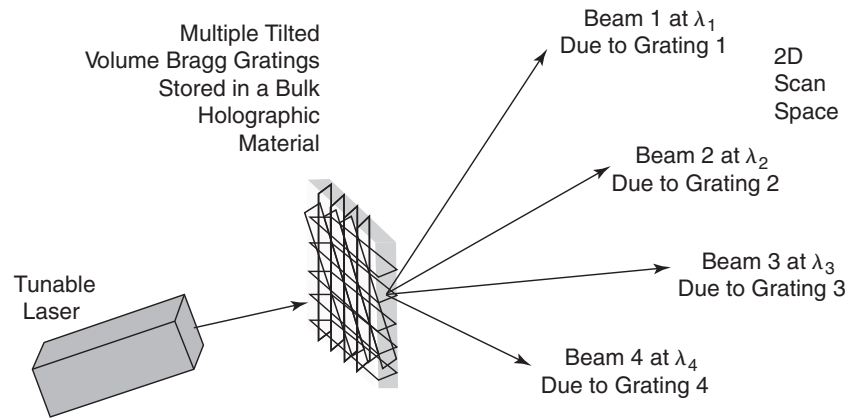


FIGURE PS.48

13 Shown in Figure PS.49 is the Code Multiplexed Optical Scanner or C-MOS based on holography. 3D scan requires the creation of beams in 3D space. This means an input beam should be scanned in the x -, y -, and z -directions. X-Y are the standard 2D tilts, but the z -scan is the beam focus/defocus control

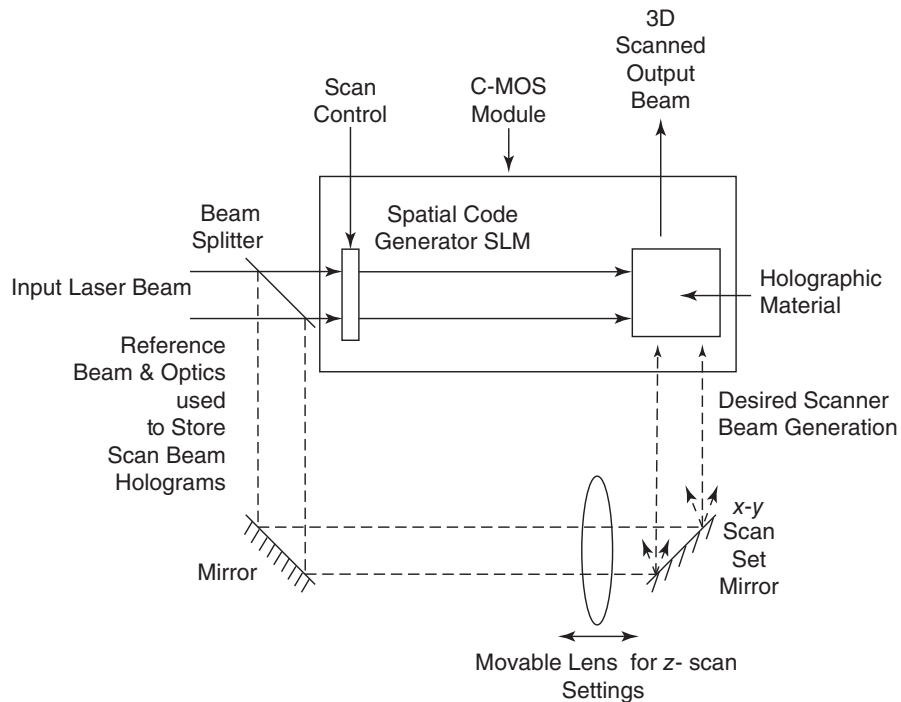


FIGURE PS.49

so a voxel or 3D volume element with a minimum 8 points is created in 3D space. The beauty of holography is field recall capability. In other words, when a hologram is formed and recorded with optical fields C and B, both full C and B field information is stored in the interference pattern in the hologram. Now if this hologram is exposed by the exact input field, say the C field, then the hologram diffracted beam exactly produces the stored B field. The same works when the B field acts as the input beam, then the output beam is the C beam. One can design a C-MOS by using different spatial coded beams to represent the reference C beams while using the desired 3D scanned beams created by tilted mirror and variable focal length lens optics to make the B beams. One must use spatial codes that are orthogonal to each other so when a read beam with a given code is input to the hologram, only the desired scan beam exits the hologram. In such a way, a powerful hologram based 3D C-MOS is realized.

14 Shown are two designs for the W-MOS based scanner. The design in PS.50 uses an off-axis bar code reading via scattered captured light while the design in PS.51 system requires higher precision alignment for on-axis no-scattered retro-reflective light reflection from the bar codes. Components labeled as G: Diffraction Grating; FL: Fiber Lens; BS: Cube Beam Splitter; PD: Photodetector; SMF: Single-Mode Fiber; F: Focal Length of Focus Lens.

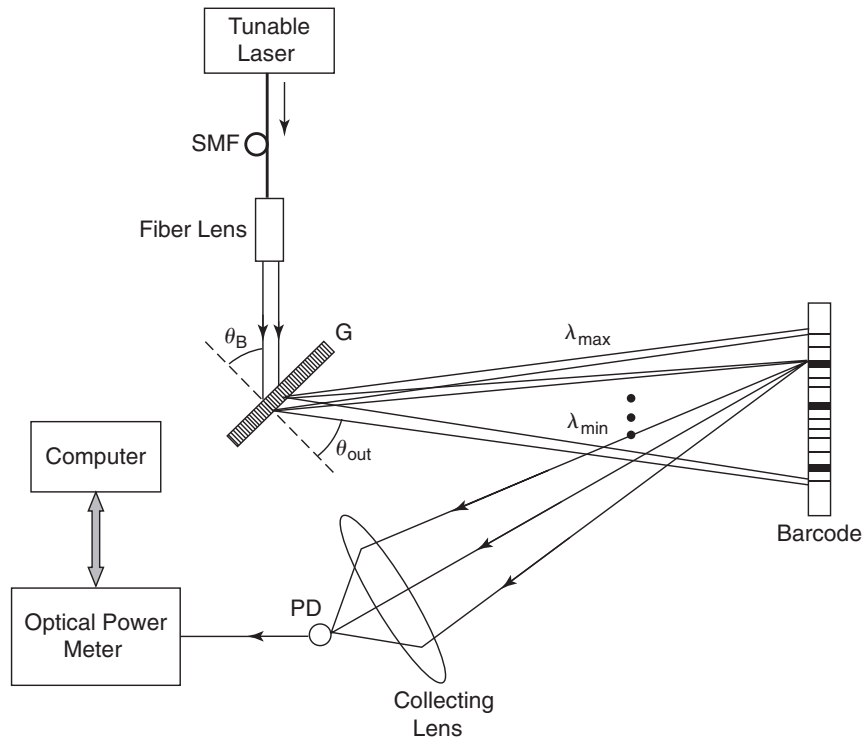


FIGURE PS.50

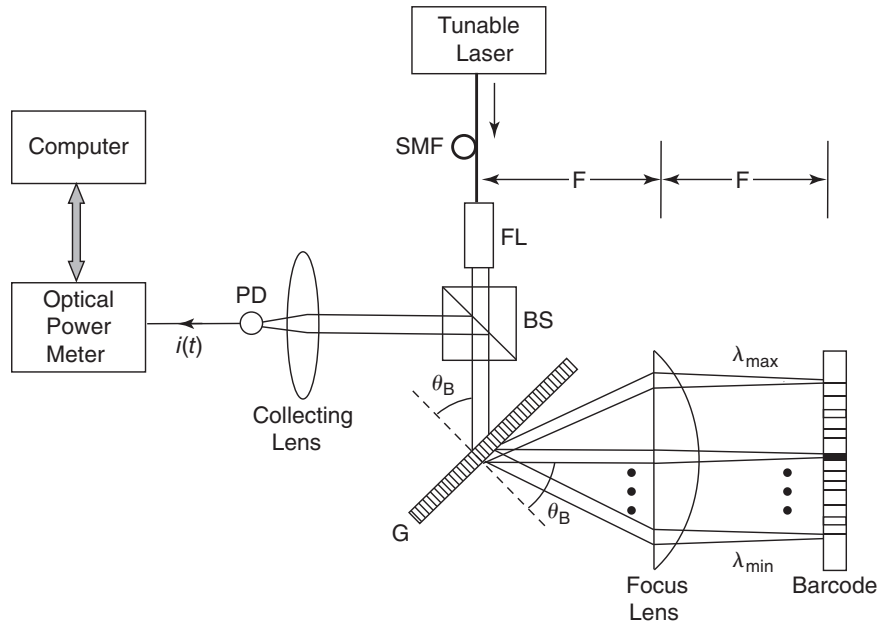


FIGURE PS.51

15 Shown in Figure PS.52 is the desired confocal microscope that does not require objective lens or sample motion to achieve 3D confocal imaging. The key design innovation is the use of a weak Dioptric power ECVFL (e.g., a NLC lens) in cascade with the high power (short focal length high NA: Numerical Aperture) objective lens to form a smart objective. The combined power of the two-lens assembly is simply the sum of the Dioptric powers of the two

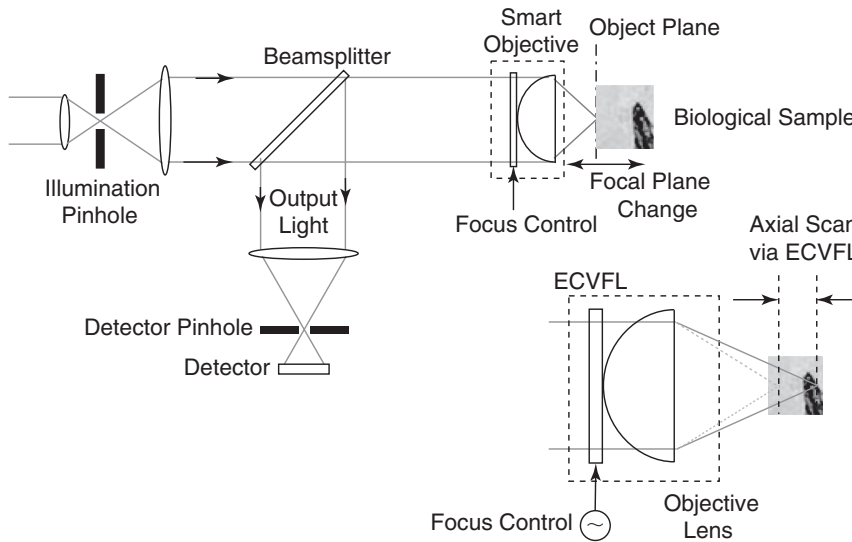


FIGURE PS.52

lenses. Electronic control of the weak lens focal length will move the focal spot over the specimen thickness zone and typical ranges are under $500\text{ }\mu\text{m}$, highly suited for weak lensing via an NLC ECVFL. In plane x - y motion of the focal spot on the test sample is achieved via x - y tilt motion of a mirror that interacts with the input light beam that is the source of the confocal microscope. Such an agile focal length microscope design applies to both single wavelength and broadband coherent light microscopy methods including systems that use coherent optical interferometric detection for 3D imaging.

16 Shown in Figure PS.53 is the desired 2×2 SMF-based optical switch design that uses two liquid lenses. With voltage on shown in (a), the liquid lenses bend the input light towards the lens focus, causing the beam switching operation. Each ECVFL has an on-state focal length of F with the two ECVFLs separated by a distance of $2F$. With no voltage applied as shown in (b), the beams pass through the liquid lenses as though passing through a clear piece of glass.

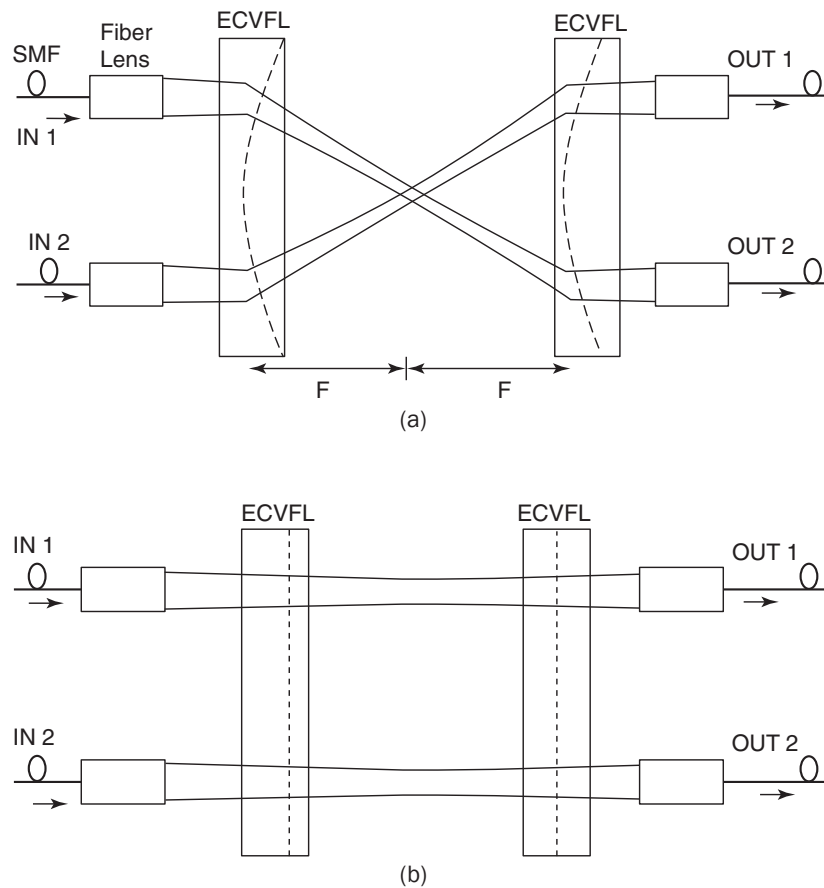


FIGURE PS.53

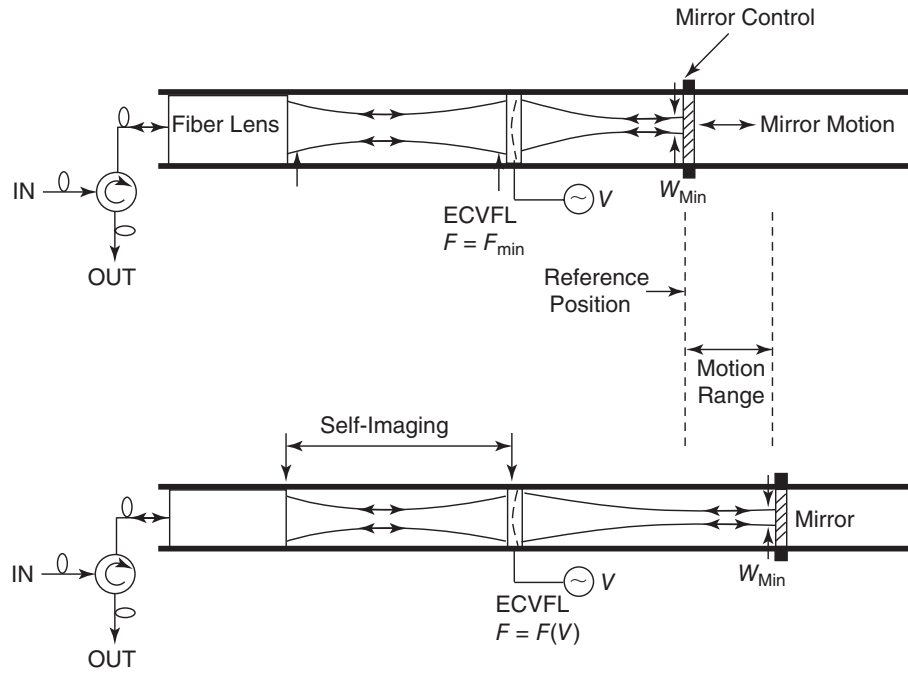


FIGURE PS.54

17 Shown Figure PS.54 is the desired low-loss variable optical delay line for broadband light using mirror motion in a long tube-like guide where a magnetized broadband mirror can be moved using external magnetics. The key innovation is that an ECVFL such as a liquid lens adjusts its focal length so the Gaussian beam returning to the SMF-fiber lens achieves high optical coupling via the self-imaging effect. As shown in the Figure PS.54, when the mirror is moved to change the delay, the ECVFL focal length is adjusted electronically to maintain efficient beam coupling with the fiber lens and SMF.