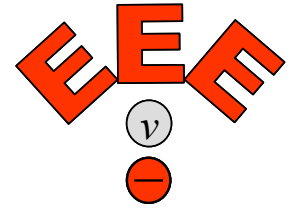




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University College Cork, Ireland



Liquid Crystal Agile Photonics – From Fiber to the Free-Space Domain - A Review

by
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Ref: N. A. Riza, Photonic Signals and Systems – An Introduction, McGraw Hill, 2013.

Topics Covered using Agile (i.e., Programmable) Liquid Crystals Includes:

- History and Material Fundamentals**
- Fiber-Optic Switches, Attenuators, Filters**
- RF Phase Shifters, Time Delay Units,
Attenuators, Filters, Beamformers**
- Optical Imaging Endoscopes and
Microscopes**
- Optical Scanners (1-D, 2-D, 3-D)**
- Optical Lenses (Focus/Defocus Control)**
- Optical Spectrum Shapers**
- Optical Beam Profilers/Imagers**

What are Liquid Crystals (LCs)

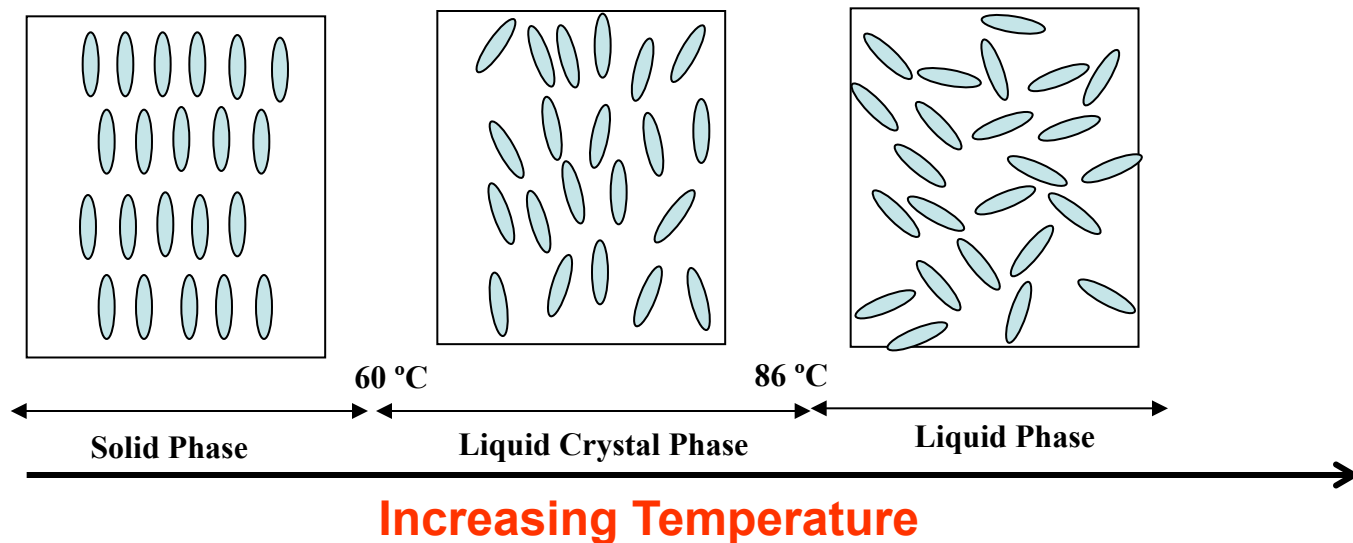
The Classic 3 States of Matter are Determined by the Degree of 3-D Spatial Positional and Orientational Order of the Molecules

- Solid (Higher Order – Tightly Positioned and Oriented)
Crystalline (Fixed Pattern of Molecules) and Amorphous Solids (No Pattern)
- Liquid (Medium Order- Very Loosely Positioned & Oriented)
- Gas (Low Order- Not Positioned – Free Molecular Motion)

LCs can be considered the 4th State of Matter

Between a Solid and Liquid State Determined by Material Temperature

(No Positional Order and Some Orientational Order)
More Like Liquids than Solids



What are Nematic Liquid Crystals (NLCs)

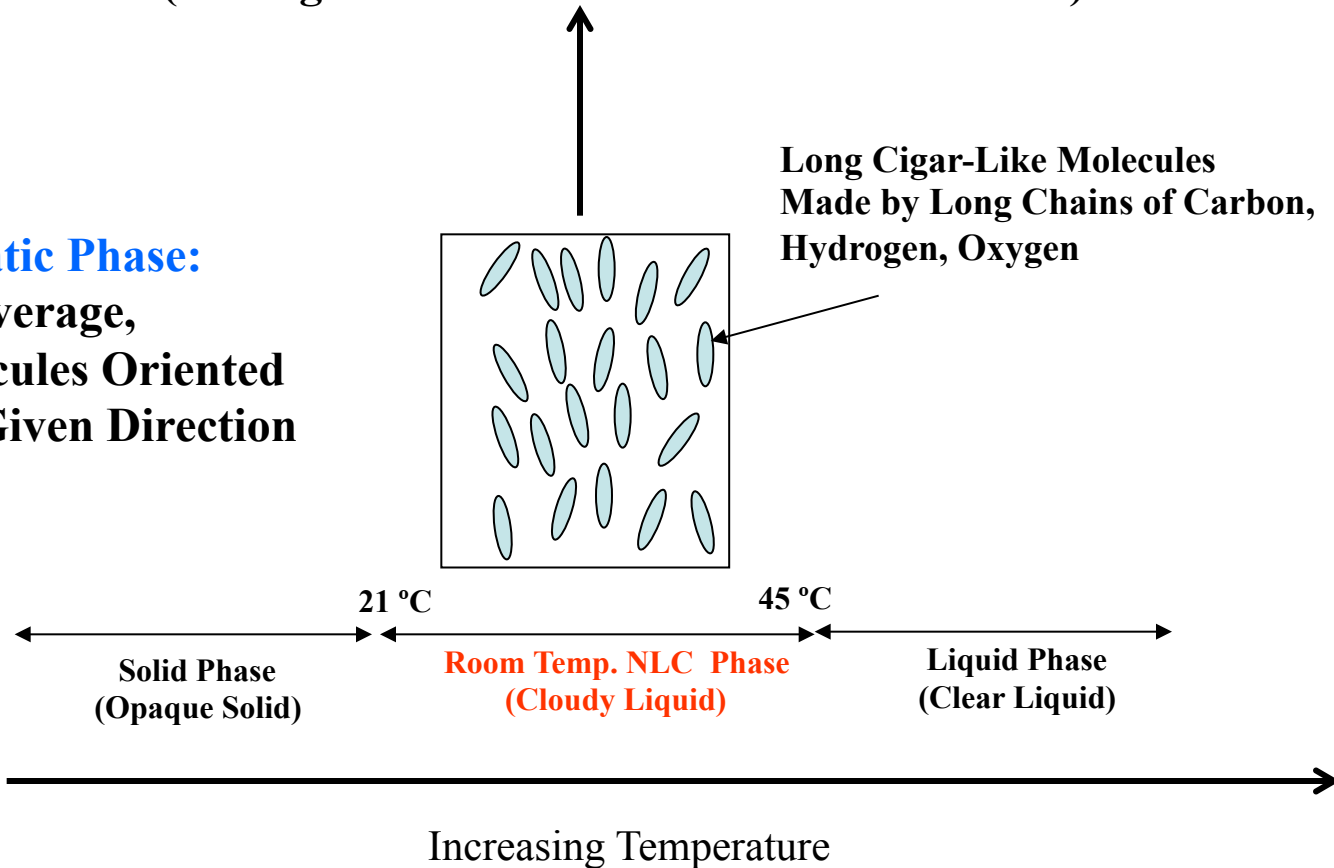
Nematic - *In Greek means Thread*

**Arrow Represents Nematic Director
(Average Direction/Orientation of Molecules)**

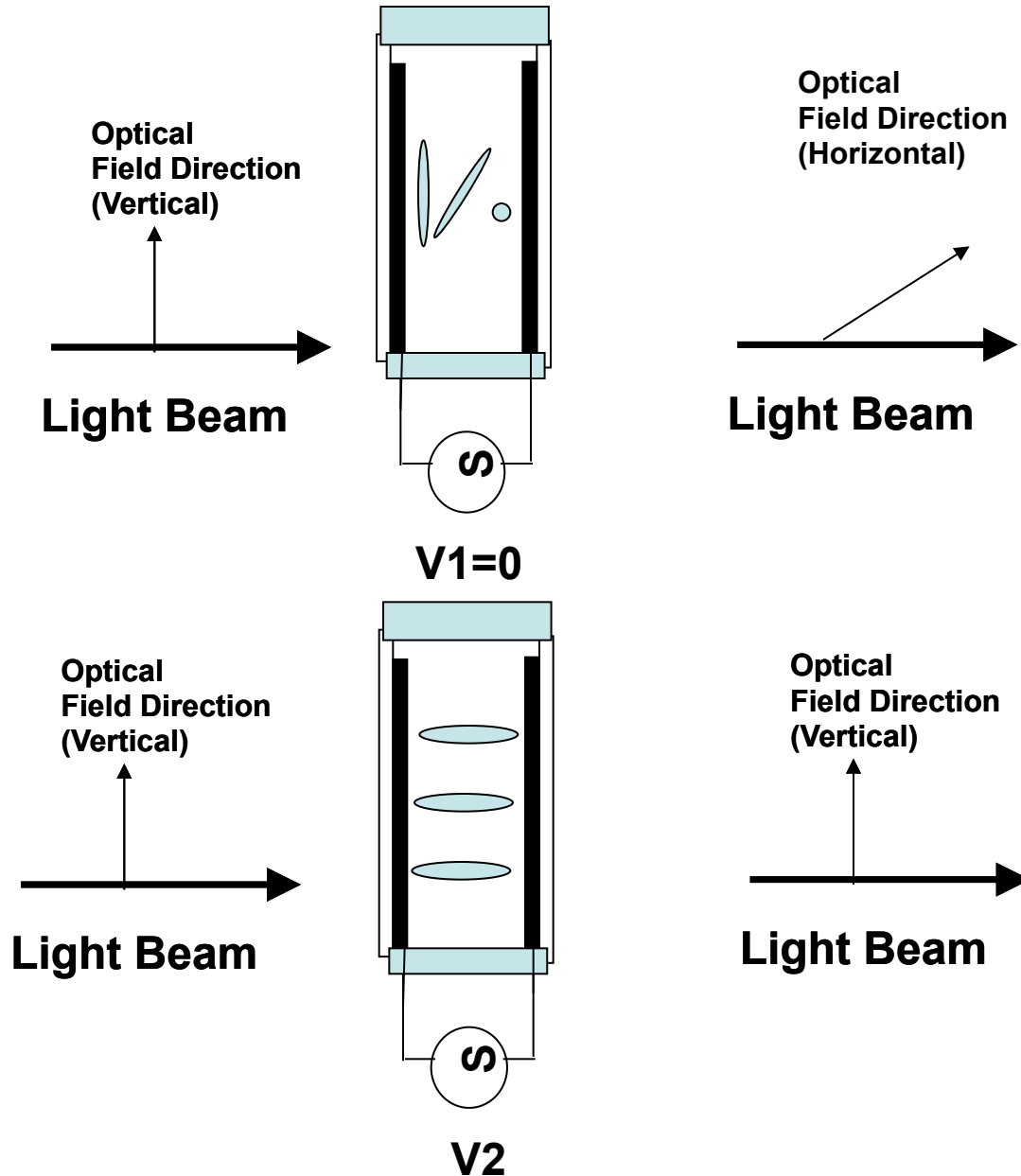
Nematic Phase:

**On Average,
Molecules Oriented
in a Given Direction**

**Long Cigar-Like Molecules
Made by Long Chains of Carbon,
Hydrogen, Oxygen**



Basic NLC Device- 90 degree Twist Mode



LC History – The Human Touch

Austrian Botanist **Friedrich Reinitzer** is Credited with the Discovery of LCs in 1888 - Observed Two Melting Temperatures for Cholestrol (a Chiral NLC phase) in Plants

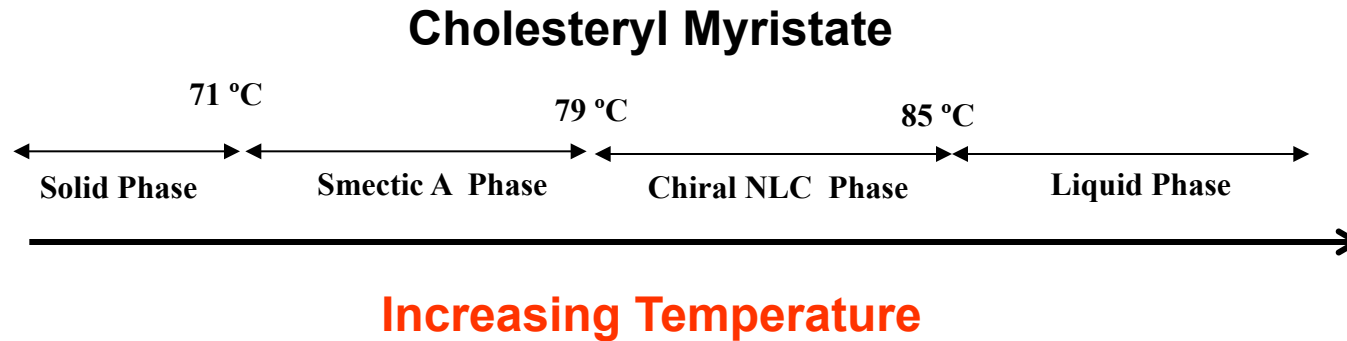
German Physicist **Otto Lehman** invented and developed a Polarization Microscope (1850-1888) with a Material Heating Stage to Study Properties of LC Materials –The instrument was critical to the study of LCs.

French Scientist **Georges Freidel** 1922 paper described the different Liquid Crystal Phases.

Swedish Scientist **Carl Oseen** and English Scientist **F. C. Frank** between 1922-1939 developed the elastic and continuum theory for LCs

American Scientist (1969) **James Fergason** , German Scientist **Wolfgang Helfrich** (1970) and Swiss Scientist **Martin Schadt** (1970) co-pioneered Twisted NLC displays (Early R & D /TN-NLC Devices at RCA and GE Research Labs)

Various Temperature Dependent LC Phases



Nematic: On the average, the molecules are oriented along one direction

Chiral (*Greek for Handedness: Twisted*) NLC: The Nematic Director undergoes a periodic Twist about a horizontal axis

Smectic (*Greek for Soap*) A: (Molecules arranged in layers with molecular director at 90° to Layer Planes)

Smectic C: Molecules arranged in layers with molecular director not at 90° to Layer Planes

Chiral Smectic C* (Ferroelectric/FLC Phase): Like Smectic C except the Titled Director rotates from one molecular layer to another layer, tracing a cone of a fixed angle with 1 complete rotation called a pitch or distance between layers.

(The FLC Phase maintains Molecules with a Permanent Inherent Dipole Moment- Sensitive to Direction of Electric Field)

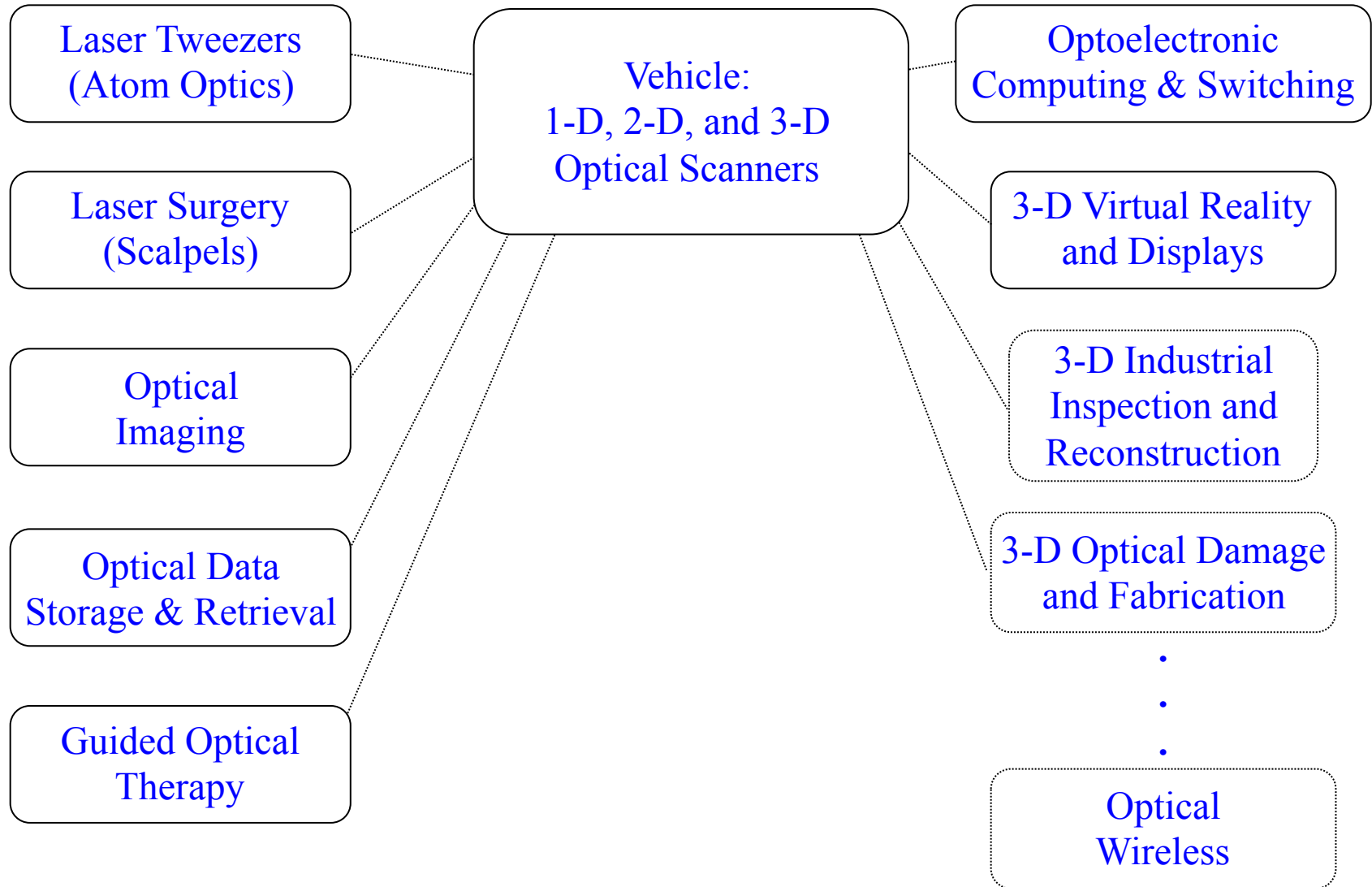
Liquid Crystal Devices – Why Engineers Use Them?

- **Reliable** -- Repeatable Electrical and Optical Control
- **Volume Manufacturing** – Cost Effective
- **Power Efficient Thin Films** – Low Electrical Power Penalty
- **Large Planar Designs** – Engage Well with Large Free-Space Optics
- **Small Planar Designs** – Engage Well with Compact Fiber-Optics
- **High Density Planar Designs** – Many Pixels to Control – Gives Intelligence
- **Hybrid Optical-Electronic Planar Design** – Control Electronics on Same Substrate
- **Planar Device Optics and Electronics** – Good Form Factor for Stacked Packaging

Liquid Crystal Devices – Still an Engineer's Challenge

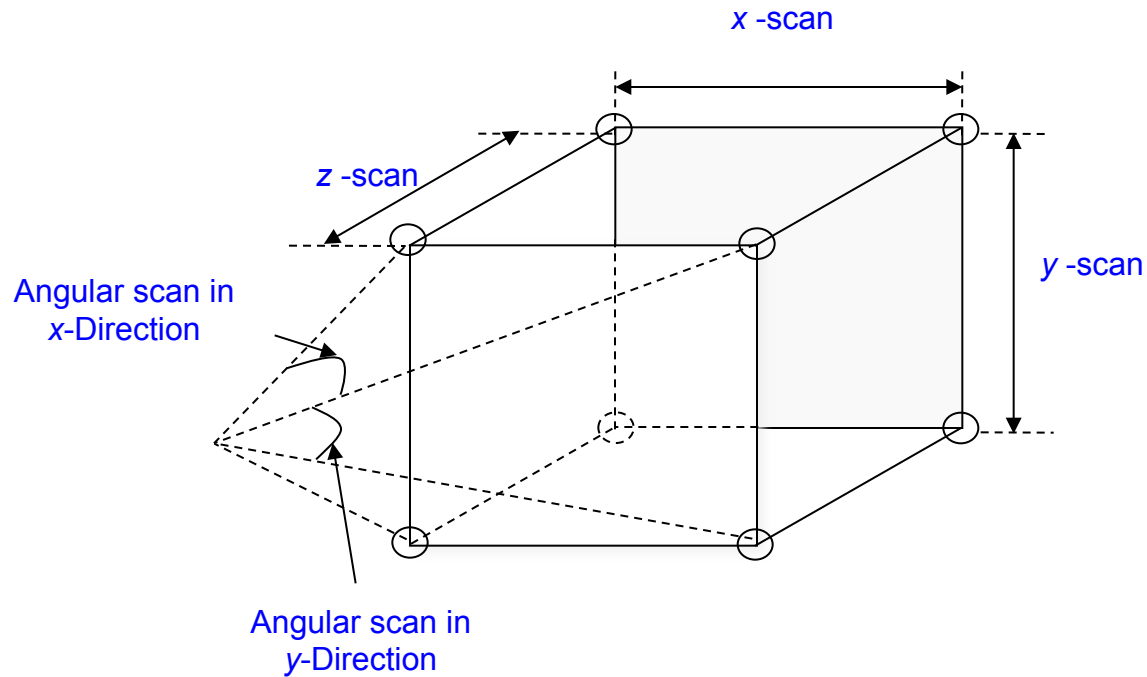
- **Reliable** -- Increase Device Lifetimes
- **Volume Manufacturing** – Lower Costs Further for Improved Performance
- **Power Efficient Thin Films** – Lower Electrical Power Penalty
- **Large Planar Designs** – Increase Size of Planar Substrates – Larger Displays
- **Small Planar Designs** – Smaller Size and Higher Density – Micro-Displays
- **Polarization Control**– Improve Polarization Extinction Ratios – Noise Reduction
- **Polarization Sensitivity** – Eliminate Polarization Dependence in Fiber-Optical Design
- **Device Controls** – Make Faster Response Speed and Electronics Friendly (lower voltage) Devices

Free-Space Domain Light Applications



3-D Optical Scanning

8-Point Motion of Light-The Basic Element is a Voxel of Volumetric Scanning



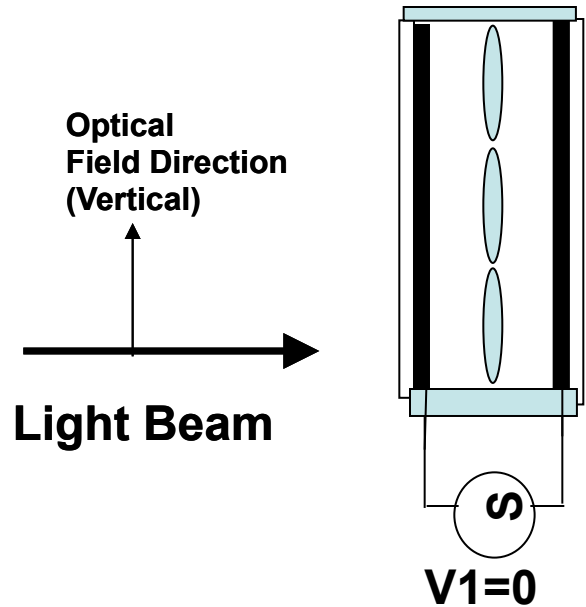
A Key Focus Application: Example Scanner Requirements for Wireless Laser Communications

Parameters	Laser Communications
Wavelength Range	1500 nm Band
Laser Damage Threshold	Tens of mW
Scan Range (degrees)	$\geq \pm 45^\circ$
Beam Pointing Resolution	$< 0.1 \text{ mrad}$ ($< 0.006 \text{ degrees}$)
Number of Beams (Scan Spots)	$\geq 1,500$
Pt. to Pt. (Linear Access) Time	$< 25 \mu\text{s}$
Pt. to Pt. (Random Access) Time	$< 100 \mu\text{s}$
Loss	$< 50\%$
Scanner Aperture (Exit Beam Diameter for $< 0.1 \text{ mrad}$ divergence)	2 cm
Range	500 m – 3 km

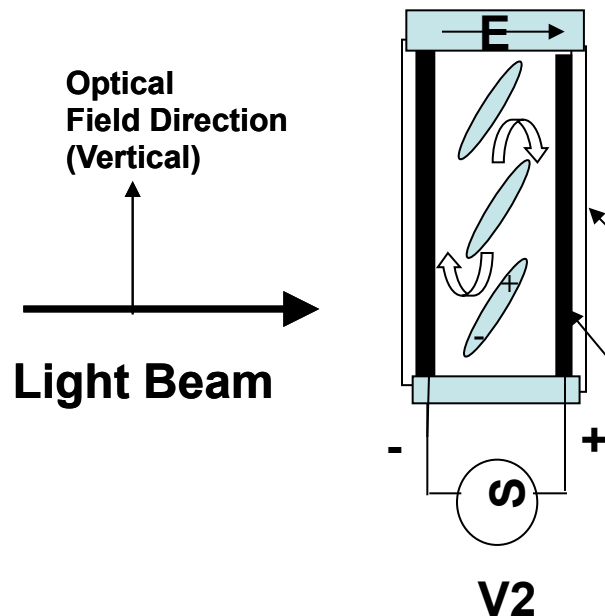
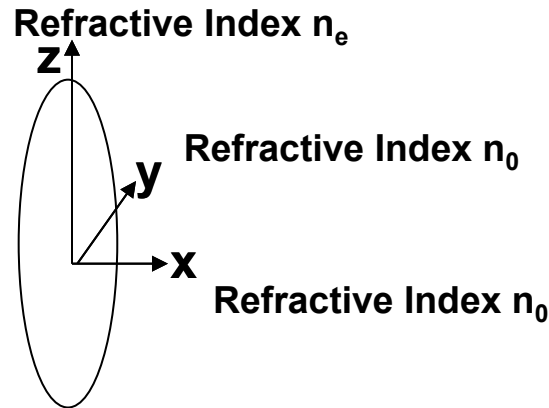
Can We Use Polarization Multiplexing to Simultaneously Enable ?

- 3-D Beam Fine Power Manipulation
- Electrically Reconfigurable Beamforming Scan Optics
- Clear Aperture (No Pixelation) → No Diffraction Losses
- Same Beam Setting Time For Scanning Any Position In Space
- Modular And Scalable Scanner Architecture
- Simple Control → Unprecedented Repeatability

Basic NLC Device- Parallel-Rub Birefringent Mode (Optical Phase Shifter)



Refractive Index n_e seen by Optical Field



External Electric Field Induces a Dipole Moment In the NLC Molecules that rotates the molecular Director towards the E-Field Direction

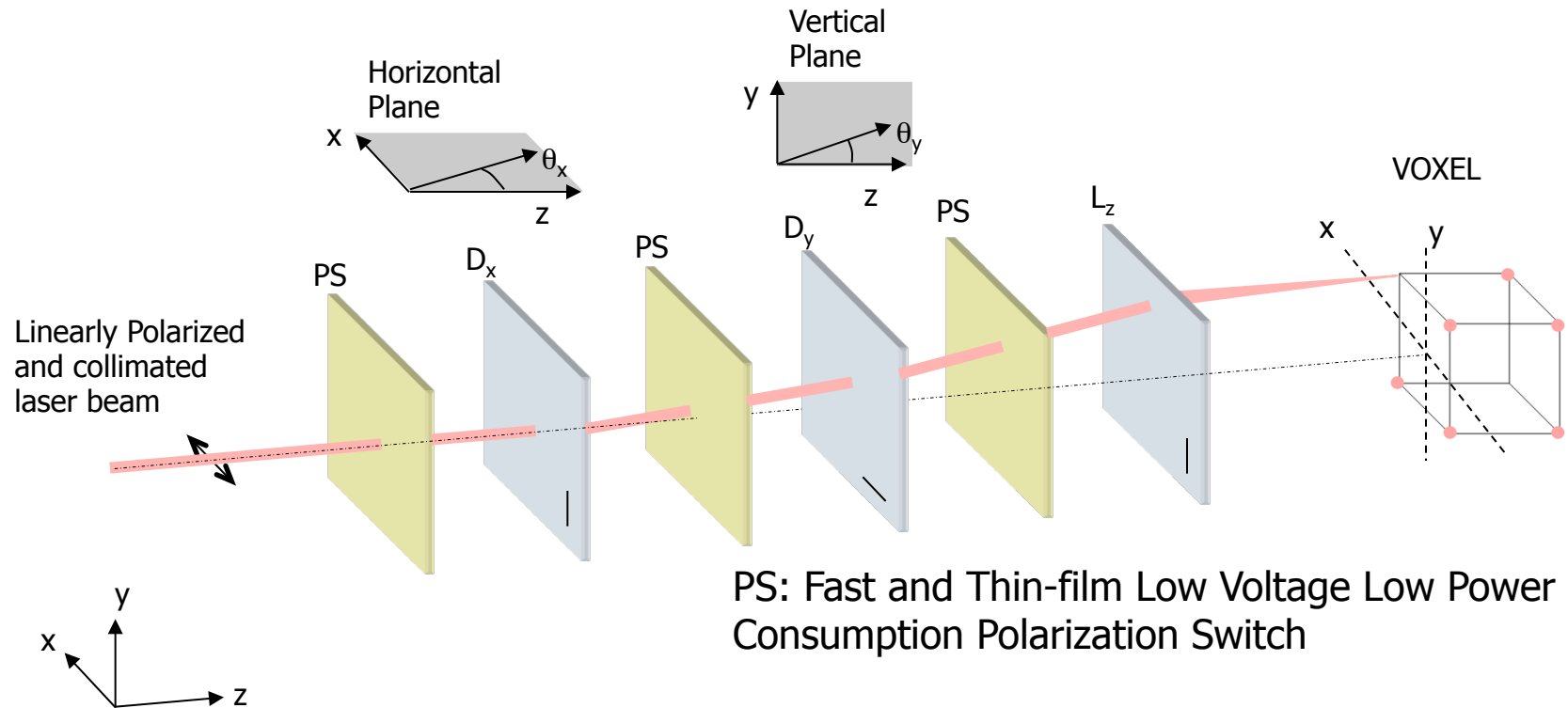
Voltage Dependent Refractive Index $n(V)$ Seen by Optical Field

Glass

Electrode (ITO: Indium Tin Oxide)

- Electric Dipole Moment per Unit LC Volume = LC Electric Polarization P
- External E Field and LC Polarization P are directly connected by the LC Refractive Index $n(V)$ Seen by the Optical Field

Full Programmability Polarization-Multiplexed Optical Scanner (Single VOXEL Scan Design)



PS: Fast and Thin-film Low Voltage Low Power Consumption Polarization Switch

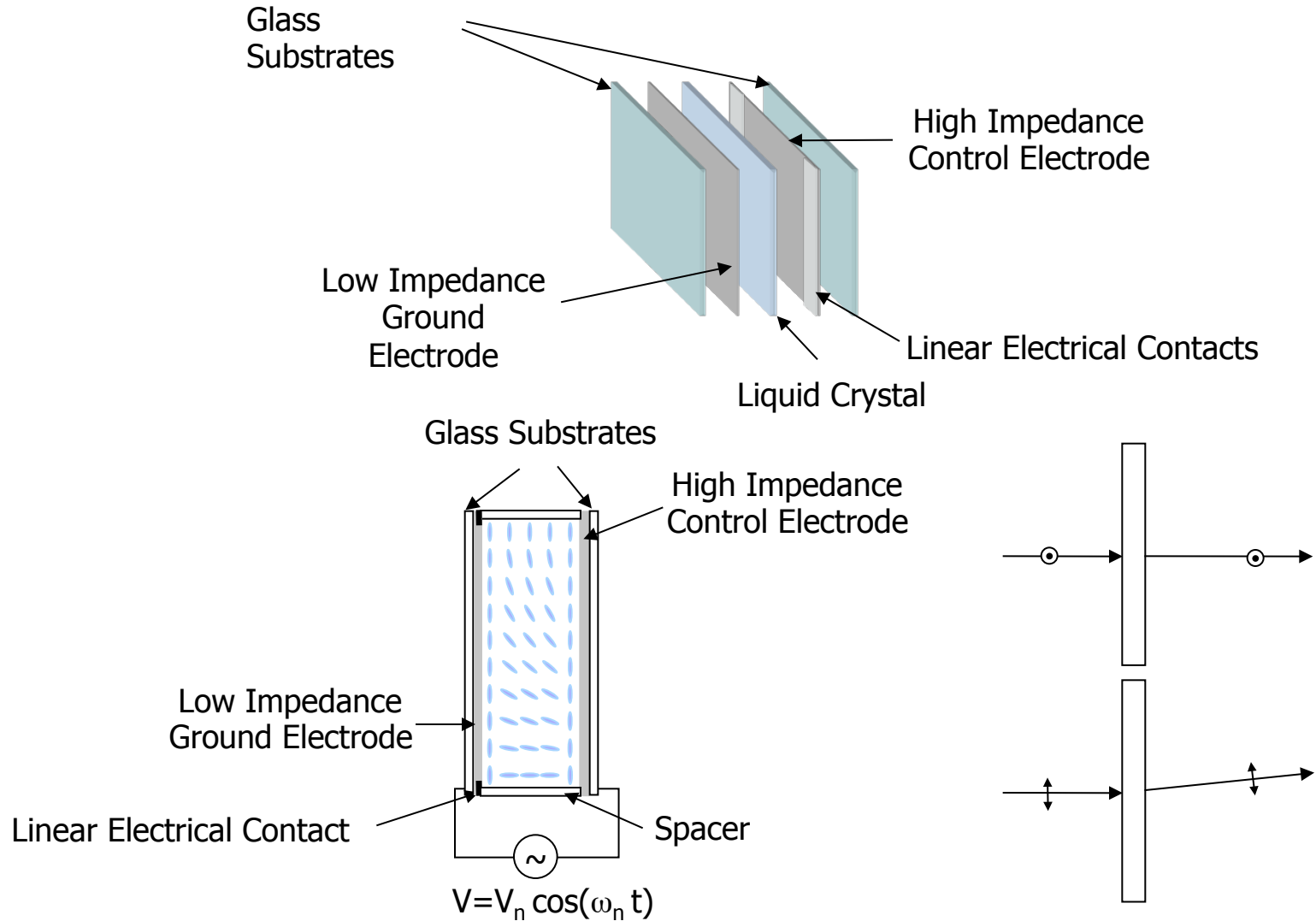
D: Electrically Reconfigurable Non-Pixelated Birefringent Beam Deflector Device

L: Electrically Reconfigurable Non-Pixelated Birefringent Lens Device

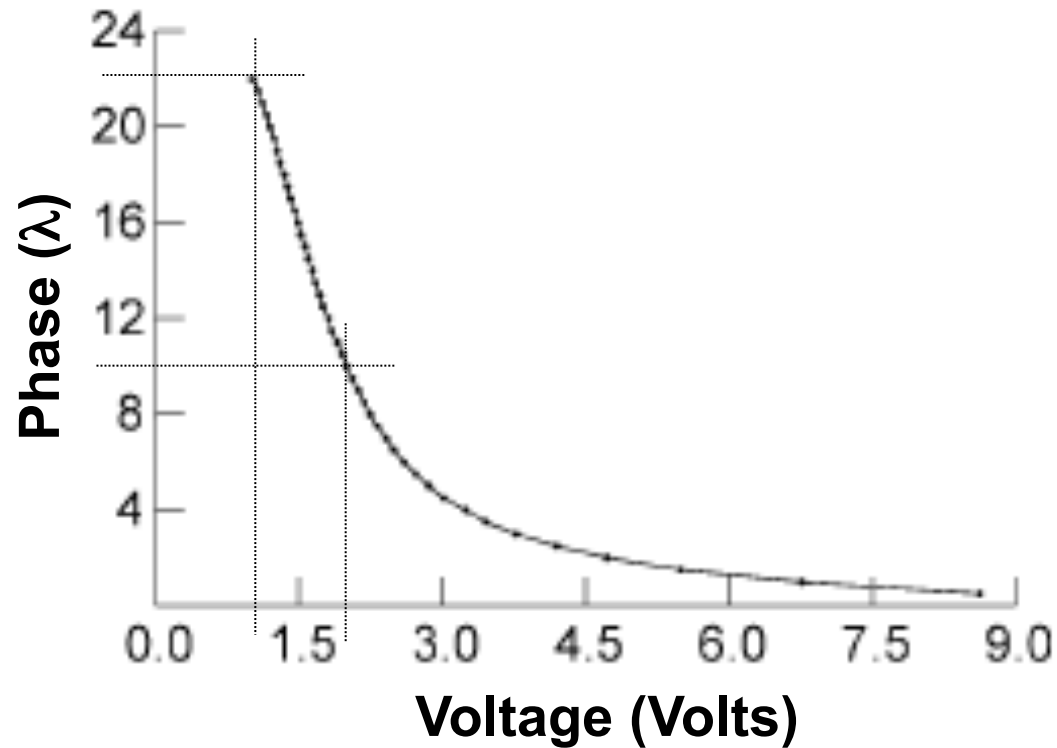
N. A. Riza, OSA Top. Mtg., Proc. SPIE, **3482**, 572, 1998.

N. A. Riza, US Patent 6,031,658, 2000.

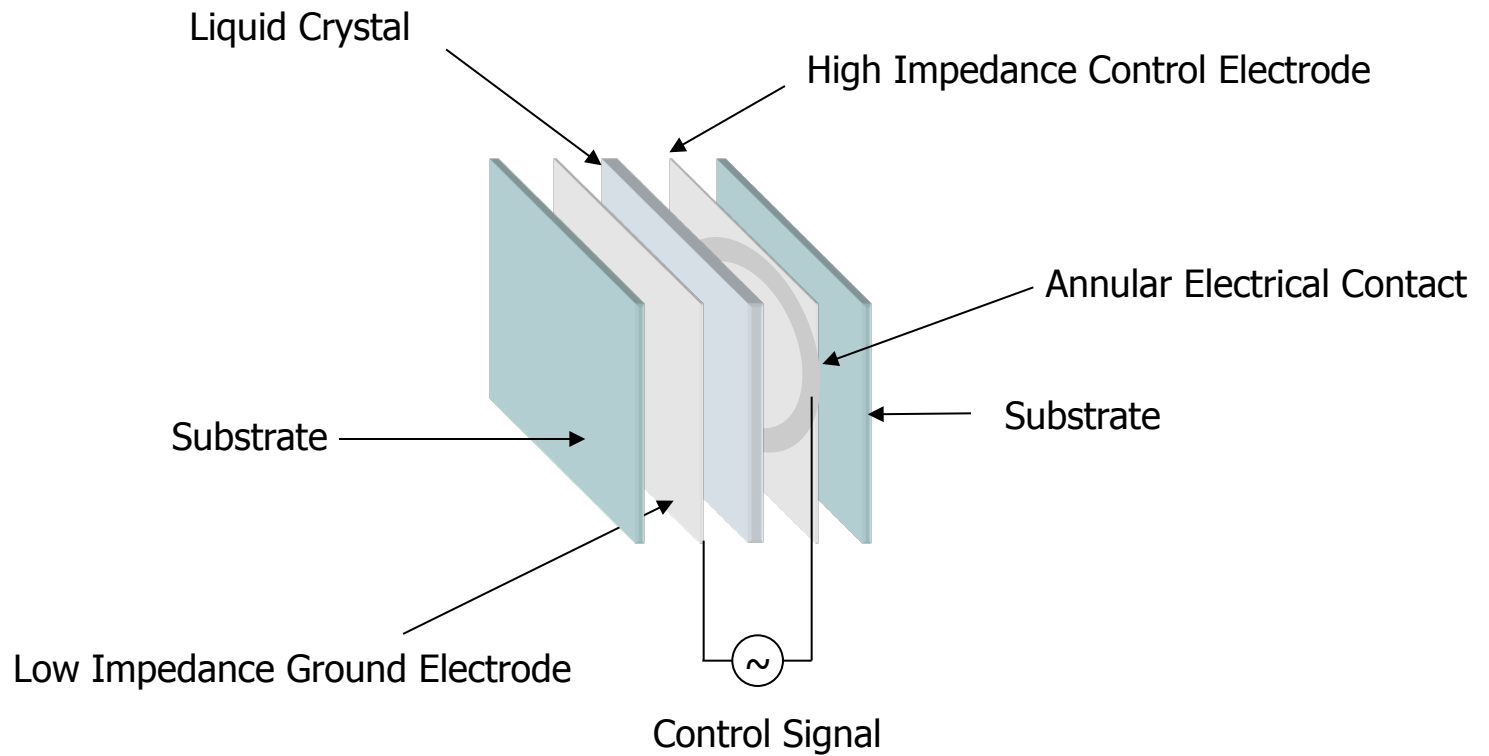
Example Pixel-Free Deflector Structure and Working Principle



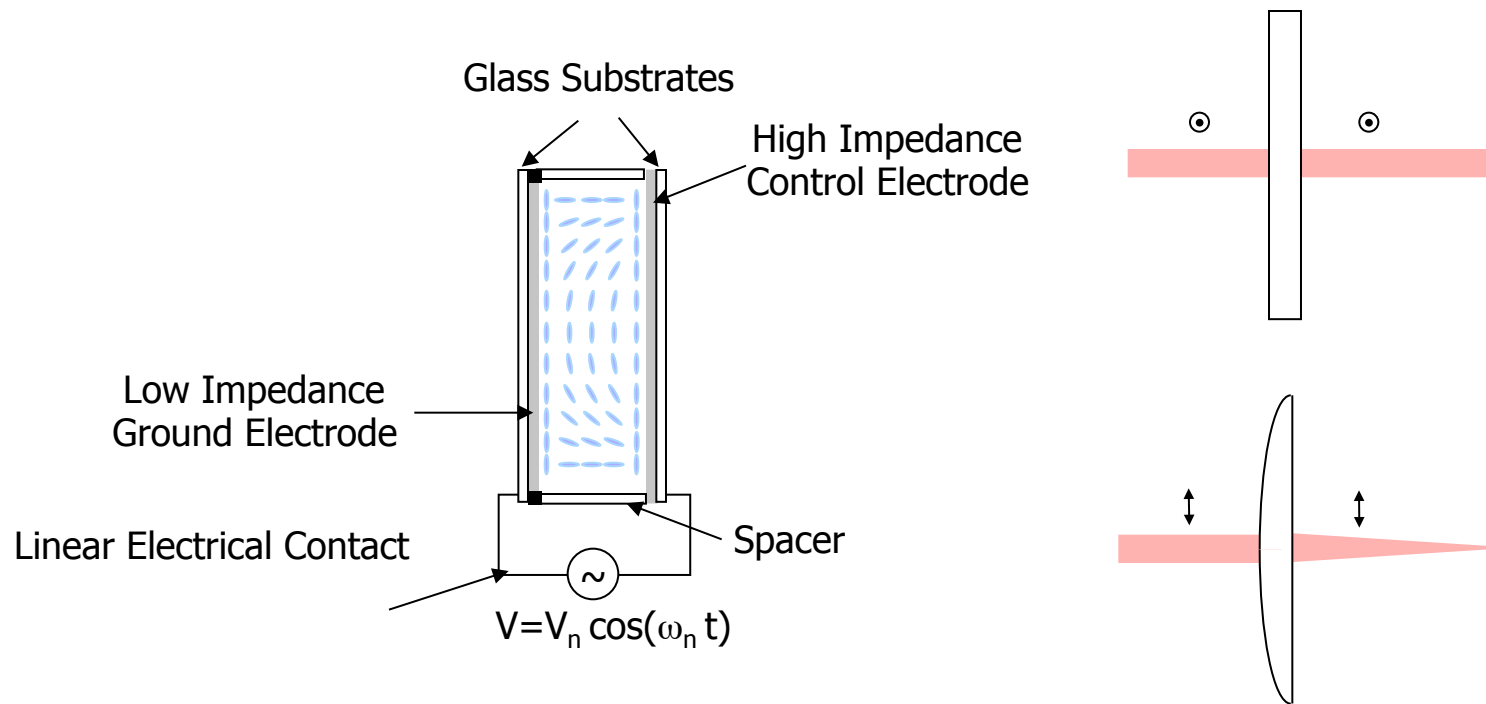
Example Phase Response of the Liquid Crystal



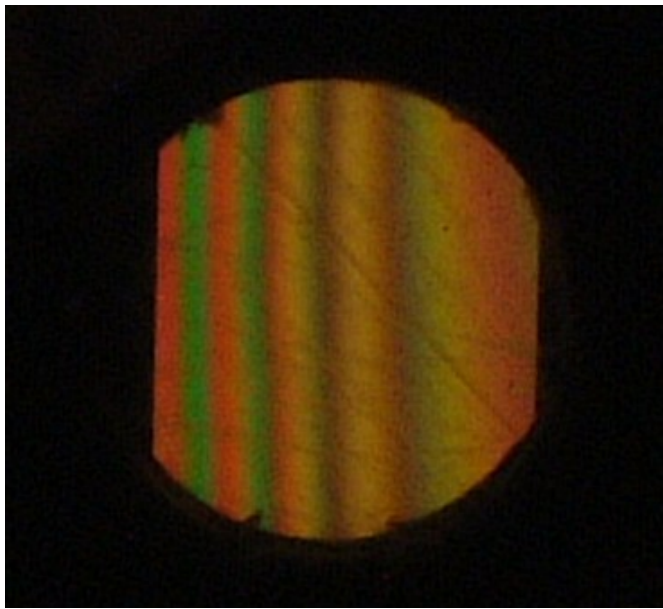
Example Pixel-Free Lens Structure



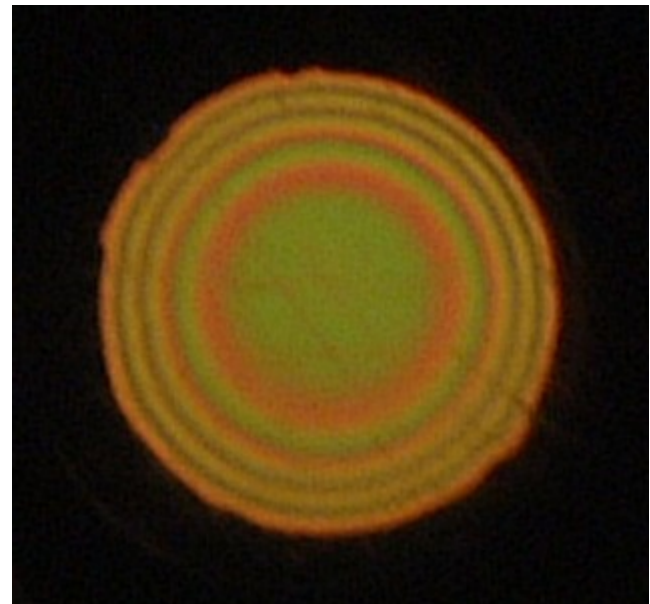
Pixel-Free Lens Working Principle



Interferograms of the Pixel-free LC Deflector and Lens



Deflector



Lens

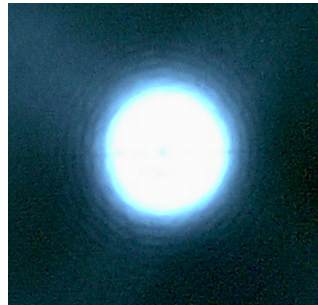
Digital LC Lens

2 bit P-MOS (Only Longitudinal Scan) at 1310 nm

P-MOS Digital
Control State



00



Collimated beam

01



L2 focusing

P-MOS Digital
Control State

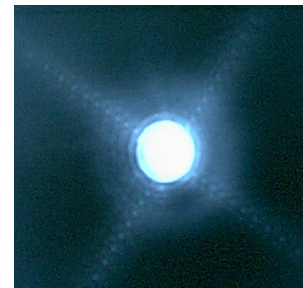


10



L1 focusing

11

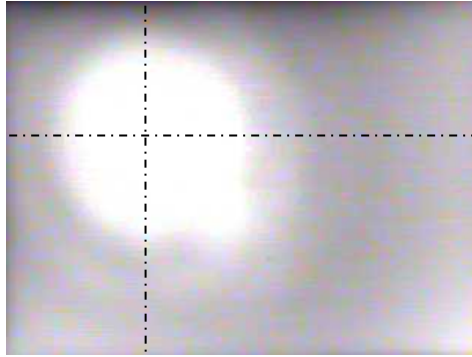


both L1 and L2
focusing

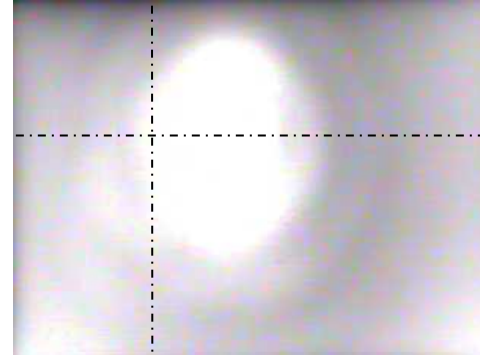
All pictures taken at the same longitudinal position from P-MOS
(Distance of 1 m from P-MOS Exit Face).

3-D P-MOS Results

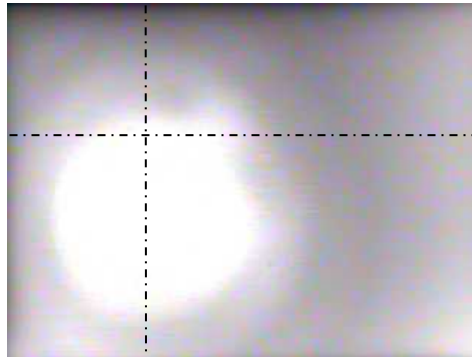
Incident beam



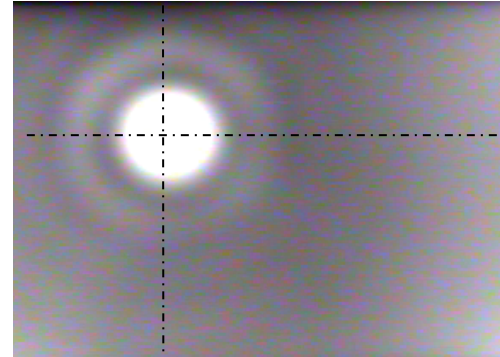
Horizontal Deflection by
0.66mrad



Vertical Deflection by
0.75mrad



Longitudinal focusing at 1.84 m
from P-MOS



Goal: Need Fine Scan + Wide Scan

Solution:

Combine Fixed Birefringence Crystals with Programmable Crystals
to get both **large angular dynamic range**
and **fine tunability**

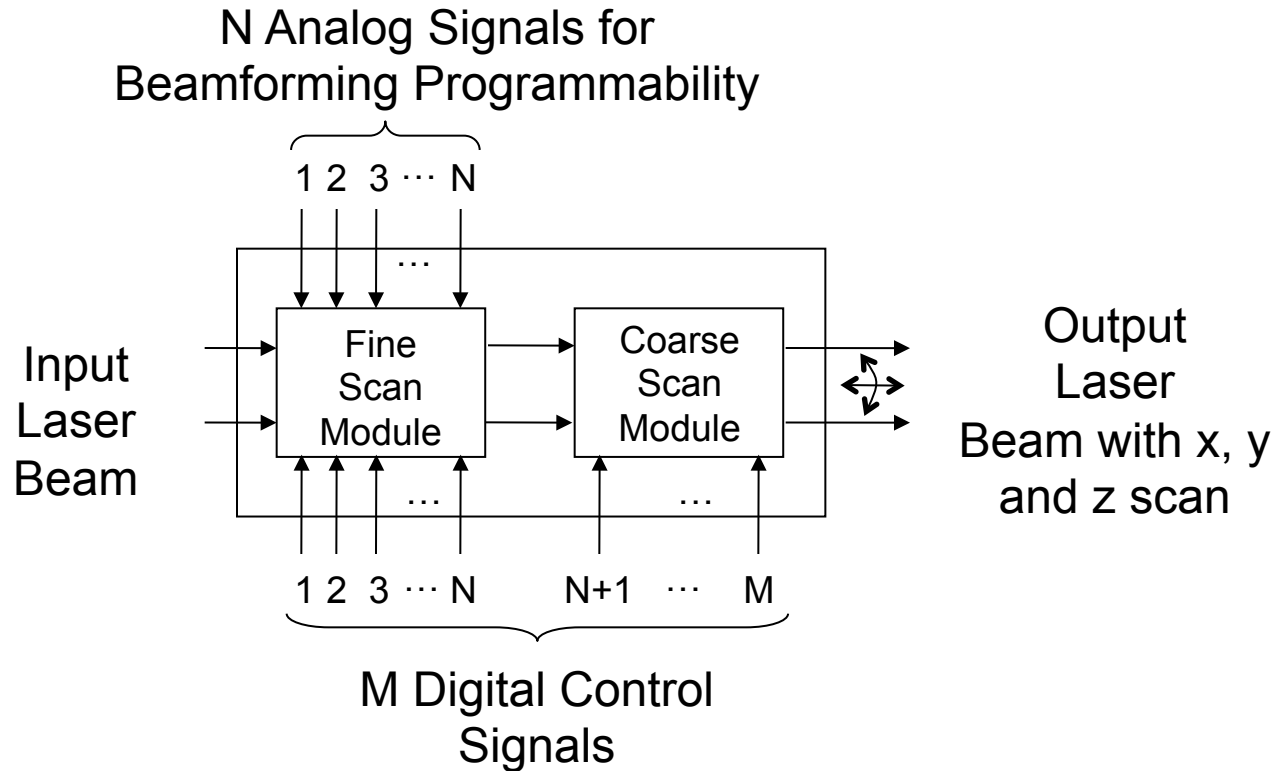
Fixed Birefringence Crystals

- Large deflection angles
- θ depends upon n_o and n_e
- Fixed angles

Nematic Liquid Crystals

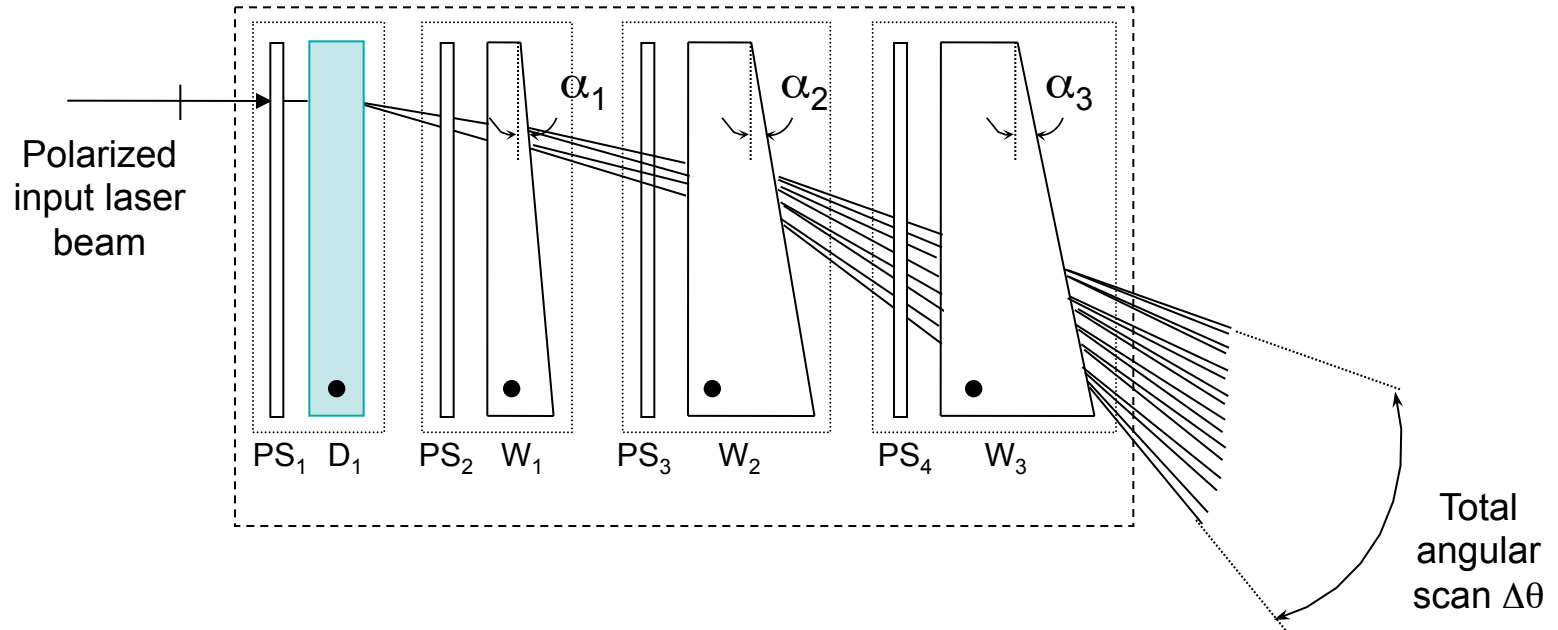
- Small deflection angles
- θ depends upon n_o and $n_e(V, x)$
- Angle tuning possible

Coarse-Fine P-MOS Architecture



Solution:

1-D Coarse-Fine Scan P-MOS Module

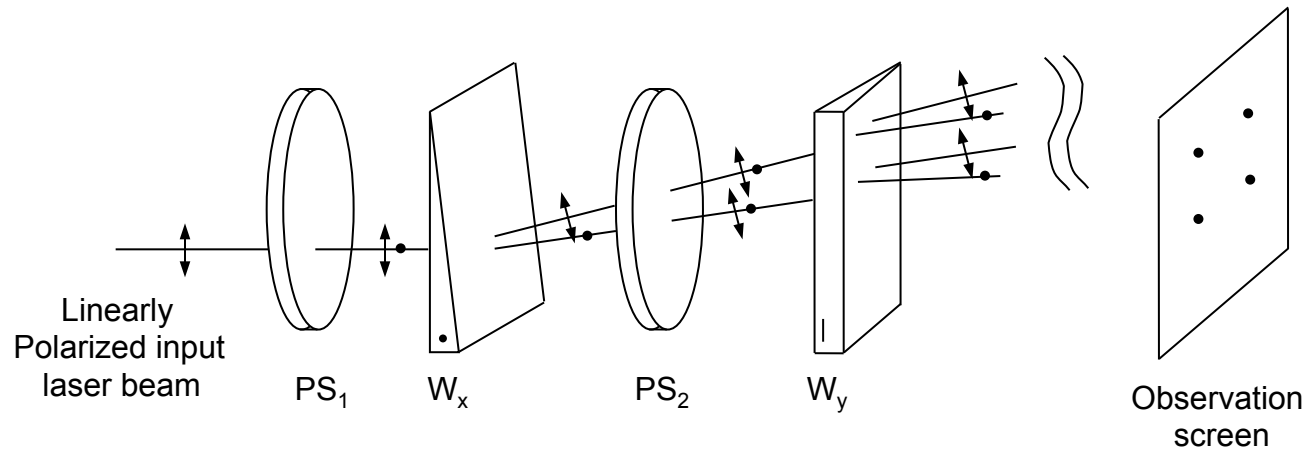


Three Birefringent Wedges, four Polarization Switches and one NLC deflector used.
Total scan addressability: $2^4 = 16$ discrete points plus Continuous Scan Between Points

The Fine Stage Corrects for the Non-Uniform Scan Operation of the Digital Coarse Stage

W: Bulk Birefringent Wedge
PS: Polarization Switch
D: NLC deflector

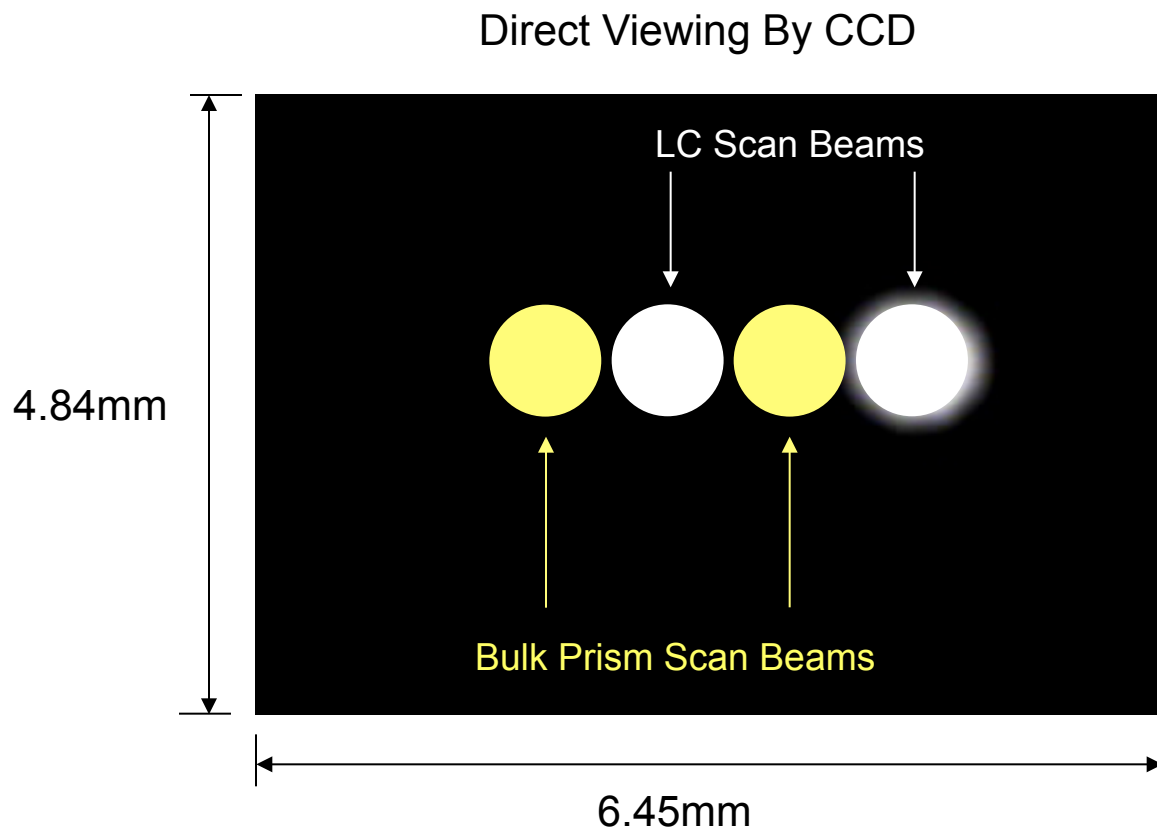
2-D Coarse Scan P-MOS Module



W: Bulk Birefringent Wedge

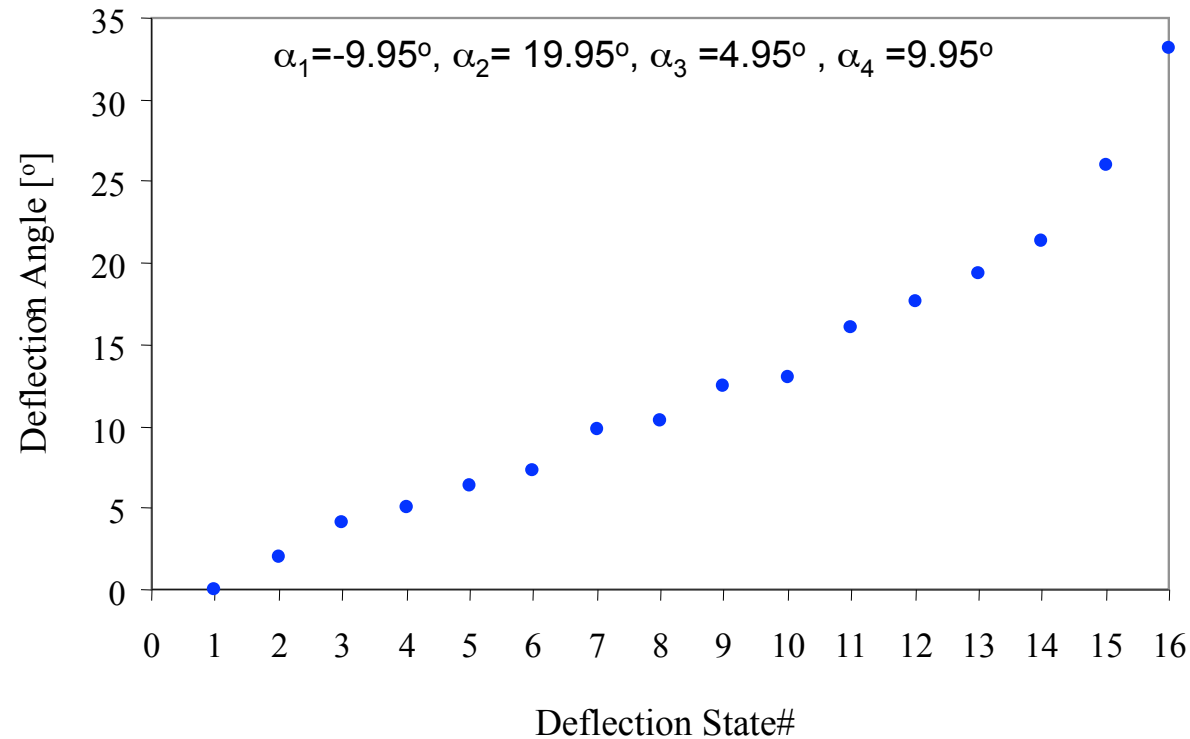
PS: Polarization Switch

1-D Coarse-Fine PMOS Demonstration



Number of FLC Polarization Switches used: 2
Number of NLC (Merck BL006) Deflectors used: 1
Number of Bulk Prism (Rutile) Wedges used: 1
 $\lambda = 1.55\mu\text{m}$

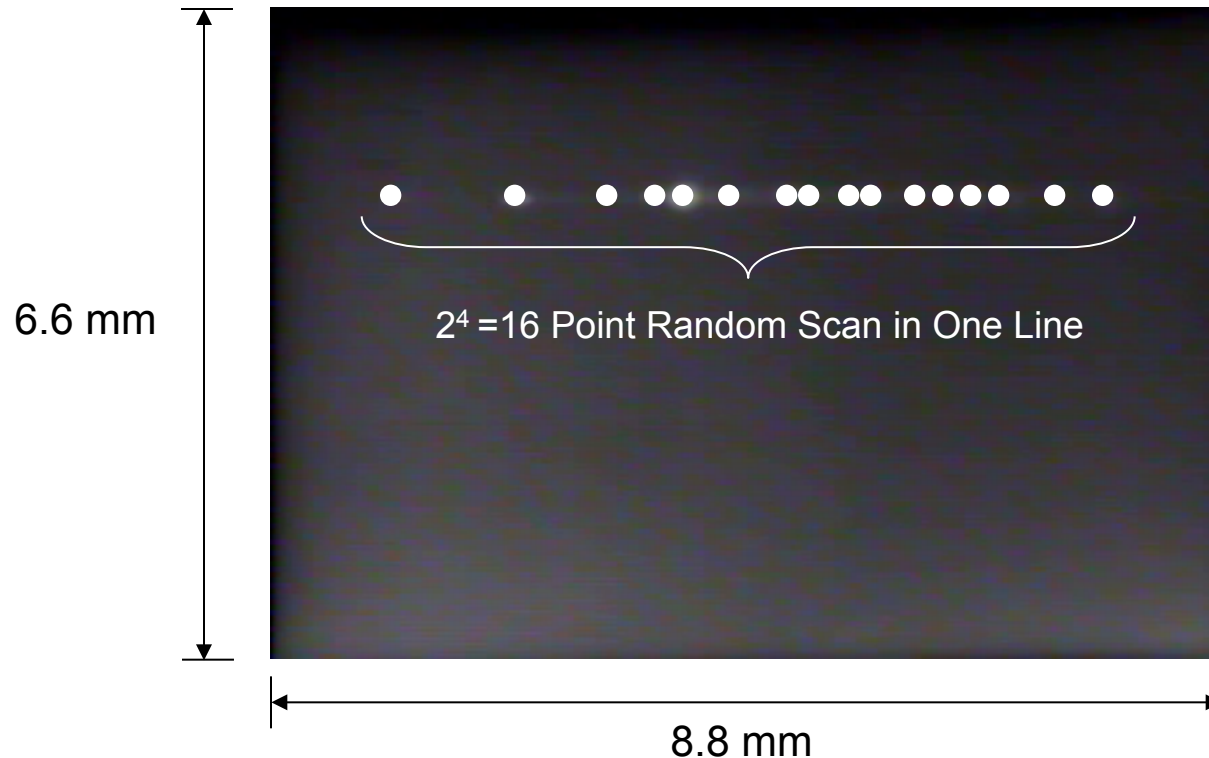
1-D 4-Bit Coarse Only Discrete Scan PMOS Analysis: 33.11° Scan



α_n : Apex Angle for n^{th} stage

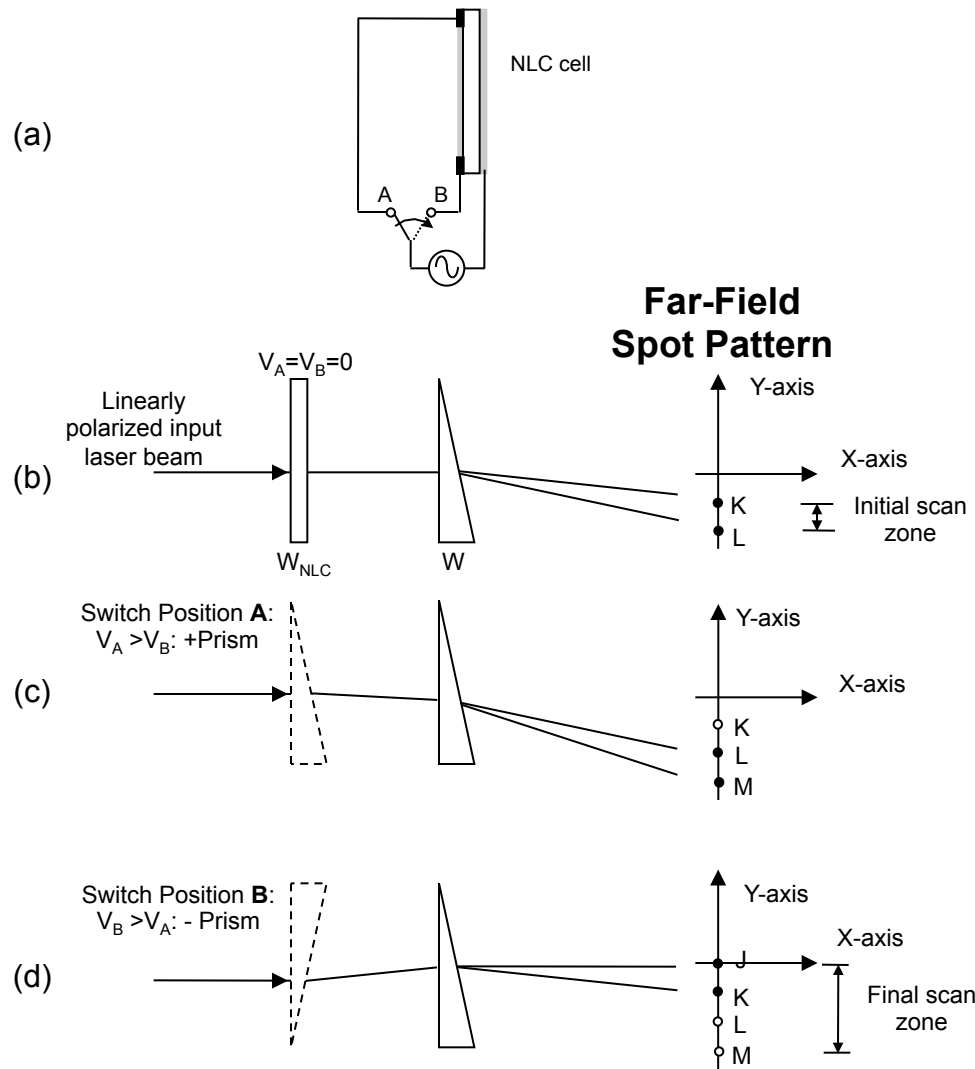
1-D 4-Bit Coarse Only Discrete Scan PMOS Demonstration: 33.11° Scan

Spot Pattern Being Imaged onto CCD



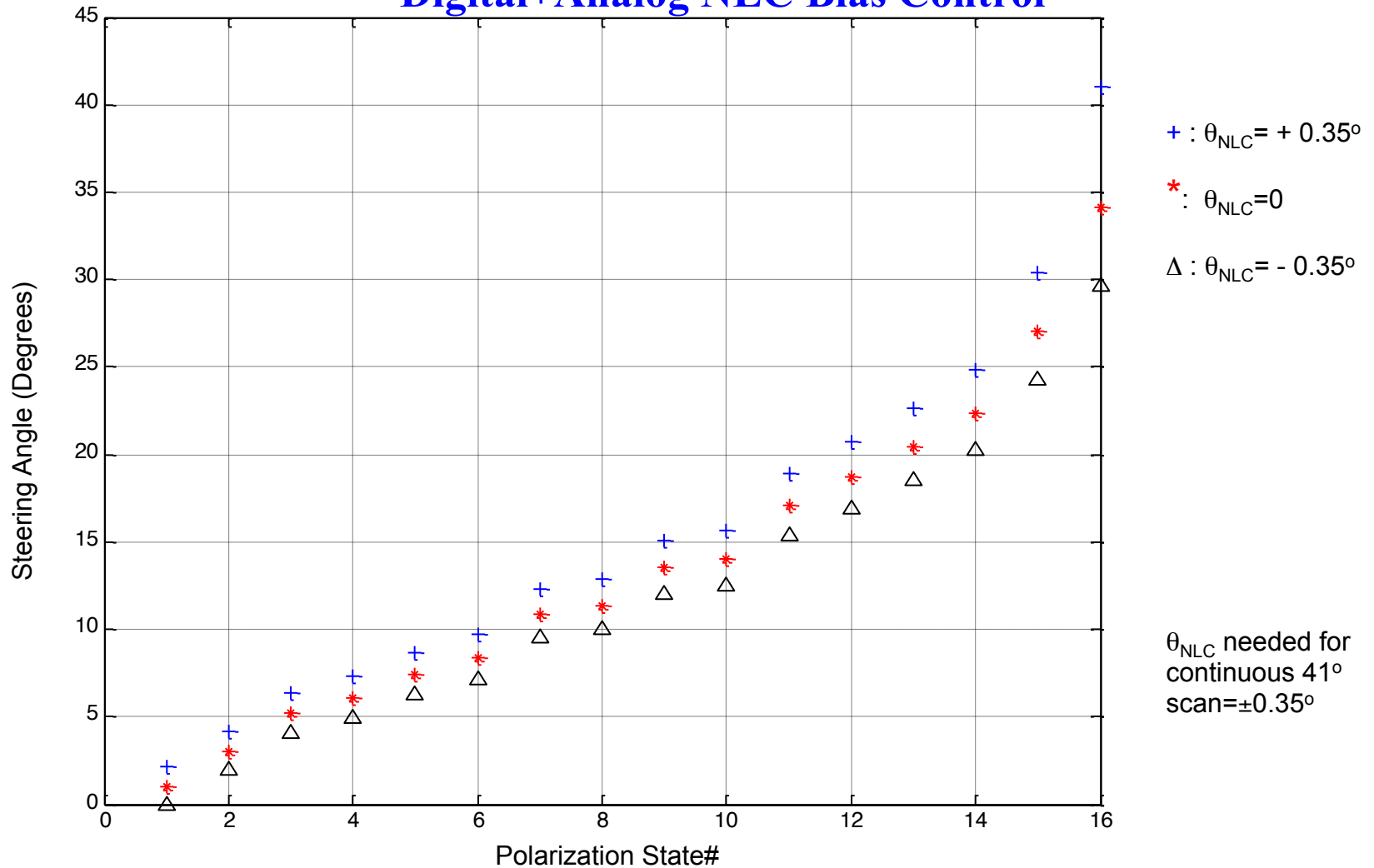
Number of FLC Polarization Switches used: 4
Number of Bulk Prism (Rutile) Wedges used: 4
 $\lambda = 1.55 \mu\text{m}$

Tripling Scan Angle Via Unique NLC Deflector Biasing Technique



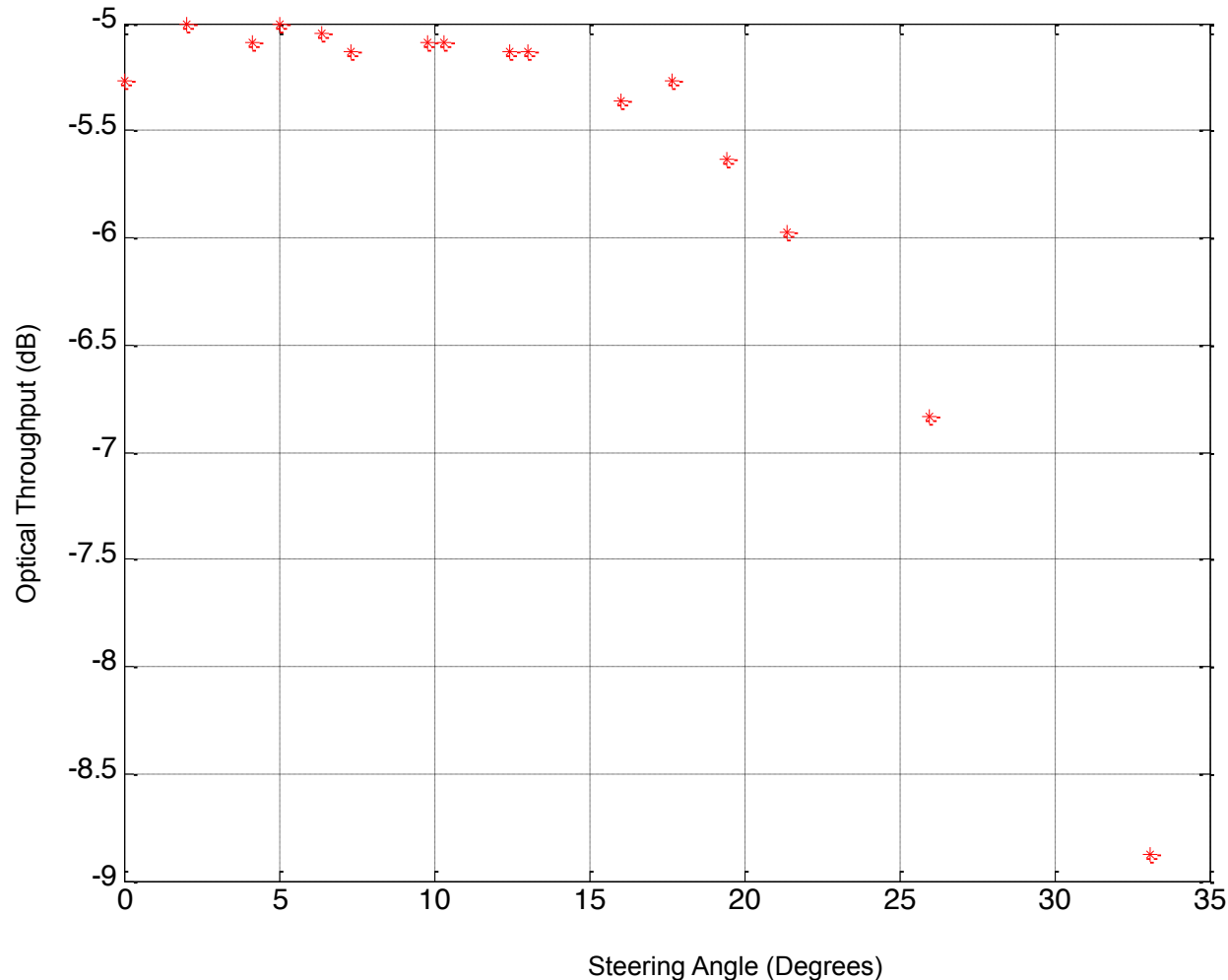
Continuous Scan
 $(\alpha_{NLC} = \pm 0.35^\circ)$

1-D 4-Bit Coarse+1 NLC Deflector Scanner: 41° Continuous Scan Via Digital Polarization & Digital+Analog NLC Bias Control



$\alpha_{\text{LC}} = \pm 0.35^\circ$, $\alpha_1 = -9.95^\circ$, $\alpha_2 = 19.95^\circ$, $\alpha_3 = 4.95^\circ$ and $\alpha_4 = 9.95^\circ$ using Rutile prisms ($n_e = 2.454$, $n_o = 2.71$ @ $\lambda = 1550$ nm)

Experimentally measured scanner optical throughput for the 4-stage 1-D coarse digital P-MOS demonstration at 1550 nm



Loss

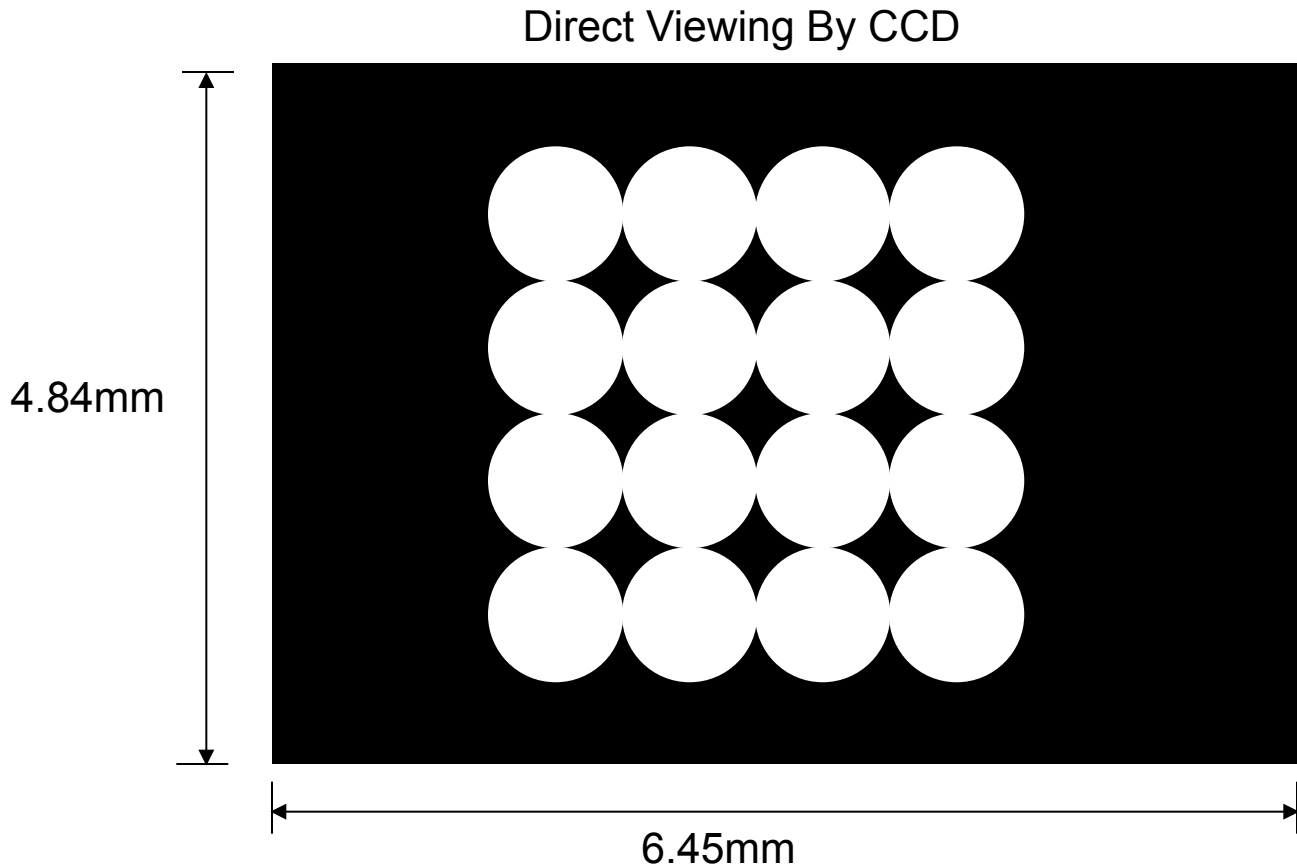
FLC=0.7 dB

NLC=0.73 dB

Used 3 NLCs + 4 FLCs

$3 \times 0.73 + 4 \times 0.7 = 5 \text{ dB}$

2-D 4-Bit Coarse-Fine PMOS Demonstration



Number of FLC Polarization Switches used: 4
Number of NLC (Merck BL006) Deflectors used: 2
Number of Bulk Prism (Rutile) Wedges used: 2
 $\lambda = 1.55\mu\text{m}$

3-D 2-Bit Coarse Only + 1-Bit Longitudinal Fine Scanning PMOS Demonstration

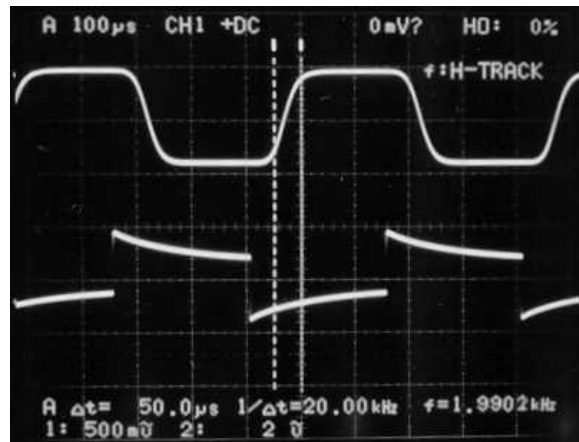


Number of FLC Polarization Switches used: 3
Number of NLC (Merck BL006) Lenses used: 1
Number of Bulk Prism (Rutile) Wedges used: 2
 $\lambda = 1.55\mu\text{m}$

FLC Polarization Switch Response at 1550nm

FLC Response

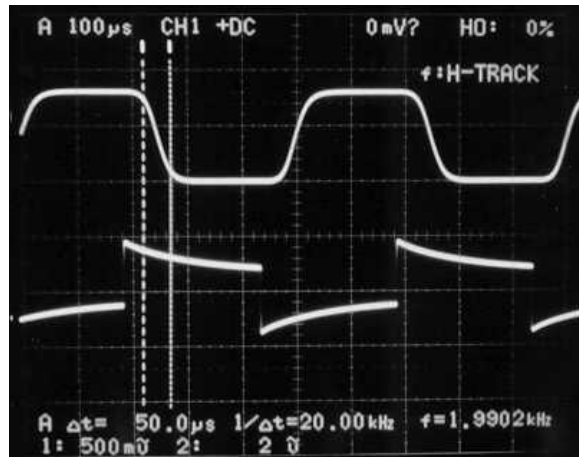
FLC Drive Signal



Rise Time: 50 μ s

FLC Response

FLC Drive Signal



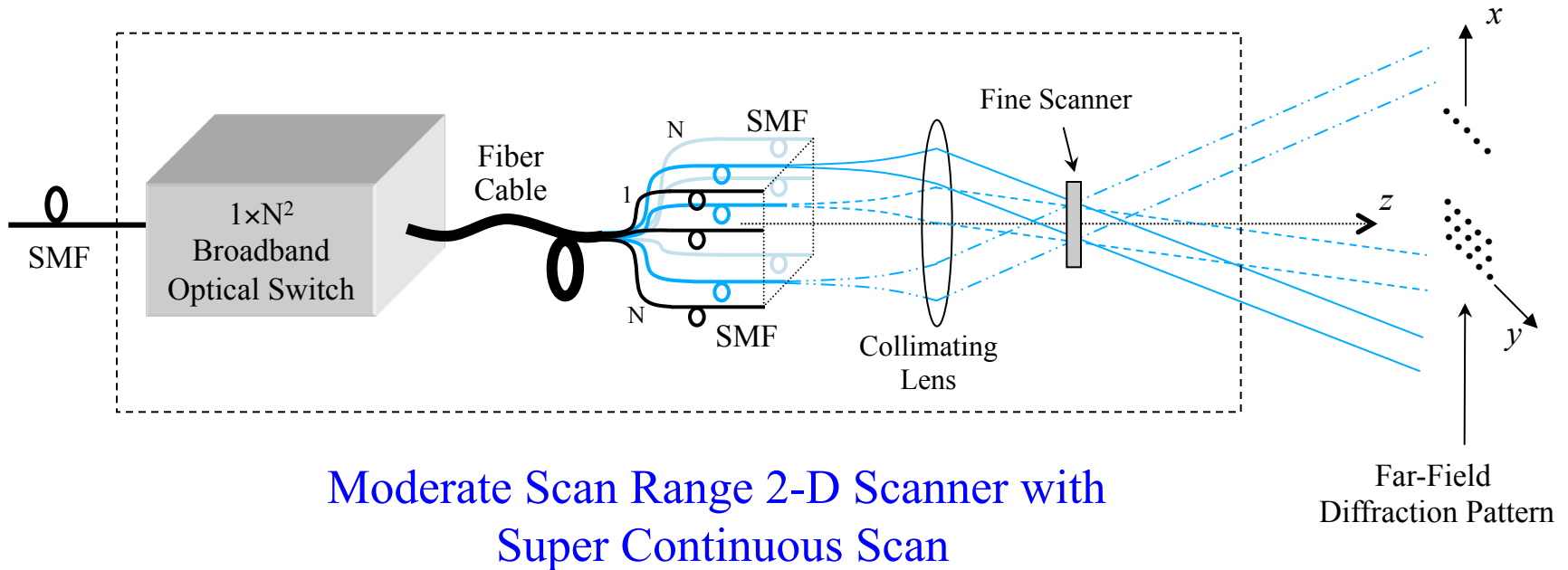
Fall Time: 50 μ s

Summary

Parameter	Status	Comment
Wavelength	1.55 μm	NLCs and FLCs also work at visible and near IR wavelengths – just recalibrate NLC cells for desired wavelength
Scanner Clear Aperture	FLC: 2 cm $\varnothing$ Bulk Prism: 2cm x 2cm NLC Wedge: 1cm x 1cm	Depends on fabrication methods.
Demonstrated Max 1-D Angular Scan	41.11°	Depends on the birefringent materials used, the cascading order and number of bits in the scanner
Number of Beams (Scan Spots)	2^N	N: Number of bits in P-MOS (e.g. >1 million for N=20)
Pt. to Pt. (Linear) Access Time	50 μs	Using FLC based polarization switches at 1.55 μm
Pt. to Pt. (Random) Access Time	50 μs	Access time is same for all the scanned positions
Insertion Loss	FLC: 0.7dB Bulk Prism: <0.03dB (AR coated) NLC Deflector: 0.73dB	NLC Deflector loss can further be reduced by AR coating, expected <0.4dB

Space-Multiplexed Optical Scanner (S-MOS)

The Space-Multiplexed Optical Scanner (S-MOS)



Moderate Scan Range 2-D Scanner with Super Continuous Scan

Angular Scan versus Optical Switch port # n : $\theta = -\tan^{-1}\left(\frac{nx_p}{f}\right)$; $-\left(\frac{N-1}{2}\right) \leq n \leq \left(\frac{N-1}{2}\right)$

Total Output Angular Scan : $\Delta\theta = -2 \tan^{-1}\left\{\frac{(N-1)x_p}{2f}\right\}$.

SMF: Polarization Maintaining Fiber
 N : Number of Fibers along x or y -axis
 x_p : Pitch of the fiber array

Design Example

- Collimating Lens (50 mm focal length) + SMF $\rightarrow$ $1/e^2$ Beam Size : $\frac{2\lambda f \cos \theta}{\pi w_{\text{inc}}} \cong 9.8 \text{ mm}$

Coarse Scanner

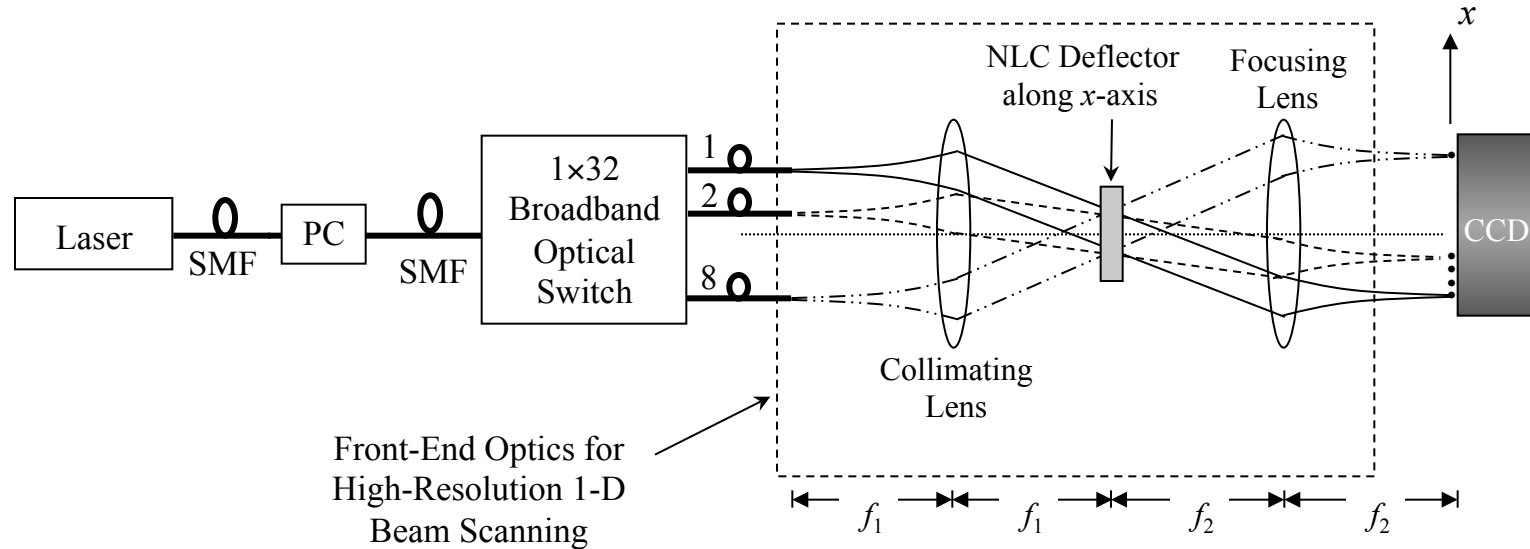
# of Output Ports of Fiber-Optic Switch	# of Fibers along <i>x</i> or <i>y</i> -axis	Fiber Pitch (mm)	Angular Scan Range (deg)	Switch-Based Scan Step (deg)	Fine Scanner Range
100	10	1	10.28	1.146	1.146
100	10	2	20.41	2.29	2.29
400	20	1	21.51	1.145	1.145

The Fine Scanner Options Include:

- Single SLM Scanner or P-MOS

w_{inc} : Waist of Gaussian Beam exiting SMF
 λ : Wavelength (1550 nm)

Experimental Demonstration of a High-Resolution S-MOS



- 1×32 Fiber-optic Switch (Opto-mechanical)
 - Speed : 4 msec
 - Maximum Insertion Loss : ~ 0.7 dB
- NLC Deflector ($\Delta\theta = 0.286^\circ$ at 1550 nm)
 - Reconfiguration Speed : ~ 1sec
 - Insertion Loss : ~ 0.75 dB
- 8-Channel SMF Array (250 μm pitch)
- $f_1 = 50$ mm; $f_2 = 100$ mm

PC: Polarization Controller
SMF: Single Mode Fiber
NLC: Nematic Liquid Crystal

First Demonstration of S-MOS

Viewing Focused Beams
on a 6 mm×4.5 mm CCD

Optical Switch Output Ports
S1 S2 S3 S4 S5 S6 S7 S8



of Coarse Scan Points : 8

of Fine Scan Points : $12 \times 8 = 96$

Total Scan Points : 104

Coarse Scan (deg) : 2.0°

Fine Scan : 0.286°

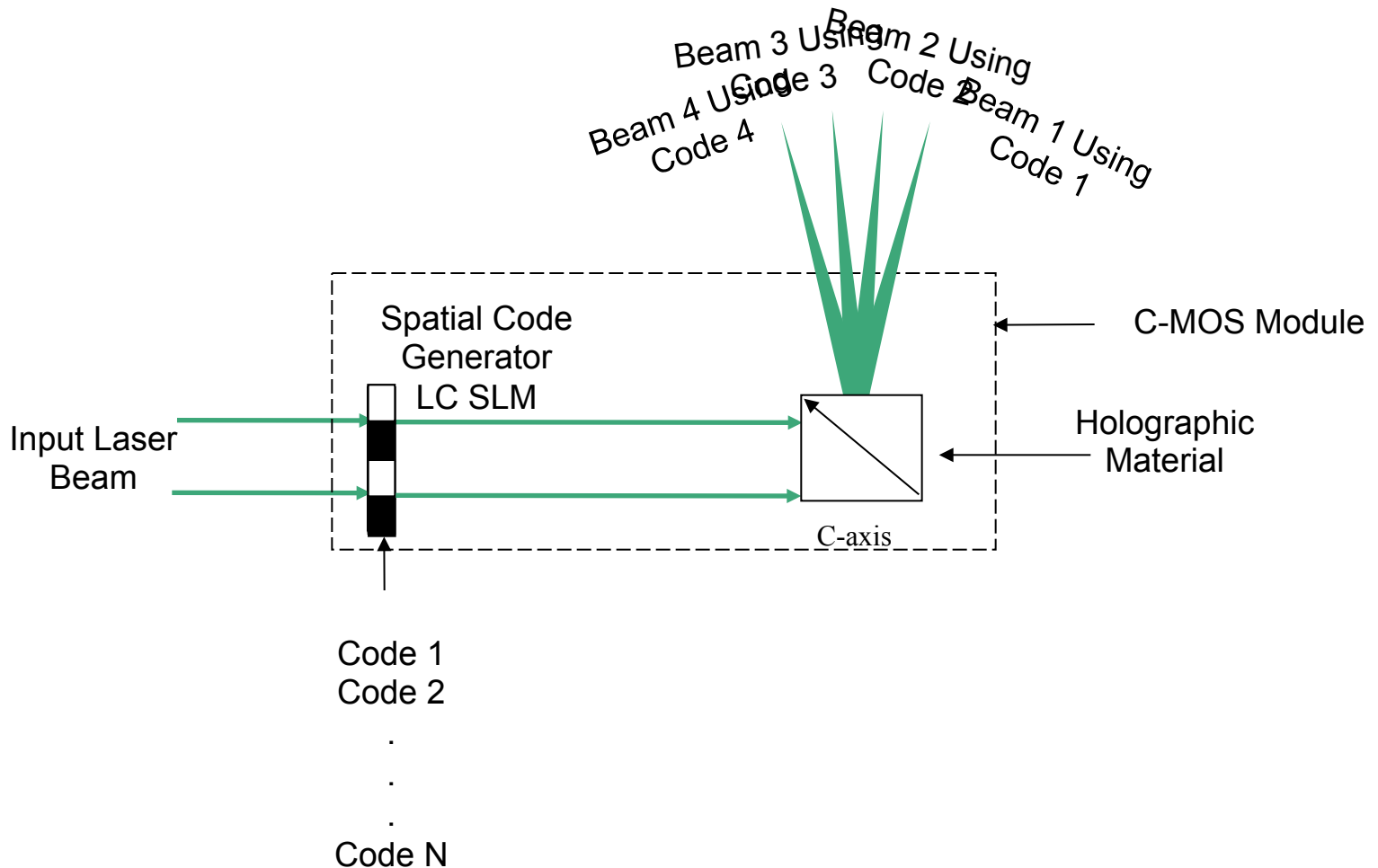
Total Angular Scan : 2.286°

Scanner Insertion Loss : ~ 1.5 dB

0.000 0.286 0.573 0.859 1.146 1.432 1.719 2.005
Scan in Degrees

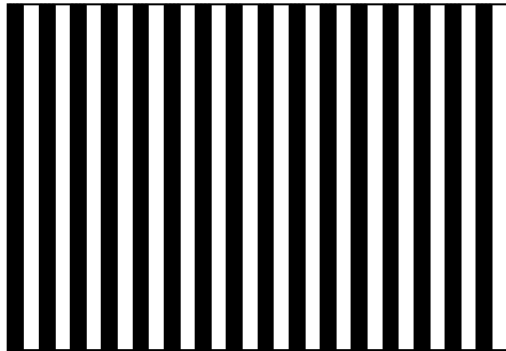
Code-Multiplexed Optical Scanner (C-MOS)

Code Multiplexed Optical Scanner (C-MOS) Operation

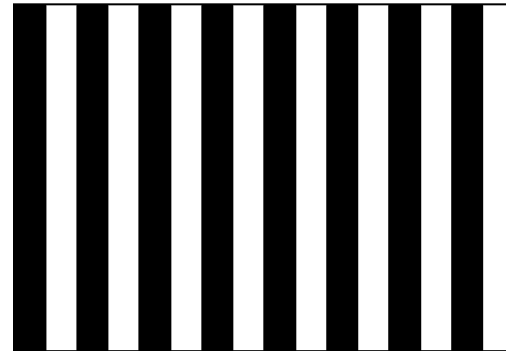


Example Code Patterns Generated by LC SLM Via Row Selection of Order 16 Hadamard Matrix

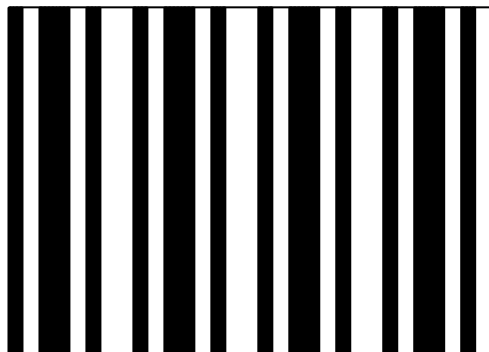
Row 2



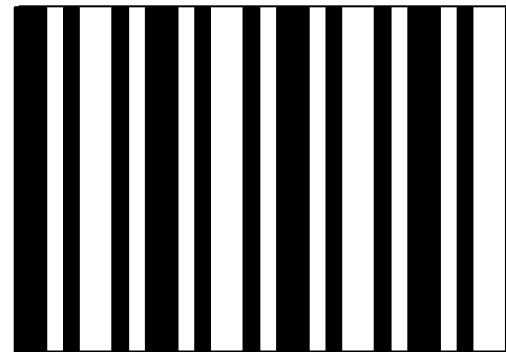
Row 3



Row 6

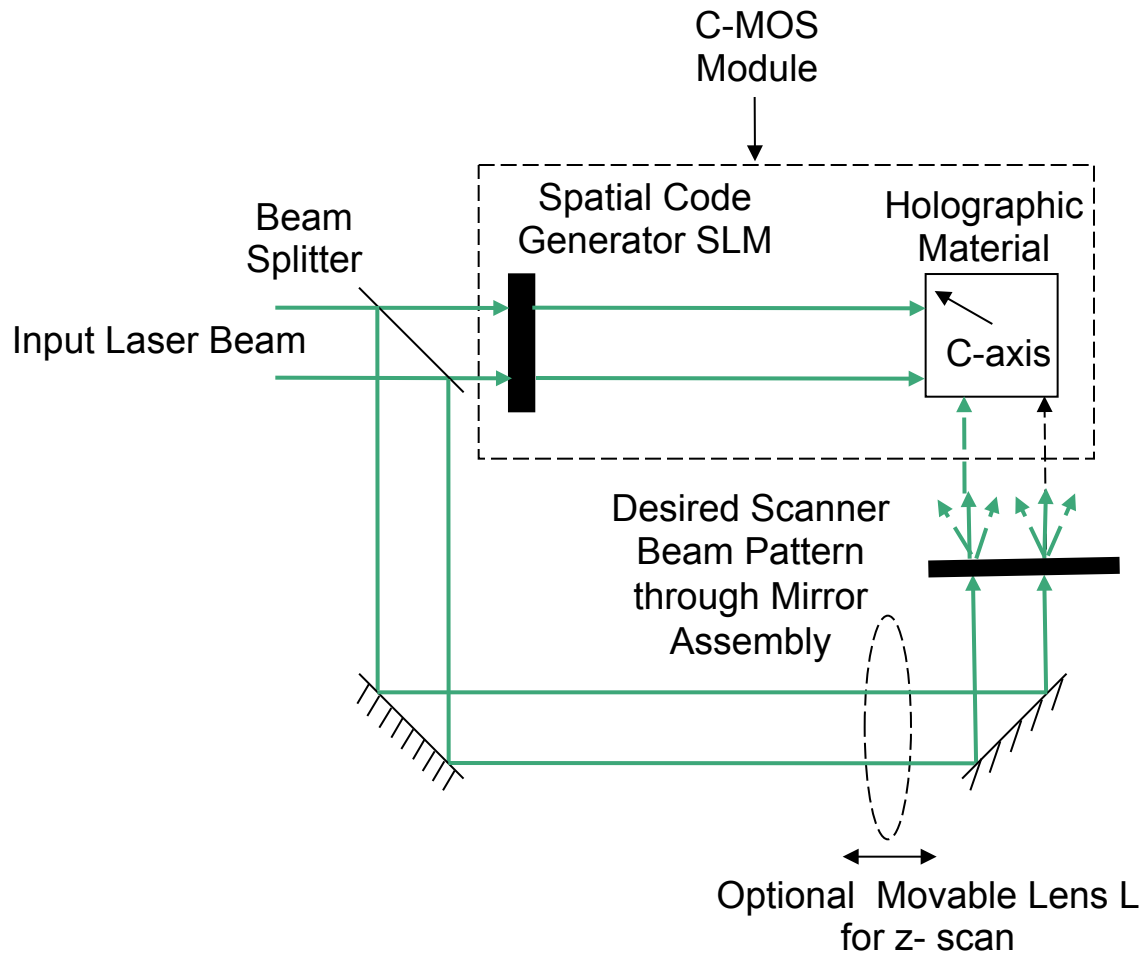


Row 8



Black Bar represents 1 in the Hadamard Matrix
White Bar represents -1 in the Hadamard Matrix

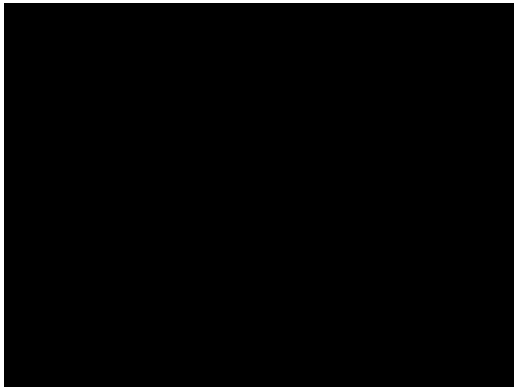
C-MOS Recording using 90° Geometry



C-MOS Demonstration Videos

This video shows half of the maximum deflection in x-direction that can be generated using the C-MOS because of the limitation of the size of CCD camera.

1-D Scan of 53°

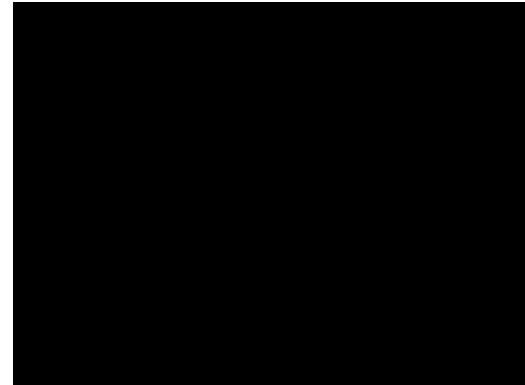


Resolution of the C-MOS

This video shows two spots at an angular spacing of 1 minute (0.02 mrad).

This video shows 2-D scanning using the C-MOS. The video shows that random accessing takes same time as linear accessing.

2-D Scan of 53°

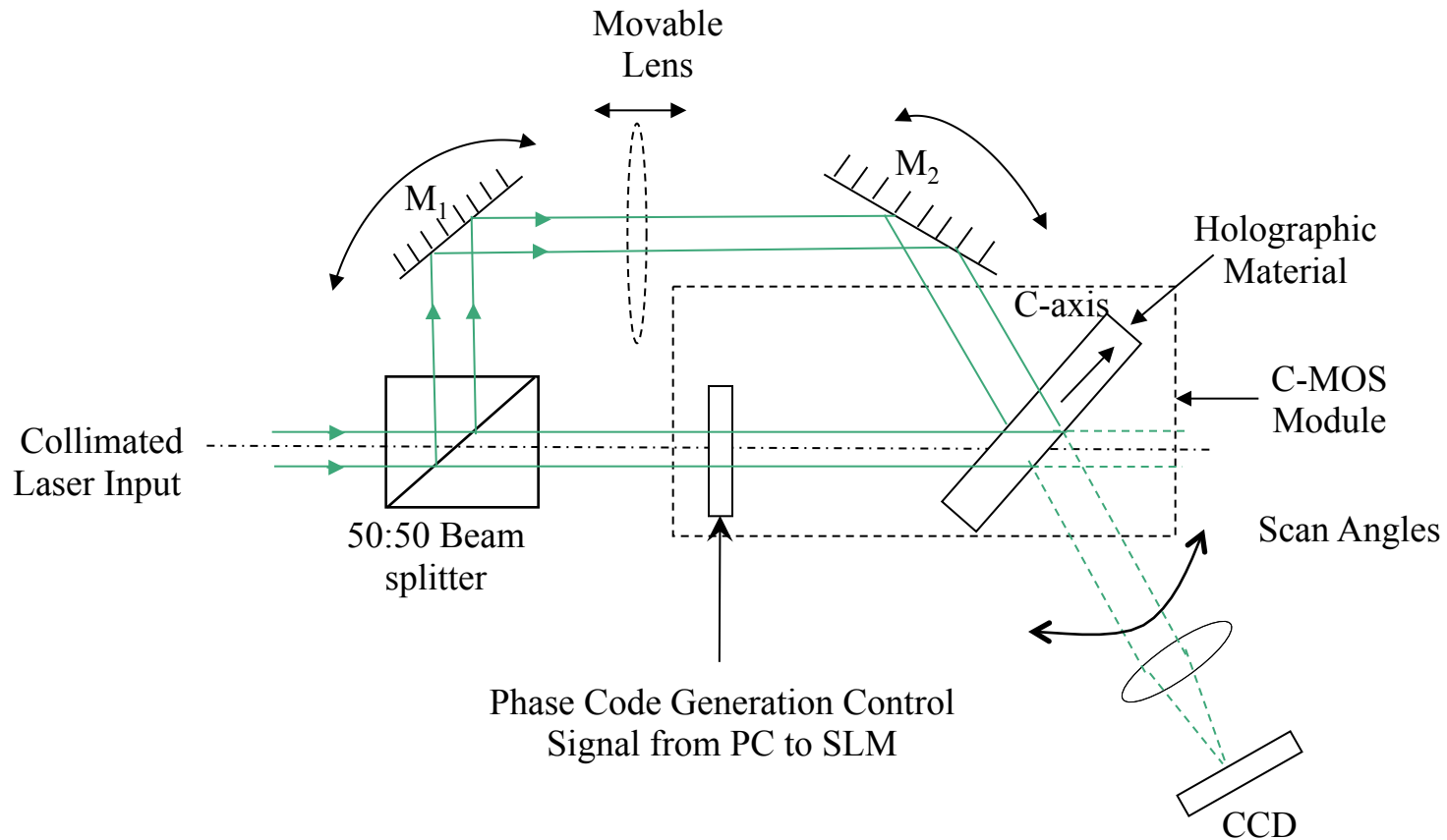


Forming a VOXEL through the C-MOS

This video shows forming of a voxel element by using 8 orthogonal codes that demonstrate the 3-D beam scanning capability of the C-MOS.

C-MOS Design for Super Wide Scan Angles

Use: 0° C-axis - In-line Geometry



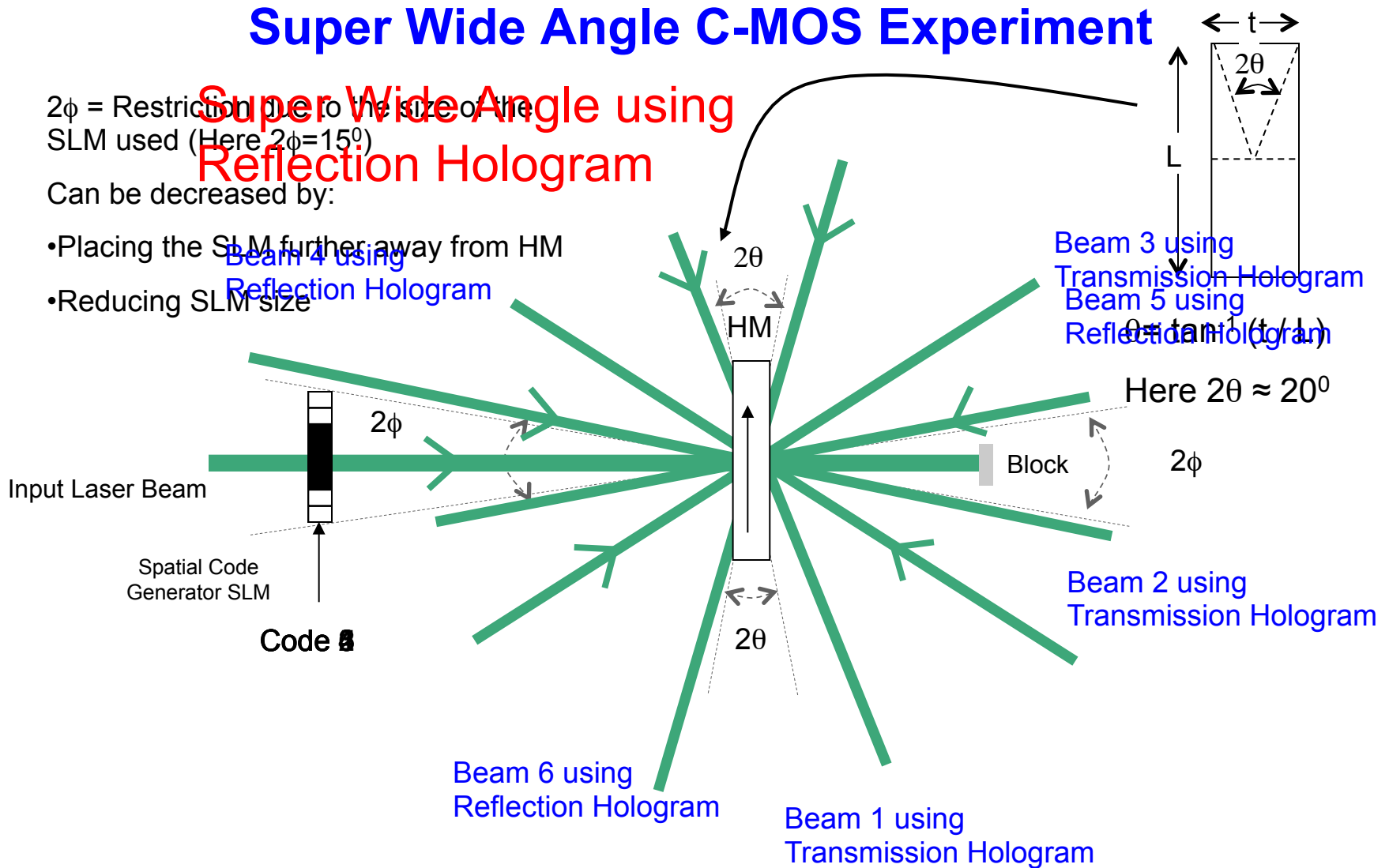
Super Wide Angle C-MOS Experiment

Super Wide Angle using Reflection Hologram

2ϕ = Restriction due to the size of the SLM used (Here $2\phi=15^\circ$)

Can be decreased by:

- Placing the SLM further away from HM
- Reducing SLM size

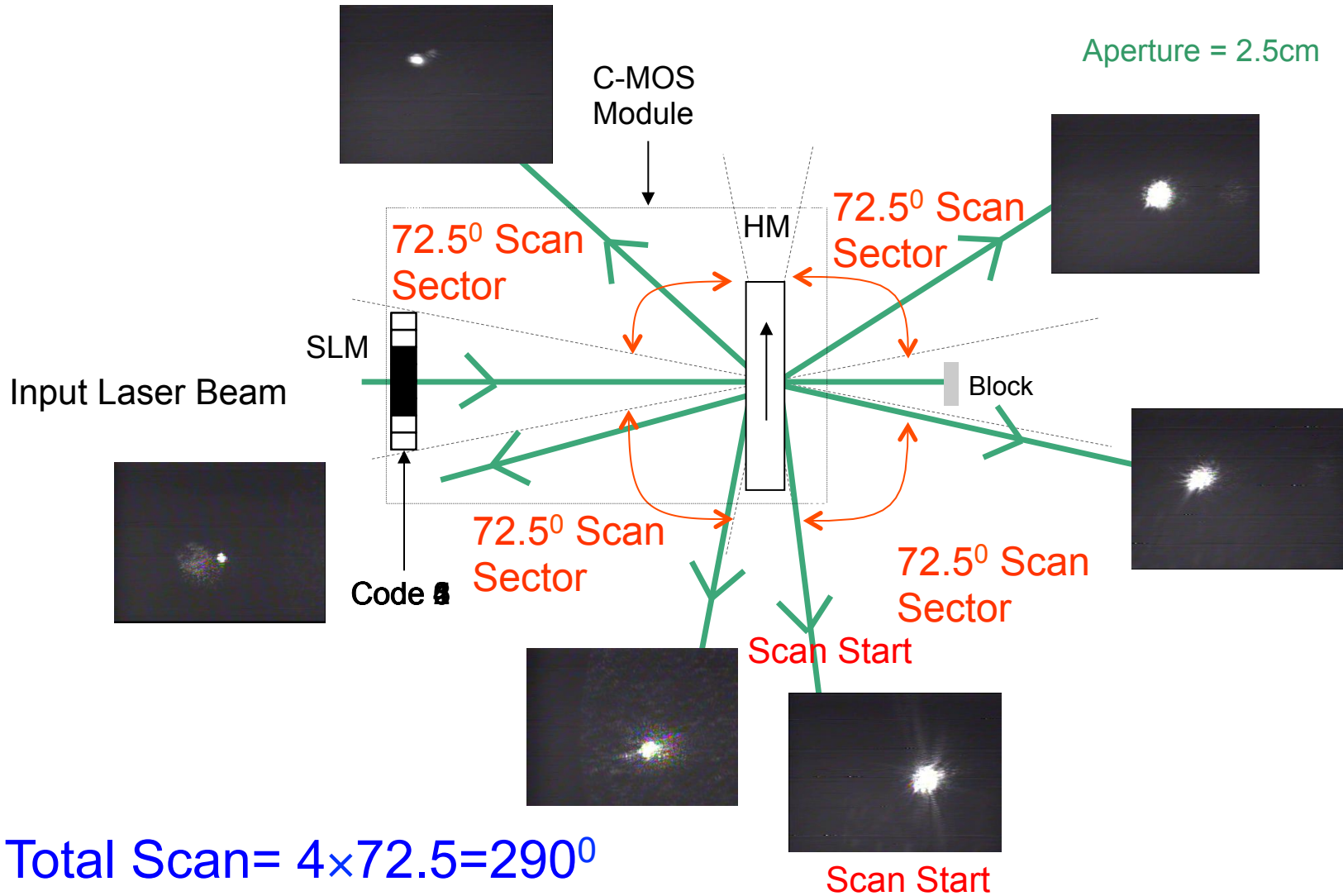


HM = Holographic Material (Here LiNbO_3 Photorefractive Crystal)

2θ = Restriction due to finite size of holographic material

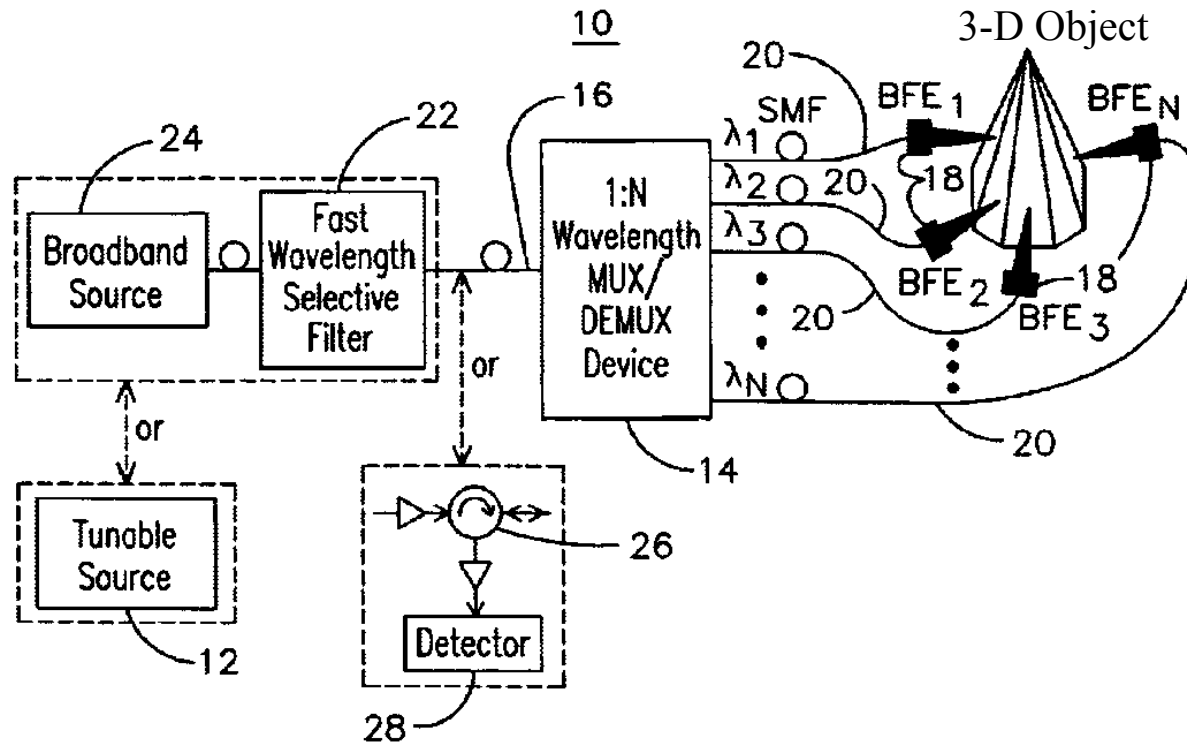
2ϕ = Restriction due to the size of the SLM

Super Wide Angle C-MOS Operation



Spectrally Coded Optical 3-D Imager

Wavelength Multiplexed Scanner for Multi-Dimensional Optical Imaging using LC Beamformers



BFE: Beamformer Element
e.g., LC Beamformer Chip

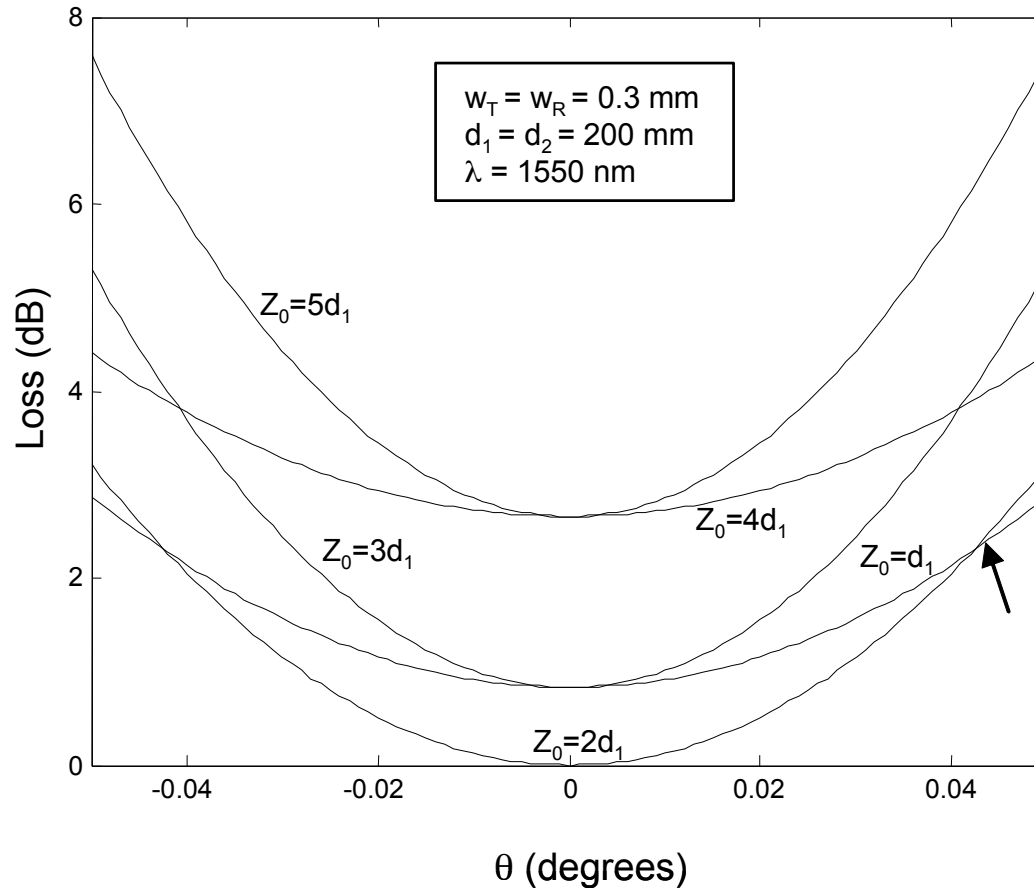
N. A. Riza, US Patent 6,687,036, Feb. 3, 2004

N. A. Riza & Y. Huang, IEEE LEOS Ann. Mtg, 1999.

Impact on Fiber-Optics for Telecommunications Using Liquid Crystals

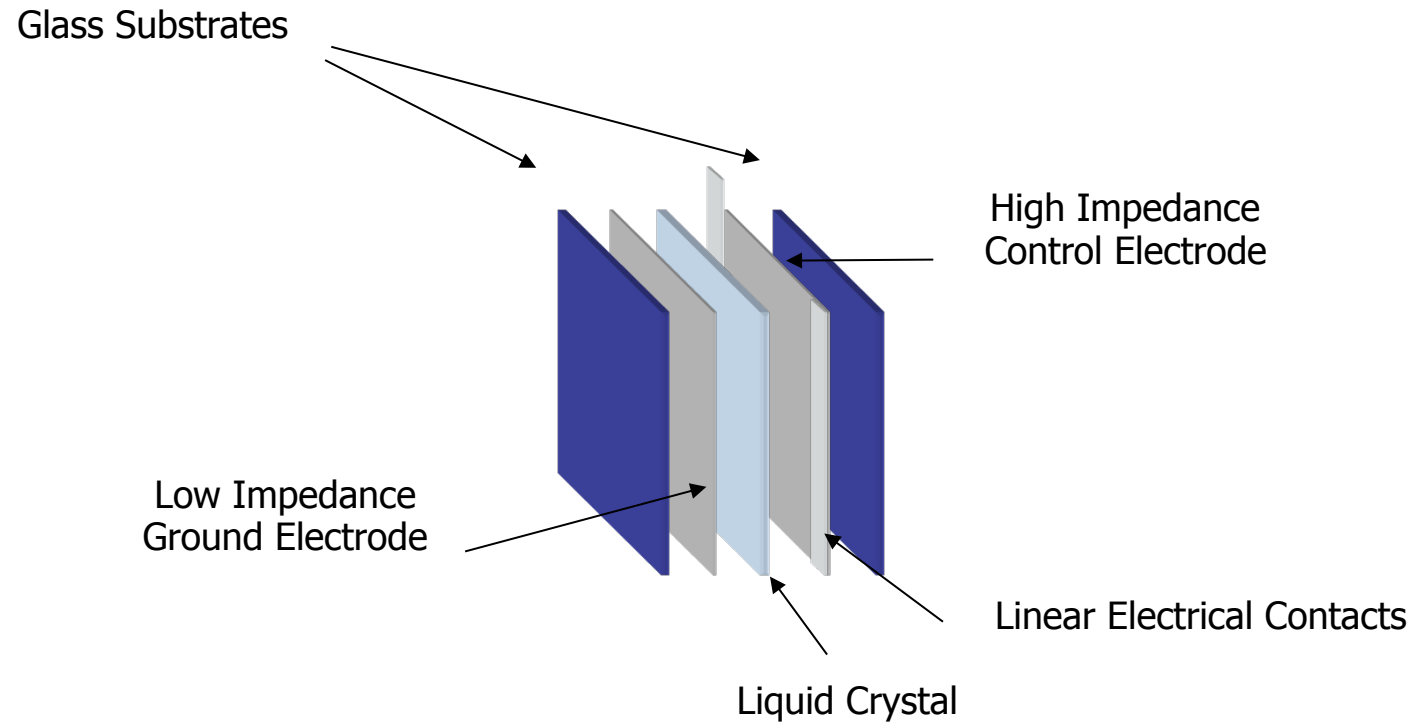
Why LC based Fiber-Optic VOA

Fiber-to-Fiber Coupling

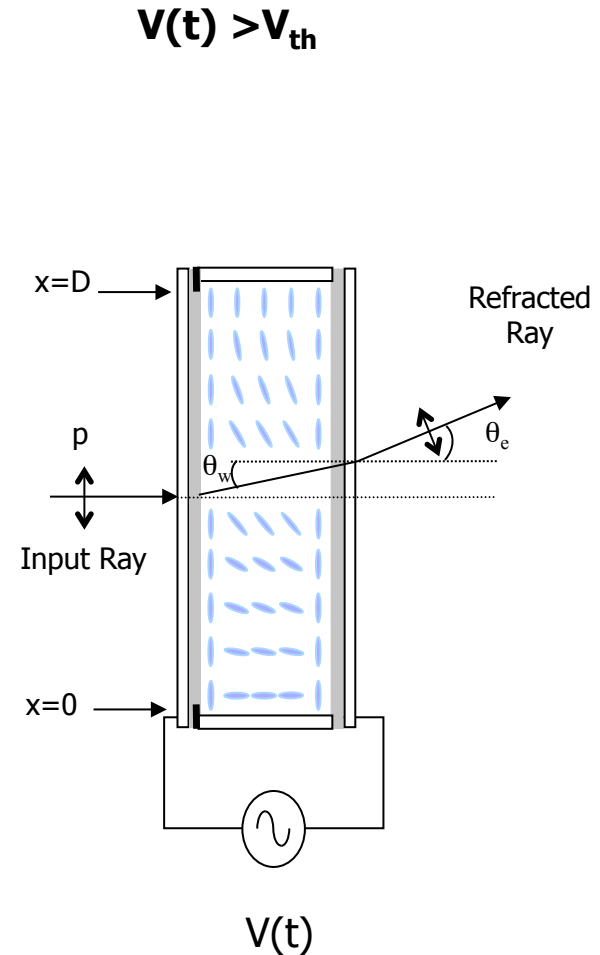
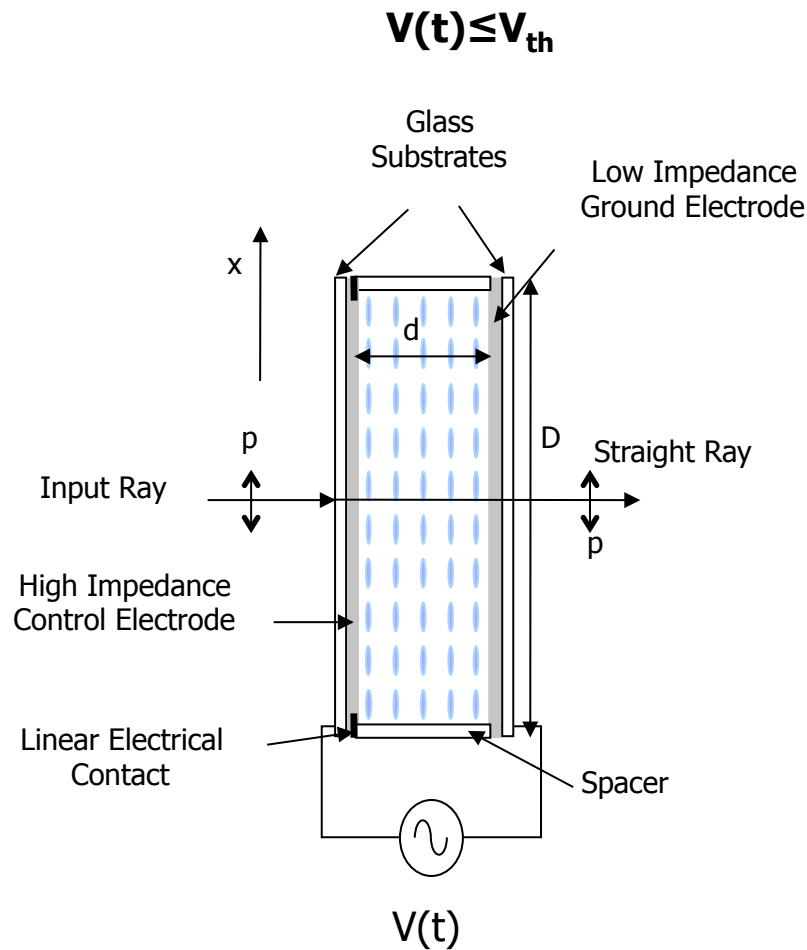


M. van Buren and N. Riza, "Foundations for Low-Loss Fiber Gradient-Index Lens Pair Coupling with the Self-Imaging Mechanism," Applied Optics-LP, vol. 42, issue 3, pages 550-565, January 2003.

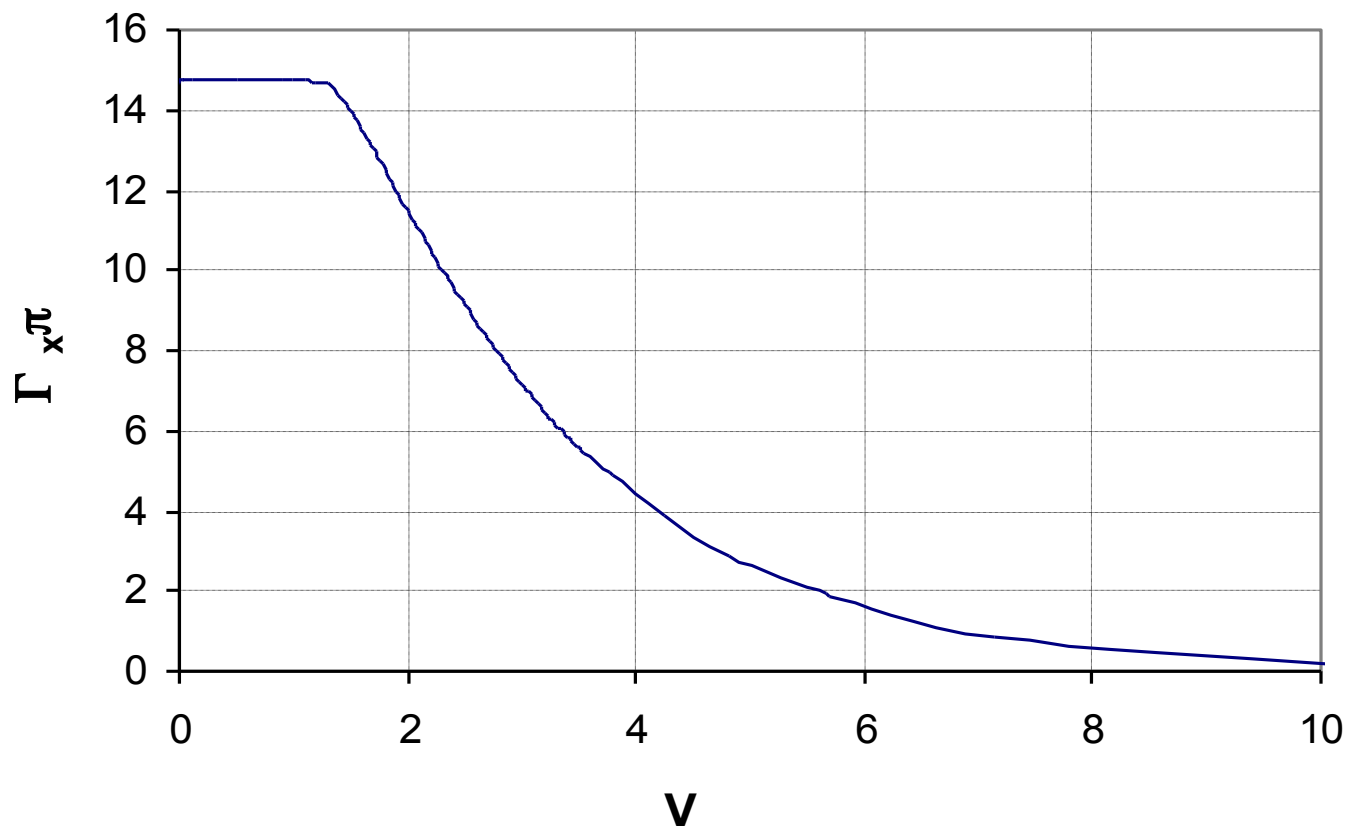
Pixel-Free NLC Deflector Structure and Working Principle



Pixel-Free NLC Deflector Structure and Working Principle

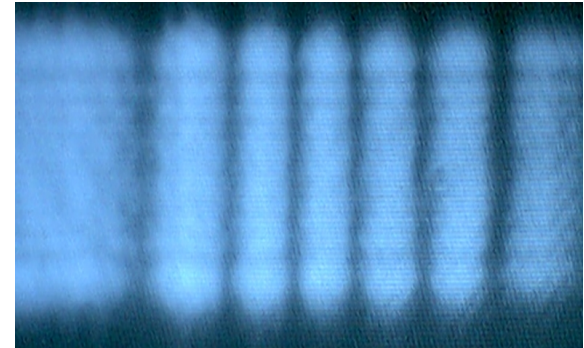
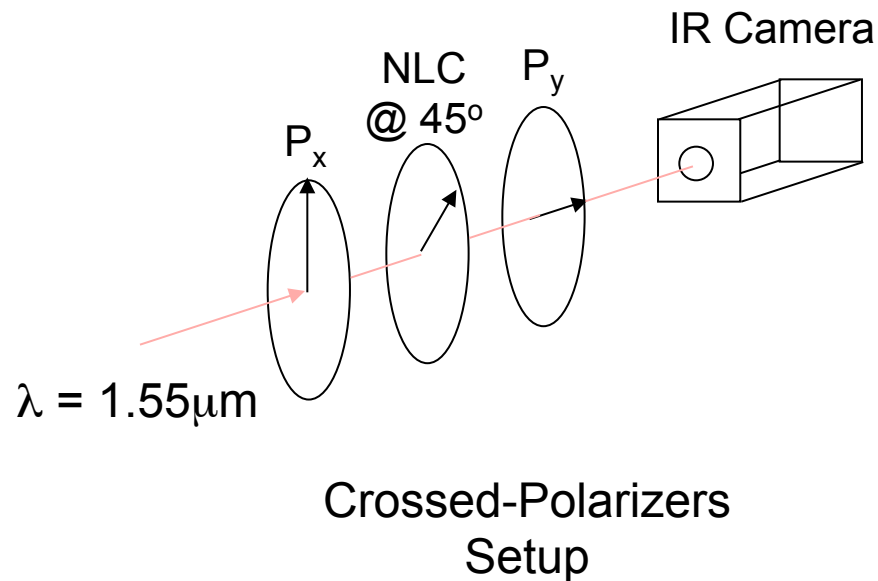


NLC Deflector Phase Retardation Measurement at 1550 nm

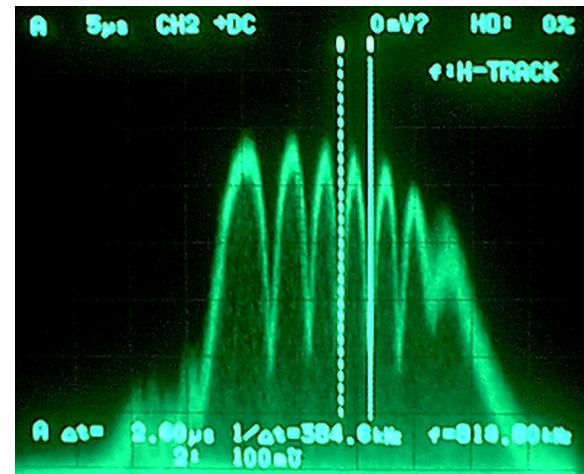


$\lambda = 1.55 \mu\text{m}$
 $d = 50 \mu\text{m}$
 $D = 5 \text{ mm}$
NLC: Merck BL006
 $\Delta n = 0.229$

Observation of Fringes for NLC Deflector

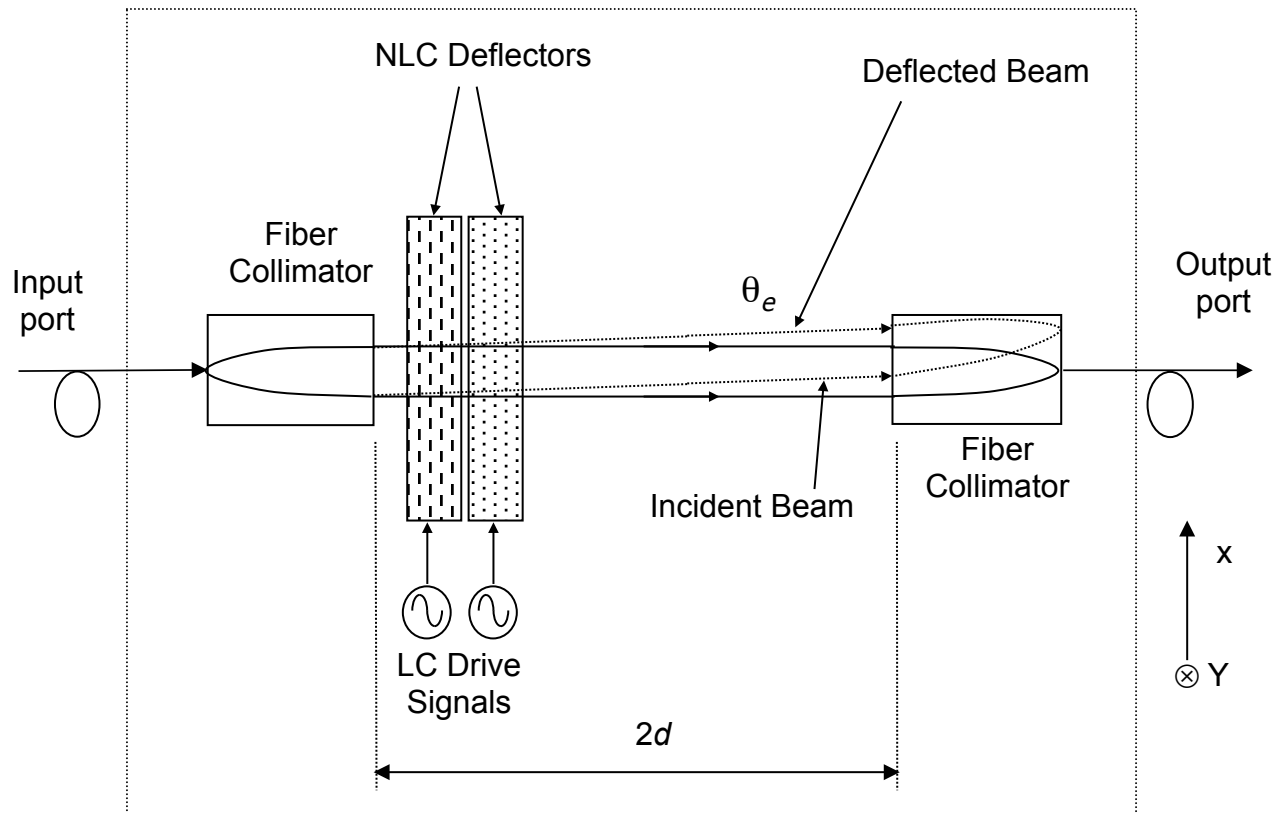


Fringes observed in crossed-polarizer setup



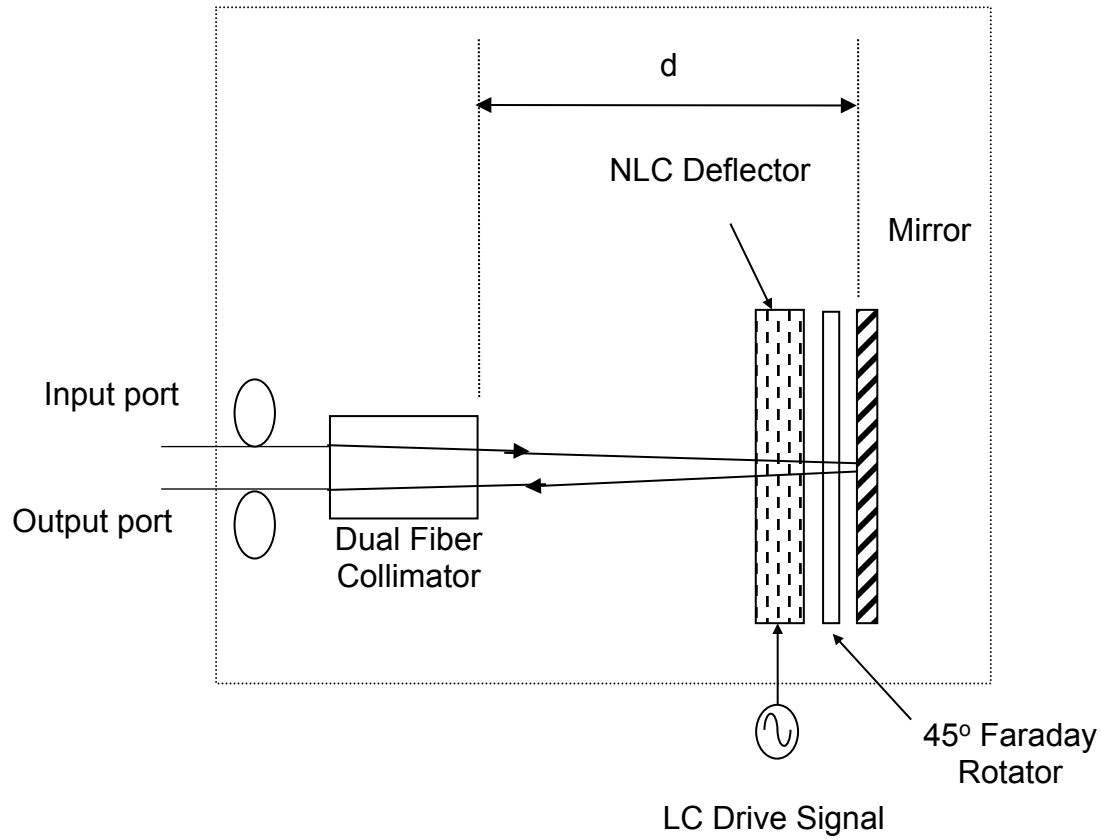
Oscilloscope trace corresponding to these fringes

Fiber-Optic VOA Architecture Transmissive

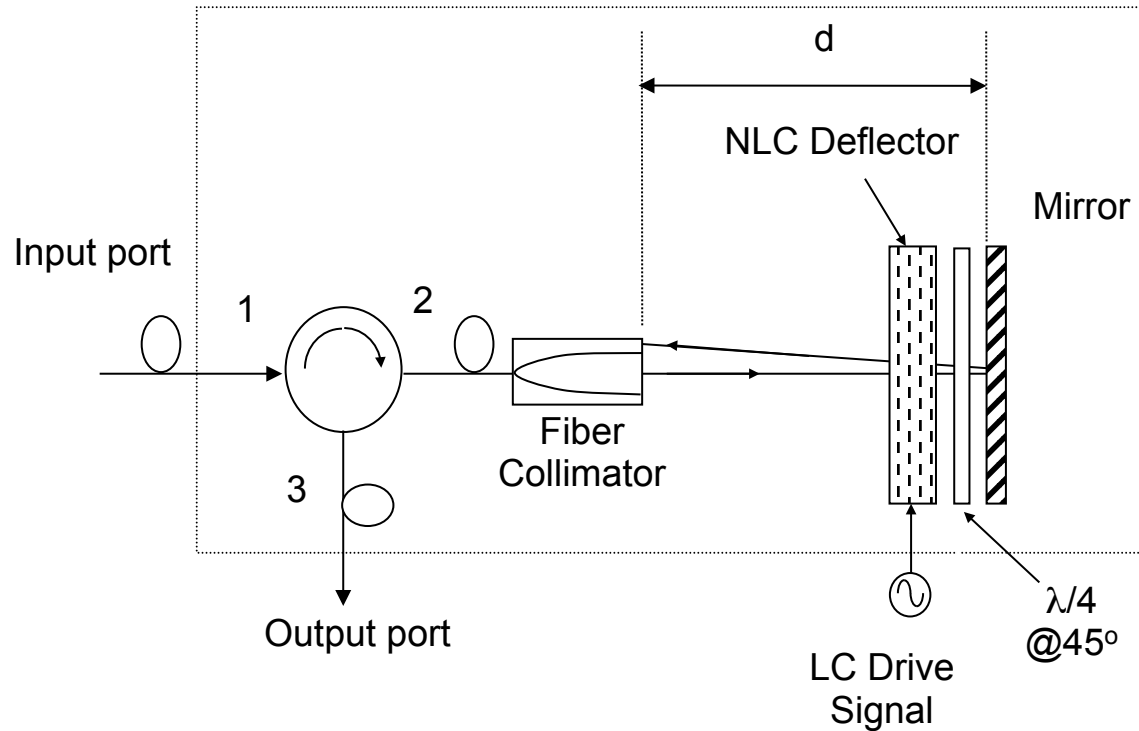


N. A. Riza, "Fault-tolerant fiber-optical beam control modules,"
U.S. patent 6222954, 24 April 2001.

Fiber-Optic VOA Architecture - Reflective

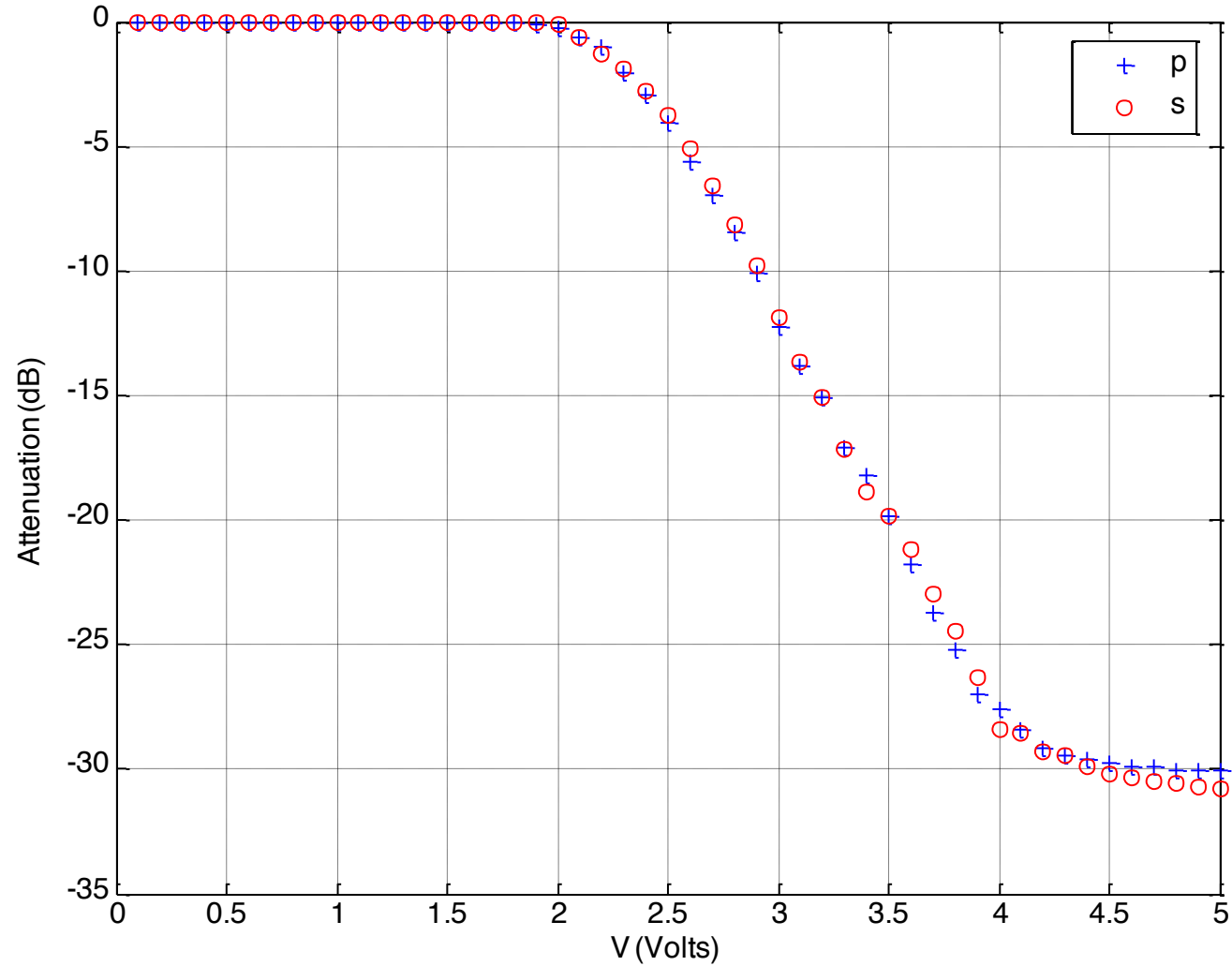


Fiber-Optic VOA Experimental Setup



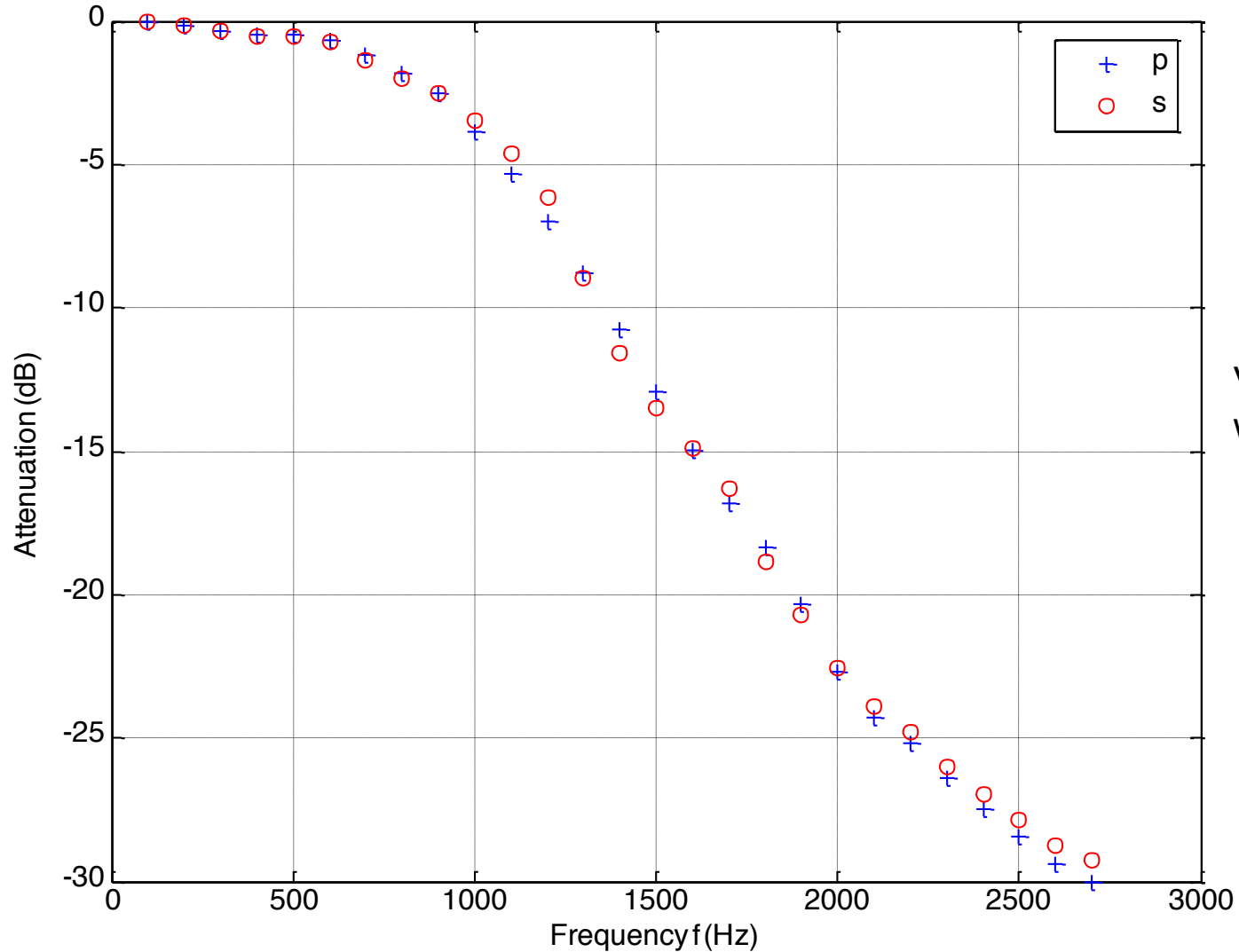
$d=25$ cm
Beam dia=2.5 mm
LC aperture= 5 mm
LC thickness=50 micron
 $\lambda=1550$ nm

VOA Attenuation Control using Voltage



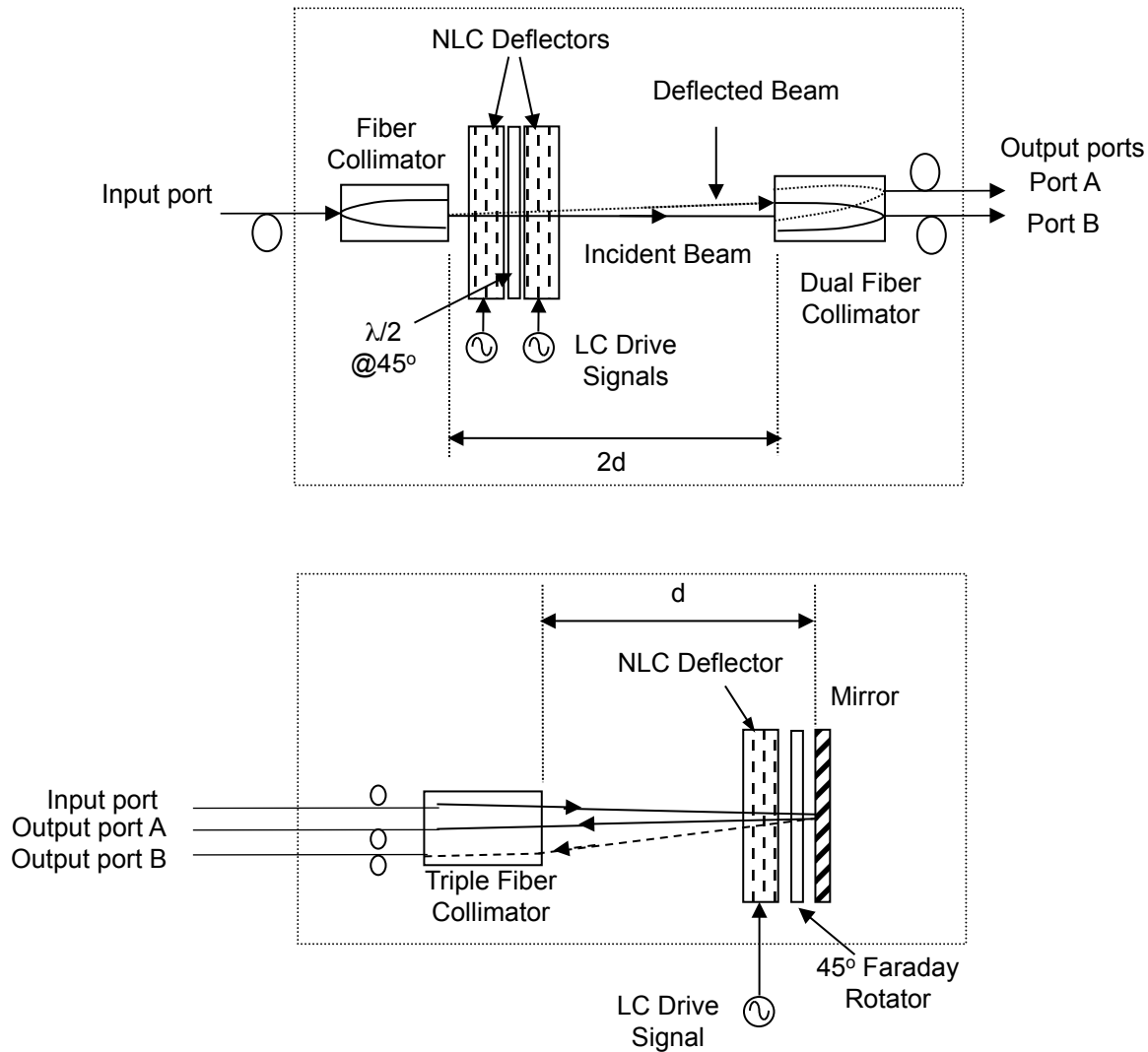
f=2.7 kHz square
wave signal

VOA Attenuation Control using Frequency



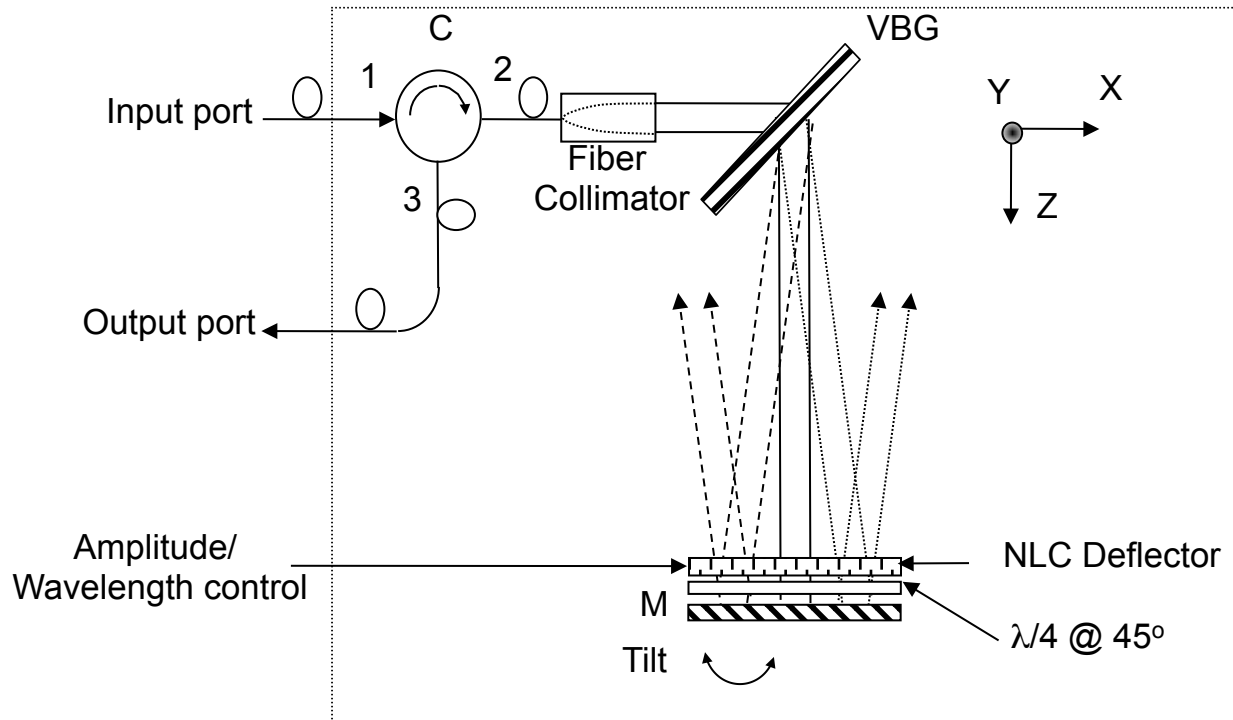
V= 5 Volt square wave signal

Extended Applications: 1X2 Fiber-Optic Switch



N. A. Riza and S. A. Khan, "Liquid-Crystal-Deflector Based Variable Fiber-Optic Attenuator," Applied Optics, Vol. 43, Issue 17, Page 3449-3455, June 2004.

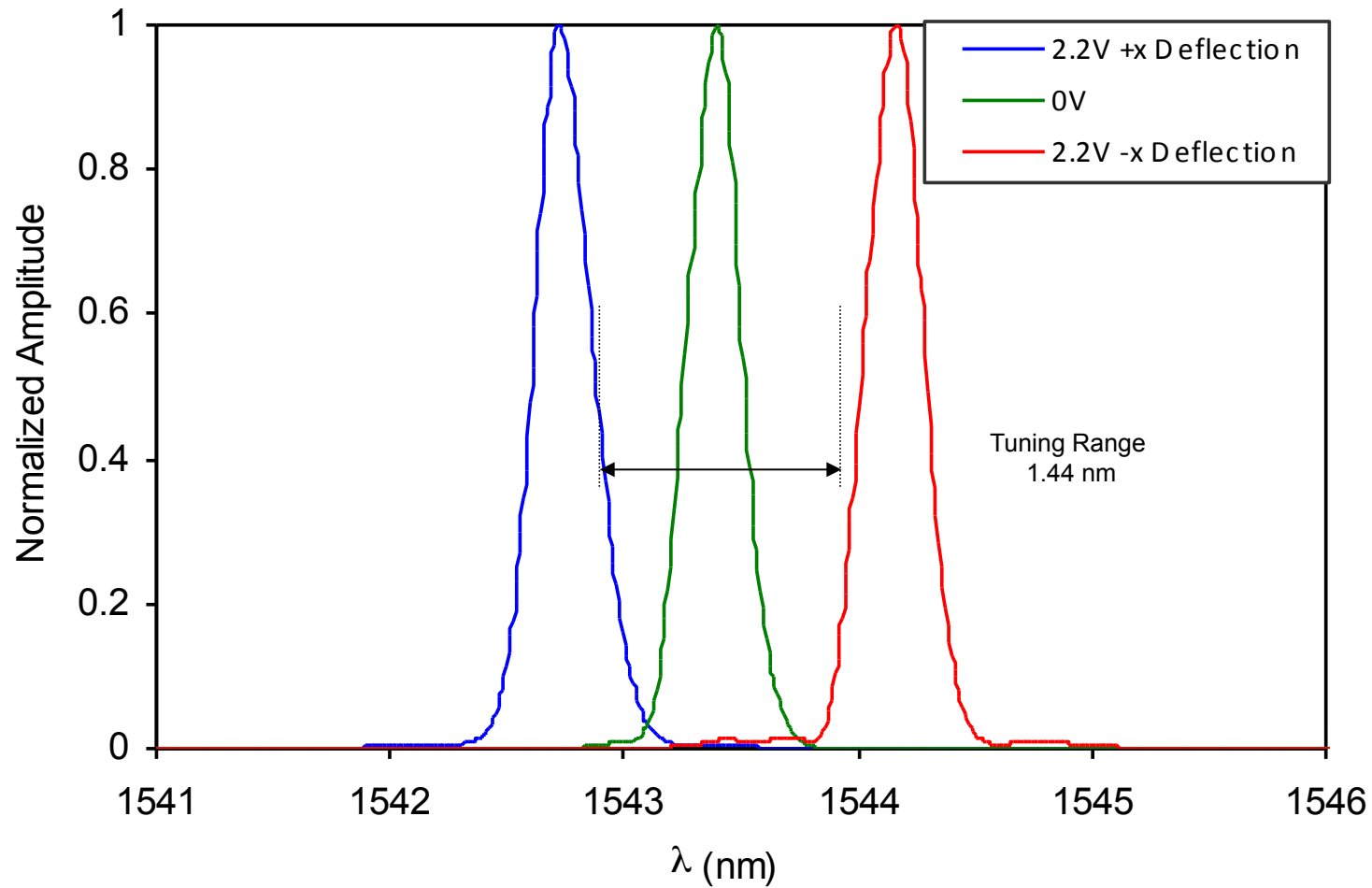
Wavelength Tunable VOA using Liquid Crystal-Mirror Hybrid Controls



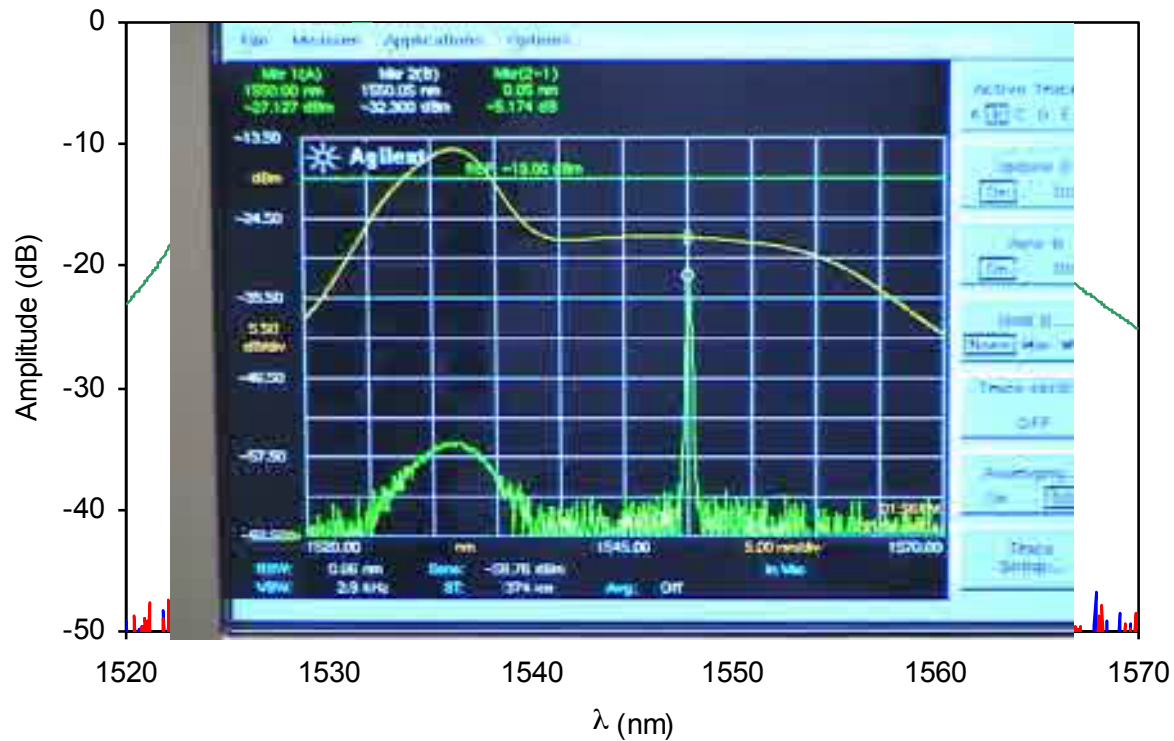
C: Optical Circulator;
VBG: Volume Bragg Grating;
M: Mirror

N. A. Riza and S. A. Khan, "Wavelength Tunable Variable Fiber-Optic Attenuator Using Liquid Crystal-Mirror Hybrid Controls," IEEE Photonics Technology Letters, Vol. 17, Issue 3, Page 621-623, March 2005.

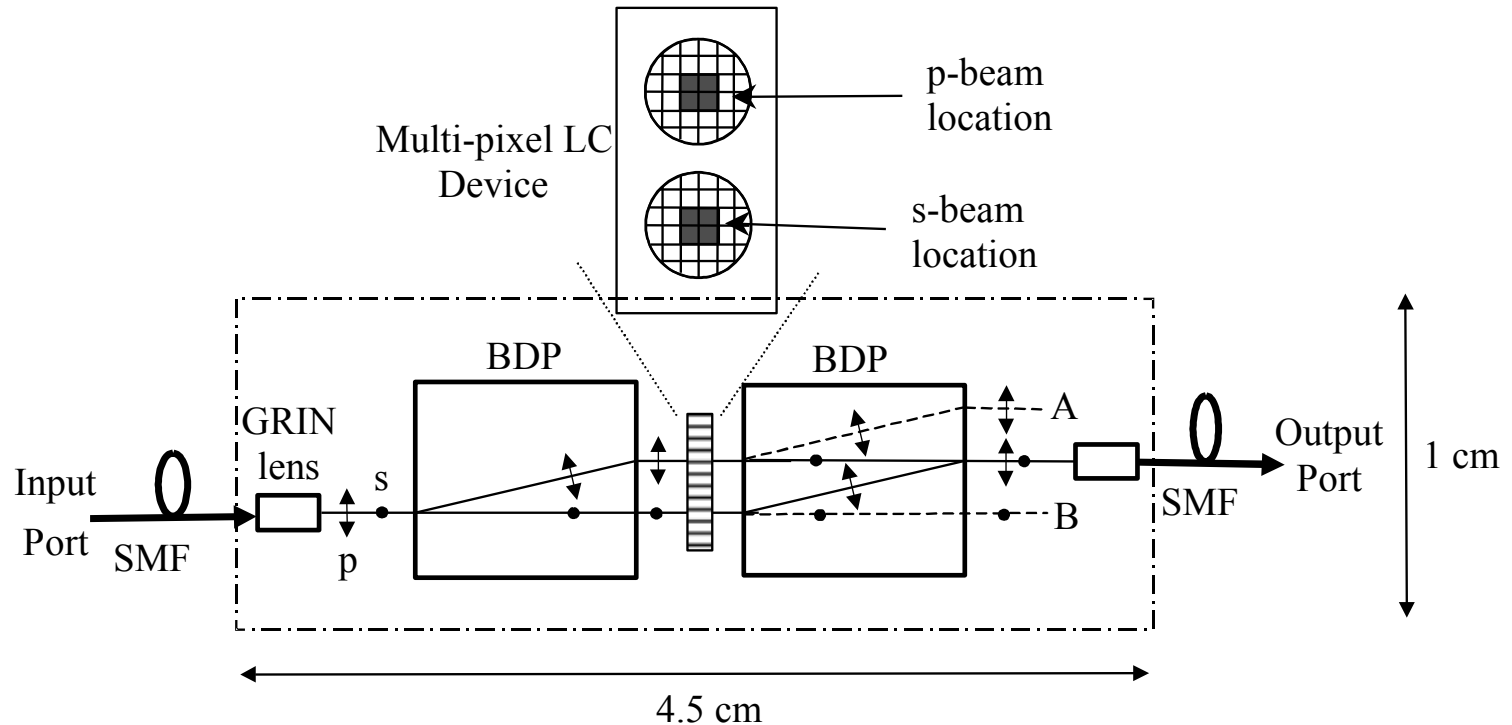
VOA Operation using LC for Fine Wavelength Tuning



Wavelength Tunable VOA Operation using LC



Fiber coupled All-Digital Variable Optical Attenuator using LCs



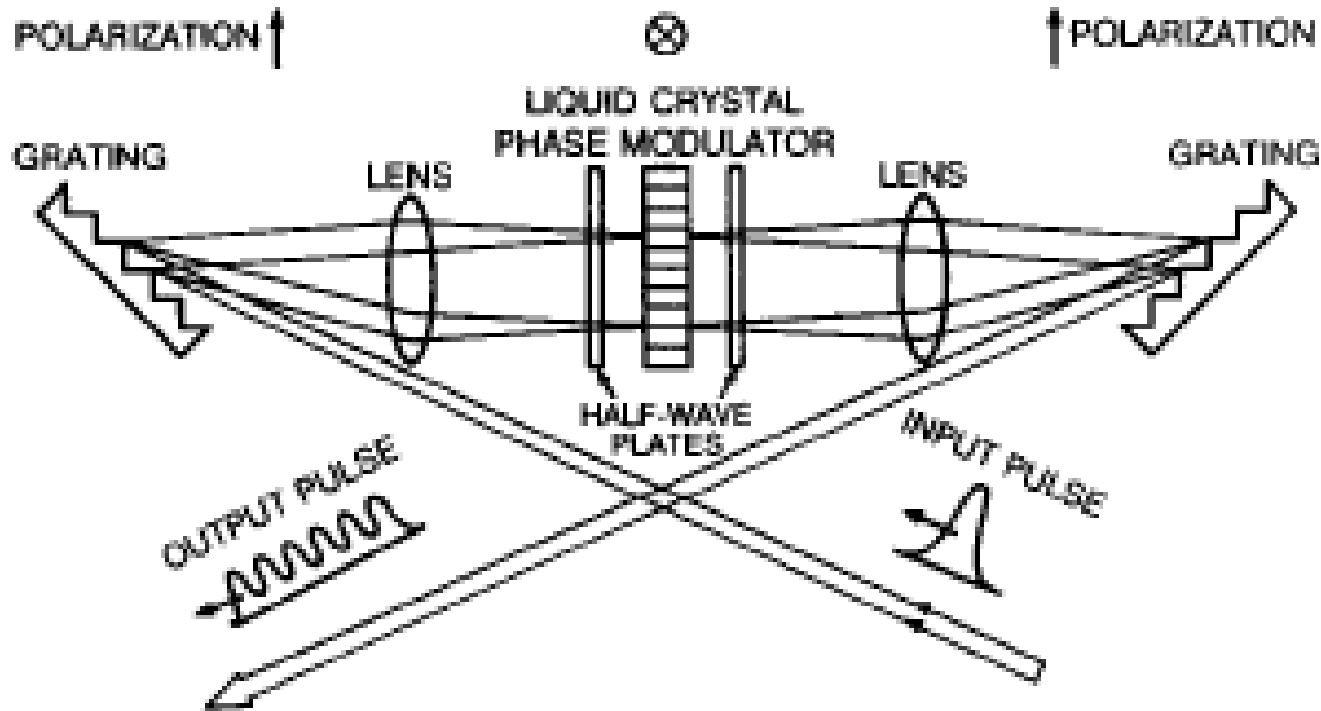
100 % Repeatable Reliable VOA Design

N. A. Riza and Y. Huang, "Digital fault-tolerant variable fiber-optic attenuator using liquid crystals," Proceedings of SPIE, Vol. 4046, paper 11, Orlando, Florida, April 26, 2000.

N. A. Riza, "Fault-tolerant fiber-optical beam control modules," Patent No. 6,222,954, April 24, 2001.

Optical Spectral Shaper:

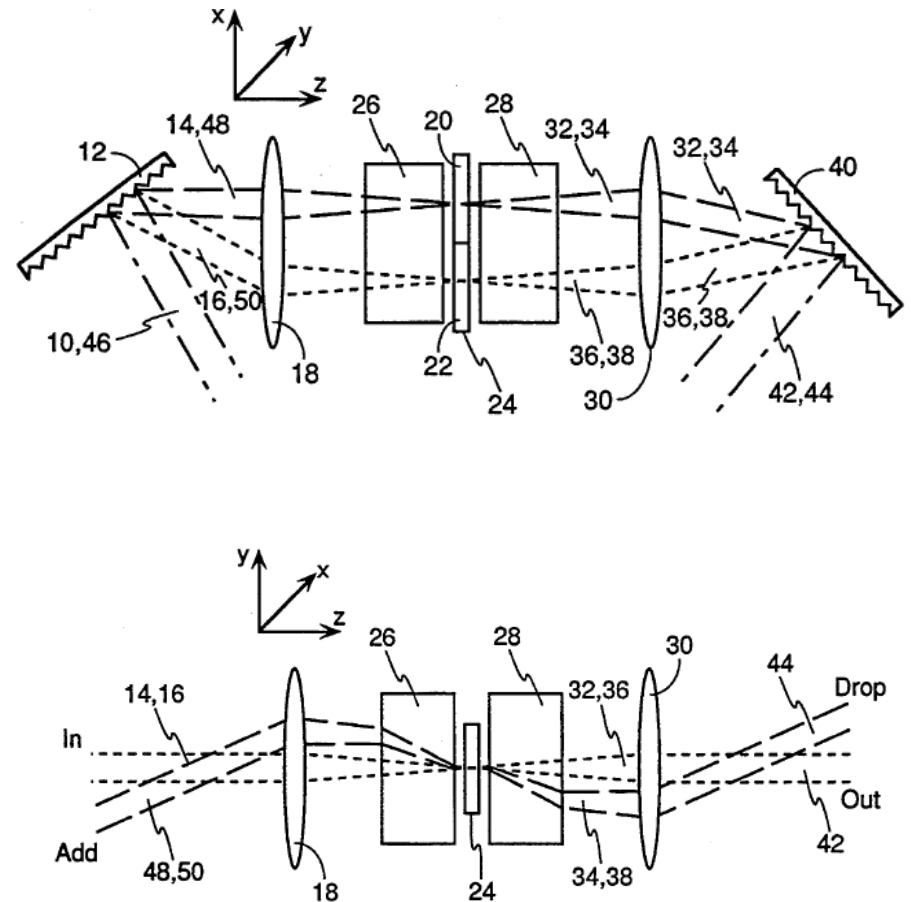
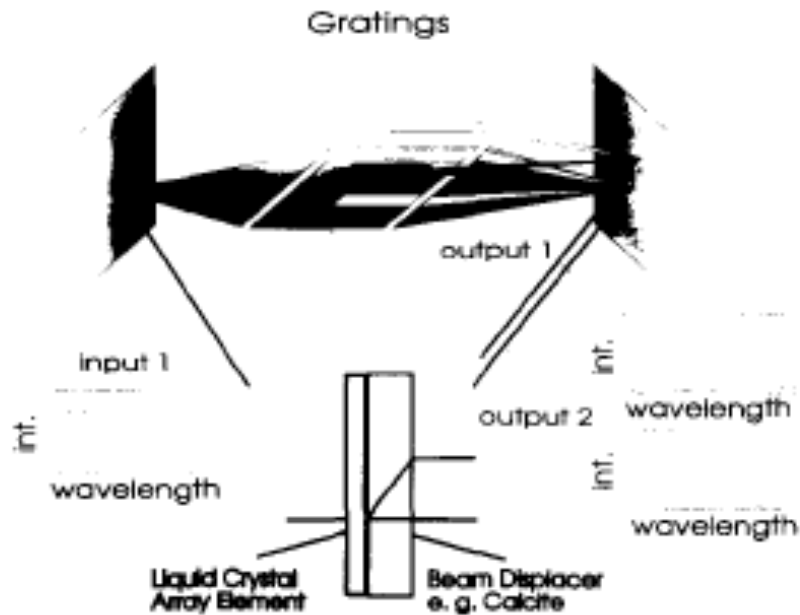
Optical Freespace Beam Pulse Shaper using Two Gratings and LC Spatial Light Modulation



- J. Desbois, F. Gires, P. Turnois, "A new approach to picosecond laser pulse analysis shaping and coding," IEEE JQE, Feb 1973.
- C. Froehly, B. Colombeau, and M. Vampouille, "Shaping and analysis of picosecond light pulses," in *Progress in Optics*, E. Wolf, Ed. Amsterdam: North-Holland, 1983.
- A. M. Weiner, D. E. Leaird, J. S. Patel, J. R. Wullert, II, "Programmable Shaping of Femtosecond Optical Pulses by Use of 128-Element Liquid Crystal Phase Modulator," IEEE JQE, April 1992. (Source of Figure)

Wavelength Add-Drop Filter

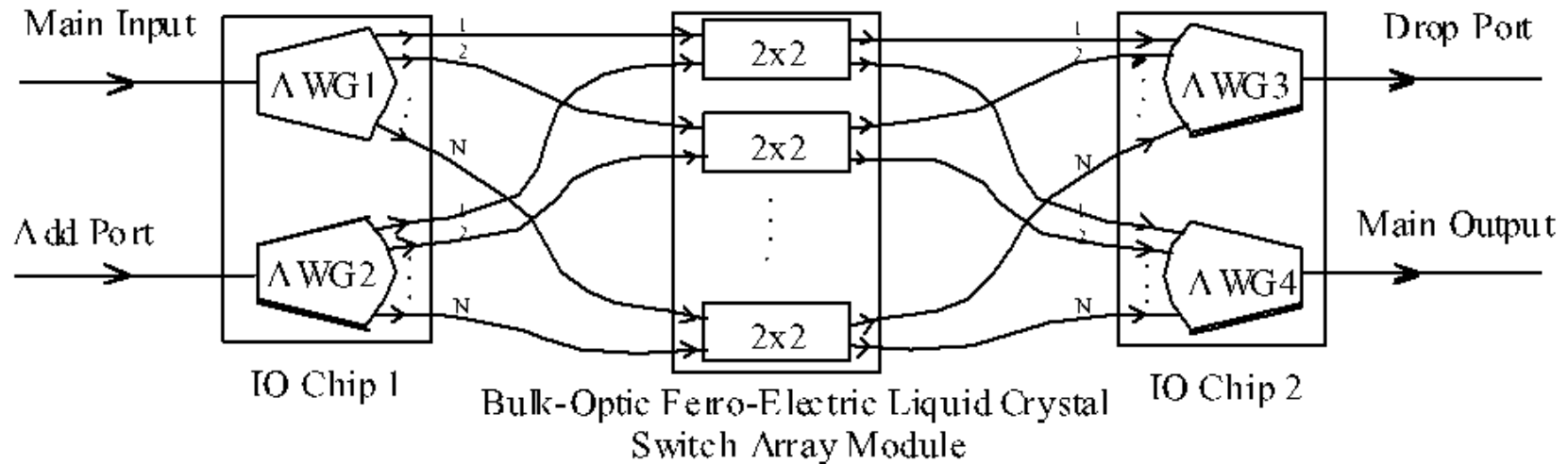
Design using Two Gratings and an LC N-pixel On/Off Polarization Switching Array



J. Patel and Y. Silberberg, "Liquid Crystal and Grating-Based Multiple-Wavelength Cross-Connect Switch," IEEE PTL, May 1995. Also J. Patel and Y. Silberberg, US Patent 5414540, May 1995.

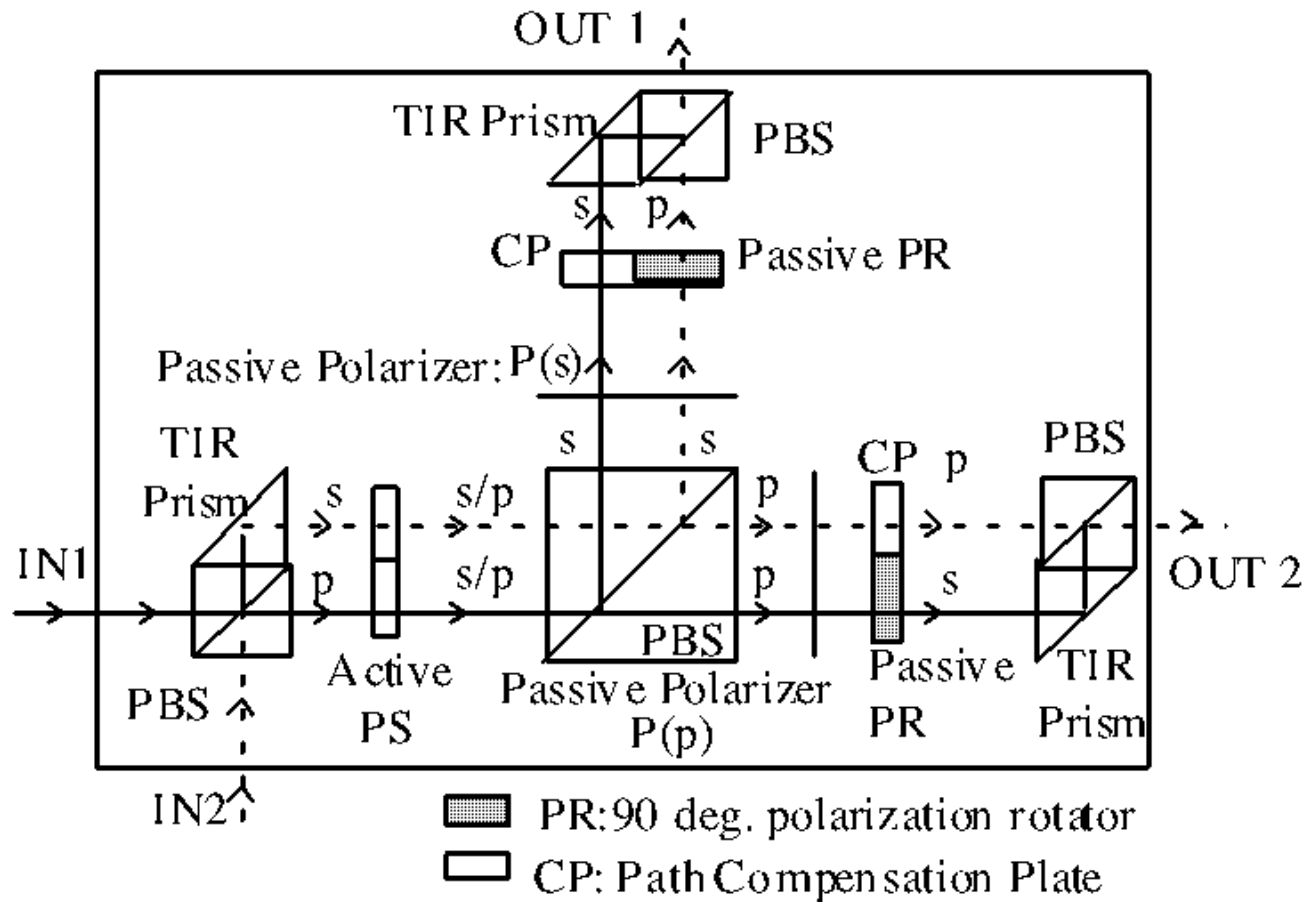
Fiber-Optic Wavelength Add-Drop Filter

Parallel Add-Drop Filter Design using 4 AWGs and an LC 2x2 Switching Array



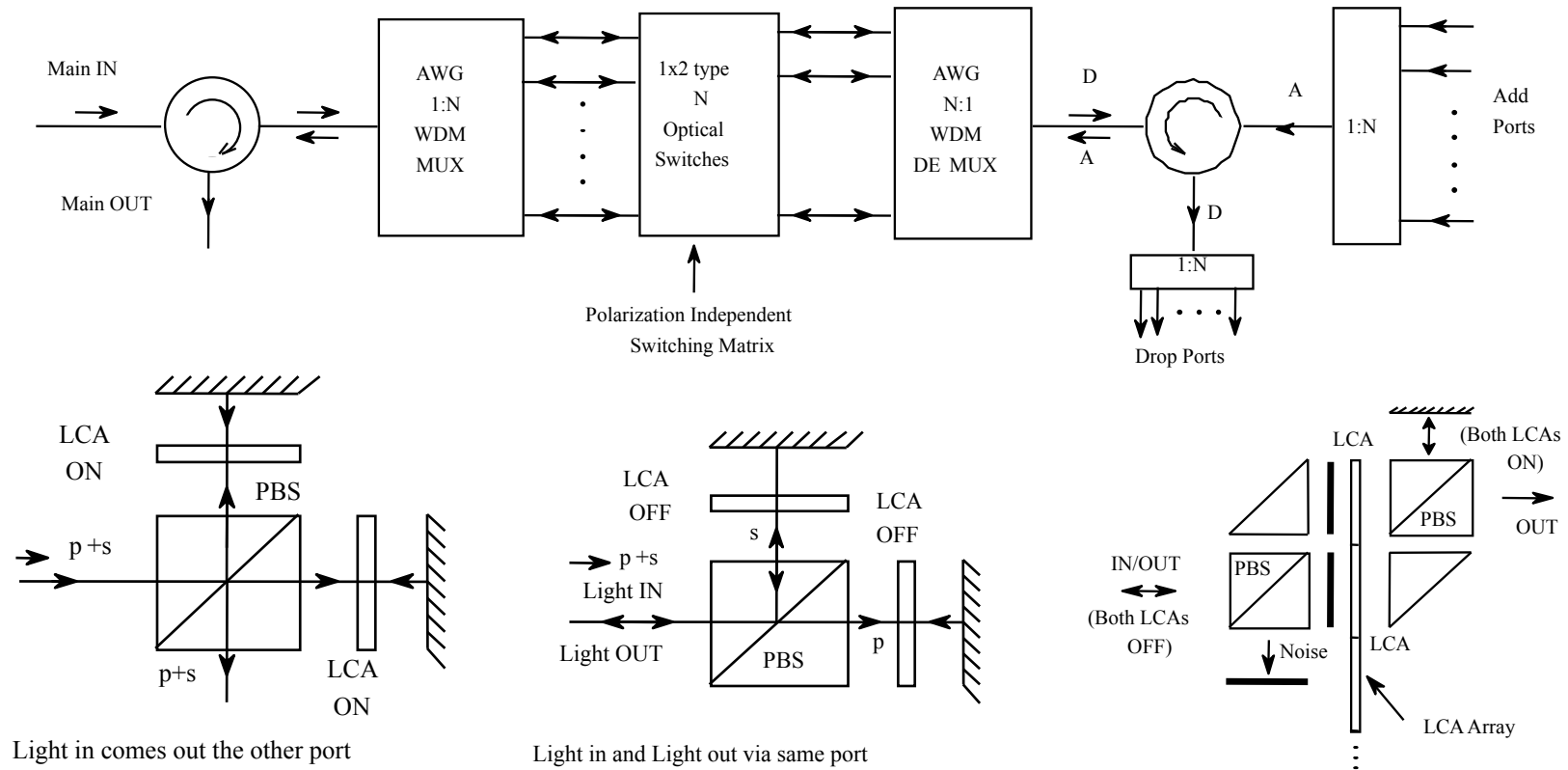
N. A. Riza, "Ferroelectric Liquid Crystal Polarization Switching-based High Speed Multi-Wavelength Add/Drop Filters using Fiber and Array Waveguide Gratings," Int. Optics in Computing '98 Conference, SPIE Vol.3490, P39, pp.335-338, June 1998.

LC-based high speed 2x2 Optical Switch



The PS is a 2-D 2N pixel device for a N-wavelength input beam

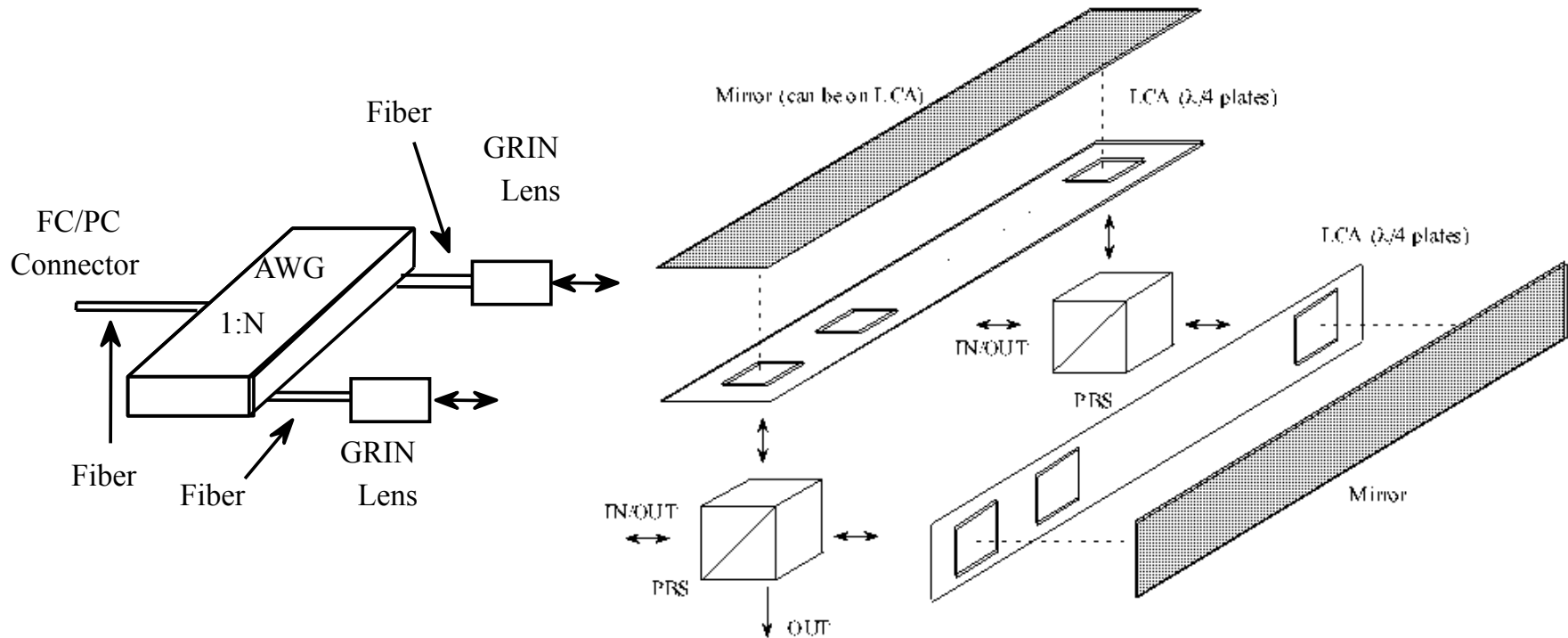
Reflective LC Wavelength Add-Drop Fiber-Optic Filter Architecture



With Noise Filtering

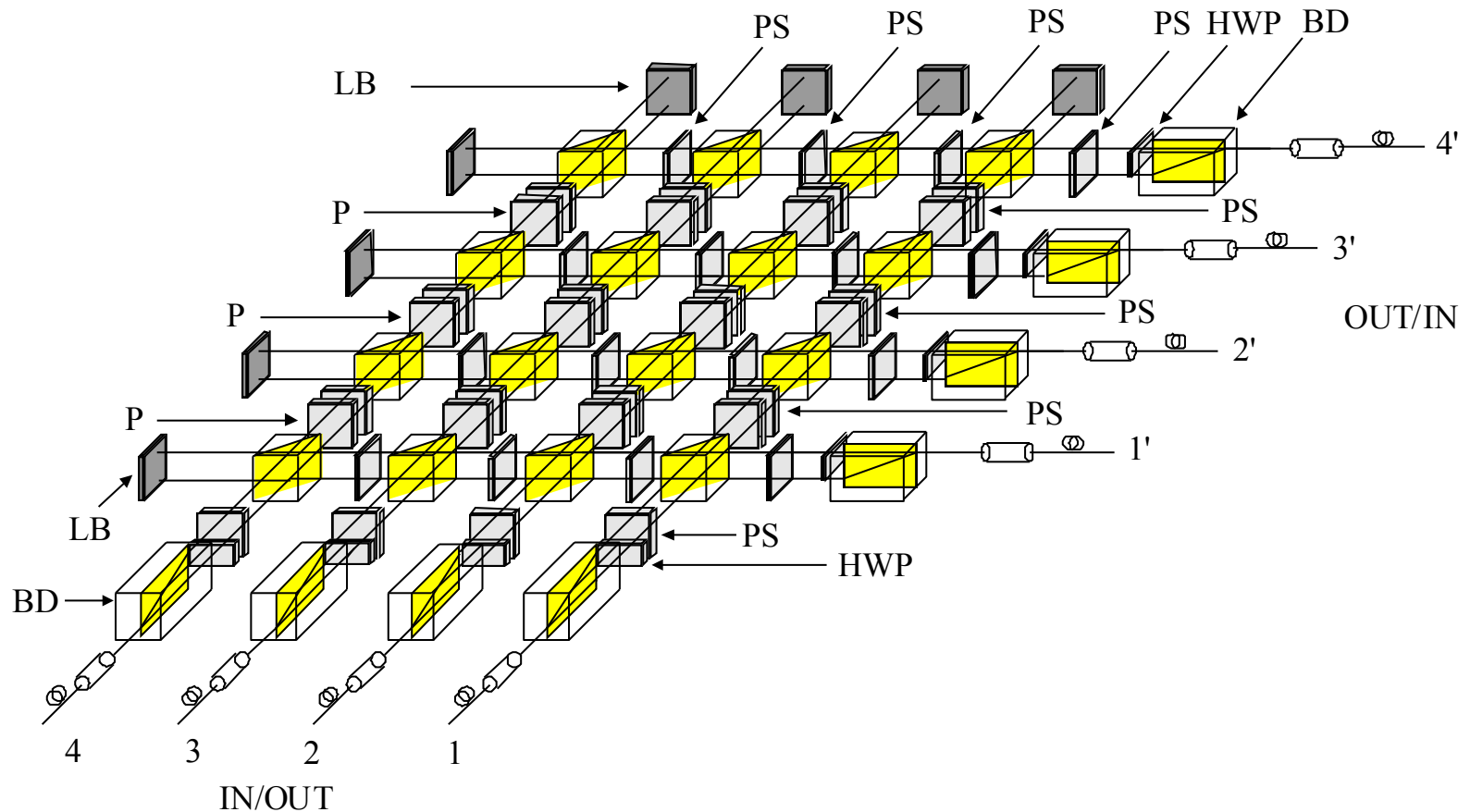
N. Riza, SPIE Conf. Proc. Paper, Belgium 1998.

3-D view of Proposed WDM filter using the Single Cube 1x2 switches



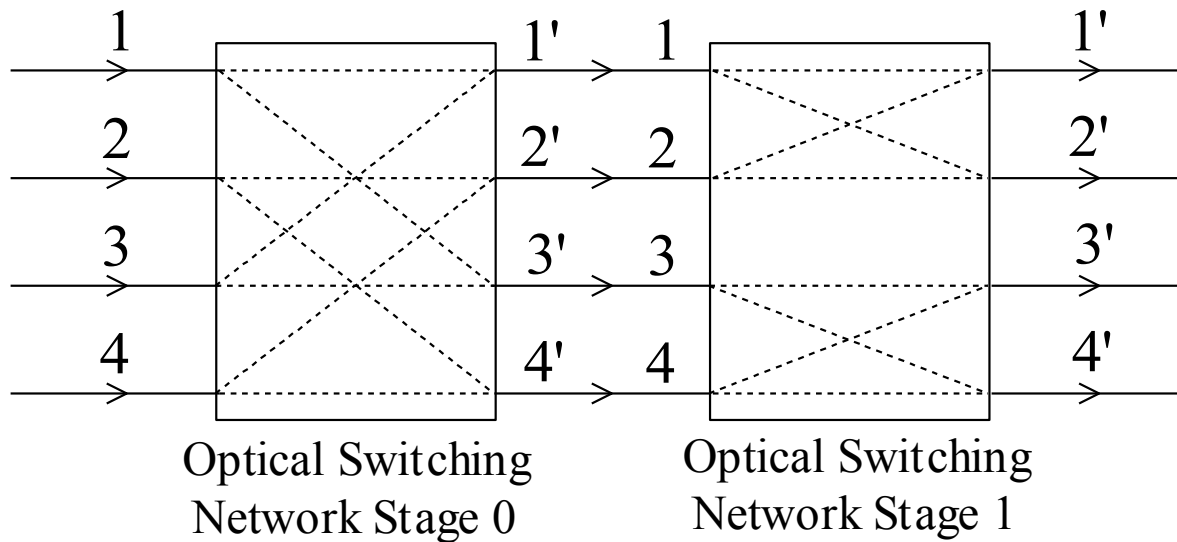
N. A. Riza, " Ferroelectric Liquid Crystal Polarization Switching-based High Speed Multi-Wavelength Add/Drop Filters using Fiber and Array Waveguide Gratings, " Int. Optics in Computing '98 Conference, SPIE Vol.3490, P39, pp.335-338, June 1998.

Proposed $N \times N$ LC switch is shown as a 4×4 switch



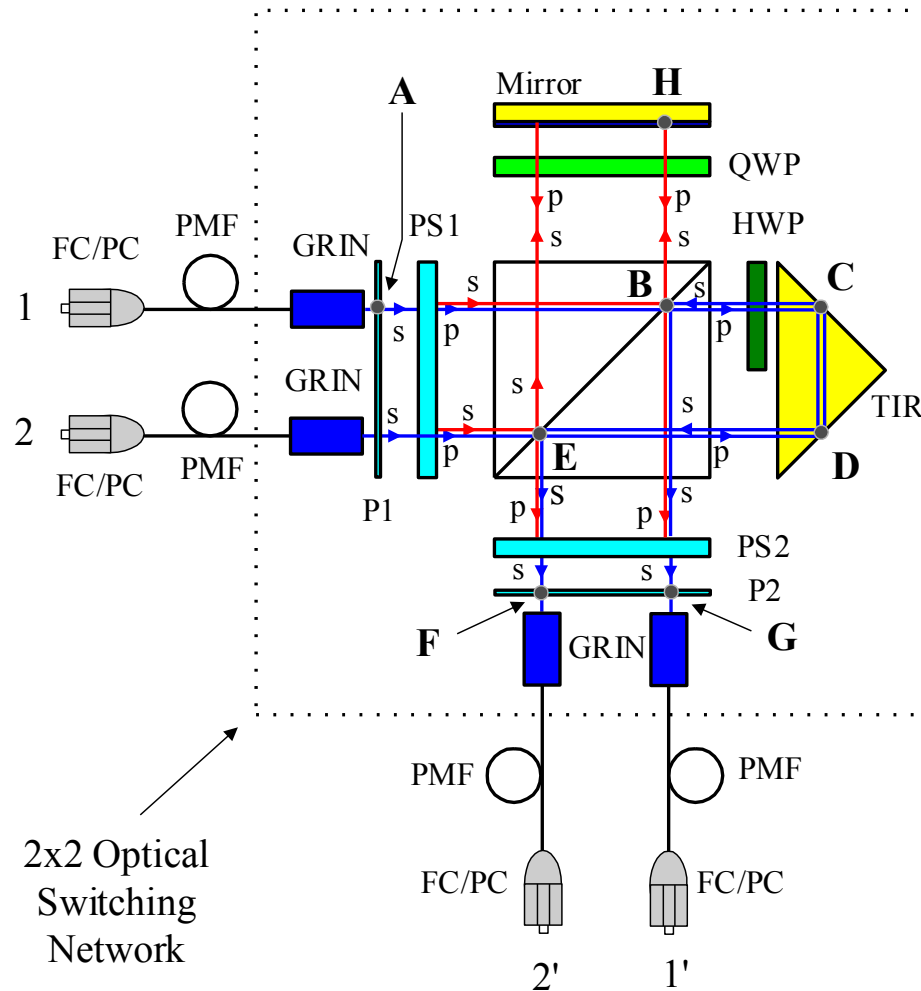
S. Yuan and N. A. Riza, IEEE LEOS Ann. Mtg, 1998.

Example Optical Banyan Network With Four Inputs Indicating The Required Two Stages And Their Binary Switching States

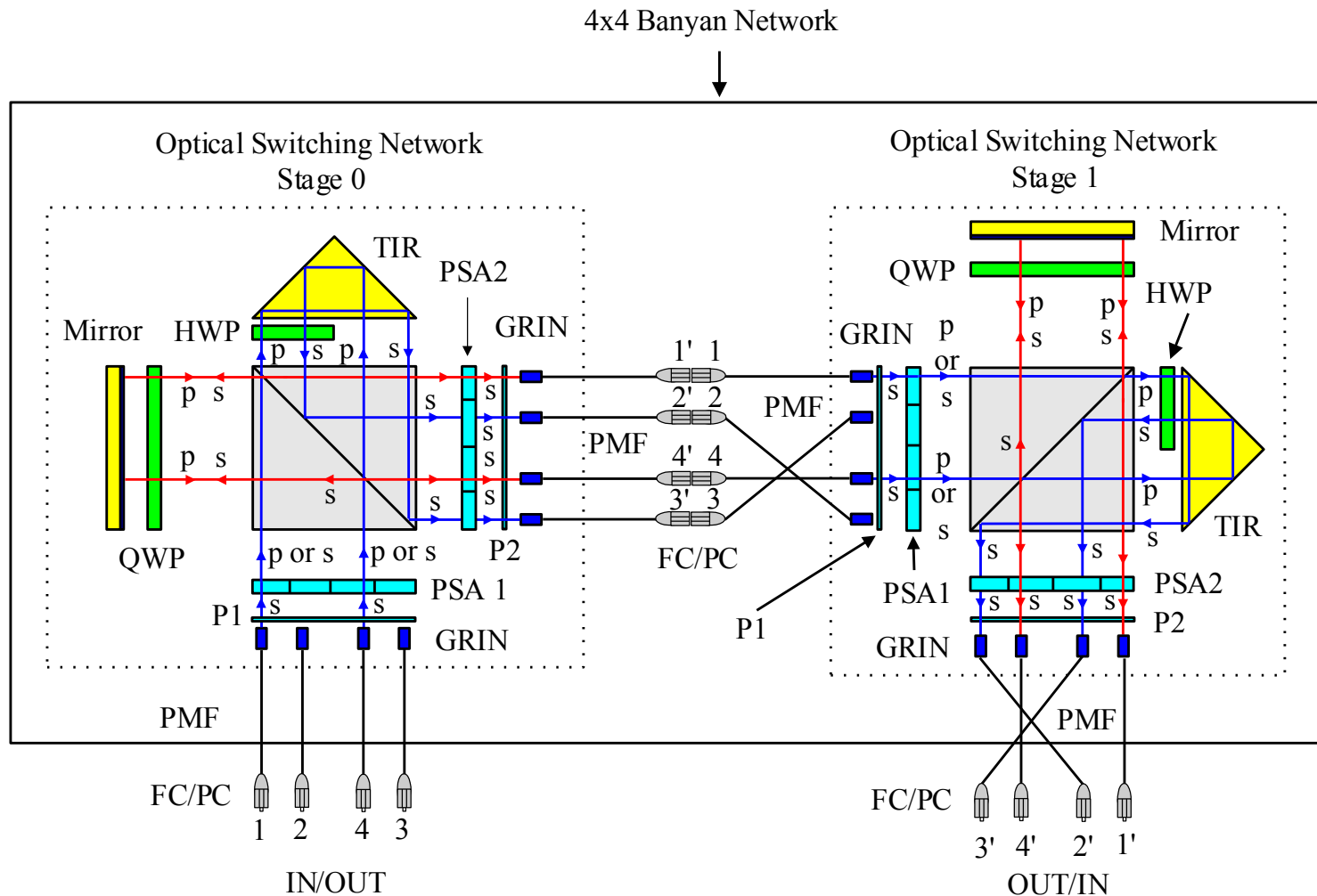


N. A. Riza and S. Yuan, IEEE JLT Sept. 1999.

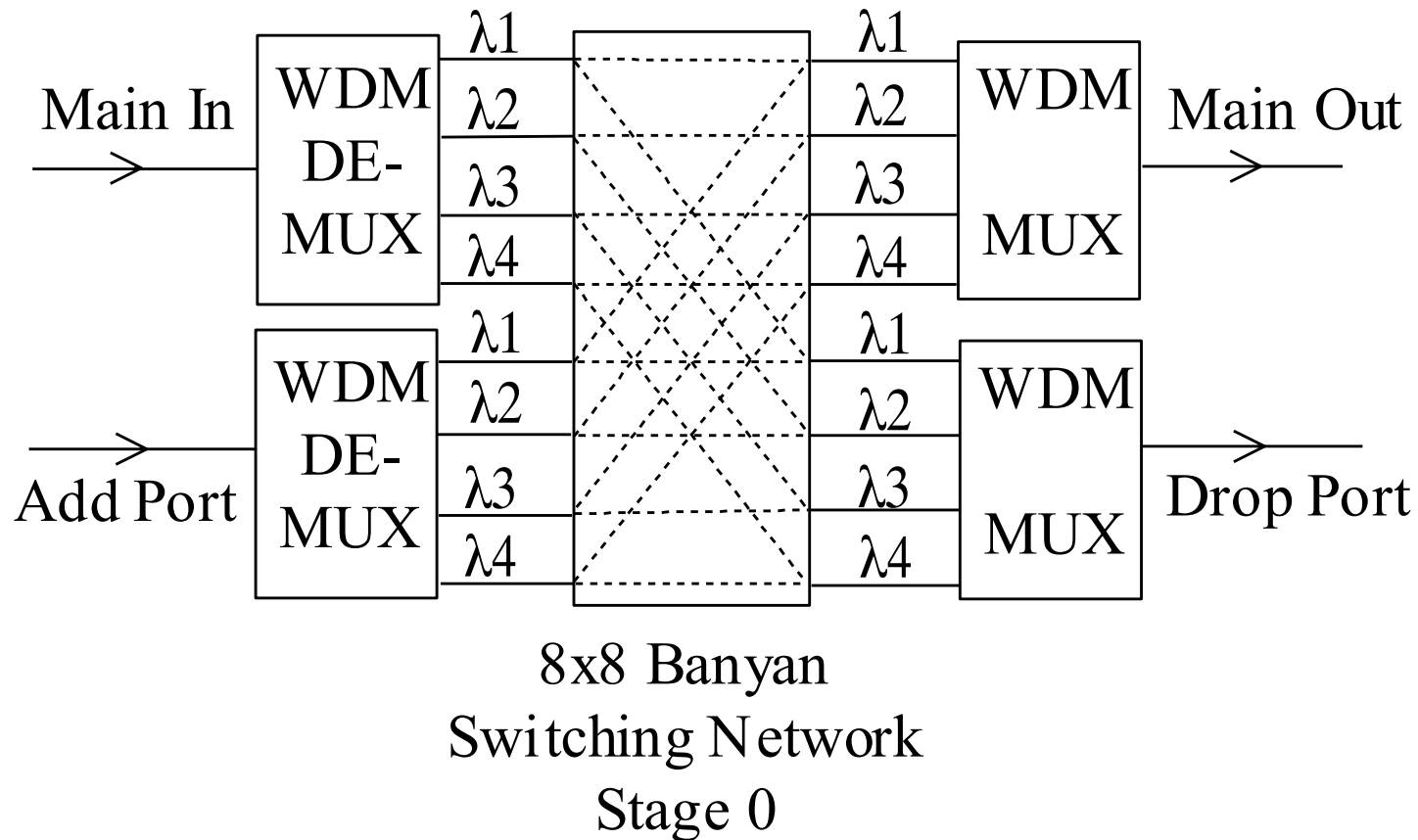
Proposed Polarization Dependent 2 X2 Fiber Optic Switch Used As The Basic Building Block Structure Of Any Banyan Network



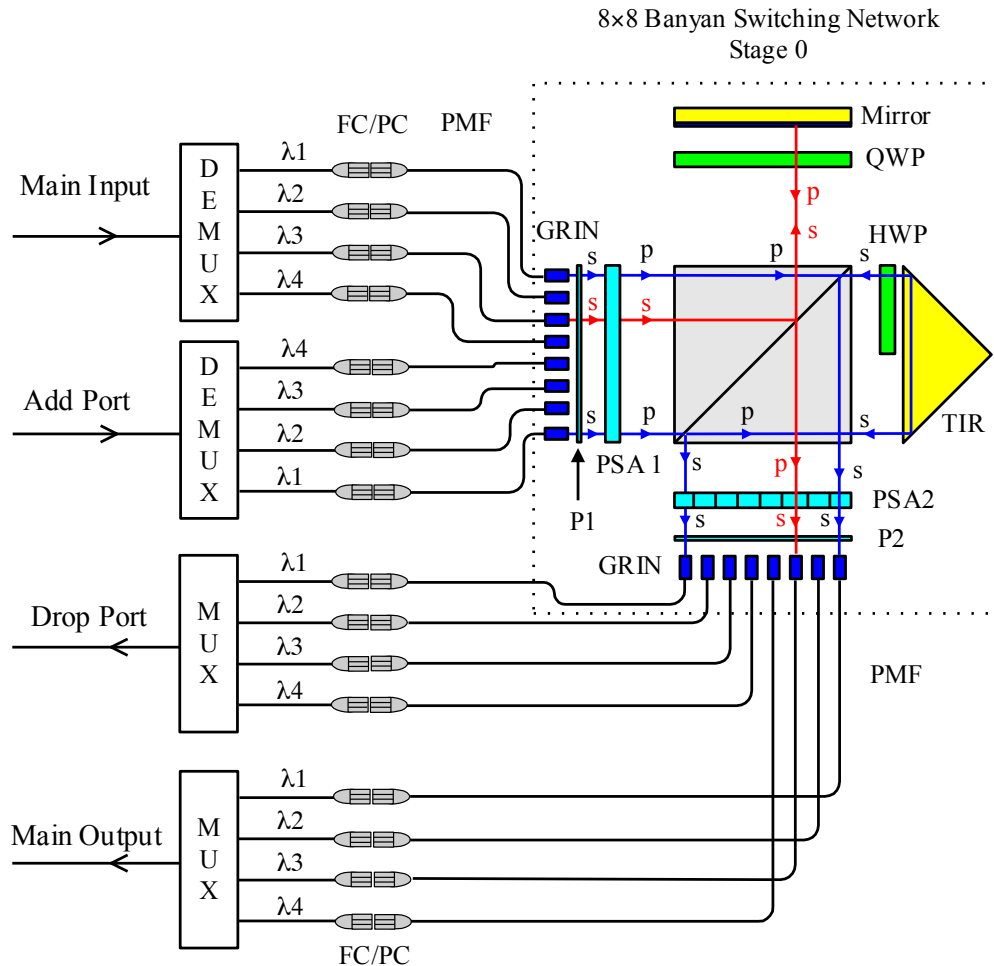
Building A Four-input Banyan Network With Our Fiber-optic Switch As The Basic Building Block



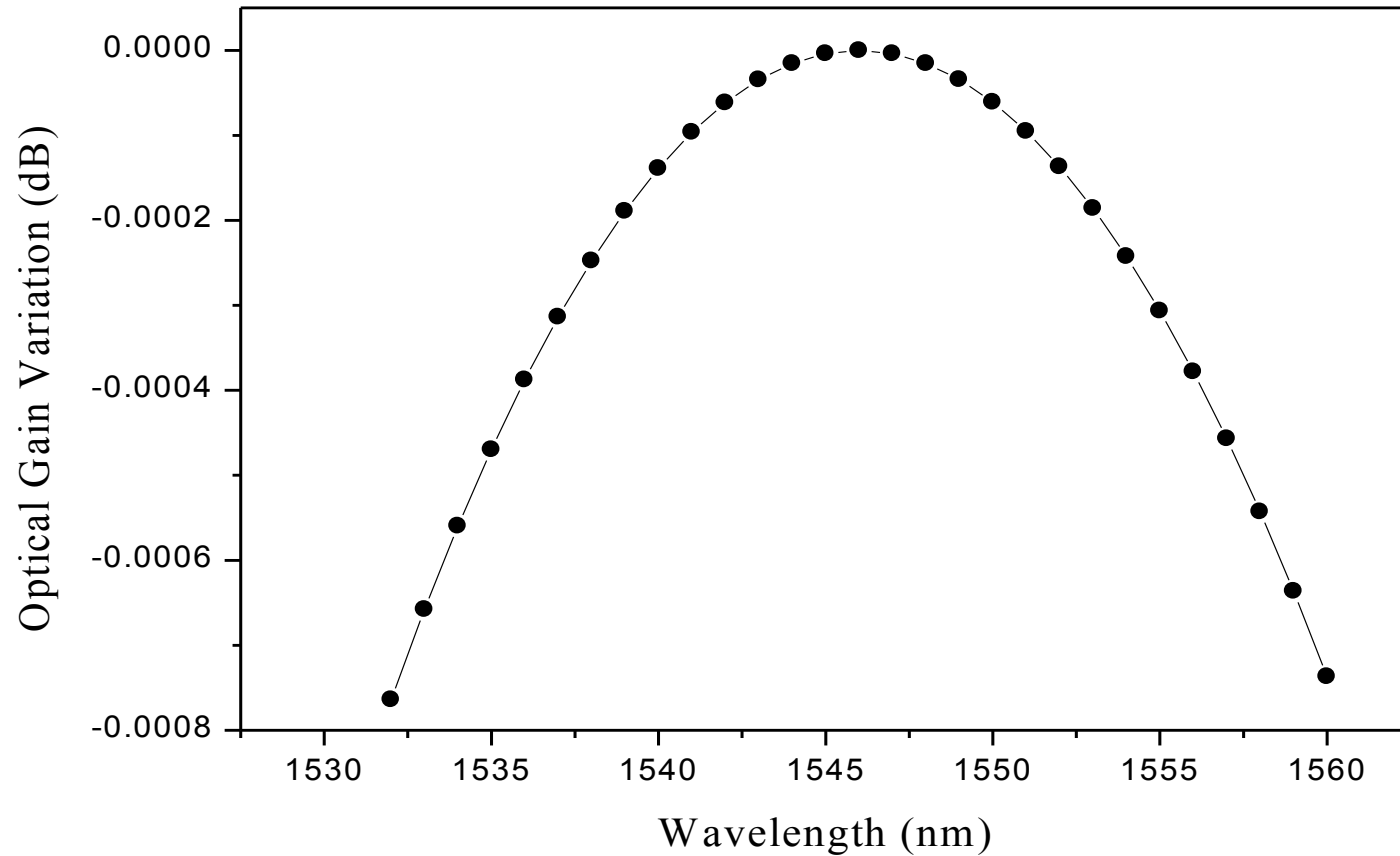
Proposed N=2 Wavelengths WDM Programmable Add/Drop Filter Based On A N N Banyan Network Stage 0



Optical Implementation Of The Four Wavelength WDM Add-drop Filter Using The Basic Switch Structure

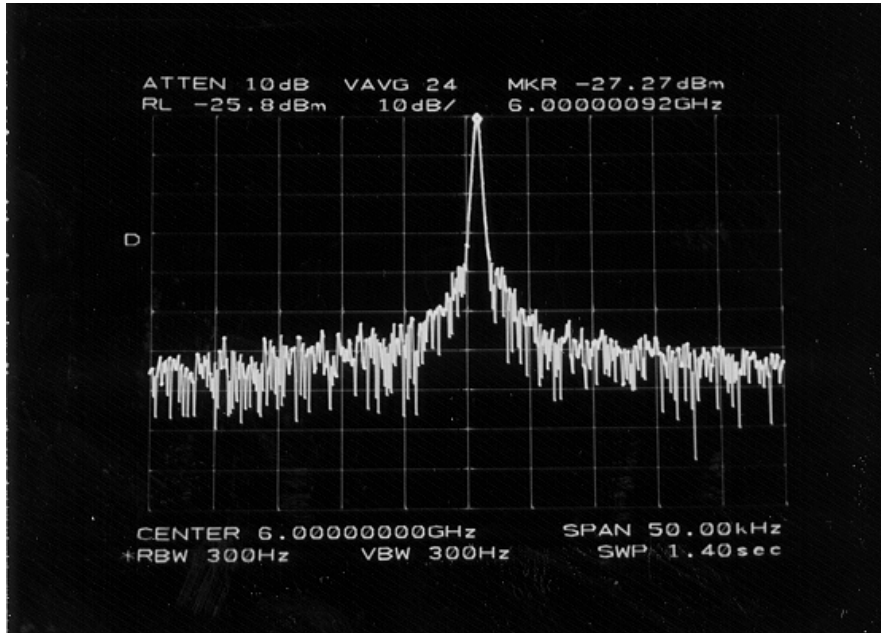


**Wavelength Dependent Normalized Optical Power Variation In dB
For a FLC Device Designed To Act as a Half-wave Retarder
at a Center Wavelength of 1546 nm**

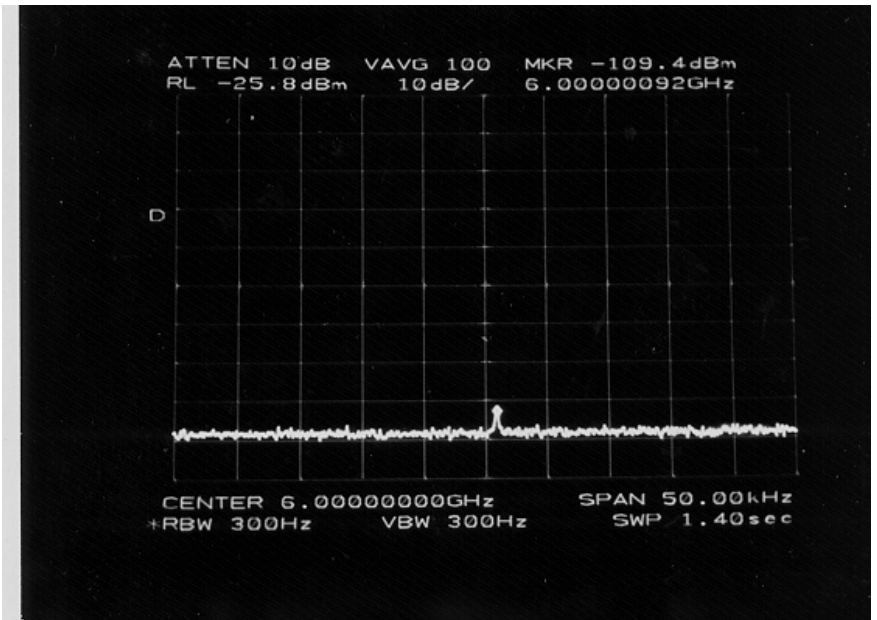


Extremely Small FLC Device Optical Throughput Variation over C-Band

Example RF interchannel crosstalk measurement for 2x2 FLC Polarization Dependent Fiber-Optic Switch when only input channel 1 has an active input signal and the switch is in straight state.



(a)



(b)

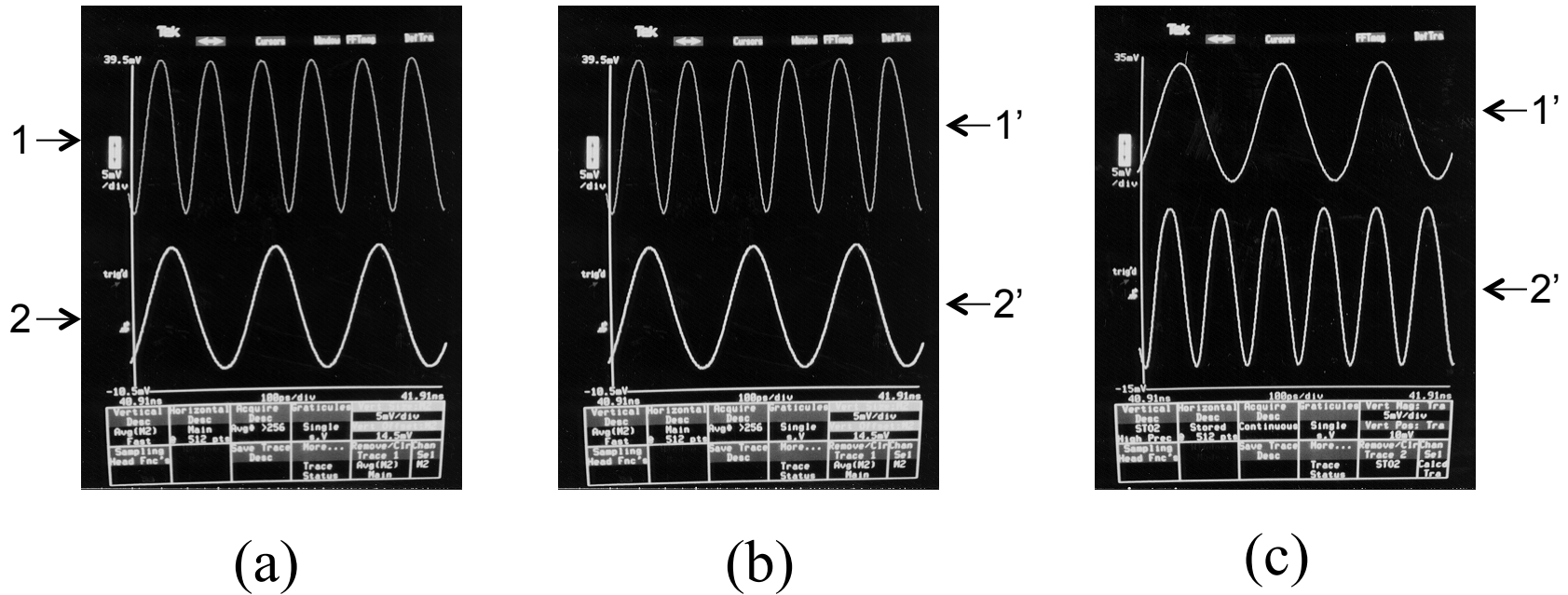
The detected RF power:

(a) of output channel 1' is -27.27 dBm

(b) of the channel 2' (i.e., leakage from 10) is about -109.4 dBm.

This indicates a -82.13 dB RF interchannel crosstalk or - 41.06 dB optical interchannel crosstalk.

Experimental results showing the exchanging operation of the 2x2 Polarization Dependent FLC-based Fiber-Optic switch

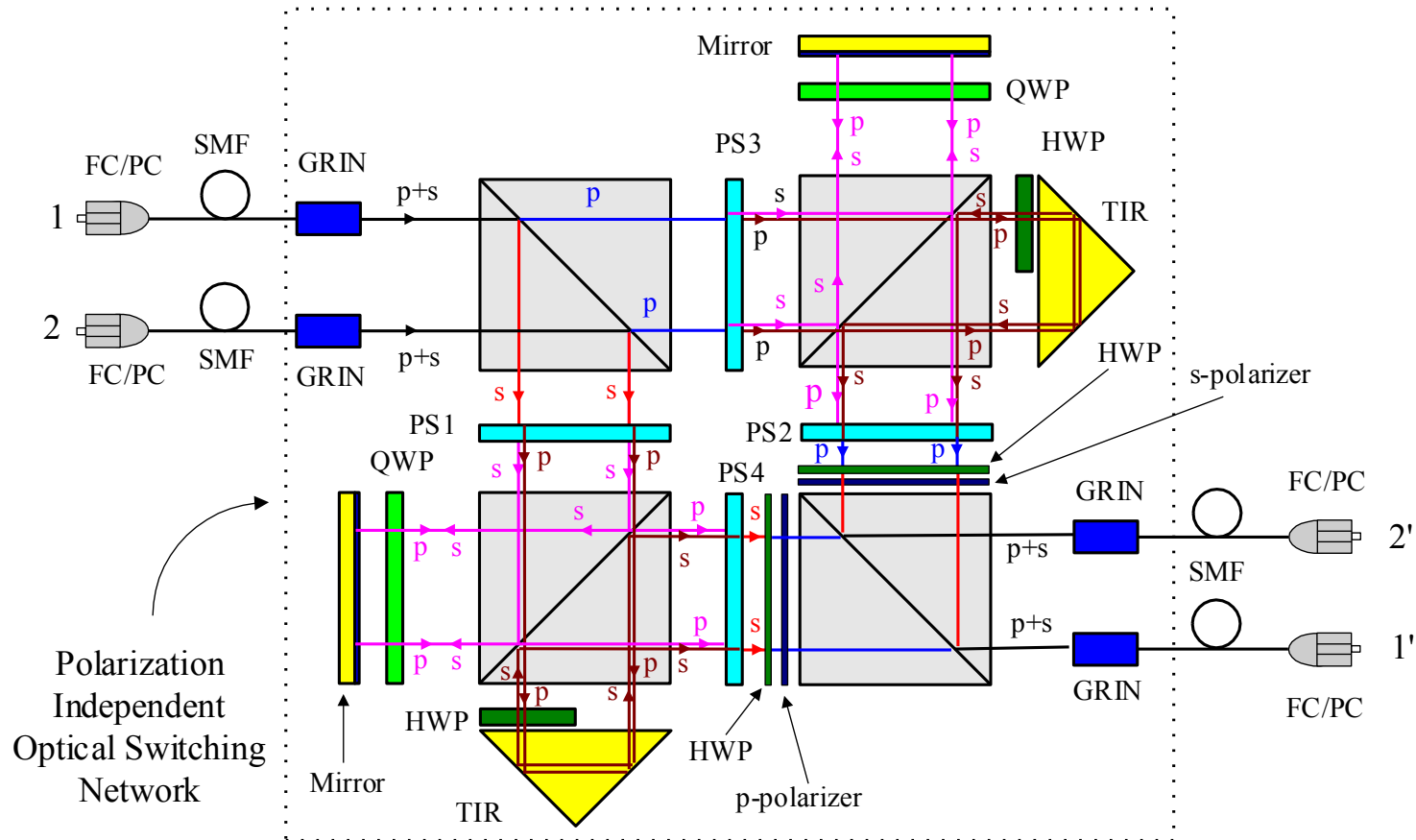


- (a) the inputs 1 and 2 modulated at 6 and 3 GHz, respectively,
- (b) the outputs 1' and 2' when the switch is in the straight state
- (c) the outputs 1' and 2' when the switch is in the exchanging state

**OPTICAL INTERCHANNEL CROSSTALK MEASUREMENTS
FOR THE EXPERIMENTAL 2x2 FLC POLARIZATION
DEPENDENT Fiber-optic SWITCH DESIGN**

	Interchannel Crosstalk
Straight State 1-1'	-39 dB
Exchanging State 1-2'	-43.91 dB
Straight State 2-2'	-38.97 dB
Exchanging State 2-1'	-38.55 dB

2x2 FLC Polarization Independent Fiber-Optic Switch

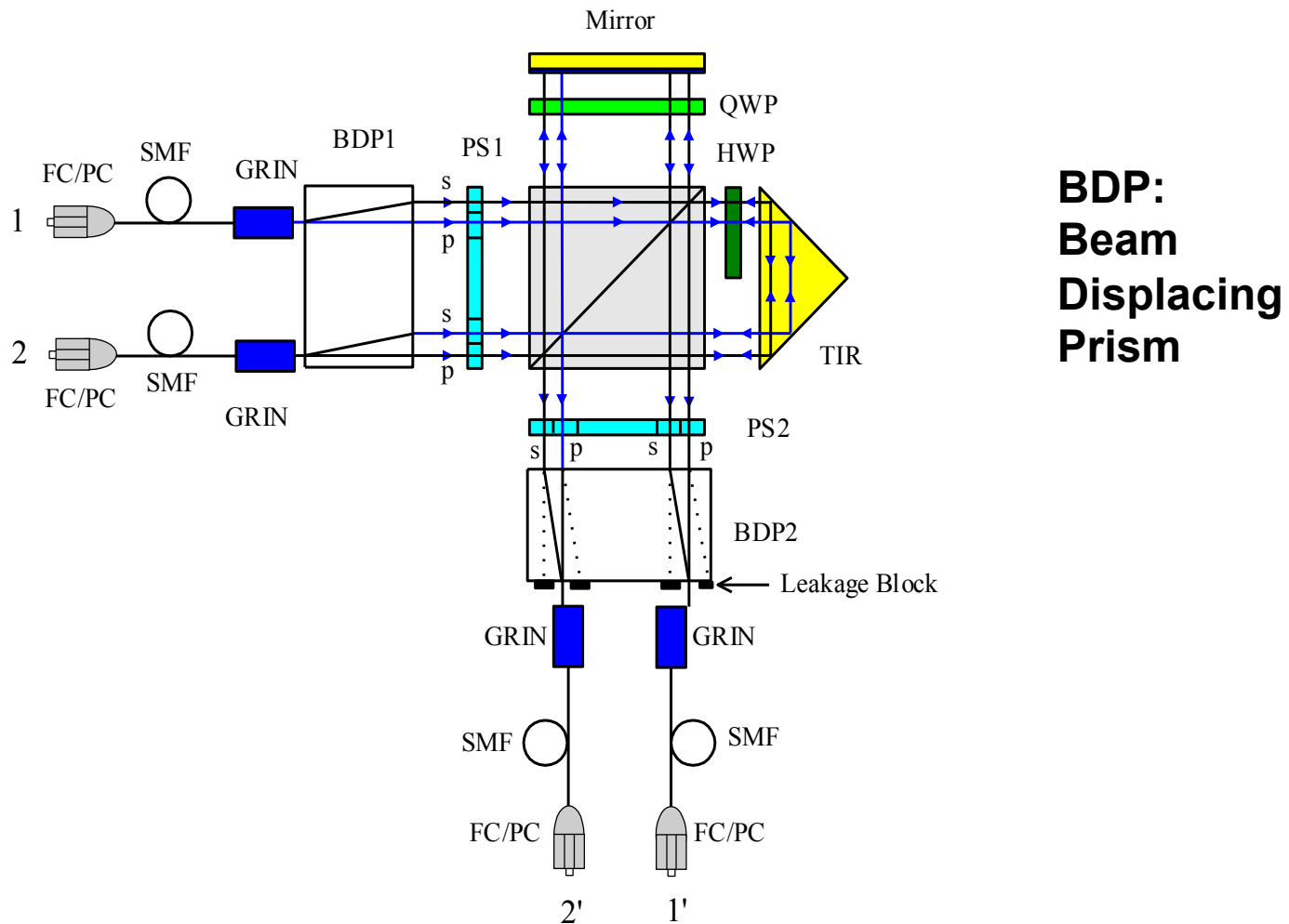


N. A. Riza & S. Yuan, IEE Electron. Letters, June 1998.

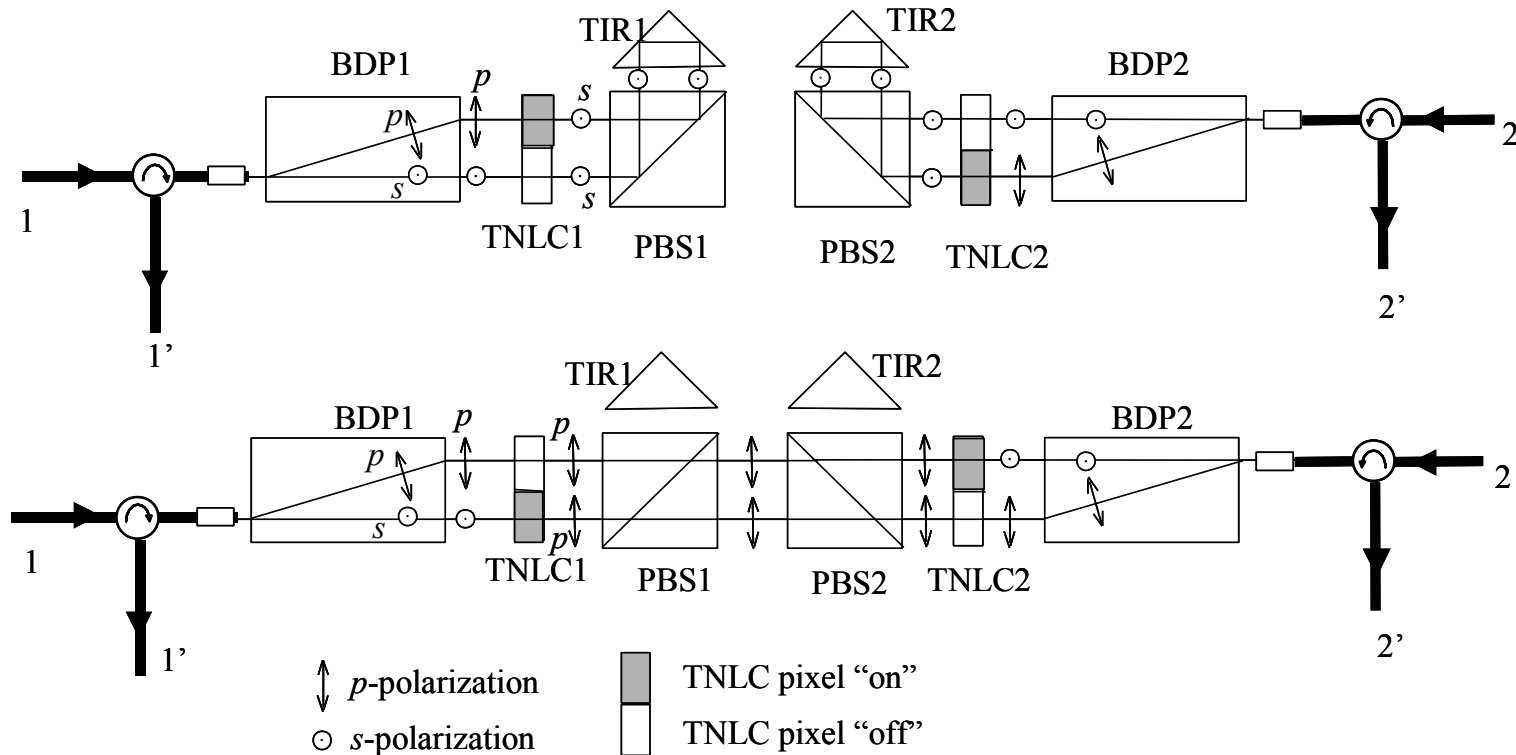
2x2 FLC Fiber-Optic Polarization Independent Switch Demonstration –Crosstalk Results

	Interchannel Crosstalk
Straight State 1-1'	-34.16 dB
Exchanging State 1-2'	-38.2 dB
Straight State 2-2'	-34.13 dB
Exchanging State 2-1'	-38.85 dB

The Polarization Independent 2 X2 Fiber-optic Switch Structure Using BDP's for Implementing Polarization Diversity-based Processing



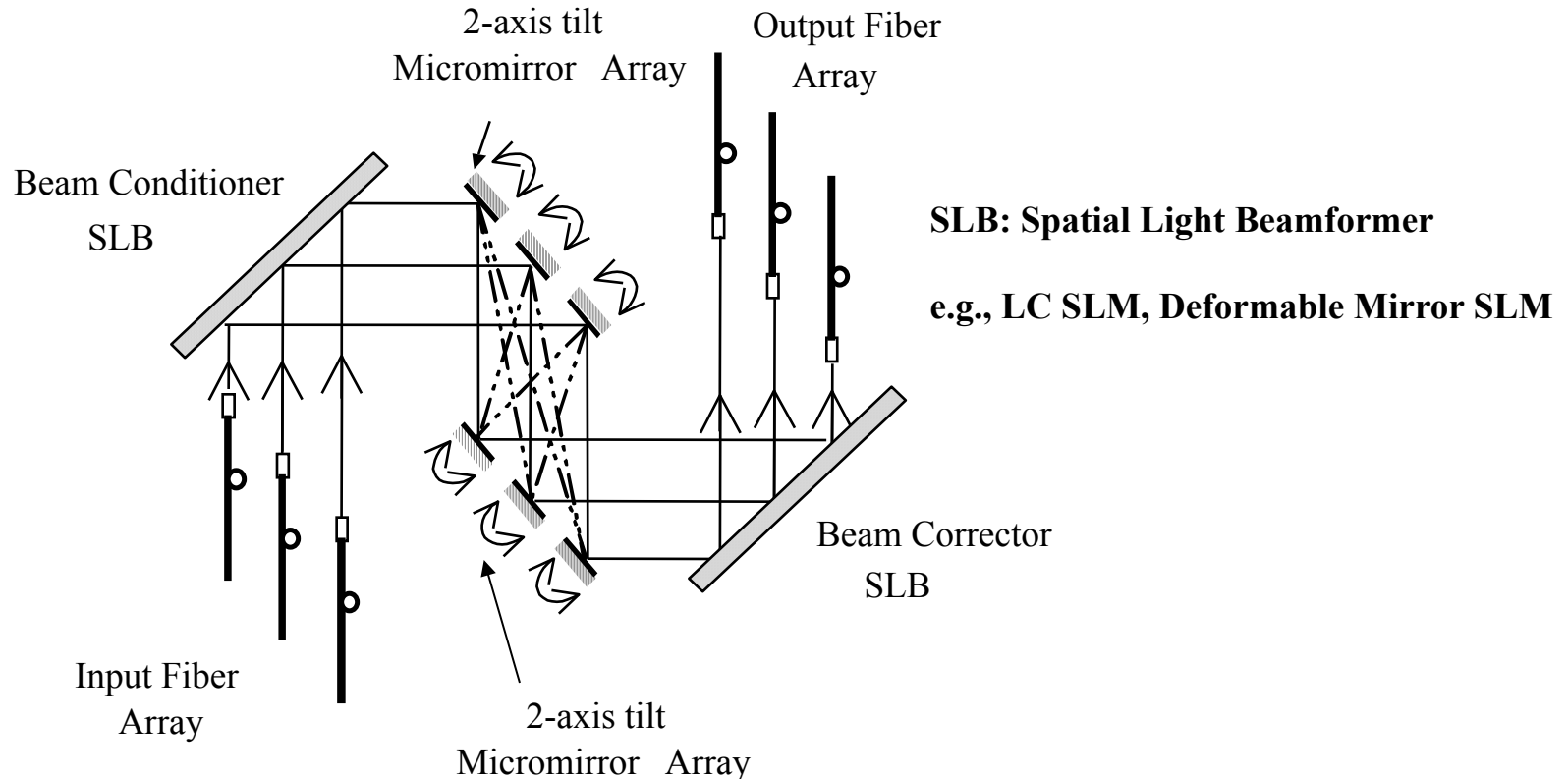
2x2 LC Fiber-Optic Switch based on Switched-Retroreflection



In-Line Self Aligning Design

- N. A. Riza, "Polarization-based fiber-optic switch," Patent No. 6,360,037, March 19, 2002.
- N. A. Riza and N. Madamopoulos, "Compact switched retroreflection-based 2x2 optical switching fabric for WDM applications", IEEE/OSA Journal of Lightwave Technology, Vol.23, No.1, pp.247-259, Jan. 2005.

Proposed 10,000 x 10,000 LC-MEMS Super-Switch that has the Built-in Alignment Capabilities for Low Loss

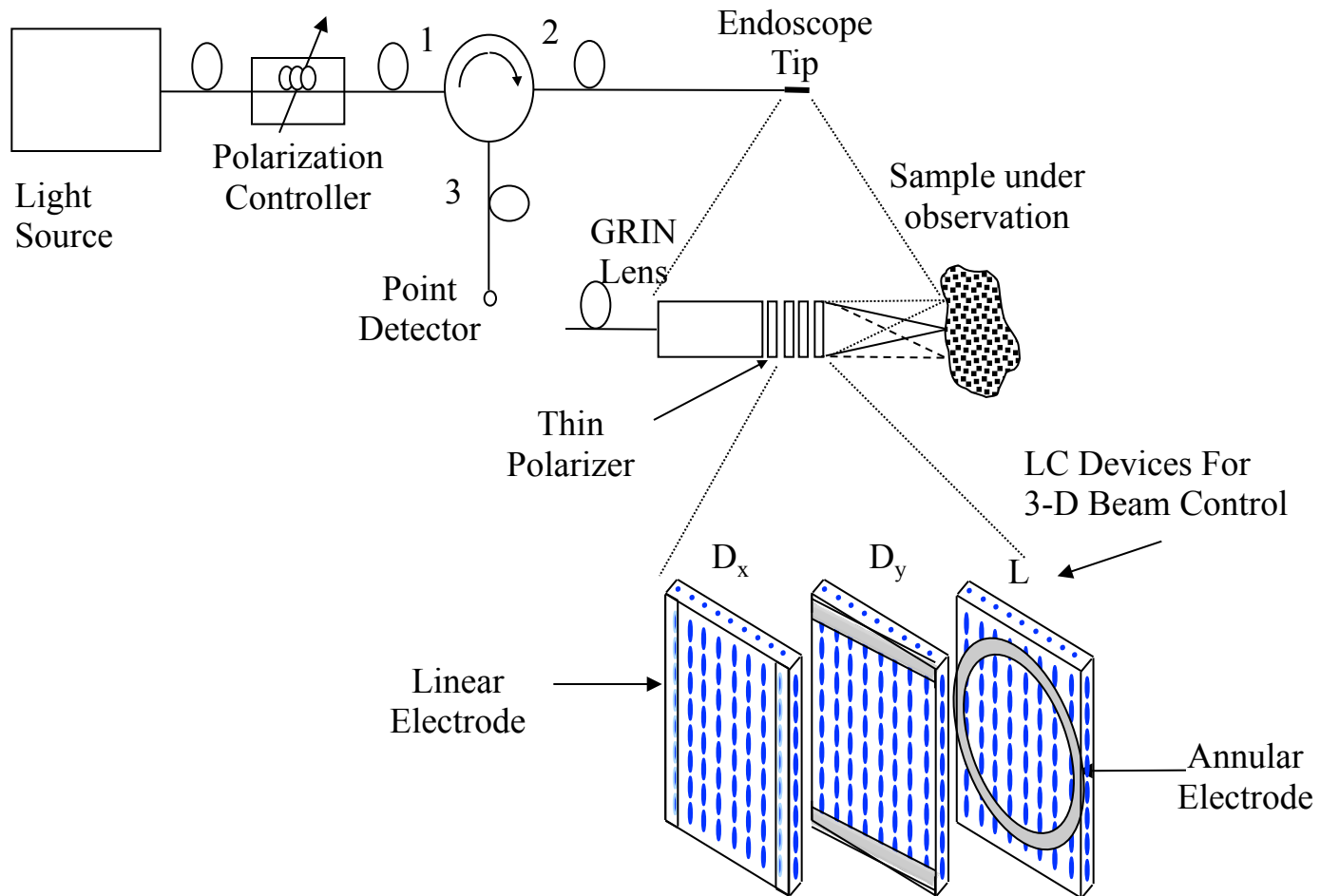


- N. A. Riza and M. J. Mughal, "An Approach towards the Holy Grail in All-Optical Circuit Switching: The Monster All-Optical Crossconnect," SPIE Photonics North Conference, Paper 101-486, May 26-29, Montreal, Canada, 2003.

- N. A. Riza, "Multi-technology multi-beam-former platform for robust fiber-optical beam control modules," US Patent No. 6,525,863, Feb. 25, 2003.

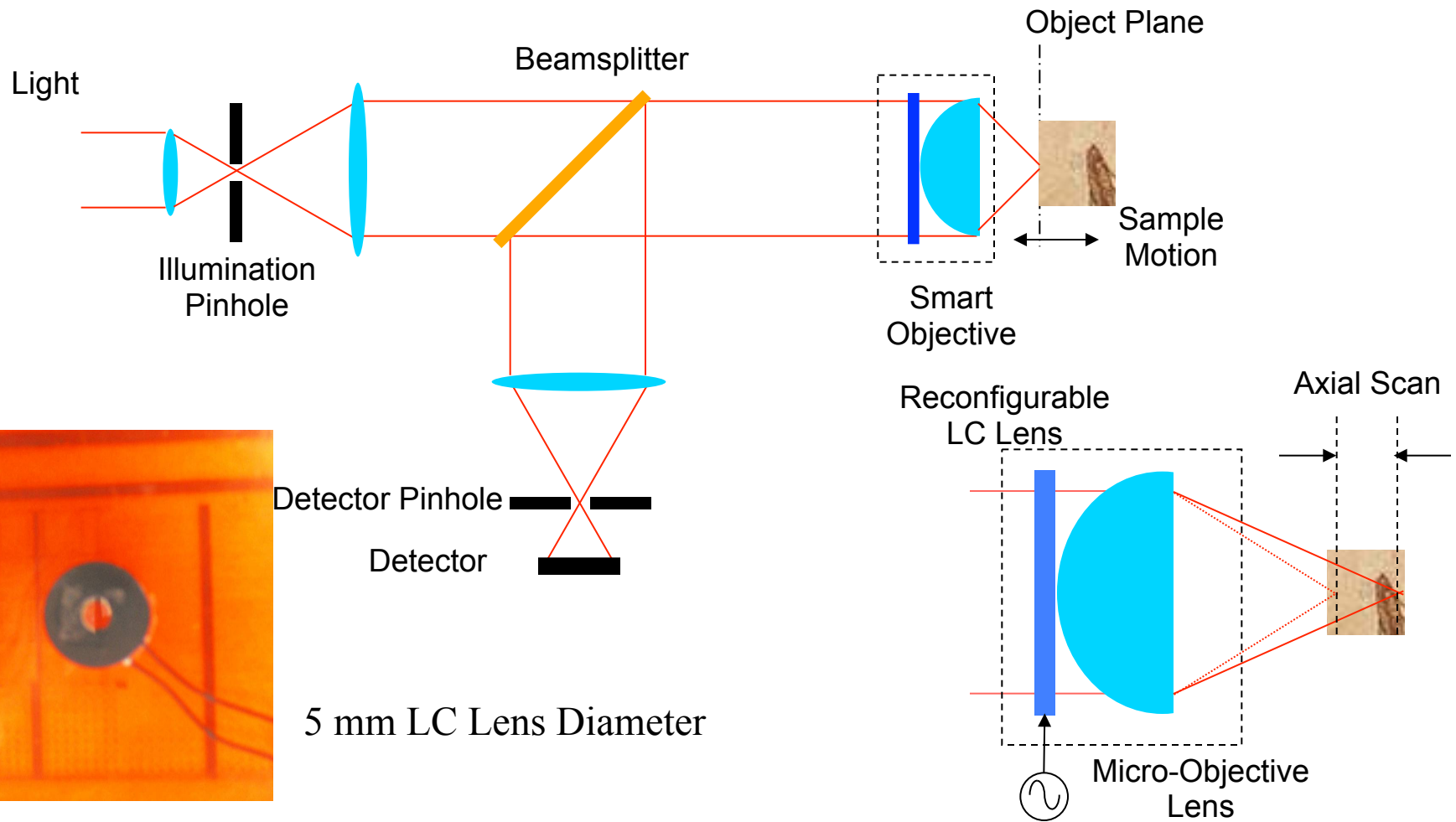
Liquid Crystal Agile Photonics
for Non-Destructive Testing
and
Medical Imaging

Proposed Fiber-Optic Endoscope using LC Beamforming



- N. A. Riza and A. Bokhari, "Agile Optical Confocal Microscopy Instrument Architectures For High Flexibility Imaging," in *Three Dimensional Confocal Microscopies*, BIOS 2004 Biomedical Optics, Photonics West, Proc. SPIE Vol. 5324, Paper No. 14, January 2004, San Jose, California, USA.
- S. A. Khan and N. A. Riza, Confocal microscopy based agile optical endoscope using liquid crystals, IEEE LEOS BioPhotonics Topical Meeting, paper MA4.2, San Diego June 28, 2004.

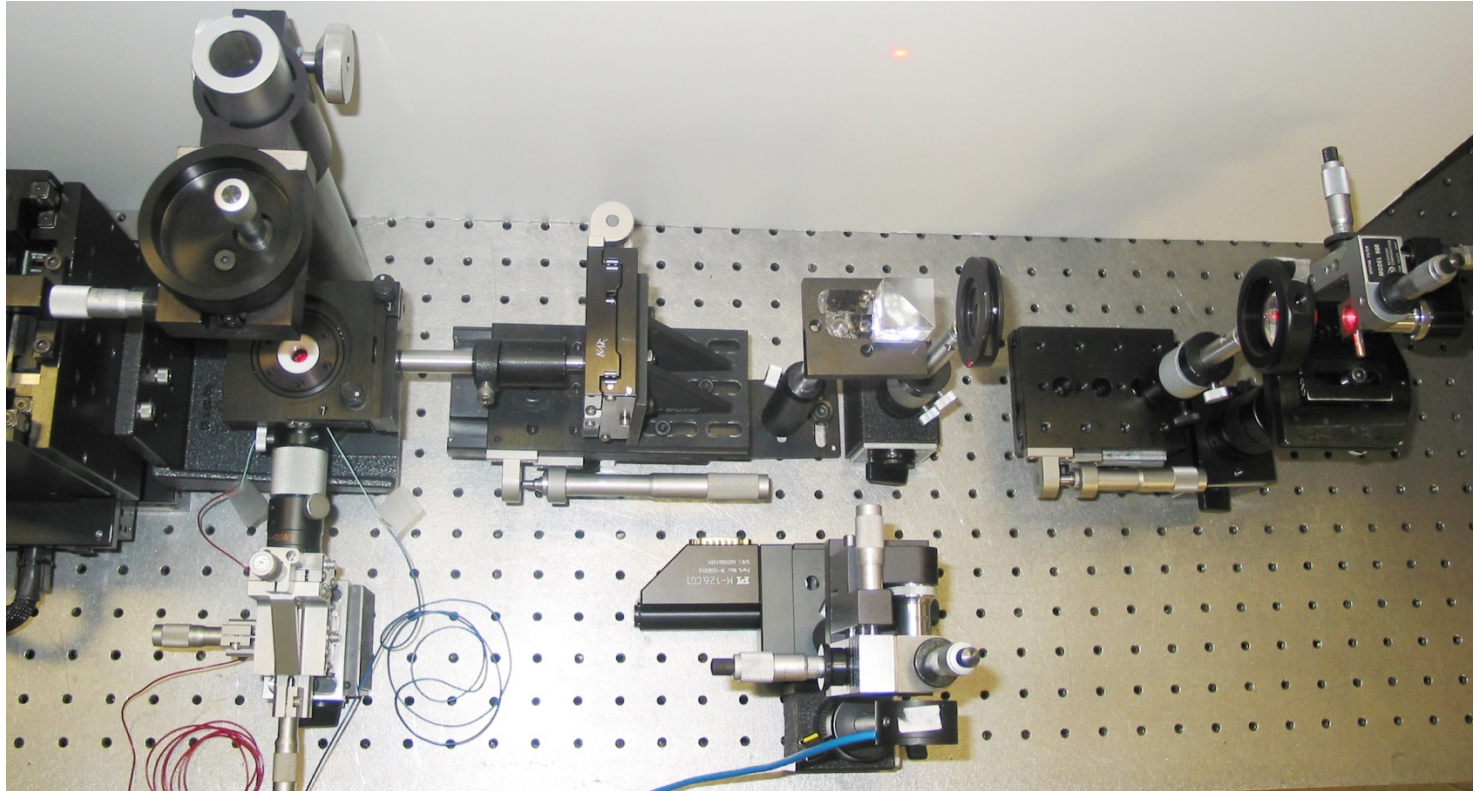
LC Based Confocal Microscope



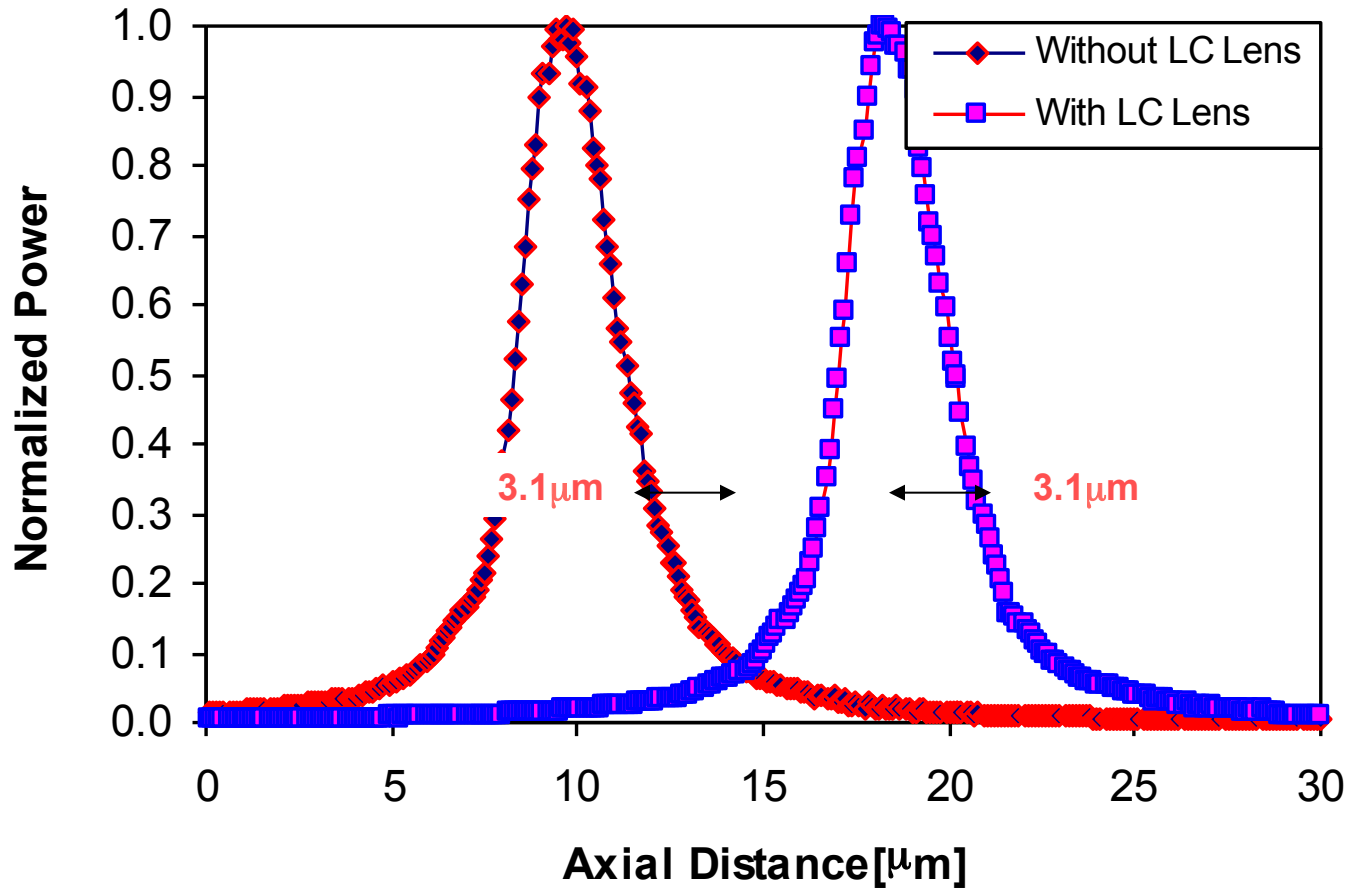
N. A. Riza and S.Khan, "Programmable High Speed Polarization Multiplexed Optical Scanner", Optics Letters, vol. 28, Issue 7, 2003.

N. Riza and A. Bokhari, "Agile Optical Confocal Microscopy Instrument Architectures For High Flexibility Imaging," SPIE Biomedical Optics, 2004, 24-29 Jan, 2004, San Jose, CA.

Experimental Setup



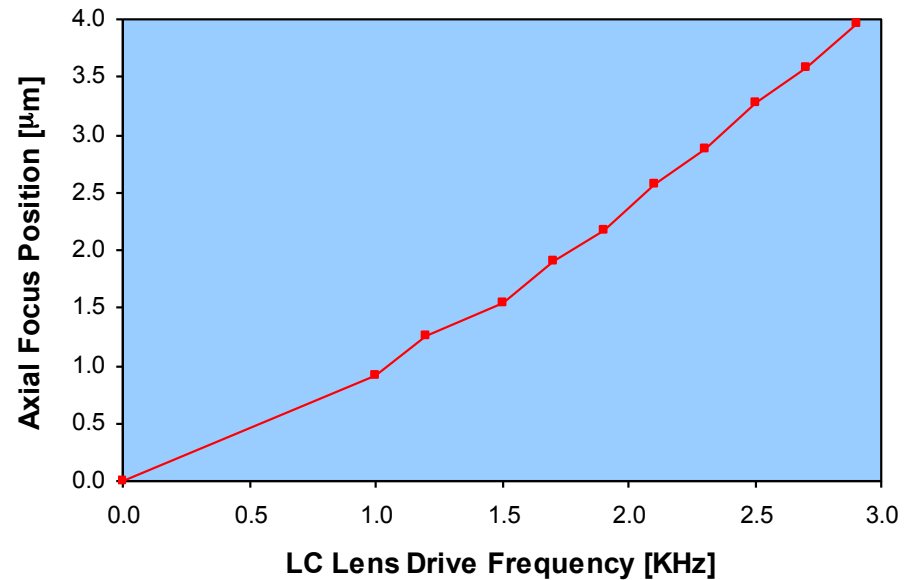
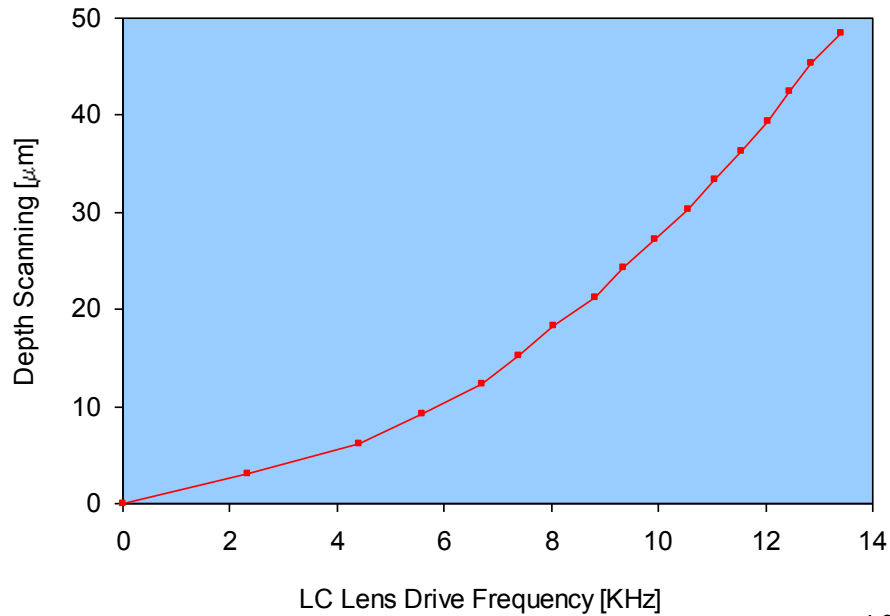
Measured Axial Resolution of the Microscope



LC Lens dia=5mm, LC Lens thickness=50 μm , Micro-objective NA=0.65

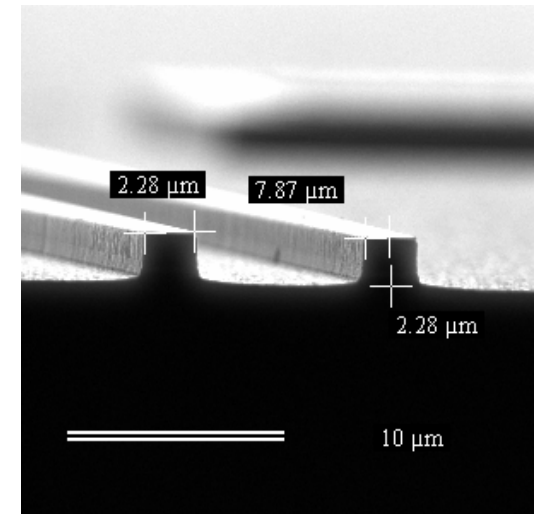
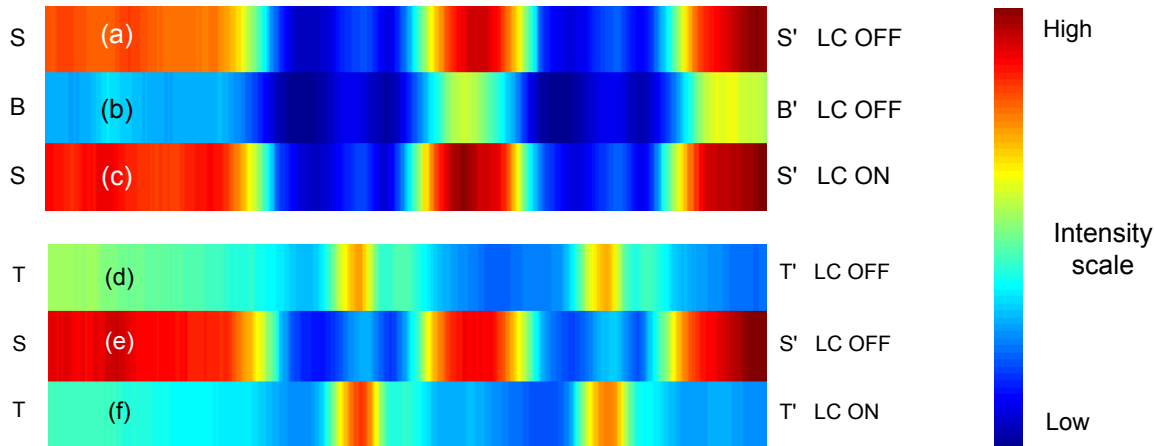
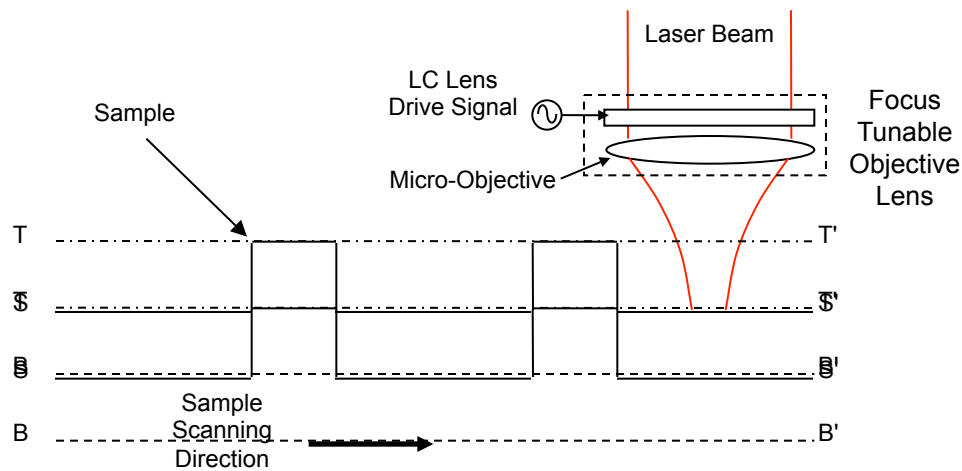
LC Lens Applied Voltage=4.8V_{PK} square wave at 2.4 kHz

Demonstrated axial scanning transfer characteristics



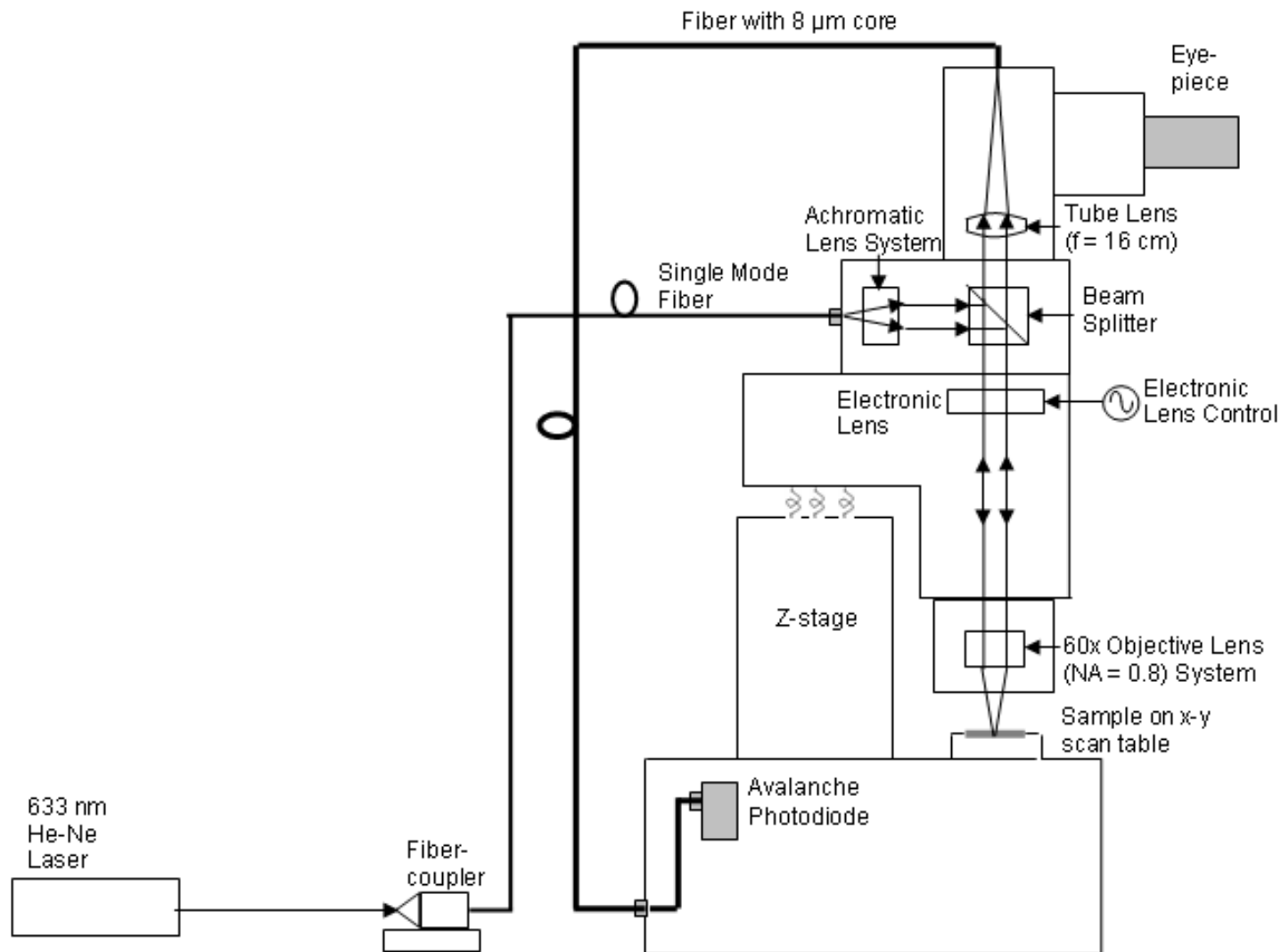
Imaging dual rectangular waveguides

Single Line scan



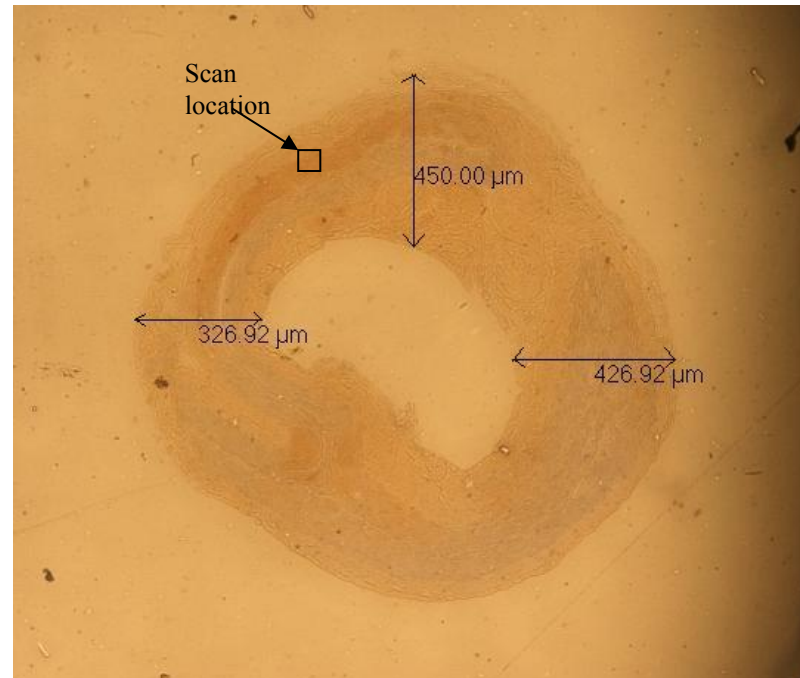
S. A. Khan and N. A. Riza, "Demonstration of a No-Moving-Parts Axial Scanning Confocal Microscope Using Liquid Crystal Optics," Optics Communications, Vol.265, No.2, pp.461-467, appeared on-line 5 May, 2006.

Proposed Electronic Lens-based Axial Scanning 3-D Imaging Confocal Microscope System realized by modifying a WITec Alpha-SNOM System



N. A. Riza, "No Moving Parts Axial Scanning Confocal Microscopy," Research Article Selected for the OSA Optics & Photonics News (OPN) Magazine, Optics in 2008 Special Issue, Dec., 2008.

Cross-section of Artery from CDC Slide produced using Standard Optical Microscope



Vessel $\sim 25 \mu\text{m}$ in Axial Direction Size

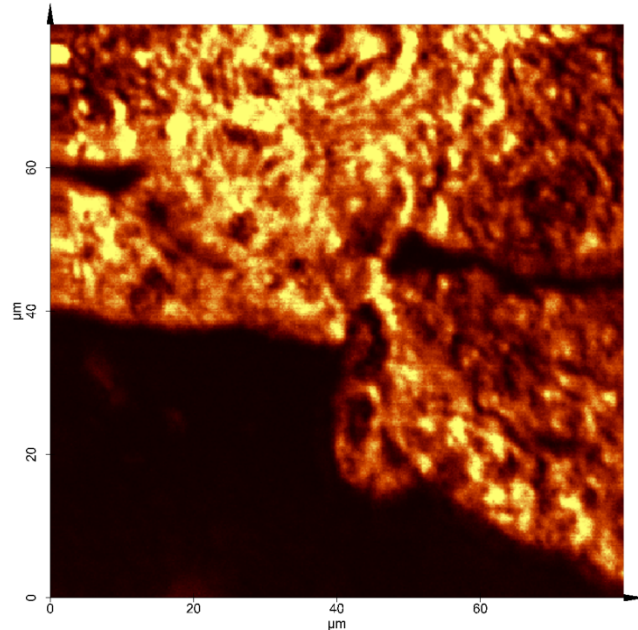
White-light image using WITec microscope with a 20x objective



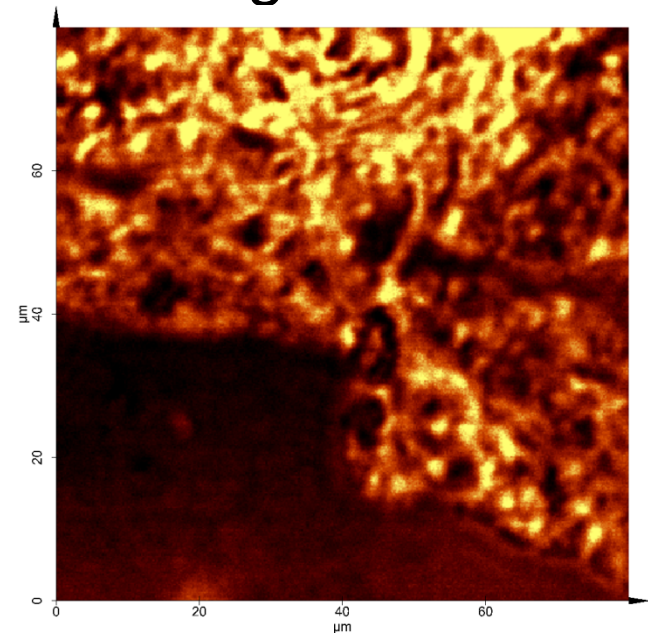
Scan Area: 80 μm x 80 μm

Comparative Transverse Scan Results using 20x objective

Conventional all-mechanical
scan confocal microscope



Modified confocal microscope
using LC E-lens

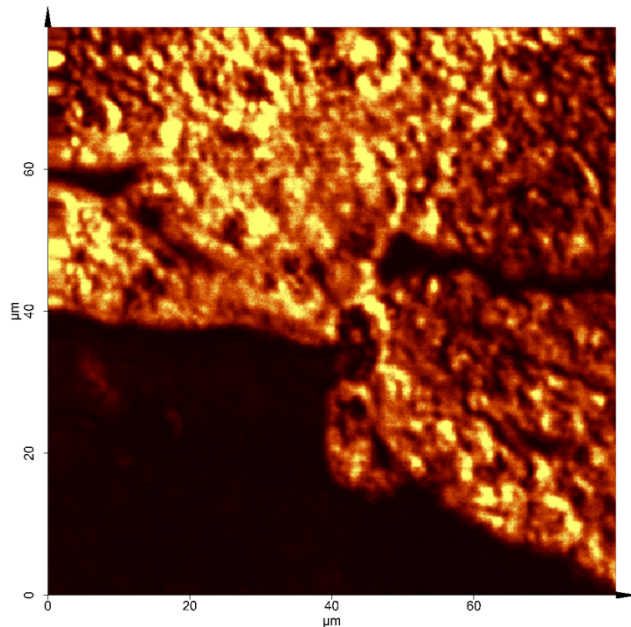


Axial Scan location $\Delta z = 0 \mu\text{m}$

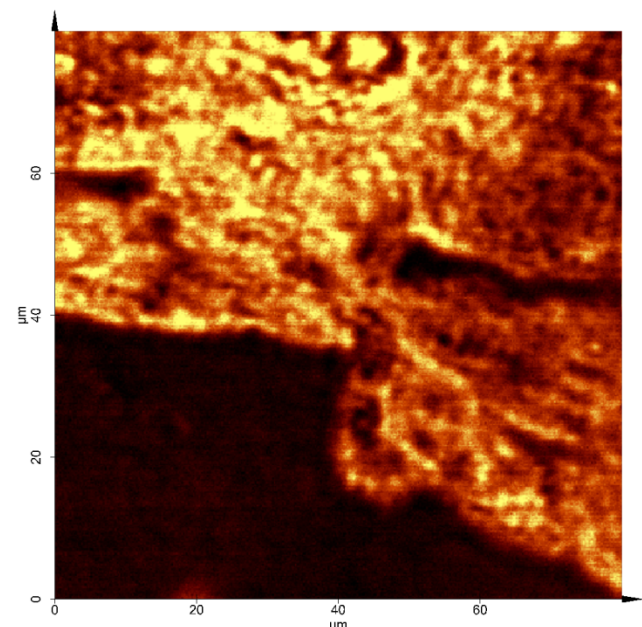
N. A. Riza, M. Sheikh, G. Webb-Wood, and P. Kik, "Demonstration of Three Dimensional Imaging of Blood Vessel using a No-Moving Parts Electronic Lens-based Optical Confocal Microscope," Conference MI03: Physics of Medical Imaging, SPIE Medical Imaging, San Diego, Feb. 2007.

Comparative Transverse Scan Results using 20x objective

Conventional all-mechanical
scan confocal microscope



Modified confocal microscope
using LC E-lens

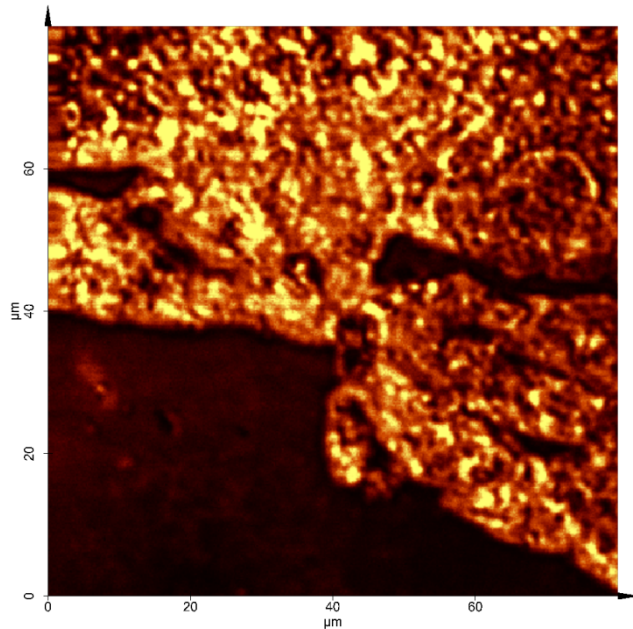


Axial Scan location $\Delta z = 5 \mu\text{m}$

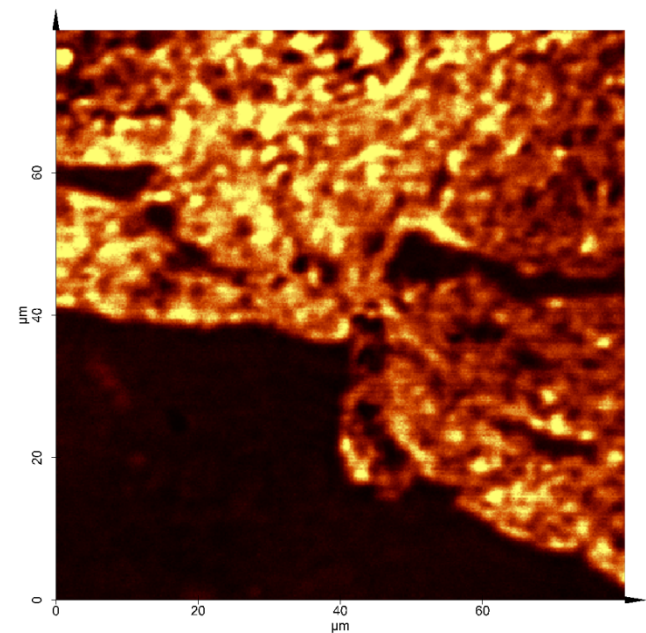
N. A. Riza, M. Sheikh, G. Webb-Wood, and P. Kik, "Demonstration of Three Dimensional Imaging of Blood Vessel using a No-Moving Parts Electronic Lens-based Optical Confocal Microscope," Conference MI03: Physics of Medical Imaging, SPIE Medical Imaging, San Diego, Feb. 2007.

Comparative Transverse Scan Results using 20x objective

Conventional all-mechanical
scan confocal microscope



Modified confocal microscope
using LC E-lens

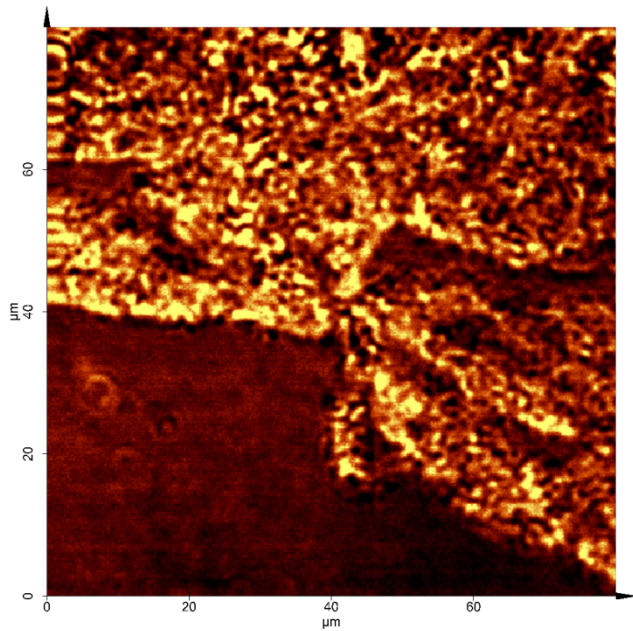


Axial Scan location $\Delta z = 15 \mu\text{m}$

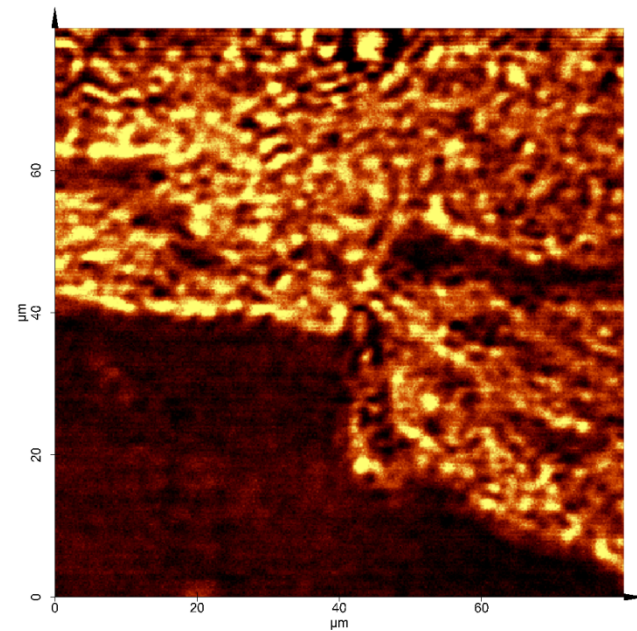
N. A. Riza, M. Sheikh, G. Webb-Wood, and P. G. Kik, "Demonstration of three-dimensional optical imaging using a confocal microscope based on a liquid-crystal electronic lens," *Optical Engineering Journal*, Vol. 47, No.6, pp.063201-1 to 063201-9, June 2008.

Comparative Transverse Scan Results using 20x objective

Conventional all-mechanical
scan confocal microscope



Modified confocal microscope
using LC E-lens

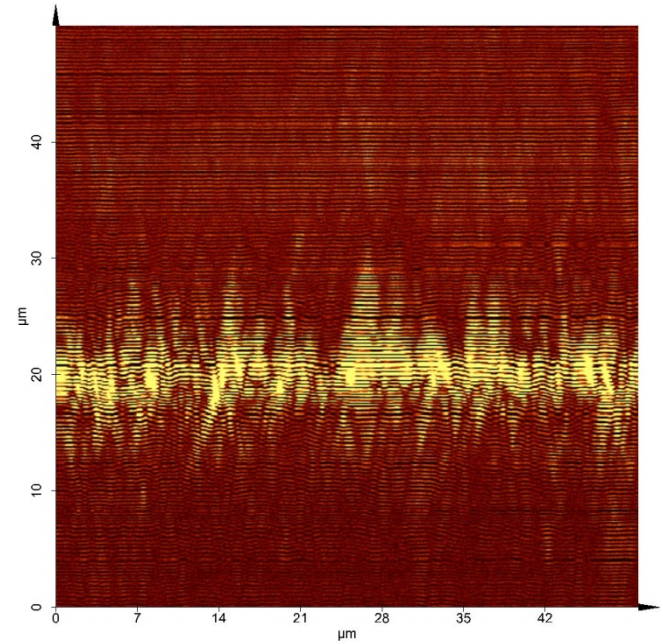
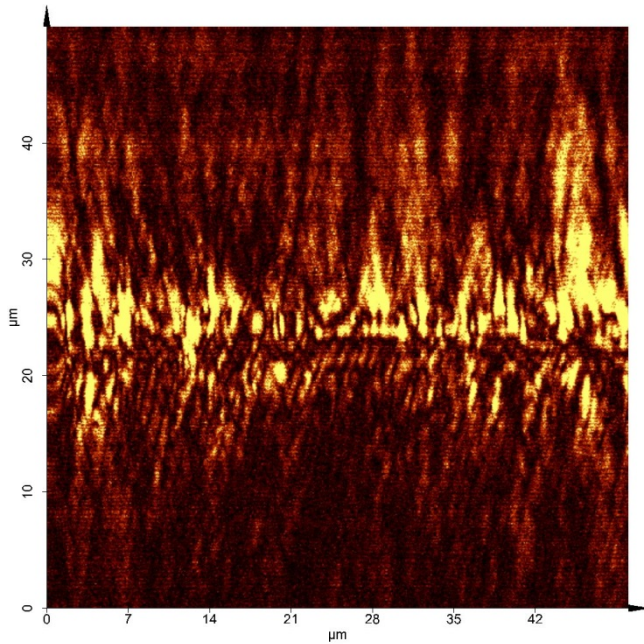


Axial Scan location $\Delta z = 25 \mu\text{m}$

Comparative Transverse Scan Results using 20x objective

- Scan area of $80\text{ }\mu\text{m} \times 80\text{ }\mu\text{m}$
- Transverse motion step of $0.2\text{ }\mu\text{m}$
- Micro-objective NA=0.4

Comparative Axial Scan Results



Shows a $5\ \mu\text{m}$ z-displacement in the image taken using E-lens based microscope (right photo) versus no-E lens scan (left)

- Motion step = $0.1\ \mu\text{m}$ in both x and z-directions
- Scan area of $50\ \mu\text{m} \times 50\ \mu\text{m}$

Liquid Crystals for Narrowband RF Antenna Controls

Free-space+ Fiber Implementations

Phased Array Antenna Advantages

- Beam steering without physical movement
- Highly accurate position
- Increased beam scan flexibility in 3-D
- Multi-target tracking

Phased Array Antenna Applications

- Military Radars
- Wireless Communications
- Radio-Astronomy
- Air Traffic Control Radars
- Mobile Platform Antenna Systems



Scientific American, 1998

Phased Array Antenna Control Techniques

Phase-based steering



Frequency Sensitive

Beam Squinting



Good for Narrowband
Applications – Uses Costly
Large Electronics

True time delay steering



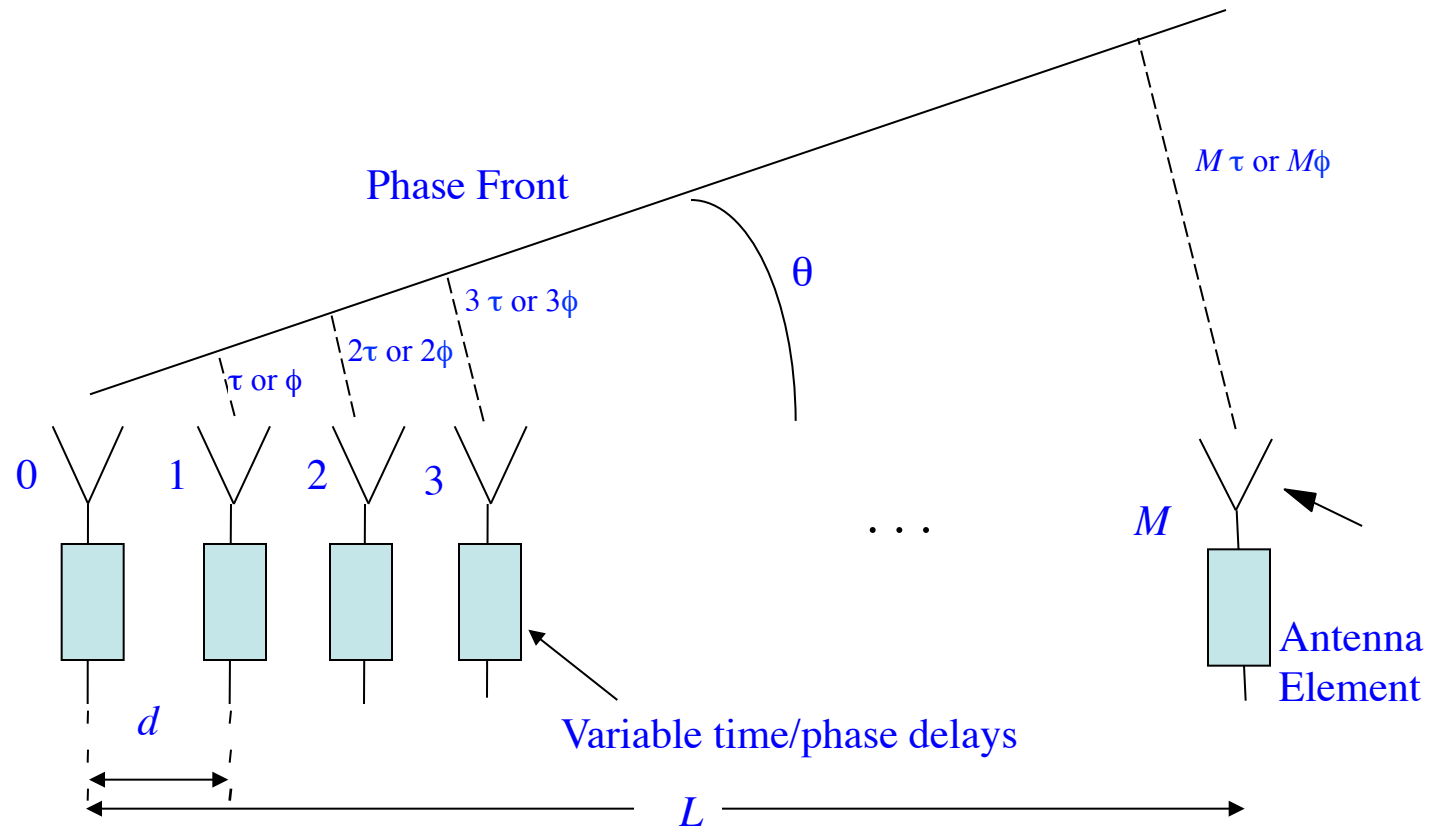
Frequency Independent

No Beam Squinting



Needed for Wideband Applications-
Hard to implement using electronics

- Complex and Hardware Intensive
- Sensitive to EMI



Time Delays

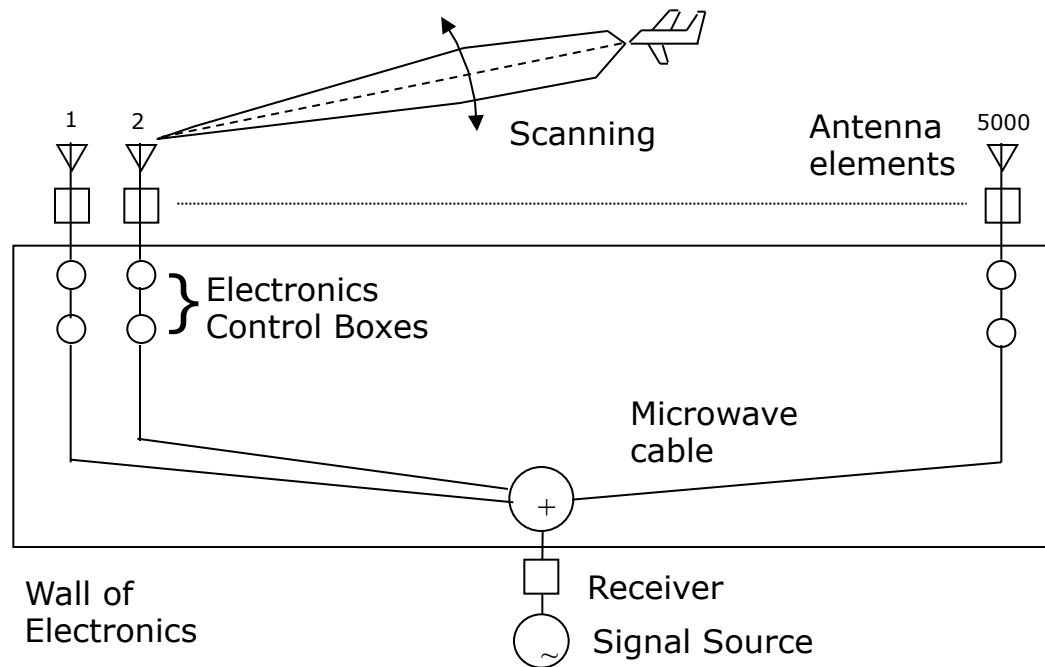
$$\tau = \frac{d}{c} \sin \theta$$

Phase Delays

$$\phi = \frac{2\pi}{\lambda_{\text{rf}}} d \cdot \sin\theta$$

The ultimate antenna system

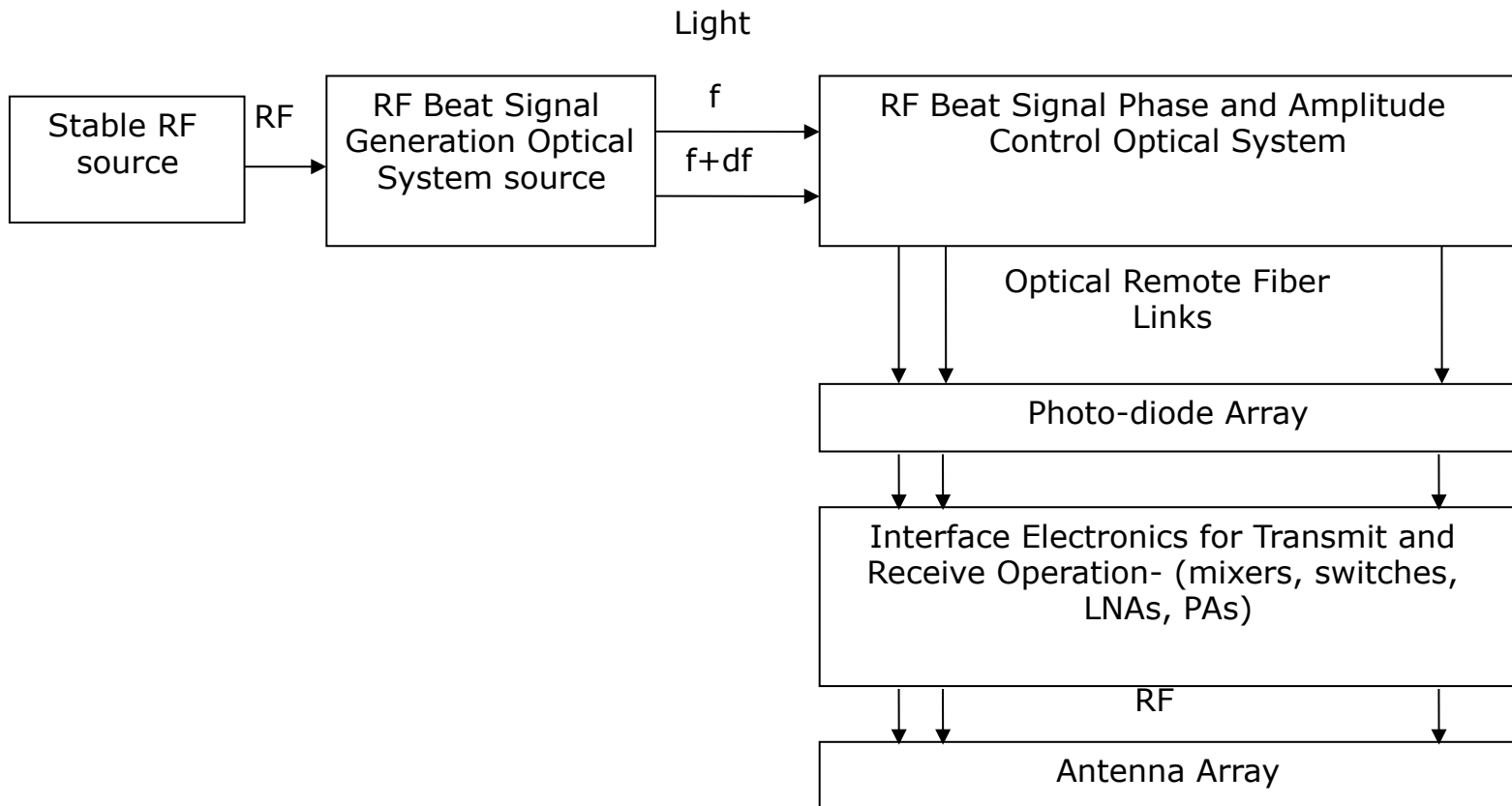
Phased Array Antenna



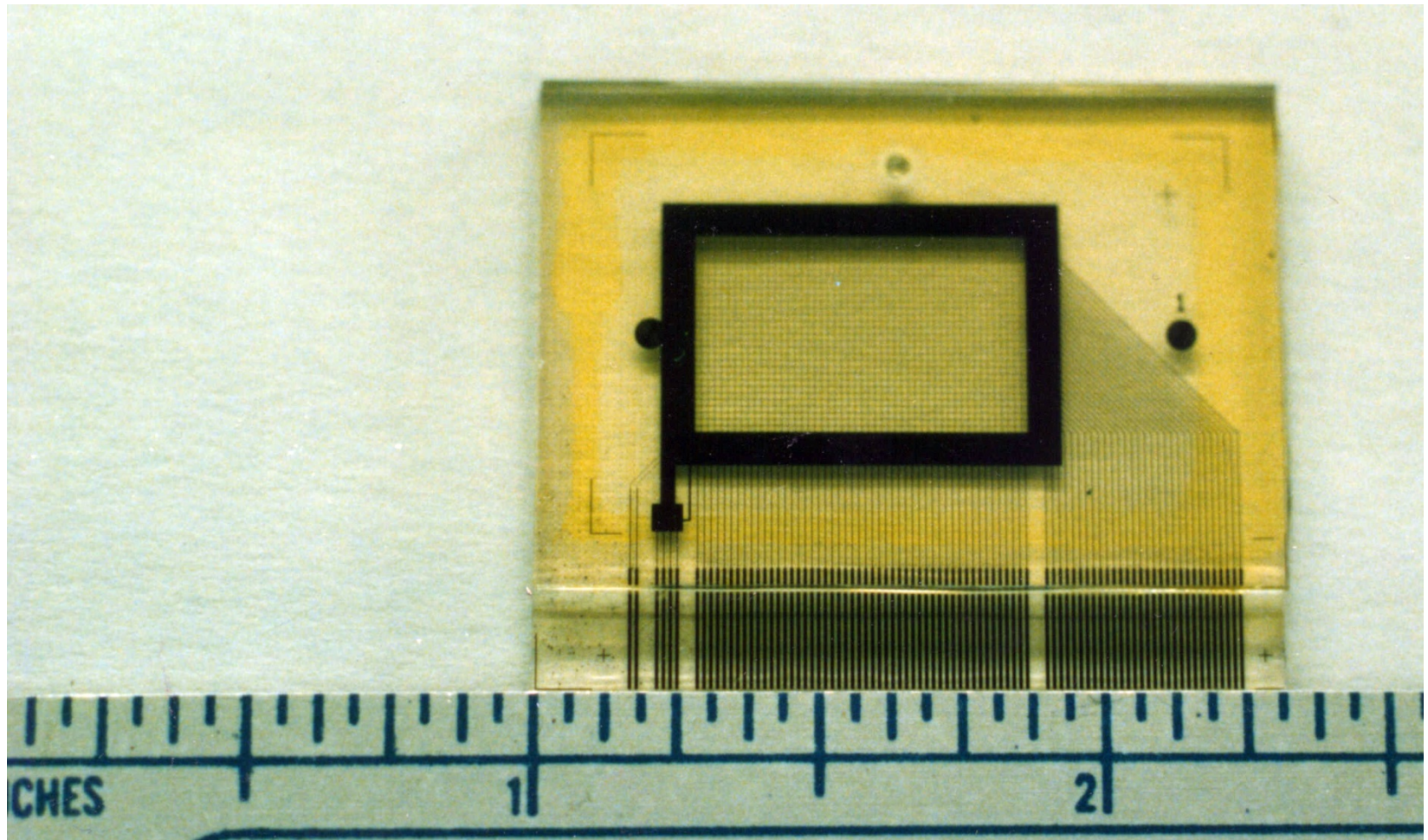
Flexible Beamformer System Components



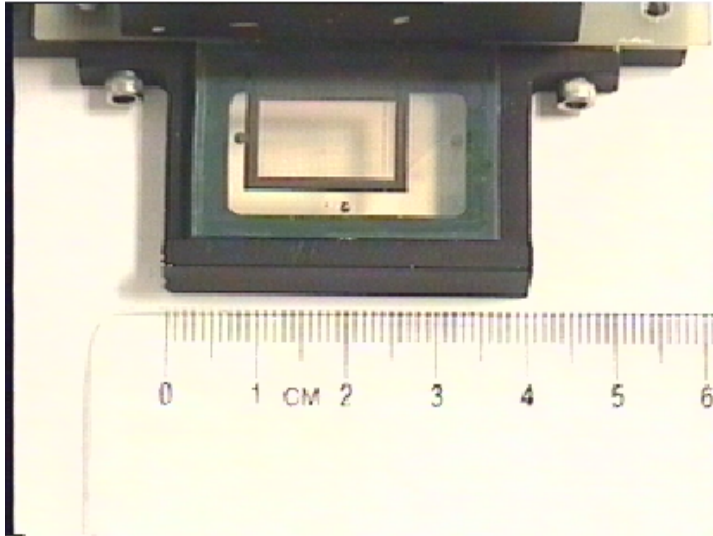
The Optical Beamformer System Diagram



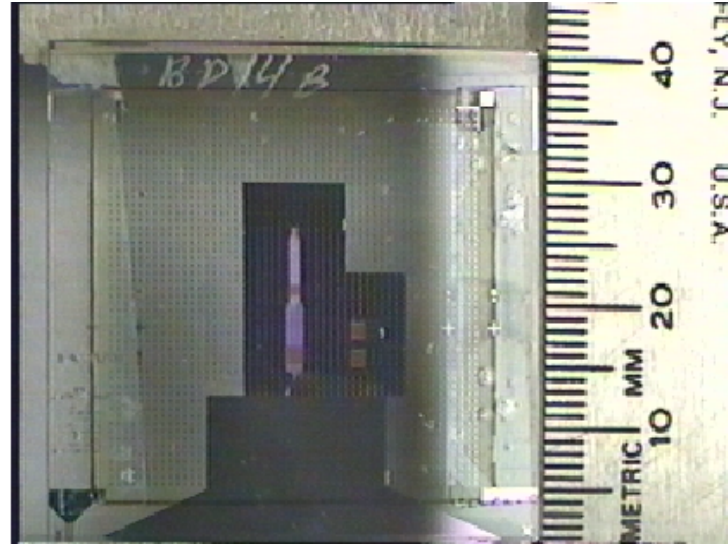
1500= 30 x 50 pixel NLC Phase-Only Control Chip – PC Controlled



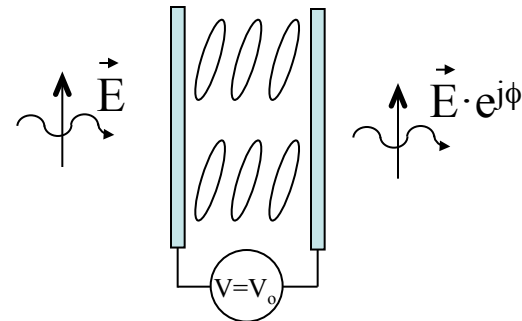
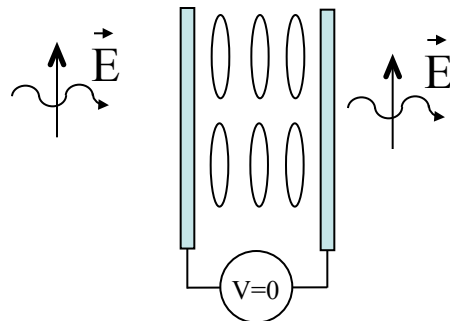
Birefringent Mode Nematic Liquid Crystal (BM-NLC) Devices



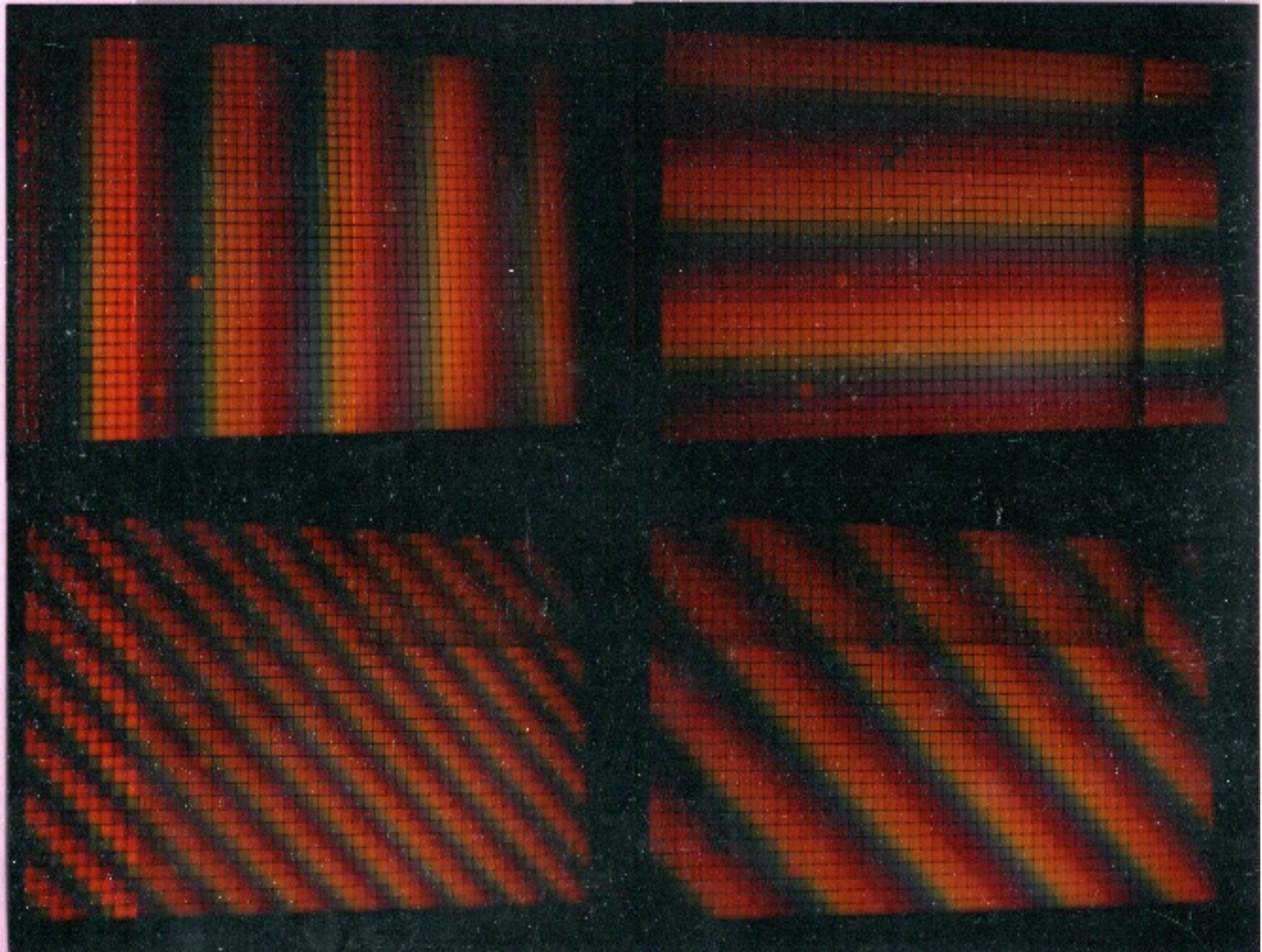
1500-pixel NLC Device



3-Terminal NLC Lens Device



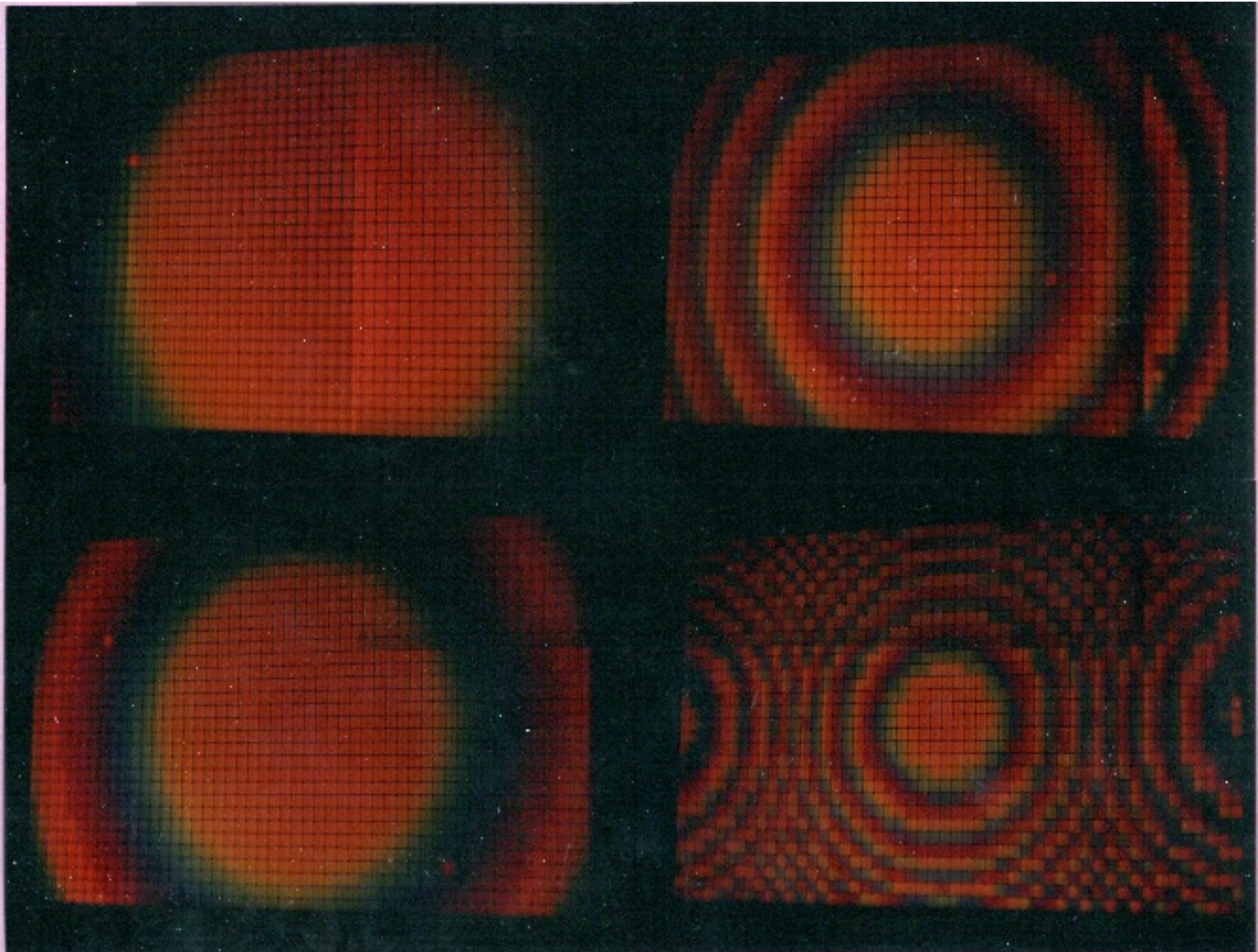
LC Chip Programmed as Optical Phased Array For RF PAA Control



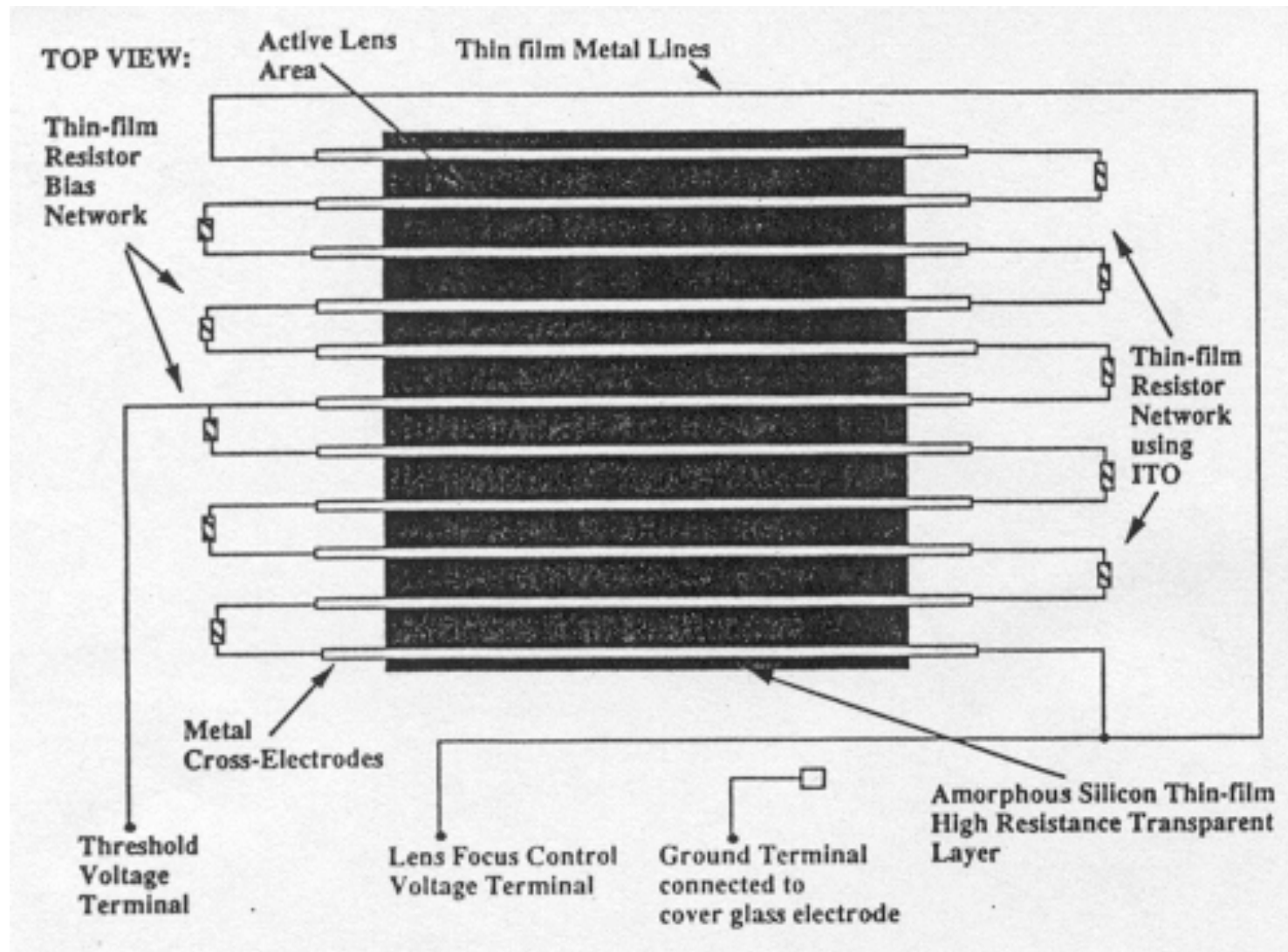
2-D X-Y Beam Steering Controls

LC Chip Programmed as Optical Phased Array For RF PAA Control

- Lensing Controls (Focus/Defocus)

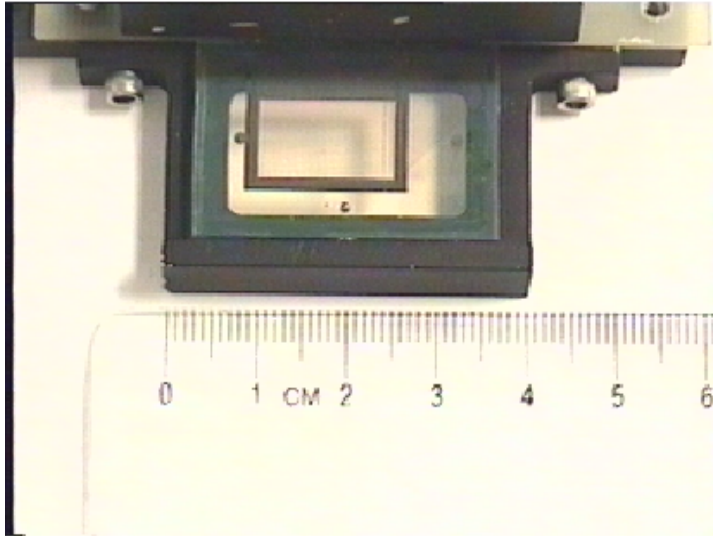


Novel LC Chip Optical Phased Array Design Using High Resistance Electrodes and On-Chip Thin-Film Resistor Network

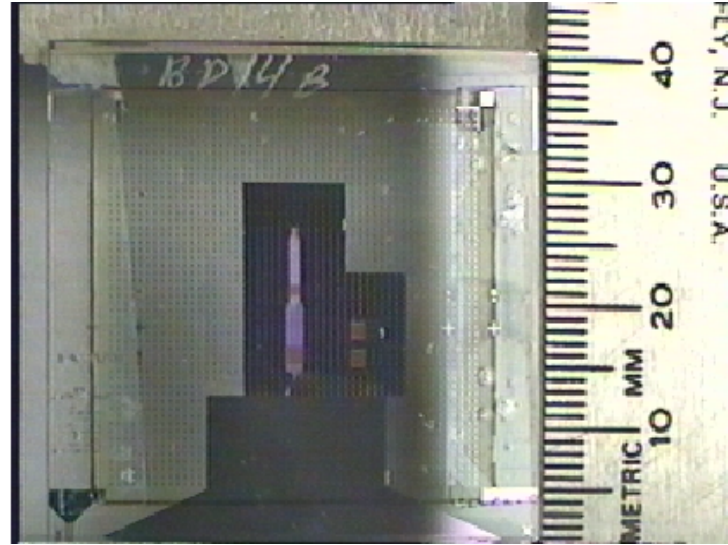


ONLY One Voltage Required for Beam Control – No PC Needed

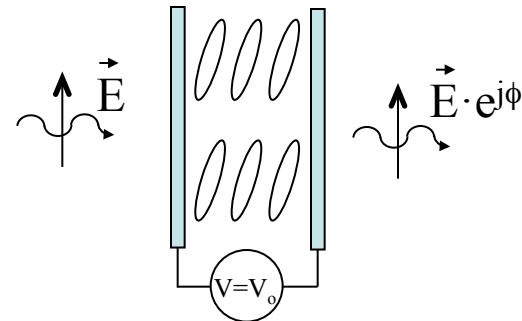
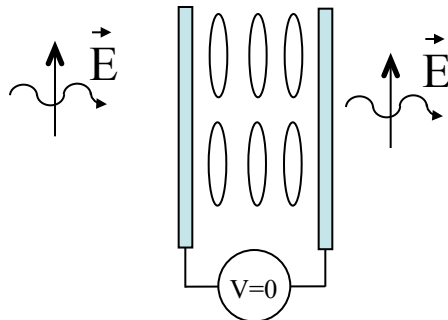
Birefringent Mode Nematic Liquid Crystal (BM-NLC) Devices



1500-pixel NLC Device



3-Terminal NLC Lens Device

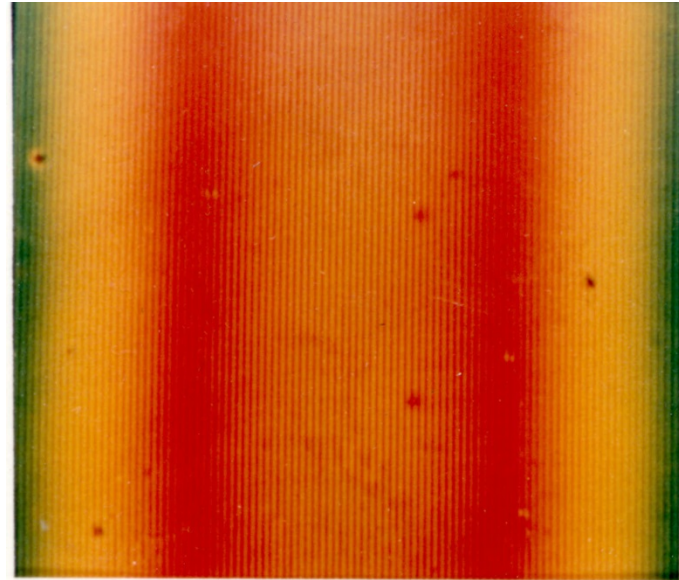
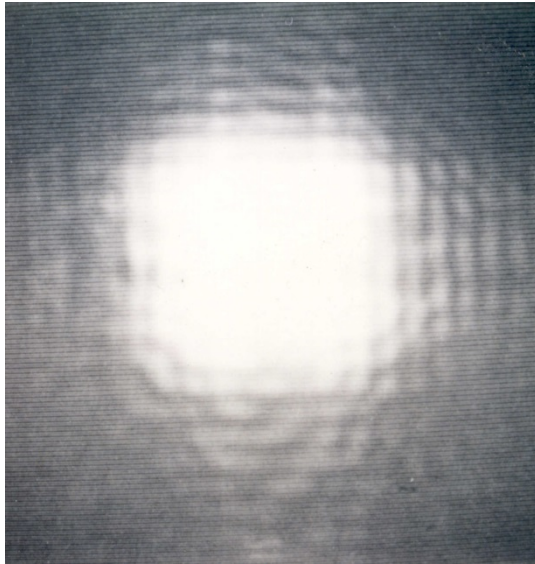


3-Terminal NLC Cylindrical Lens Experiment

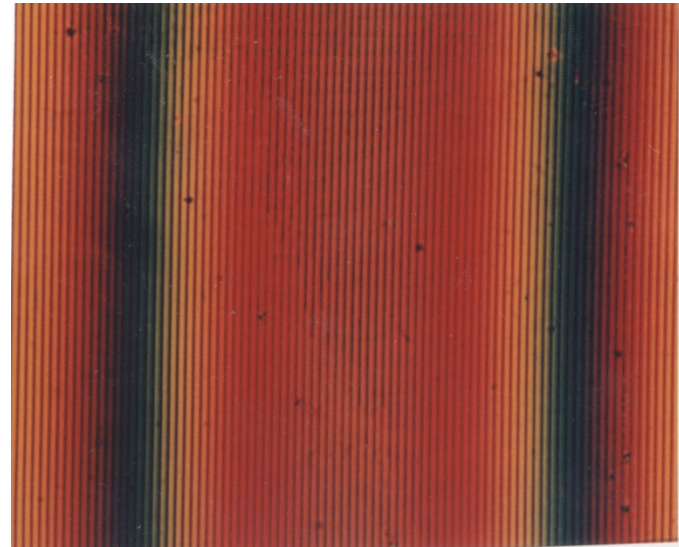
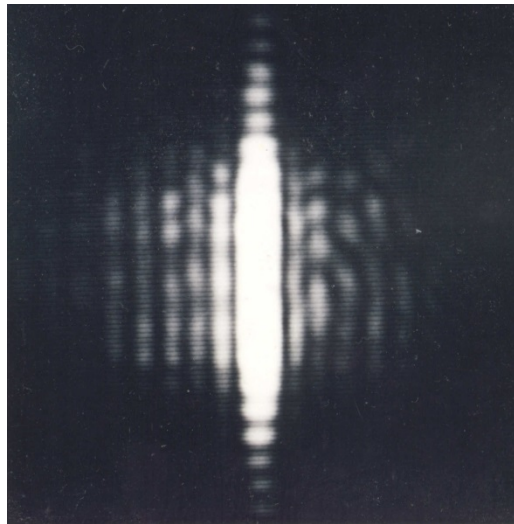
Beam View

Color Coded Phase Programmed View

No
Lens

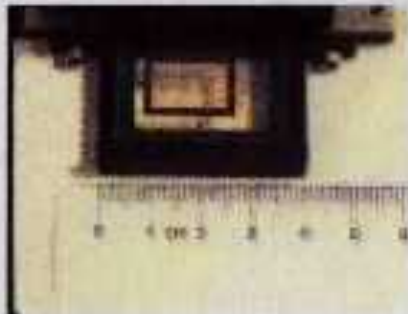


Lens
Active



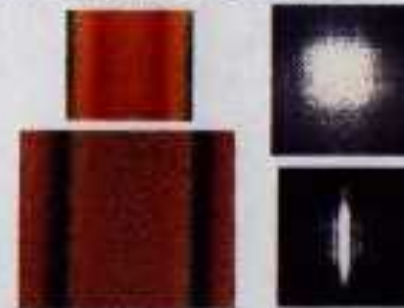
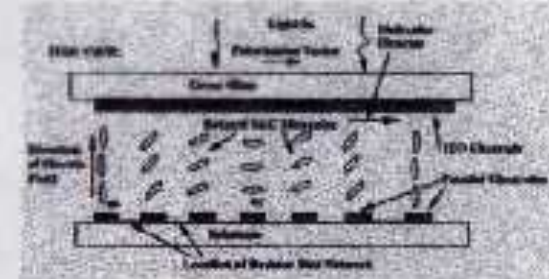
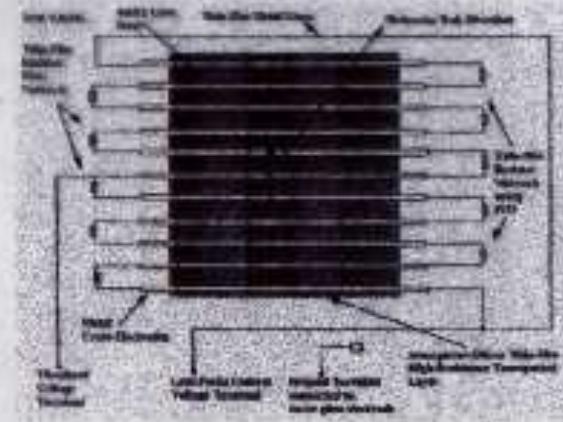
LC Analog Controls Programmable Lens Designs

Total Programmability



1500-pixel NLC Spherical Lens

Efficient Analog Controls

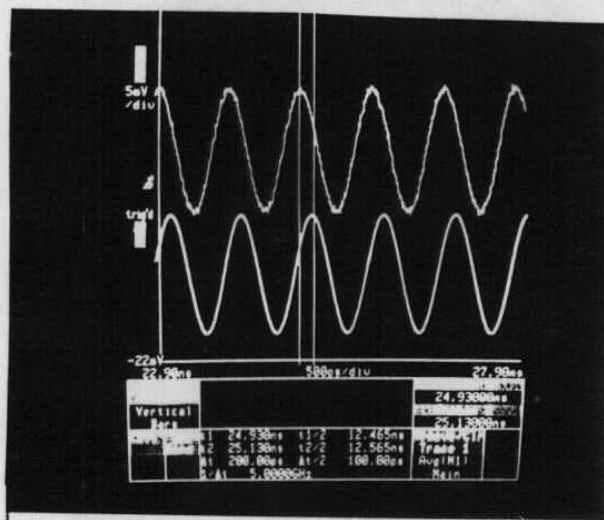


100-Electrode Cylindrical NLC Lens

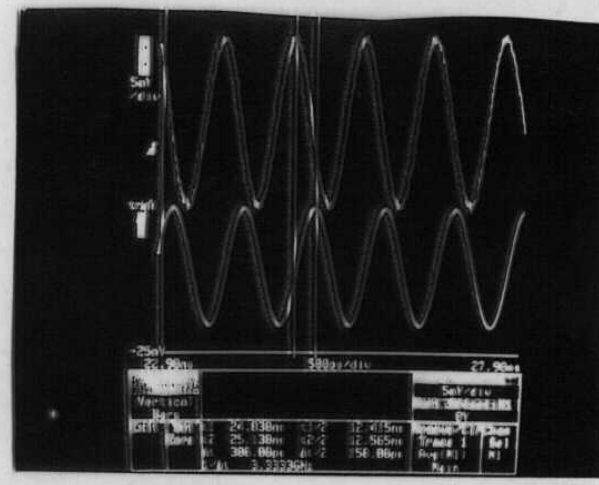
RF Phase Control using LCs



Oscilloscope Traces of the 1.017 GHz, 100 ps (or 36.6°) Phase-shifted Signal Output from the Photonic Controller



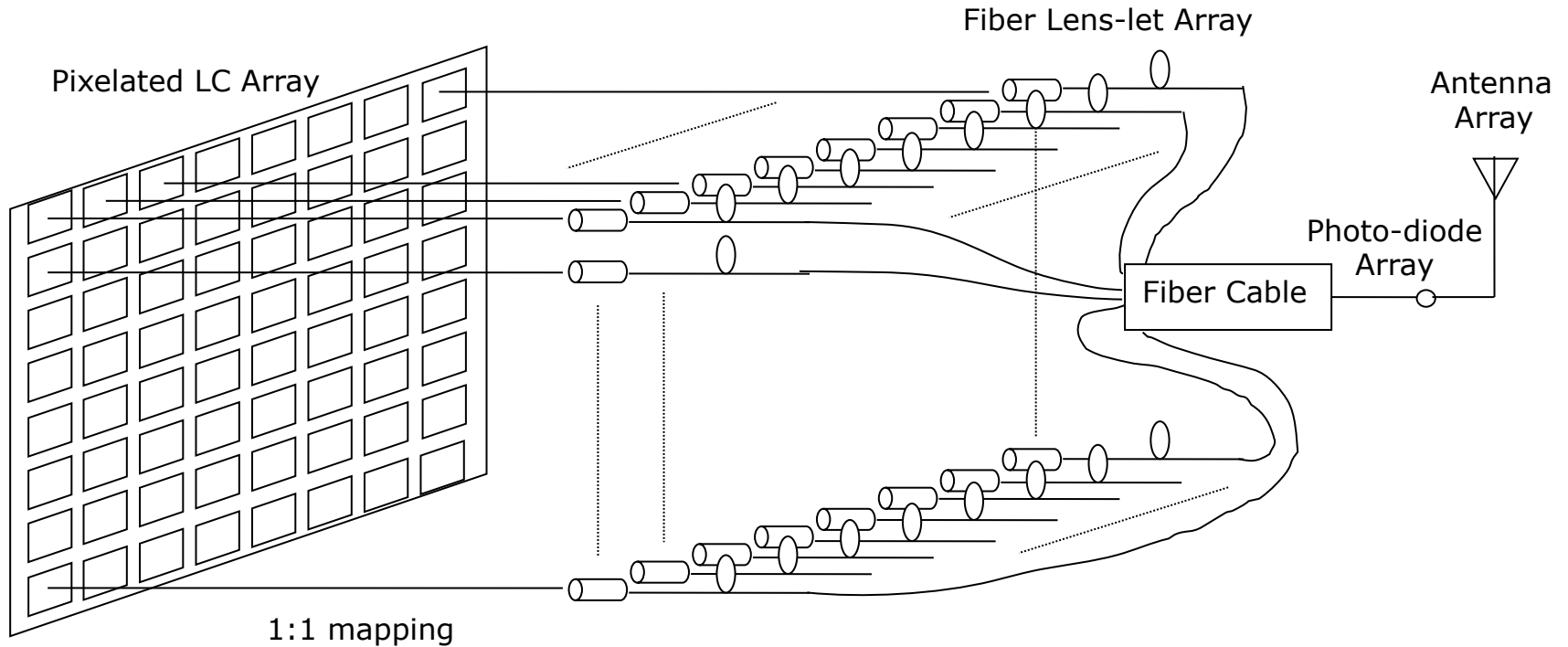
The reference time origin



The phase shifted top trace signal

Top trace (5mV/div) : photodiode output
Bottom trace : reference signal

Can we do better?



Issues and Problems:

Pixelated Device → Diffraction → System Loss

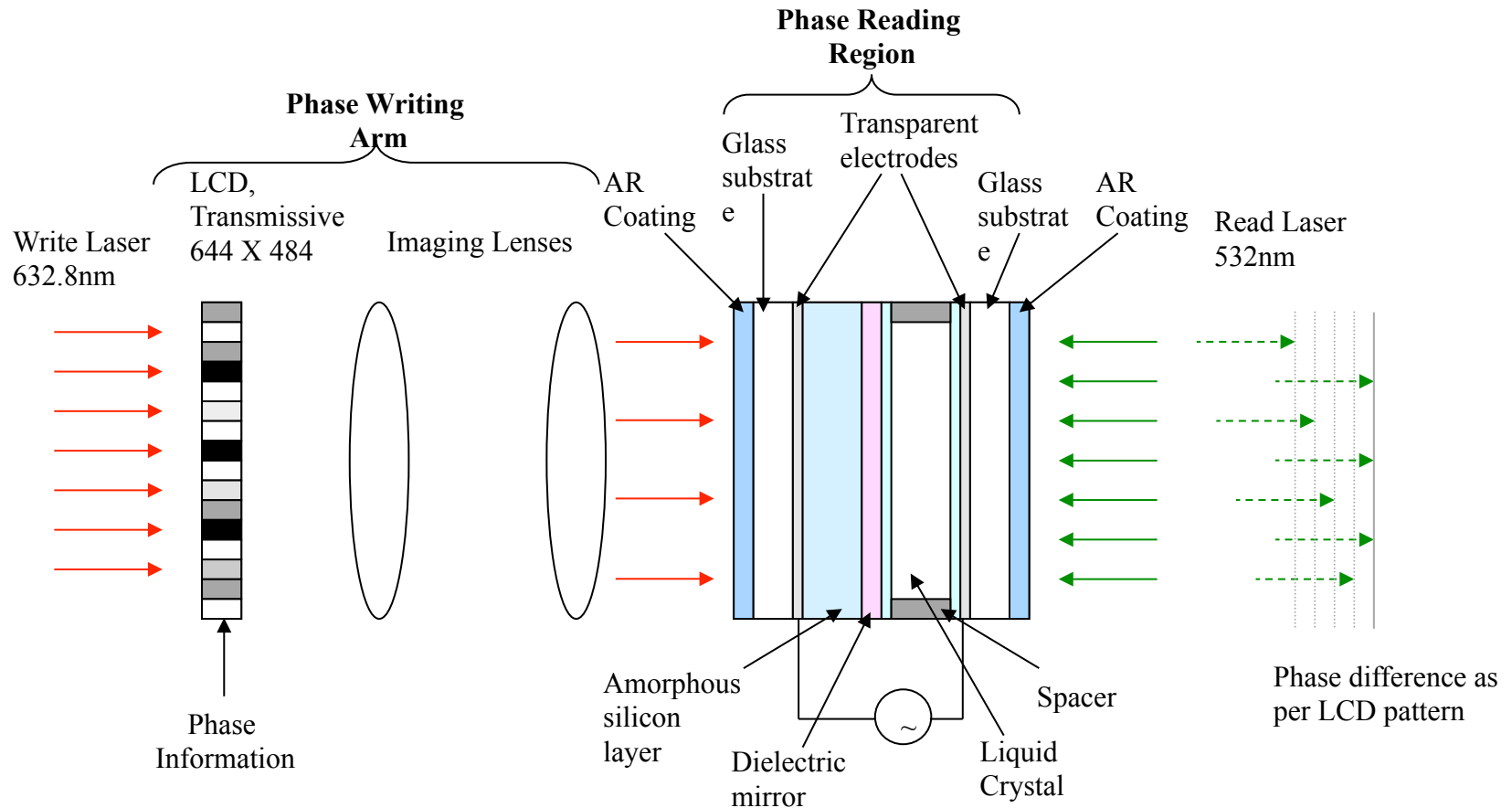
→ Inter fiber cross-talk

→ Fixed precision area mapping between pixel array & lens-let array → no flexibility

→ Number of antenna elements fixed

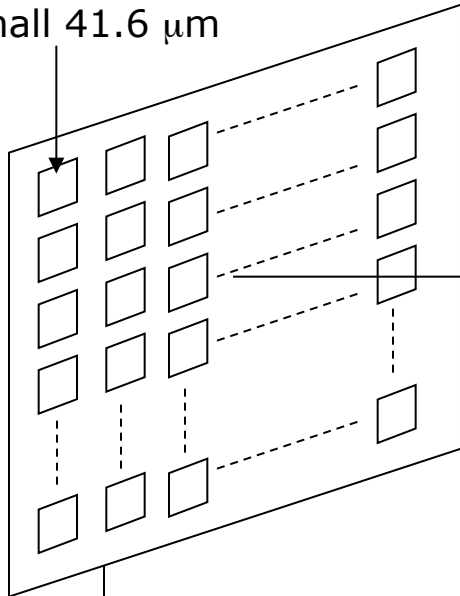
→ Zero tolerance to fiberarray fabrication and assembly misalignment

The key to doing better → Hamamatsu Optically addressed Nematic LCD Module



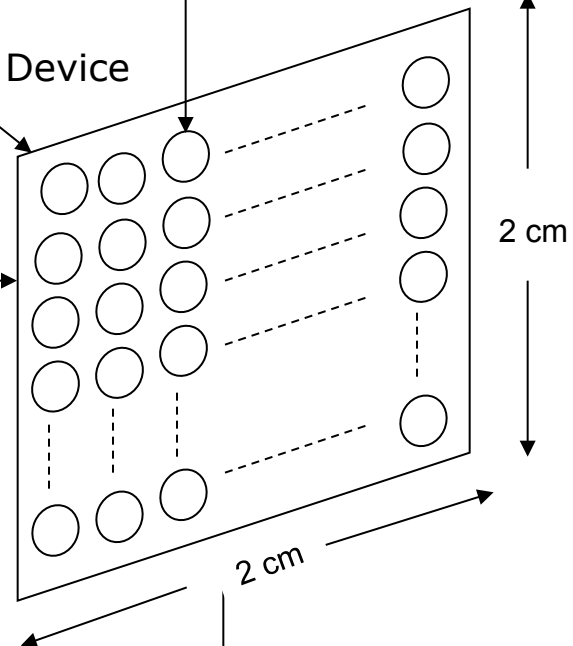
480 X 480 Pixels LCD

Small 41.6 μm



Hamamatsu Device

Macropixel
(Big)



Massive Space Bandwidth Product

$480 \times 480 = 230,400$

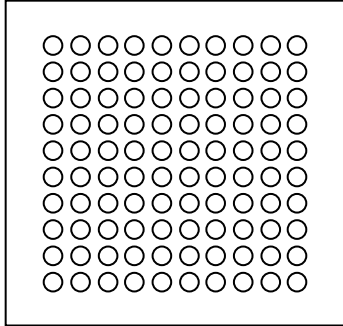
N antenna Phase control sites

N range $\rightarrow 50 \rightarrow 5,000$

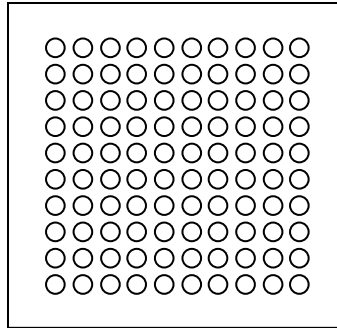
**Lots of tiny LCD pixels to make a macropixel representing
an RF Phase Shifter Site**

Options in Optical Head

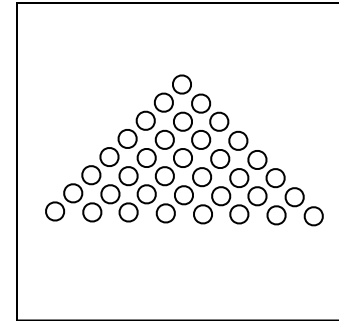
Square Array



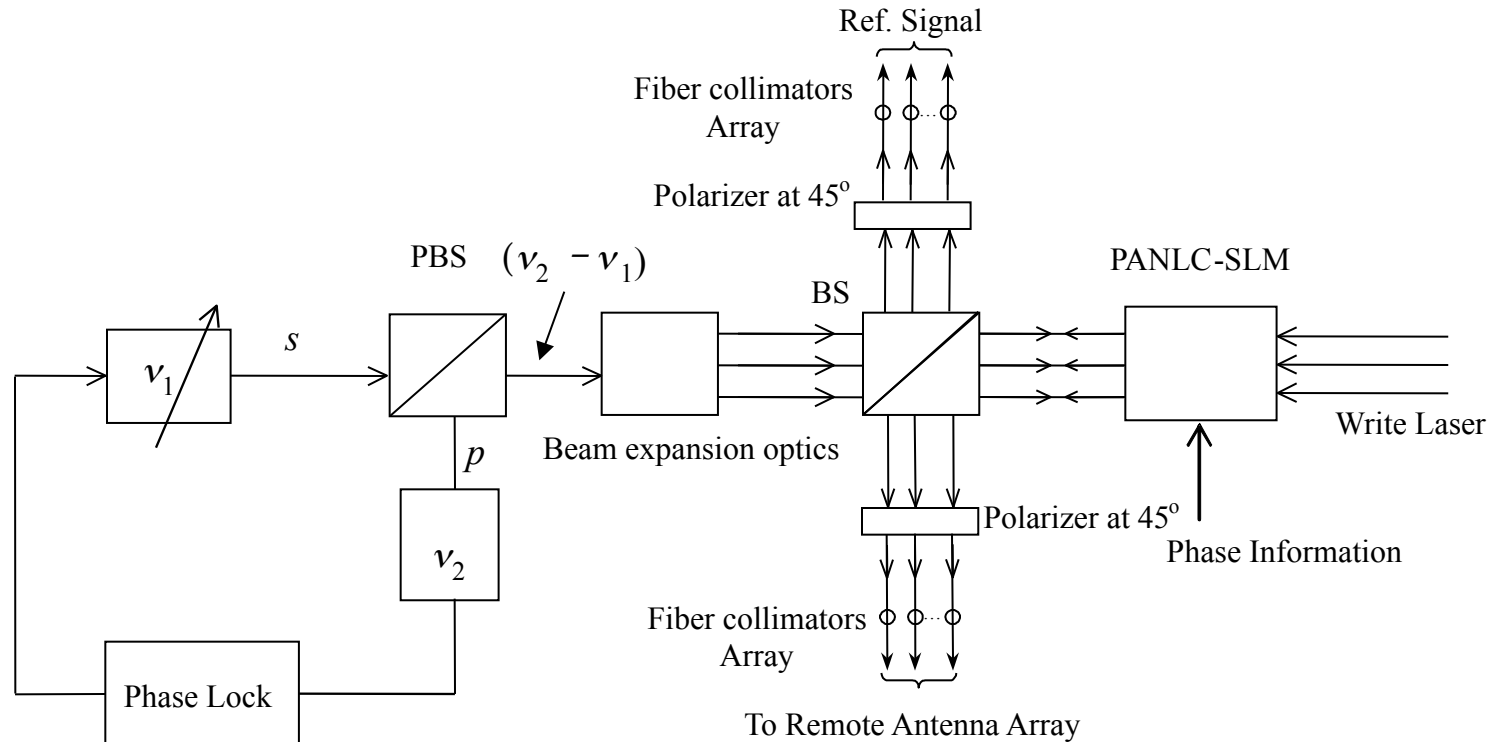
Circular Array



Tri-angular Array



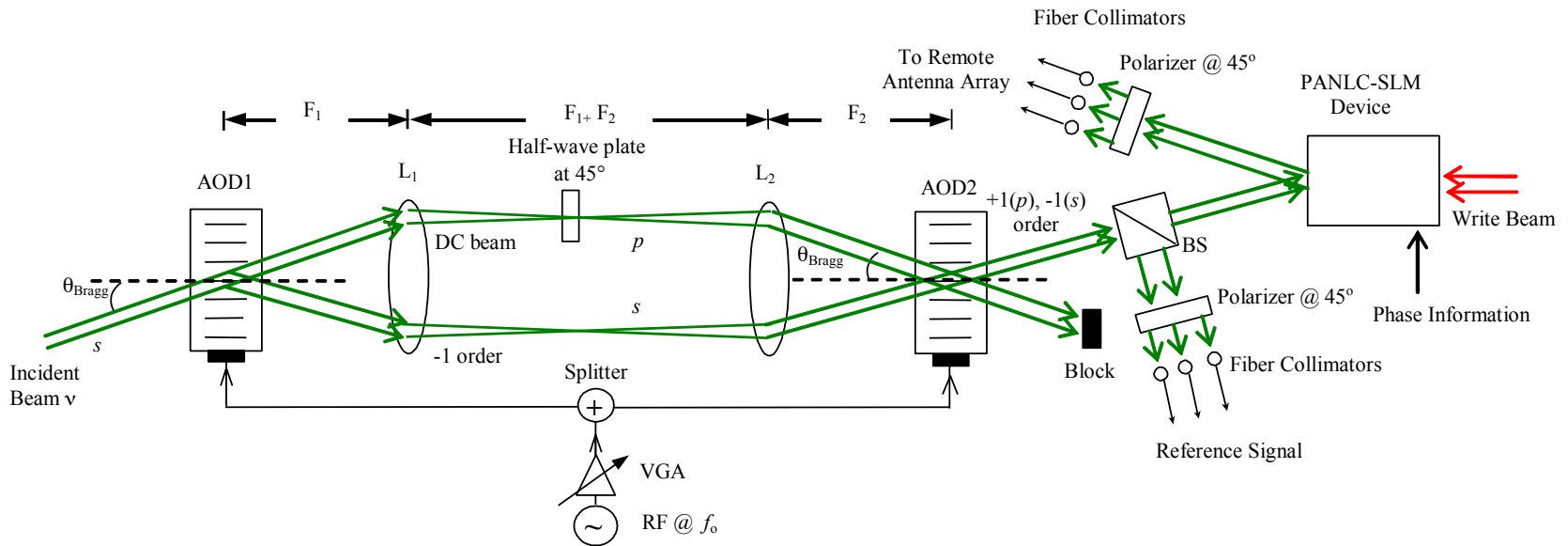
Flexible LC RF Beamformer Conceptual Design



PANLC-SLM: Parallel Aligned Nematic Liquid Crystal - Spatial Light Modulator

ν_1, ν_2 : optical frequencies

Flexible LC Beamformer Experimental Setup



ν : Optical Frequency

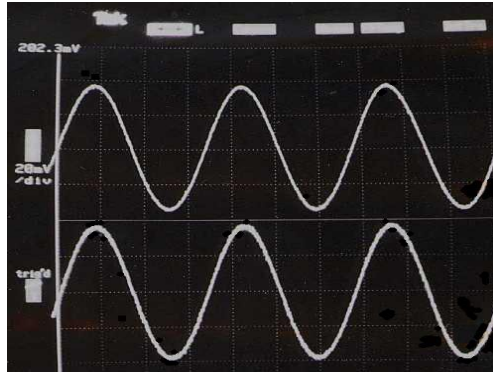
F_i : Focal Length of i^{th} Lens

AOD: Acousto-Optic Device

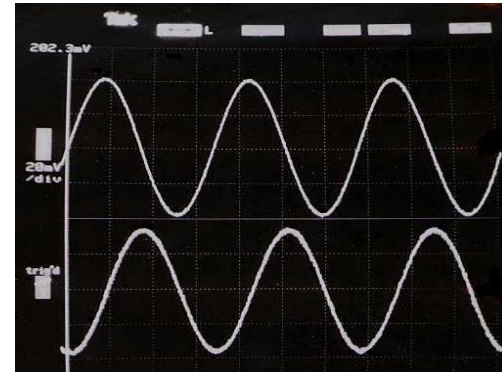
VGA: Variable Gain Amplifier

PDA: Photodetector Array

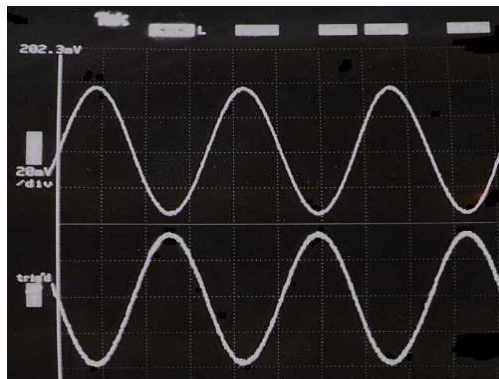
Oscilloscope traces of the RF output of the detectors



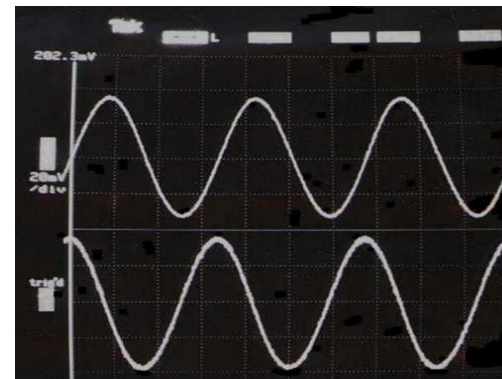
In-phase signals



90° out of phase



180° out of phase



270° out of phase

Phase Modulation Characteristics of the LC Controller



Introduced the Concept of Flexible Beamformer



Leads to Flexible Antenna Array Remote Heads



Antenna Array Application Upgrades without Changing Phase Control
Beamformer Hardware



Satellite, Wireless Base station and Air Traffic

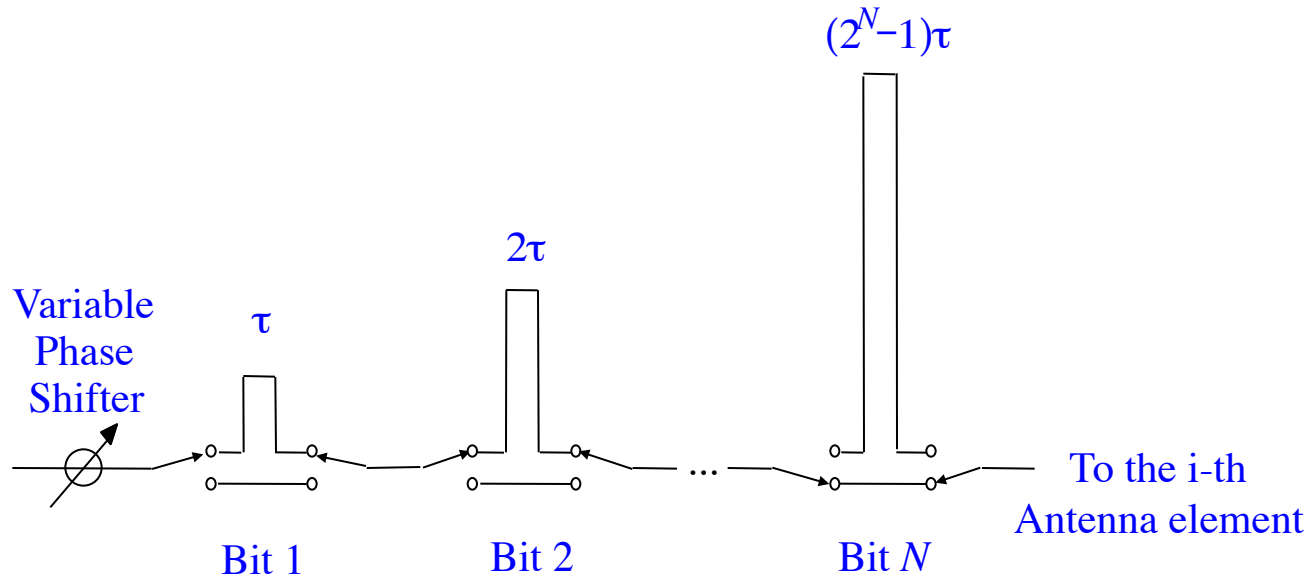


Universal Controller

RF Radar Delay Line Requirements

RF Loss/bit	2.86 dB
Least Significant Bit	0.1 ns
Most Significant Bit	6.4 ns
Time Delay Error	0.05 ns
Frequency Range	3 - 6 GHz
Within Channel Leakage Noise	< - 60 dB
RF Crosstalk between delay line channels	< - 60 dB
Time delay switching speed	10 μ s

True Time Delay Line Network



Binary architecture

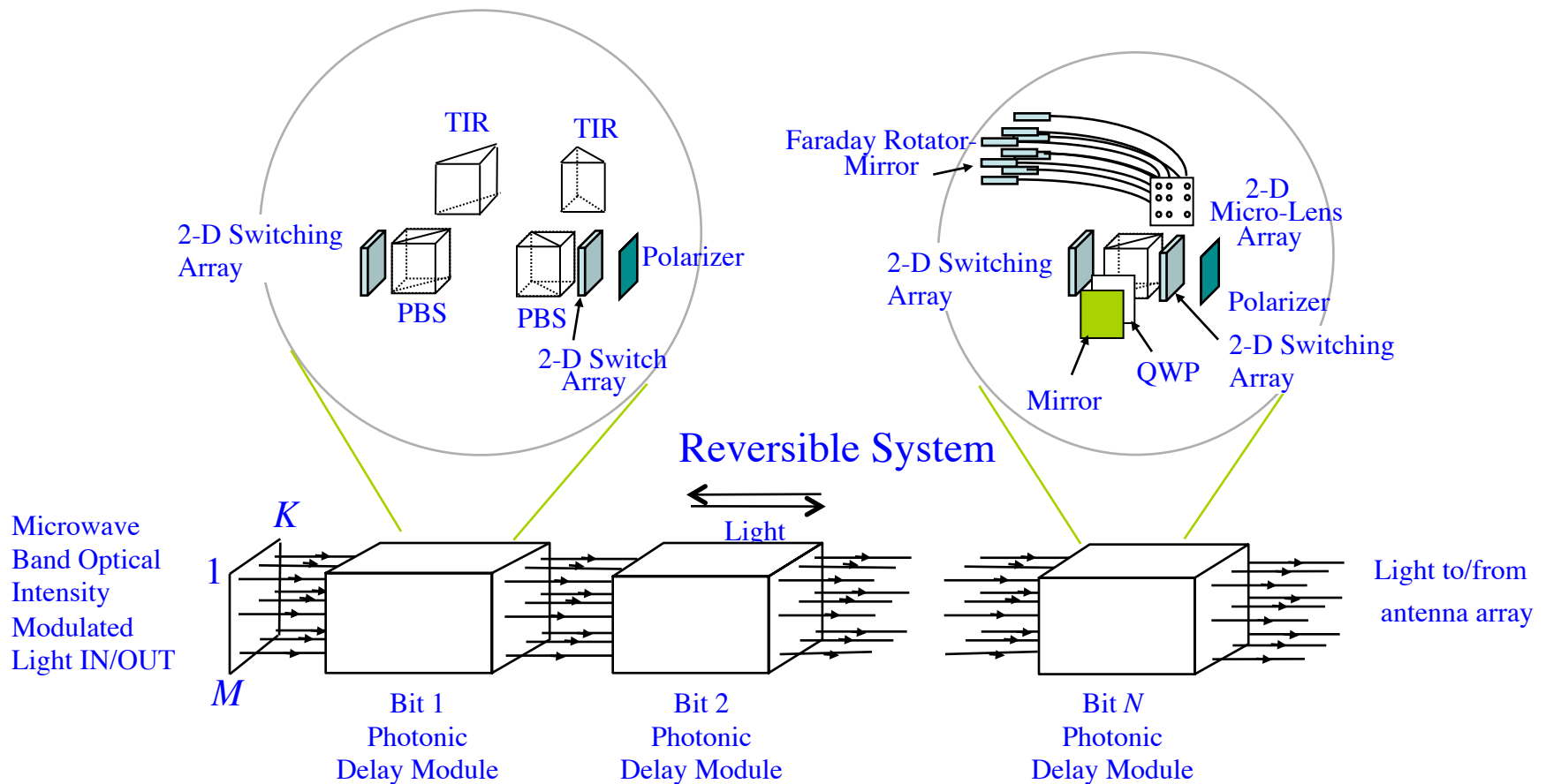
$$T_i = (b_{0i} \cdot 2^0 + b_{1i} \cdot 2^1 + \dots + b_{Ni} \cdot 2^N) \cdot \tau$$

$$b_{ni} = \begin{cases} 0 & \text{non-delay} \quad n = 1, 2, \dots, N \\ 1 & \text{delay} \quad i = 1, 2, \dots, M \end{cases}$$

Motivation for using Ferroelectric Liquid Crystal Devices

- Fast Switching Speeds (e.g., 10 μs and 1319 nm)
- Highly Scalable to Multiple Channel Devices – Arrays
- Planar Optics – Ease in Interface to Fiber & Freespace Optics
- Low Power Usage for Device Controls

Photonic Delay Lines based on Ferroelectric Liquid Crystal Polarization Switching Devices

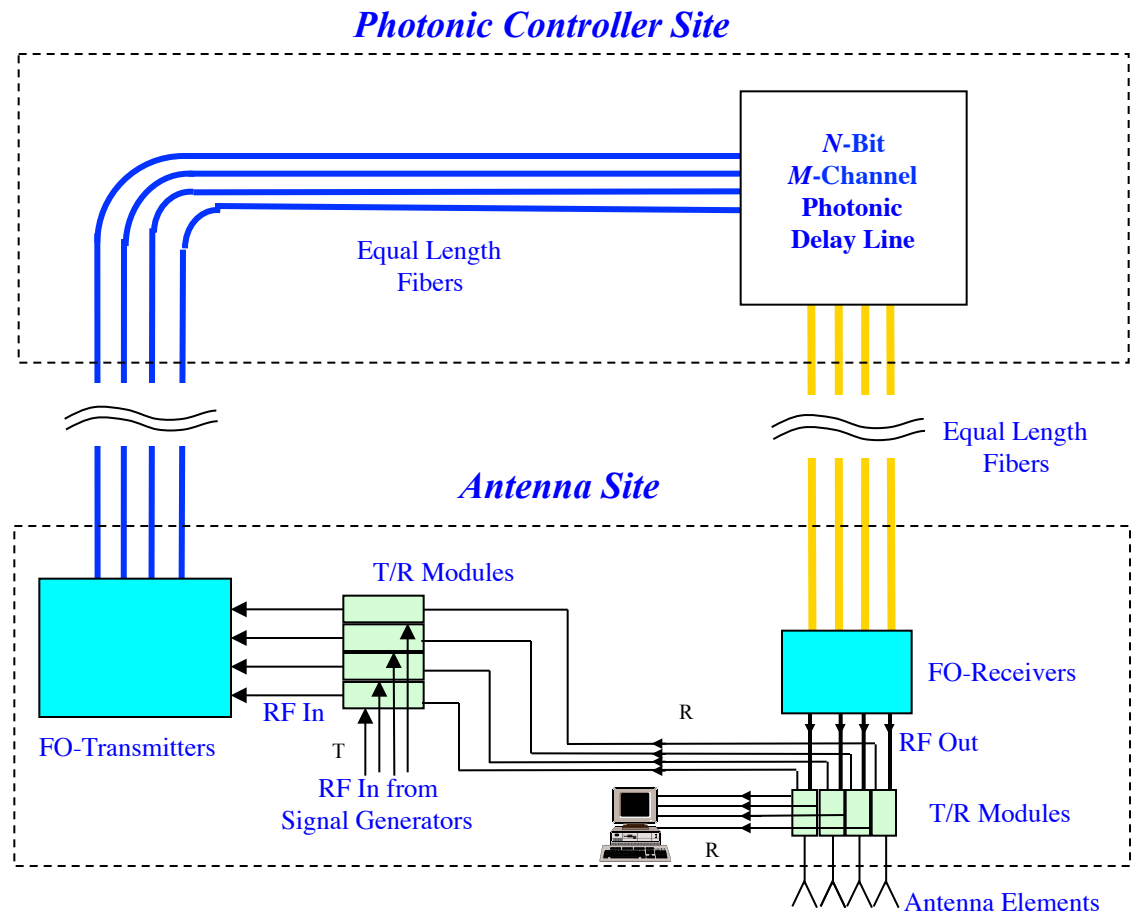


Phased Array Antenna Remote Control

Photonic processing allows fiber-optic remoting

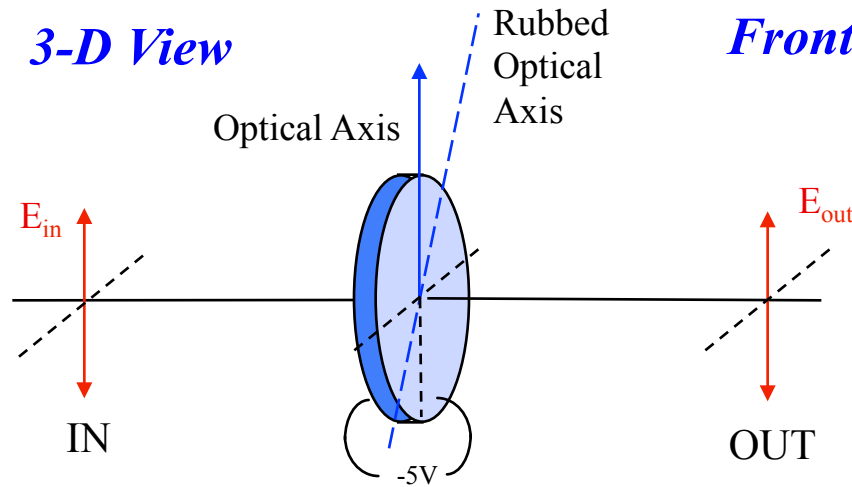
Fibers offer:

- Better transmission loss compared to coaxial systems
- Low EMI microwave frequency signal interconnection
- Compact systems

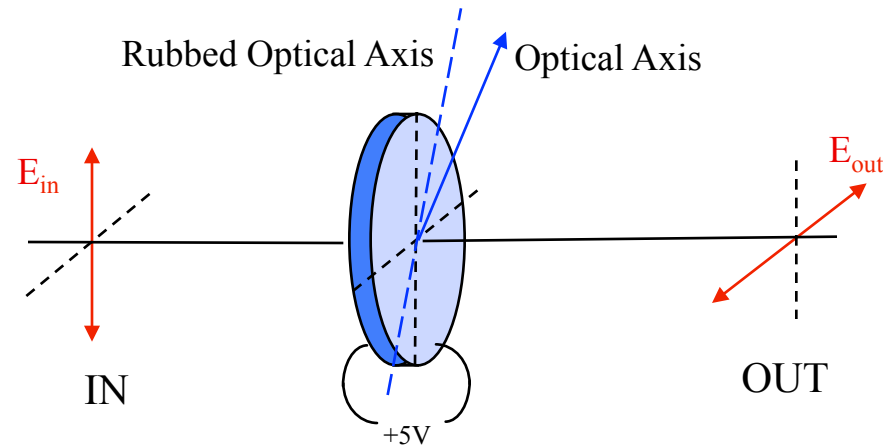


Ferroelectric Liquid Crystal Principle of Operation

3-D View

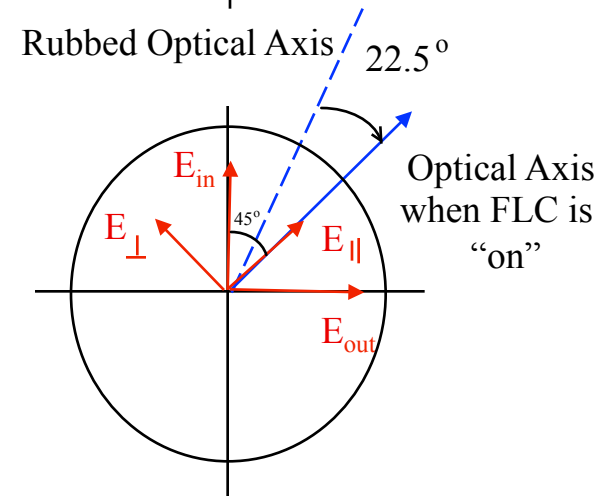
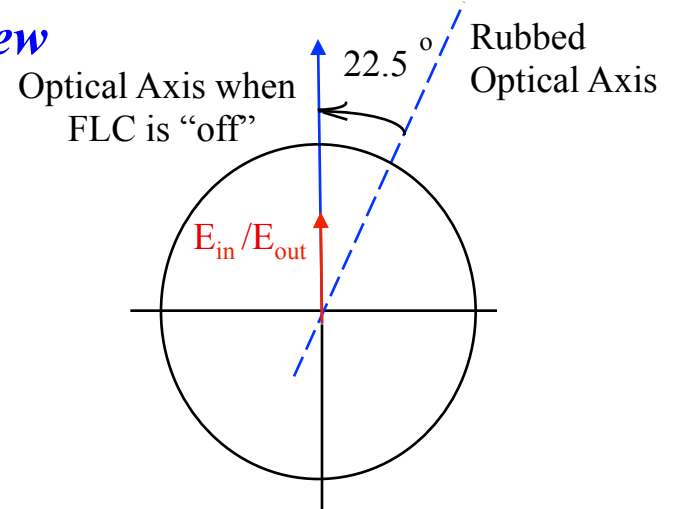


FLC: "off"



FLC: "on"

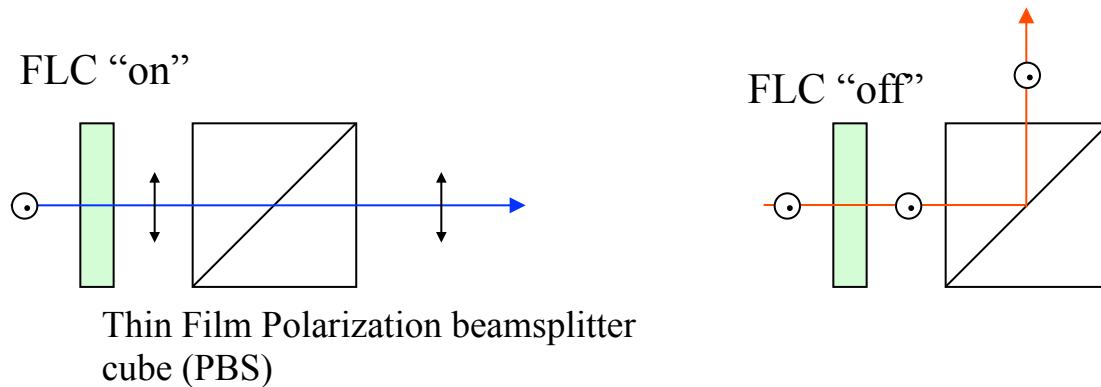
Front View



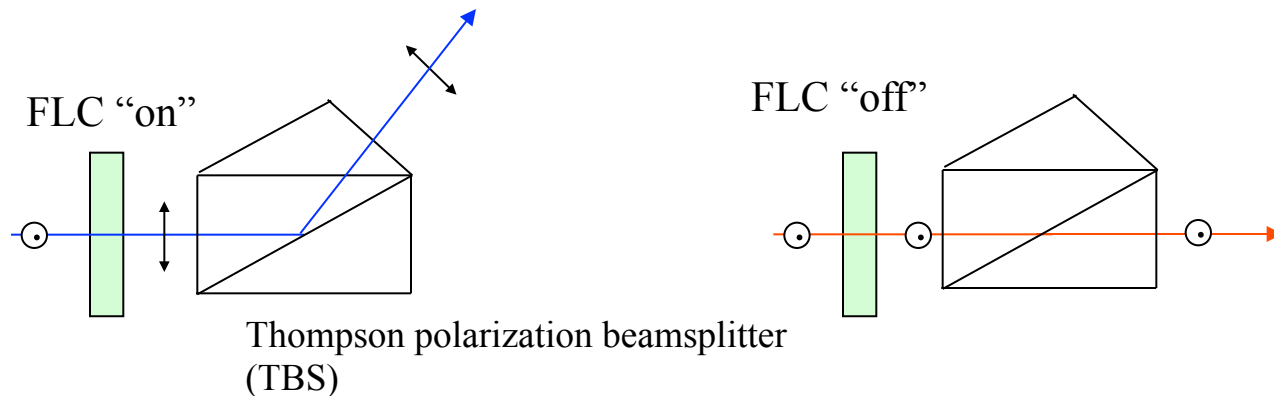
FLC-based Switching Fabrics

FLC Polarization Switch + Polarization Beamsplitter

Top View:



Top View:

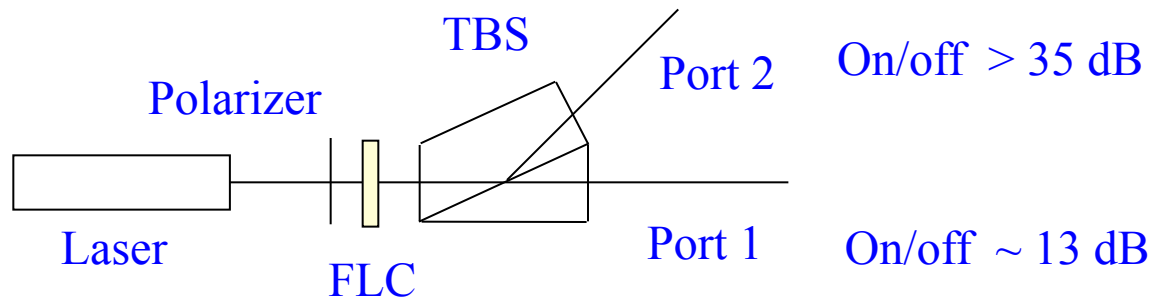


FLC Performance - The Problem

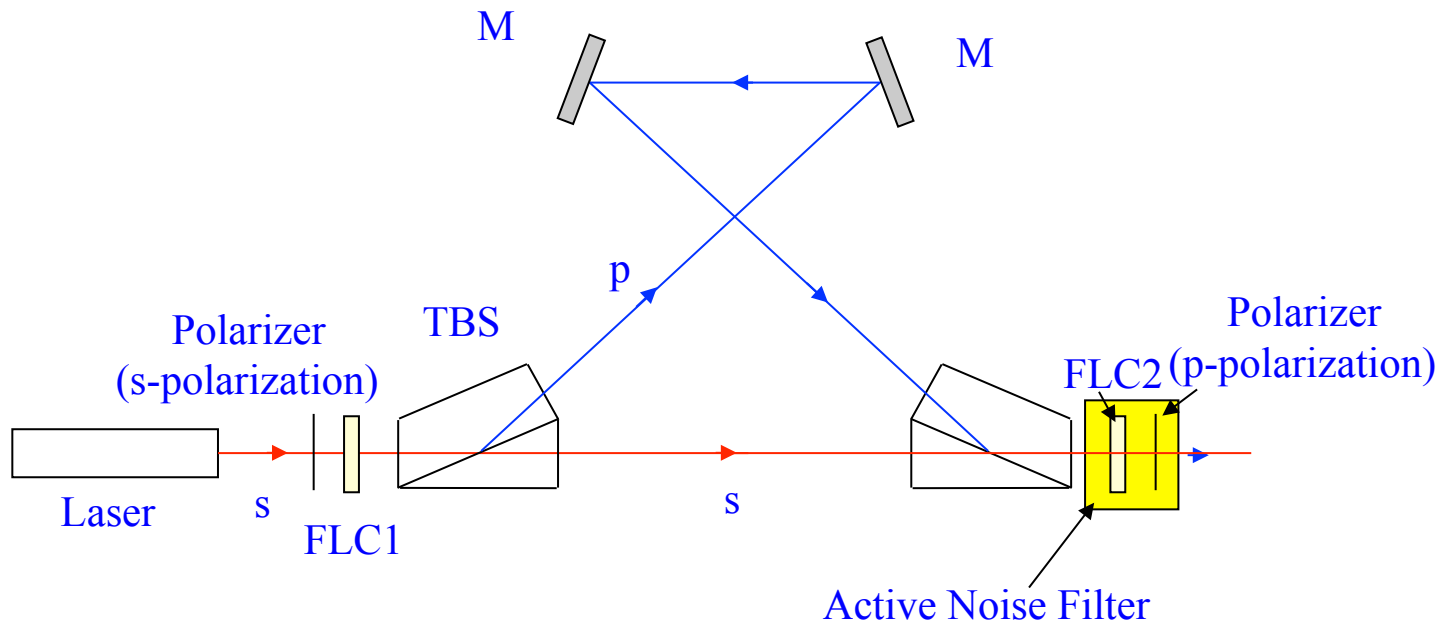
FLC Devices act as polarization Switches
We are interested in optical on/off ratios

FLC devices do not fully rotate the incident polarization

Optical on/off ratios $\Rightarrow$ Limit performance of the PDL



Solution: Active Noise Filter



$$\text{Leakage Noise} = 10 \log \frac{\text{Light traveling through the undesired paths}}{\text{Signal Light traveling through the desired path}}$$

Active noise filter
works better when



FLC1 and FLC 2 operate out of phase
Orthogonal Drive Configuration

Orthogonal Drive Configuration

Observation:

FLC devices degrade the state of polarization when they are set “on”



System has two FLC devices

If they operate out of phase, there is no setting that has both devices “on”

Polarization degradation balanced for the two PDL settings



Basis of improved noise filtering in other switching fabrics

Active Noise Filter Experimental Results using the FLC Orthogonal Drive Configuration

PDL Path	Leakage Noise (dB)		Polarization Extinction Ratio (dB)	
	Without Noise Filter	With Noise Filter	Without Noise Filter	With Noise Filter
Non-Delay	- 38.6	- 51.9	12.36	39.89
Delay	- 12.1	- 48.3	12.15	39.73



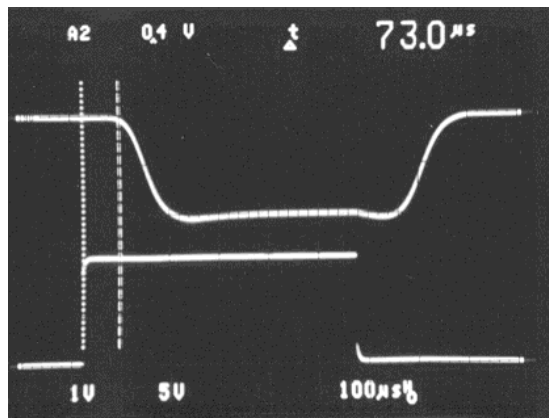
Electrical Leakage Noise < -95 dB



More than 10 dB improvement

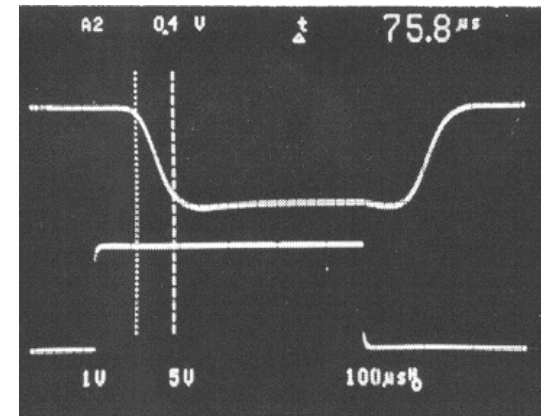
Switching Speed of the FLC Devices

- High switching speed is the key motivation for using FLC technology



Delay time 73 μs

Finite delay time for the molecules to start moving



Physics of the FLC Temporal Response

FLC Switching time: $\tau = \frac{\eta}{P \cdot E}$

η : viscosity

P : medium macroscopic polarization

E : applied electric field

Rise time: $\sim 1.8\tau$

For higher switching speeds  η : decrease

$P \cdot E$: increase

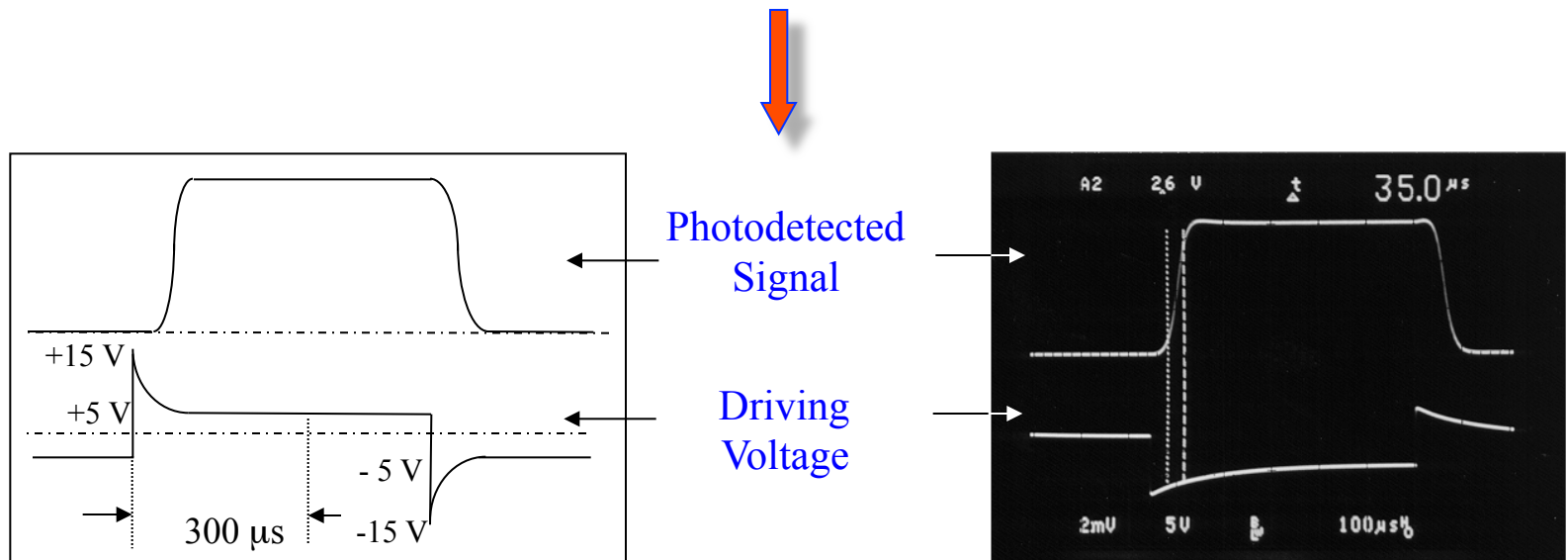
η , P : fixed for a specific material

$E = V/d$  apply higher V

Faster FLC Devices

Increase the applied voltage to the device for a very short time interval during the pulse drive condition

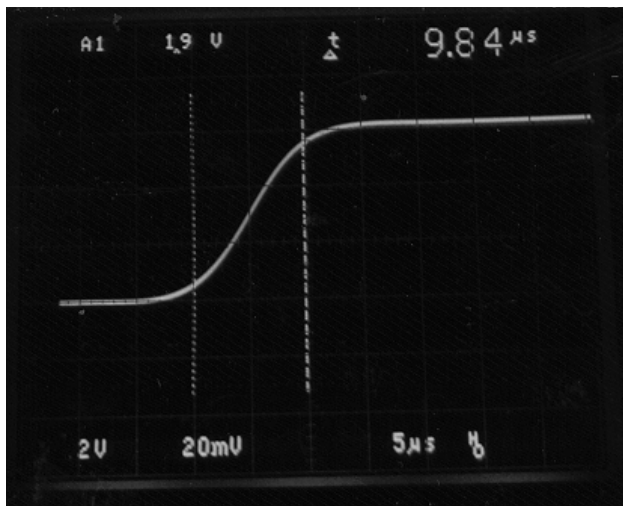
Short duration avoids permanent change in the macroscopic polarization of the FLC material



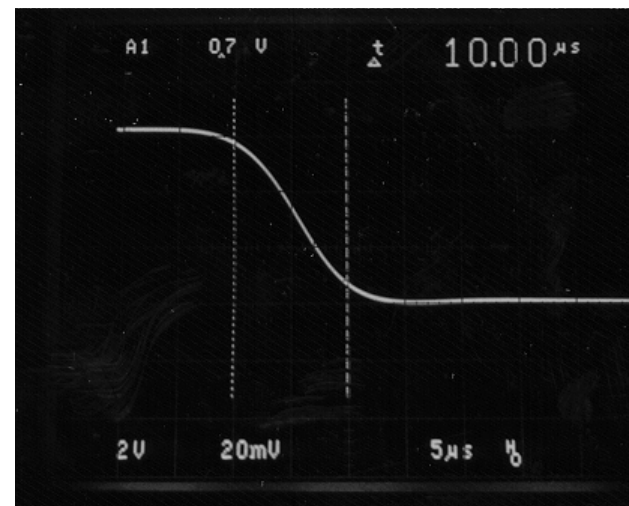
Fall time 35 μ s

Delay time $\sim 33 \mu\text{s}$

New FLC Material Development



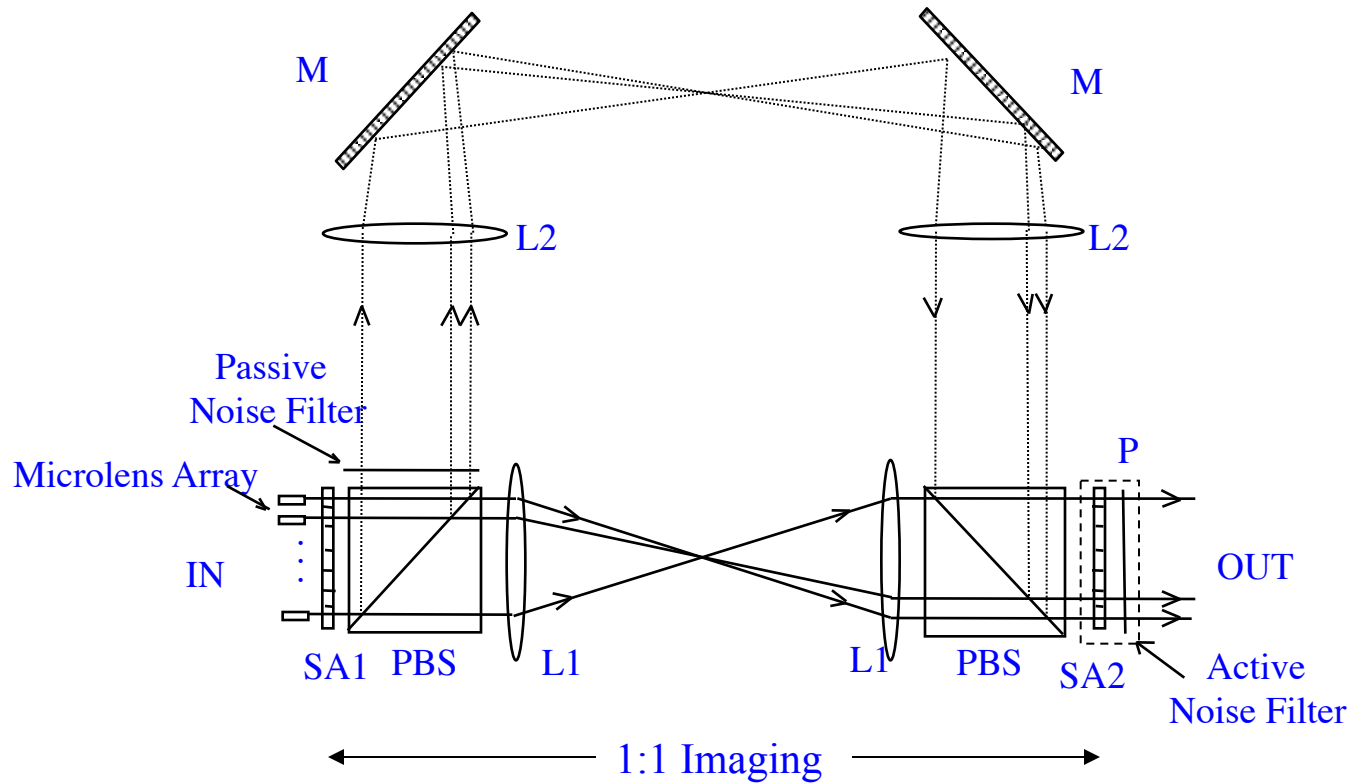
Rise time 9.84 μs



Fall time 10.0 μs

Driving signal: ± 30 V transient with a 30 μs fall time to ± 5 V.

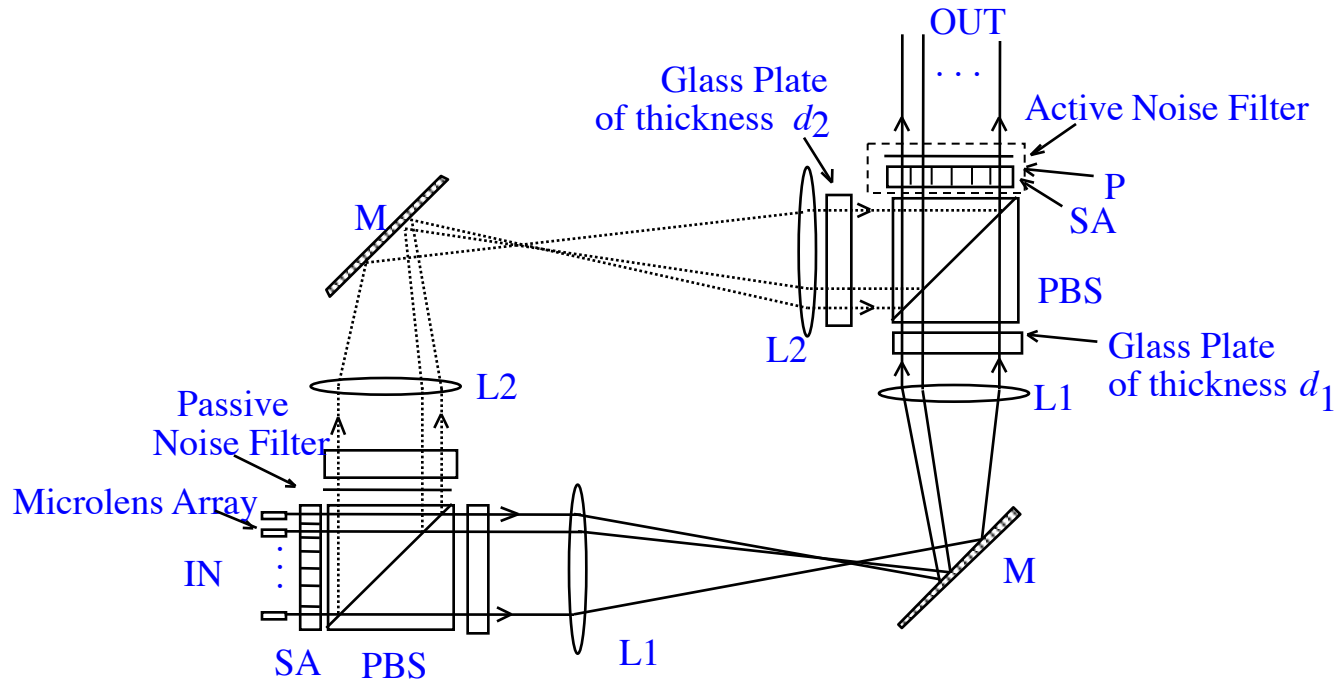
Transmissive PDL Architecture



Moderate delays

$$0.5 \text{ ns} < \tau < 5 \text{ ns}$$

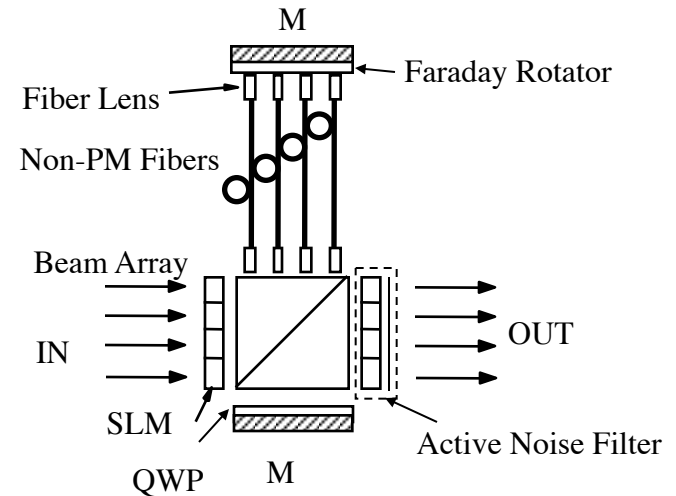
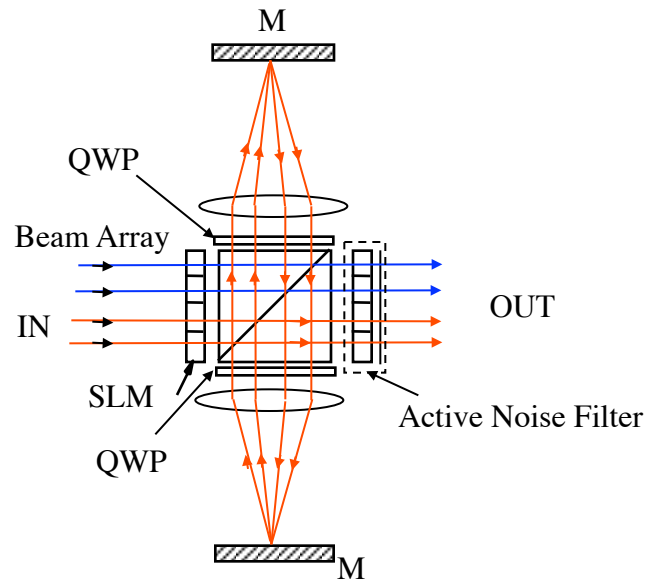
Symmetric PDL Architecture



Ultra short and short delays: < 0.5 ns

- Physical distance of the two paths equal
- 1:1 imaging for both paths limits selection of lenses

Reflective PDL Architecture



Features: Smaller physical size

Less Components

Moderate Delays using Free Space/Solid Optics

Long and Extra Long Delays (> 5 ns) using Single-mode Fibers



Novel Birefringence Compensation Technique

The Novel Birefringence Compensation Technique

The delay line system is polarization dependent

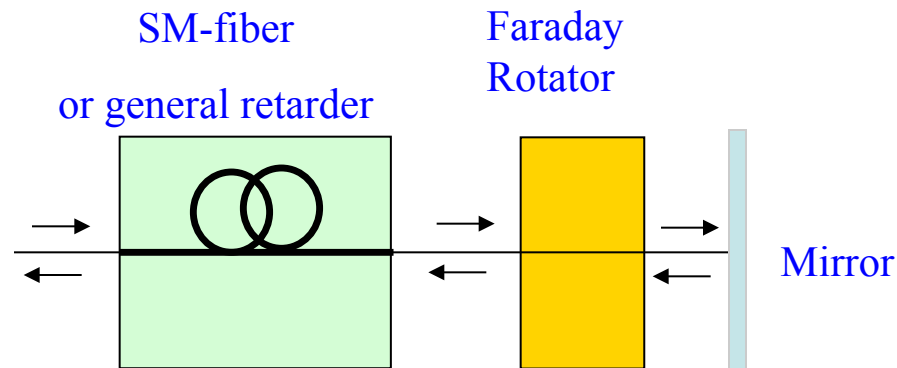


SM-fiber changes the state of polarization of the propagating light

Theory shows that the Faraday rotator and the propagation of light twice through the SM-fiber compensates any induced birefringence and rotates the polarization of the light by 90°

Non-PM Fiber based Photonic Delay Line - Theory

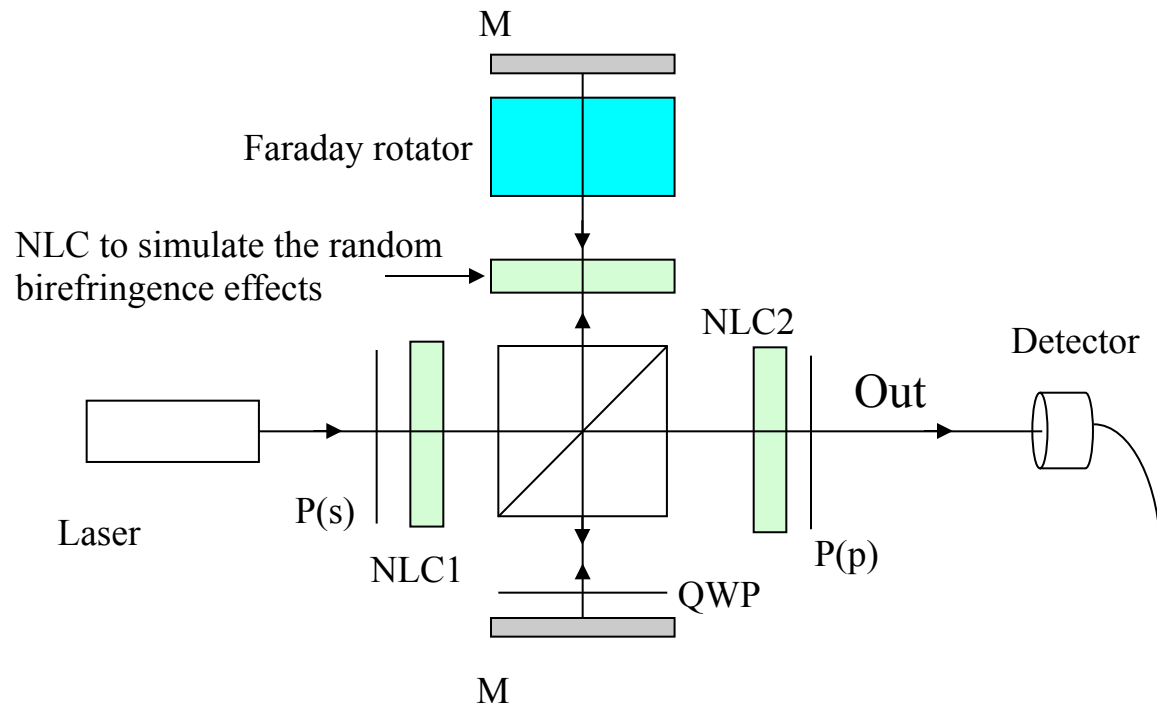
Simulate SM-fiber with a general retarder



Assumptions: Temporal random birefringence fluctuations happen over a time scale that is much longer than the temporal delay introduced by the delay medium

In general true for our application because these perturbations occur at a slow rate

Experimental Demonstration and Verification of the Novel Birefringence Compensation Technique



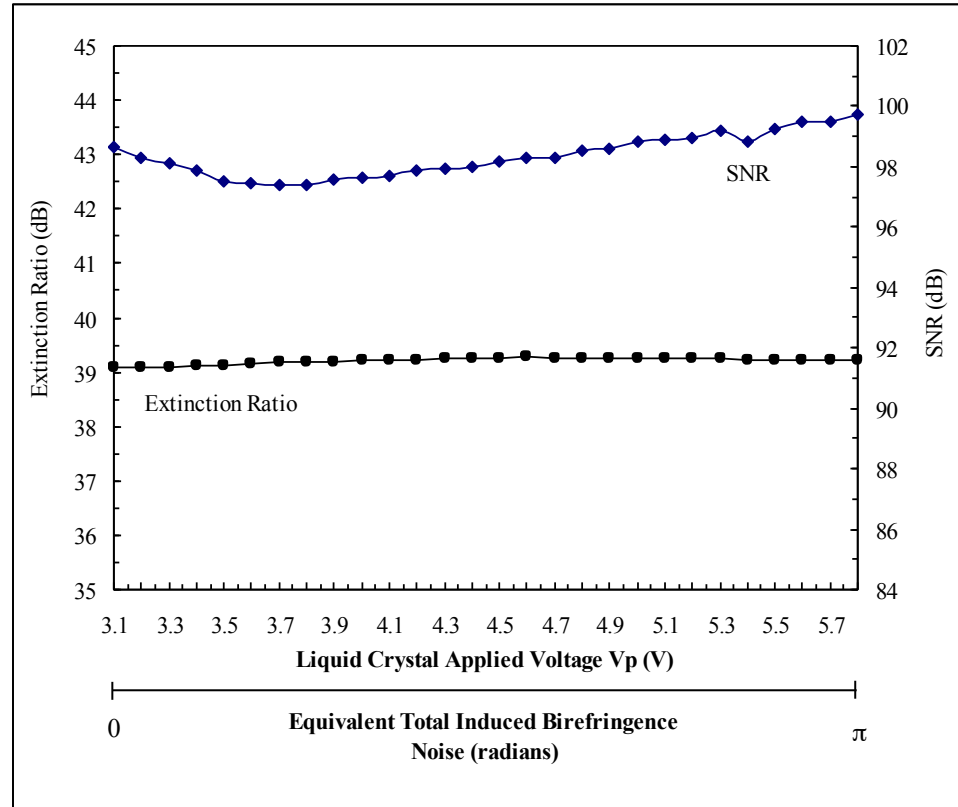
Test: Output Signal-to-Leakage Noise Ratio
Output Polarization Extinction Ratio

NLC: Nematic liquid crystal device

SNR and Polarization ER using the Birefringence Compensation Technique

$$\overline{\text{ER}} = 39.20 \text{ dB}$$

$$\Delta \text{ER} = \pm 0.048 \text{ dB}$$



$$\overline{\text{SNR}} = 98.35 \text{ dB}$$

$$\Delta \text{SNR} = \pm 0.584 \text{ dB}$$

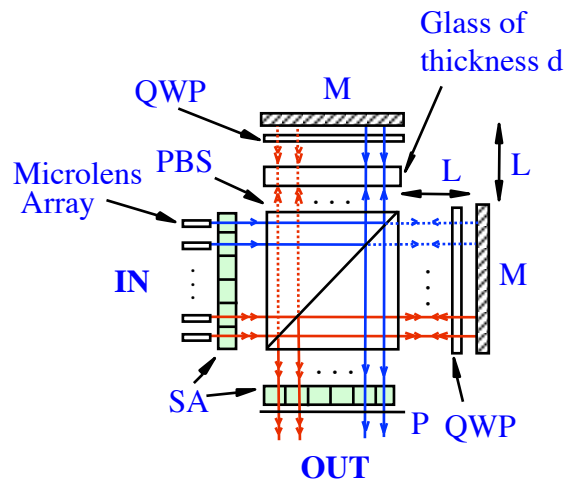
N. A. Riza, and N. Madamopoulos, "High signal-to-noise ratio birefringence compensated optical delay line based on a noise reduction scheme," *Optics Letters*, Vol. 20, No. 22, pp. 2351-2353, November 15, 1995

Photonic Delay Line Architectures

PDL Architecture	Time Delay				
	Ultra-short $\tau < 0.1$ ns	Short 0.1 ns $< \tau < 0.5$ ns	Moderate 0.5 ns $< \tau < 5$ ns	Long 5 ns $< \tau < 10$ ns	Extra long $\tau > 10$ ns
Symmetric	✓				
Reflective		✓	✓	✓	✓
Transmissive			✓	✓	

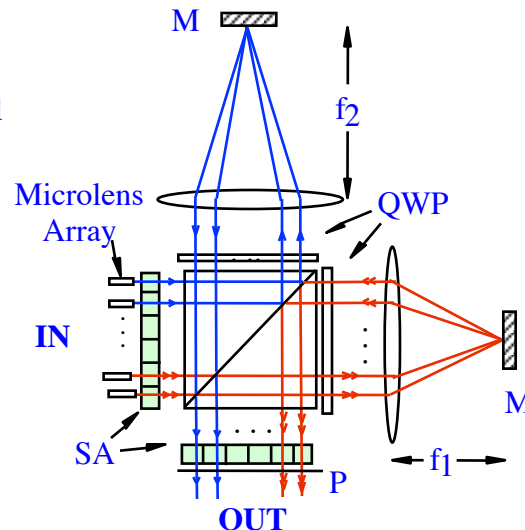
- No single PDL provides the wide range of delays needed
- Unbalanced optical signal loss between the two PDL settings
- Unbalanced SNR performance for the two PDL settings

The Reflective - Symmetric Adaptable PDL Architecture



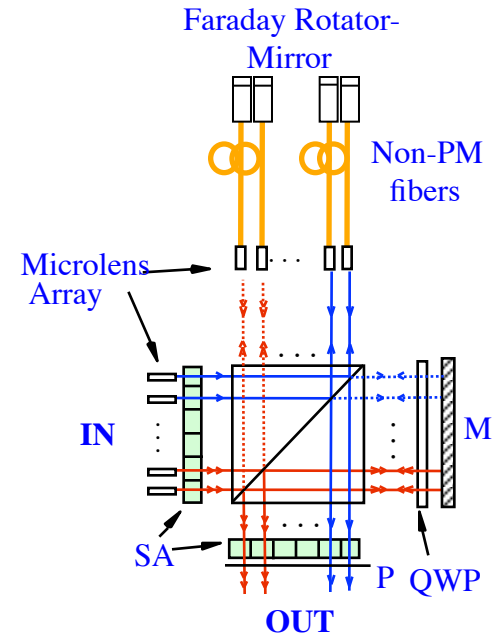
Ultra short - Short

Free space/Solid optics



Short - Moderate

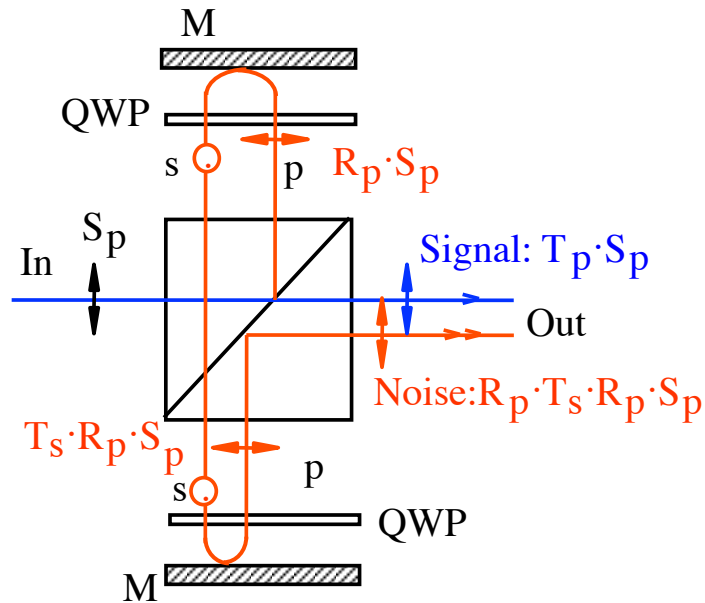
Free space/Solid Optics



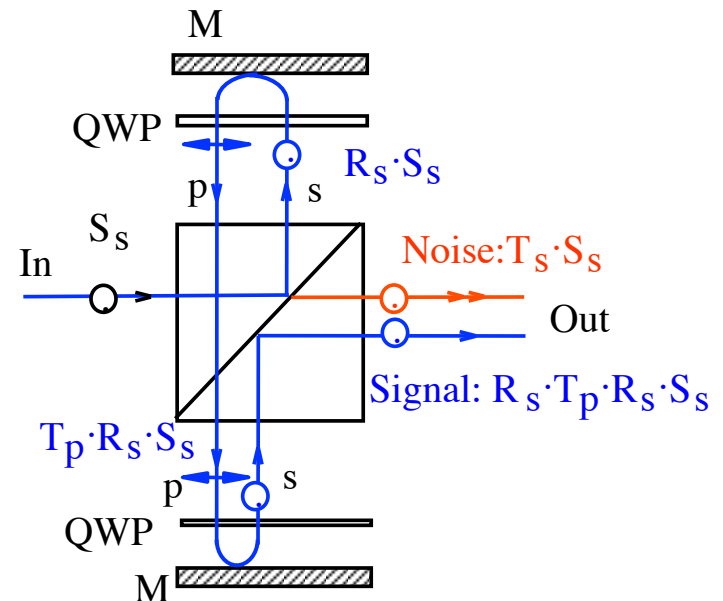
Long - Extra long

Fiber Delays

Theoretical Analysis for the SNR of the Proposed Basic Reflective PDL Architecture



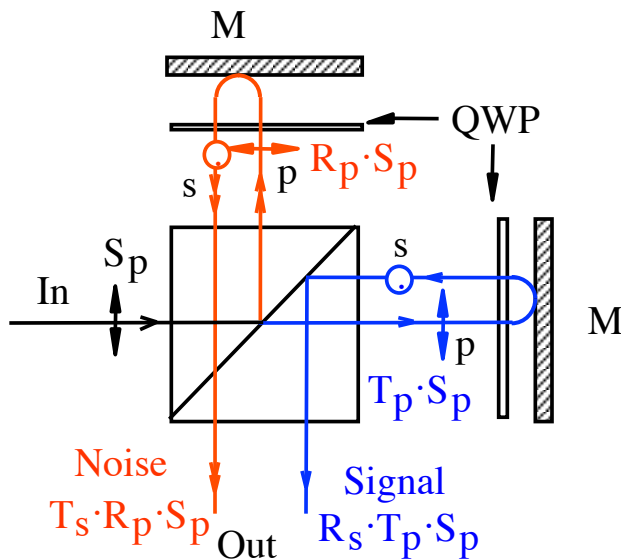
Optical SNR = 55.8 dB
 RF SNR = 116.8 dB
 for p-polarized input light



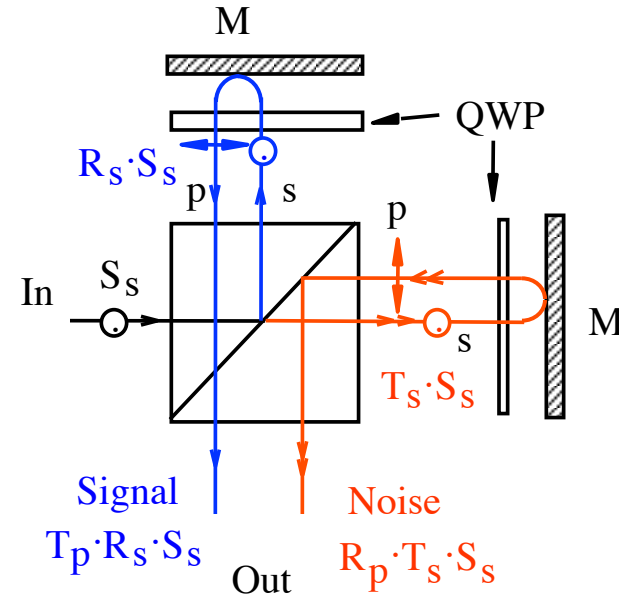
Optical SNR = 29.77 dB
 RF SNR = 59.54 dB
 for s-polarized input light

$$\text{Optical SNR} = 10 \log \frac{\text{Signal}}{\text{Leakage Noise}}$$

Theoretical Analysis for the SNR of the Novel Adaptable PDL Architecture



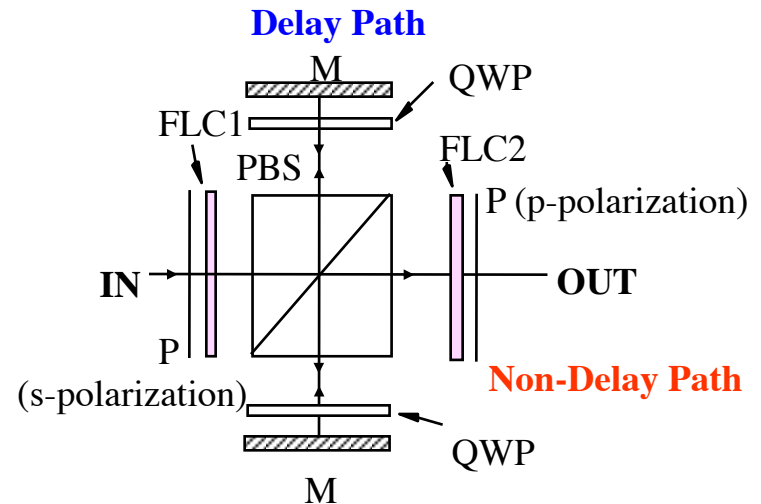
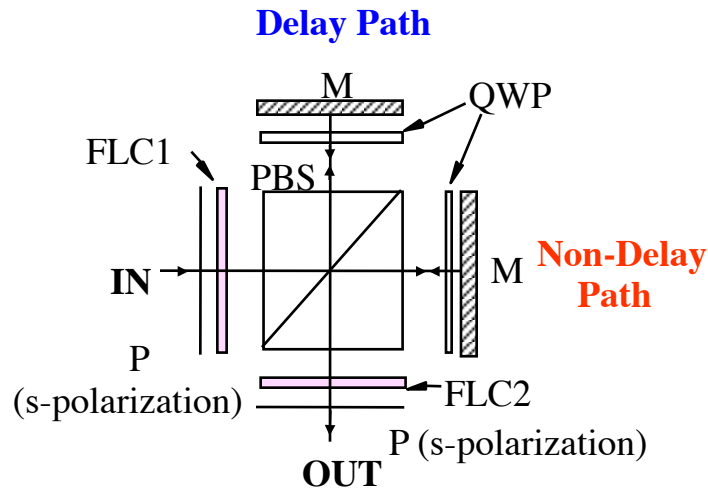
Optical SNR = 42.78 dB
 RF SNR = 85.56 dB
 for p-polarized input light



Optical SNR = 42.78 dB
 RF SNR = 85.56 dB
 for s-polarized input light

$$\text{Optical SNR} = 10 \log \frac{\text{Signal}}{\text{Leakage Noise}}$$

Experimental Demonstration of the Balanced SNR Performance



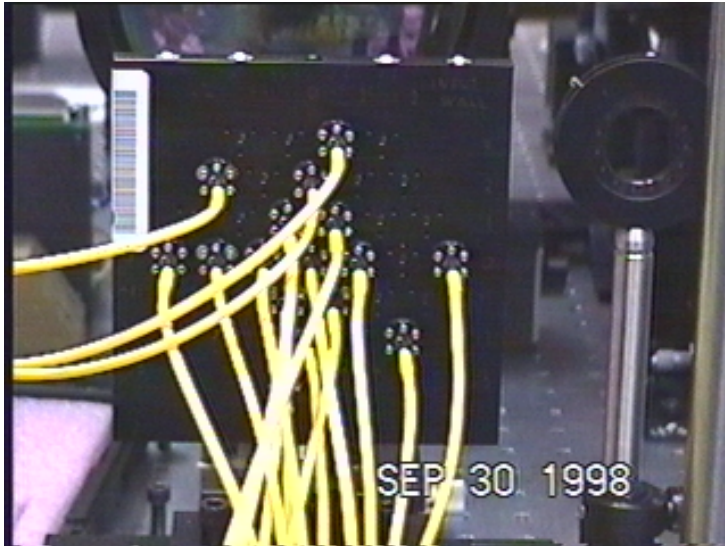
	<i>Adaptable</i>		<i>Reflective</i>	
	Optical SNR (dB)	Electrical SNR (dB)	Optical SNR (dB)	Electrical SNR (dB)
Non-delay	41.32	82.64	23.46	46.92
Delay	41.82	83.64	36.32	72.64

Photonic Delay Line Architectures

PDL Architecture	Time Delay				
	Ultra-short $\tau < 0.1$ ns	Short 0.1 ns $< \tau < 0.5$ ns	Moderate 0.5 ns $< \tau < 5$ ns	Long 5 ns $< \tau < 10$ ns	Extra long $\tau > 10$ ns
Symmetric	✓				
Reflective		✓	✓	✓	✓
Transmissive			✓	✓	
Reflective-Symmetric Adaptable	✓	✓	✓	✓	✓

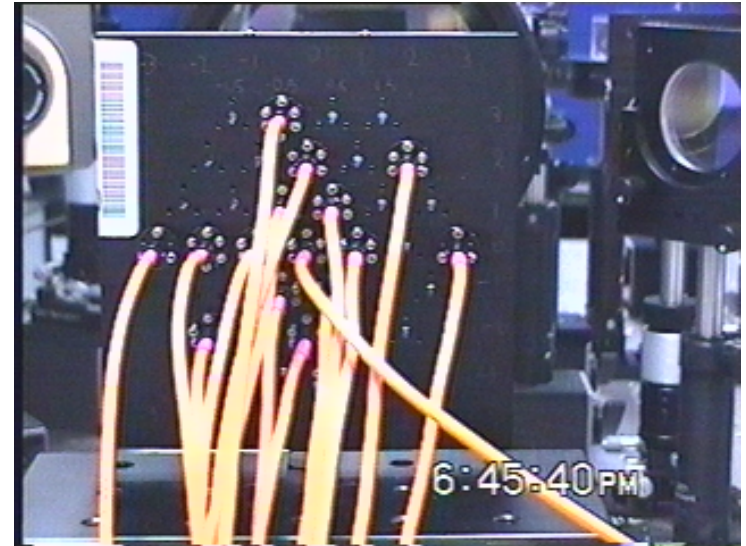
N. Madamopoulos and N. A. Riza, "Demonstration of an all-digital 7-bit 33-channel photonic delay line for phased-array radars,"
Applied Optics, Vol. 39, No. 23, pp. 4168 - 4181, 10 August 2000.

Input and Output 33 Channel Fiber Arrays



Input Fiber Array

Polarization-maintaining Fibers



Output Fiber Array

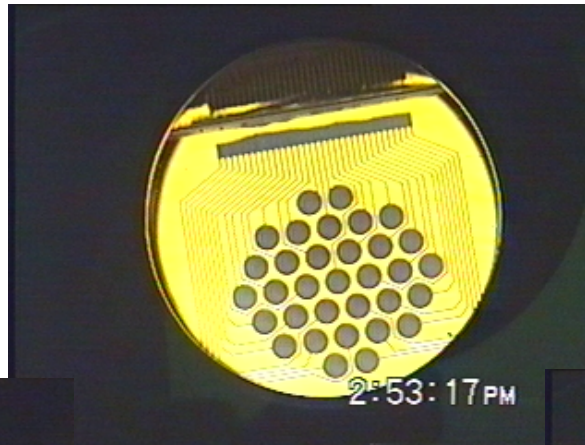
*Multimode Fibers
50 μm core diameter*

16-fiber channels connected

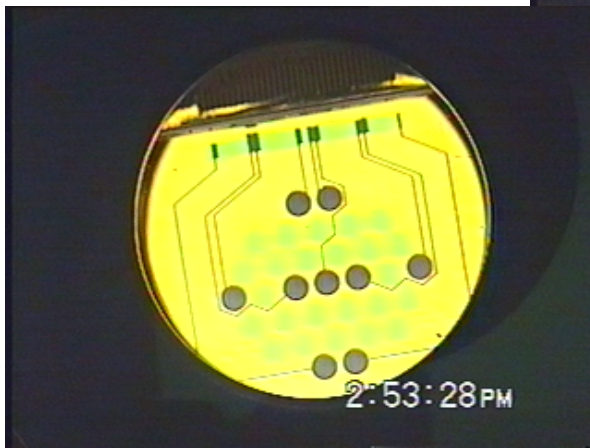


16-active channels in PDL

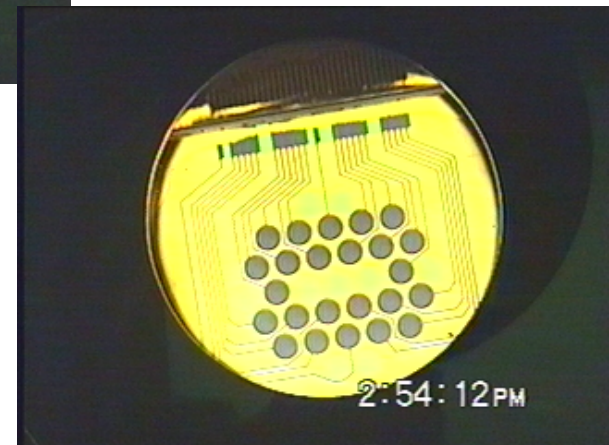
The Multichannel FLC Devices



All 33 pixels “off”



9 pixels “off”

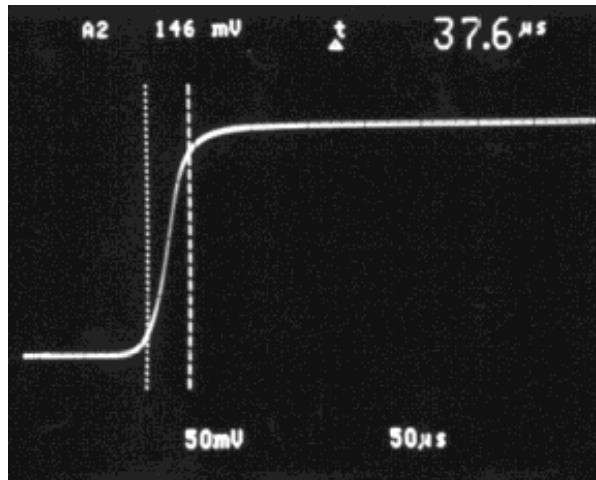


24 pixels “off”

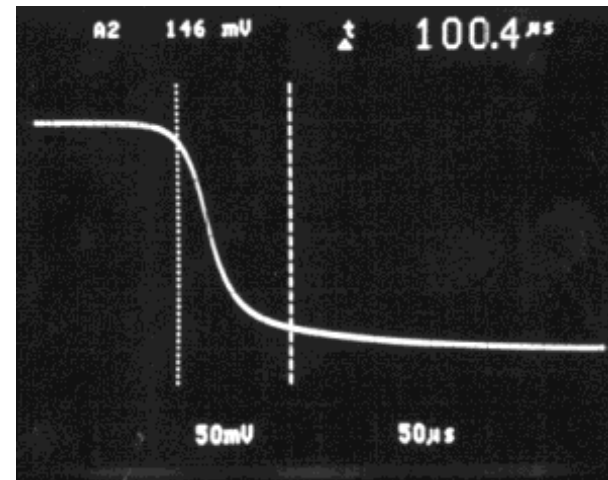
FLC arrays are single cell devices

FLC Multipixel Device Characteristics

- Temporal response



Rise Time 37.6 μs

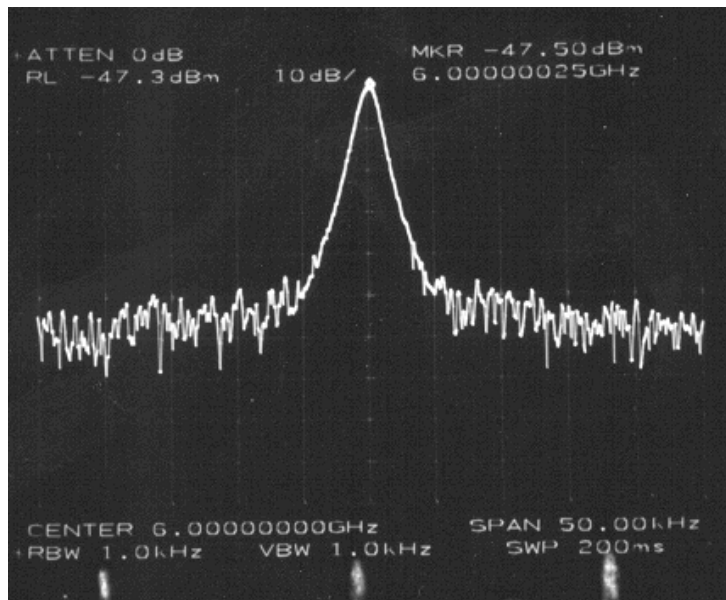


Fall Time 100 μs

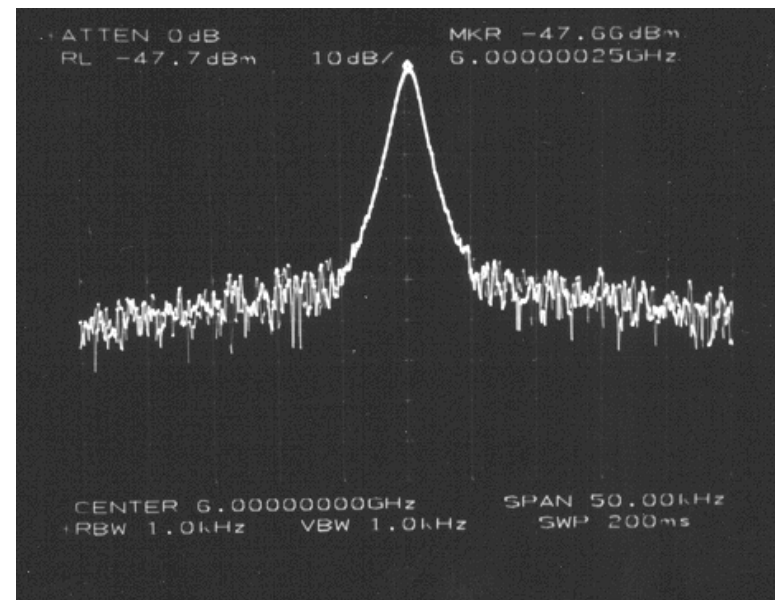


Use radar beam time multiplexing to meet faster 0.5 μs switching speed radar requirements

RF Spectrum Analyzer Measurements at 6 GHz



RF Spectrum Analyzer Trace showing
the Signal of the Fiber-Optic Link
without the PDL



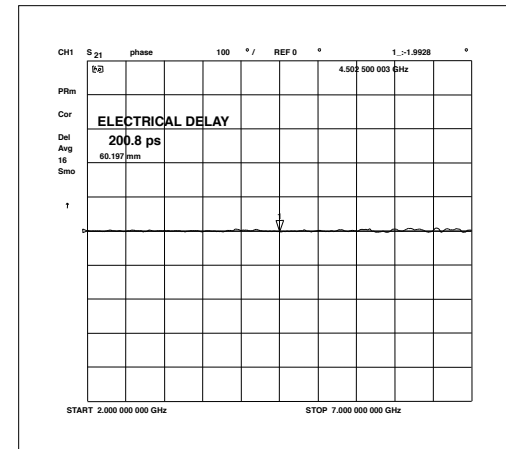
RF Spectrum Analyzer Trace showing
the Signal of the Fiber-Optic Link
with the PDL using Gain Balancing

**PDL does not introduce any
extraneous RF noise**

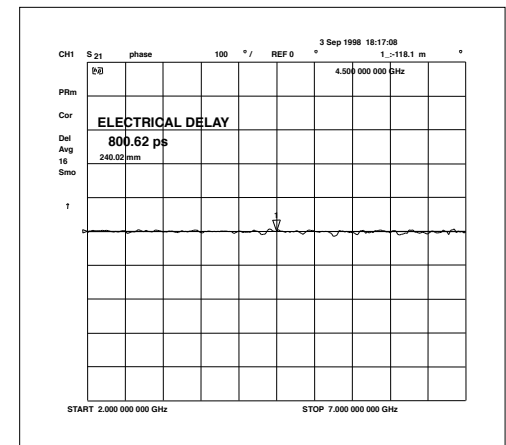
Time Delay Measurements

	<i>Goal</i>	<i>Obtained</i>
Bit 3	0.10 ns	0.11 ns
Bit 1	0.20 ns	0.20 ns
Bit 7	0.40 ns	0.40 ns
Bit 5	0.80 ns	0.80 ns
Bit 4	1.60 ns	1.60 ns
Bit 6	3.20 ns	3.16 ns
Bit 2	6.40 ns	6.40 ns

0.2 ns

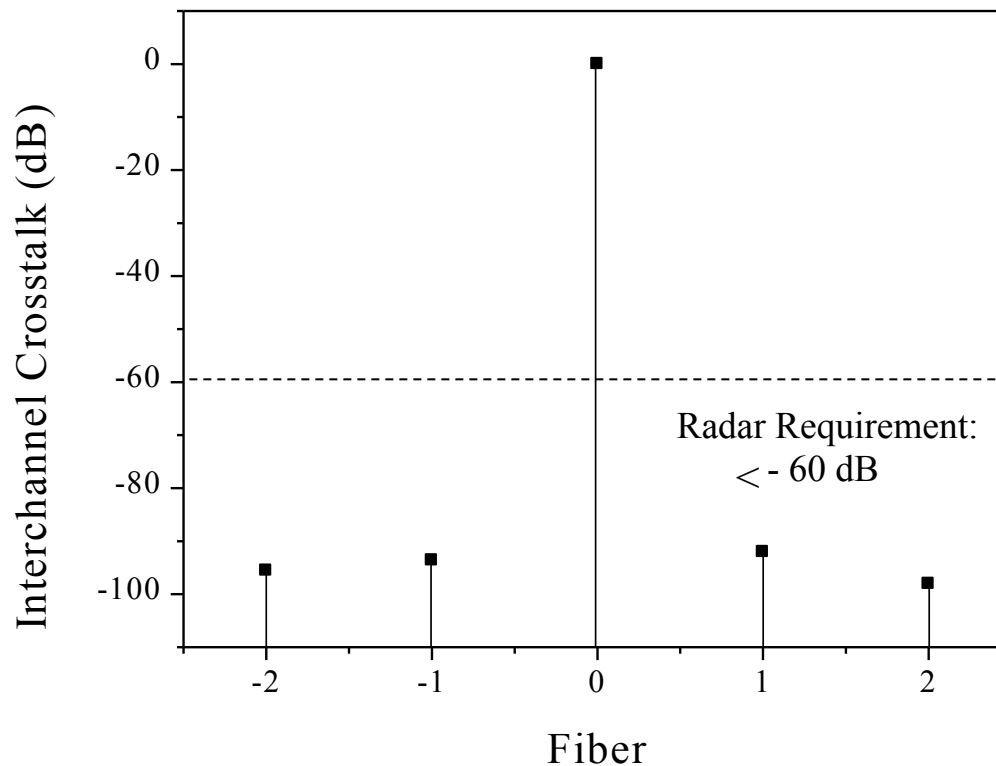


Network Analyzer Measurements



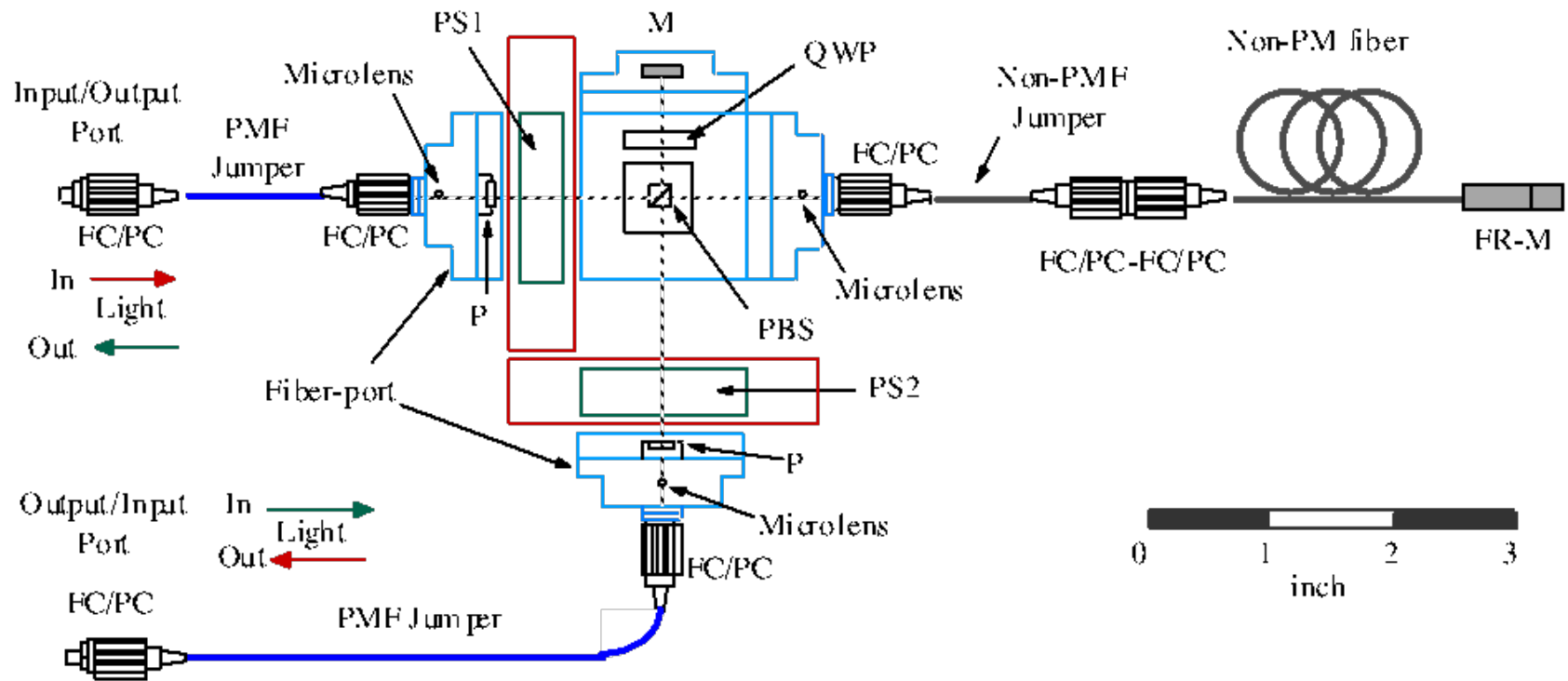
0.8 ns

Interchannel Crosstalk Measurements



$$\text{Interchannel Crosstalk} = 20 \log \frac{\text{Portion of the signal that leaked to the adjacent fiber}}{\text{Portion of the signal coupled at the desired output fiber}}$$

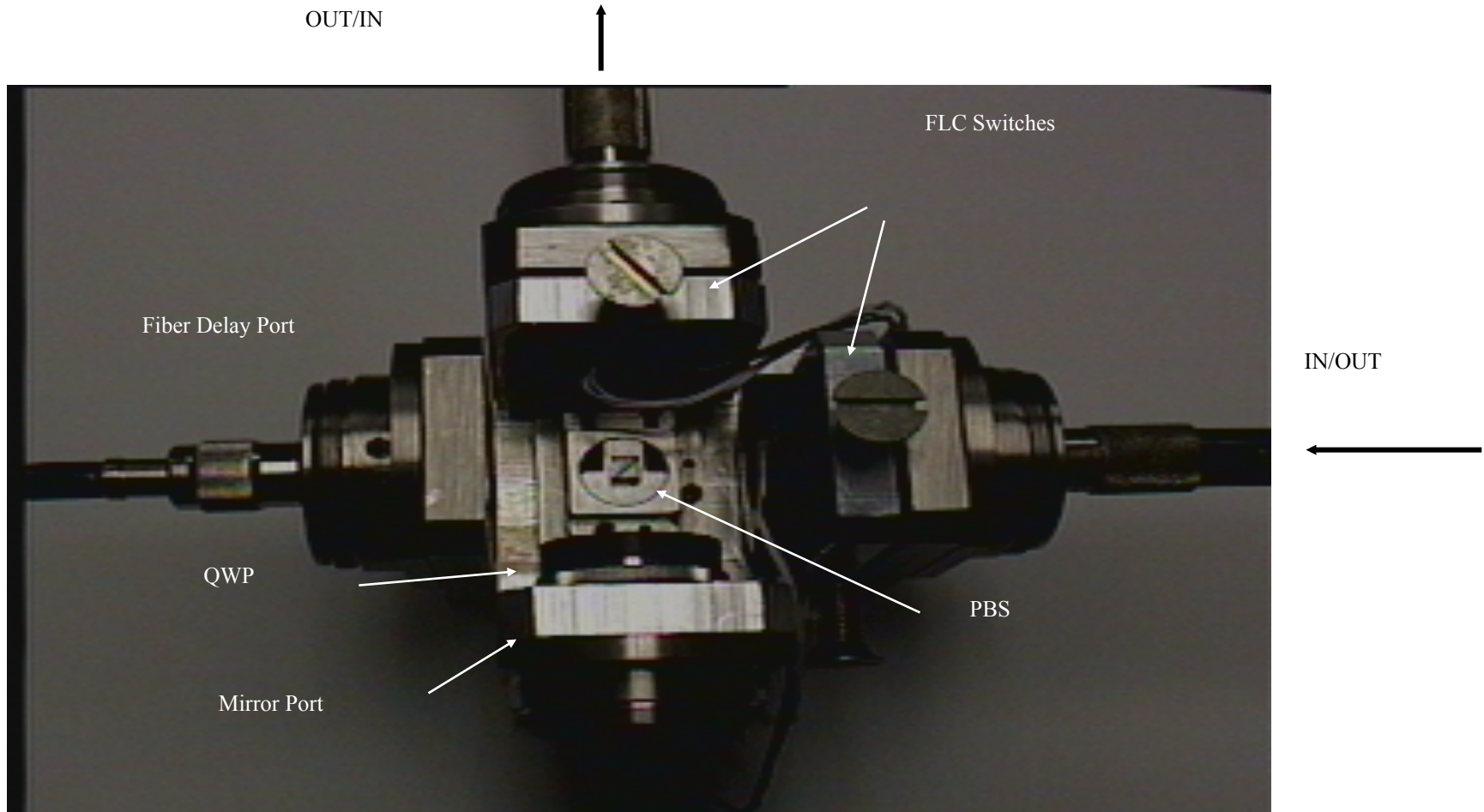
Compact Single Bit LC Polarization Switched (PS) Delay Line



PS: Polarization Switch (in our experiment FLC devices); **P:** Polarizer;

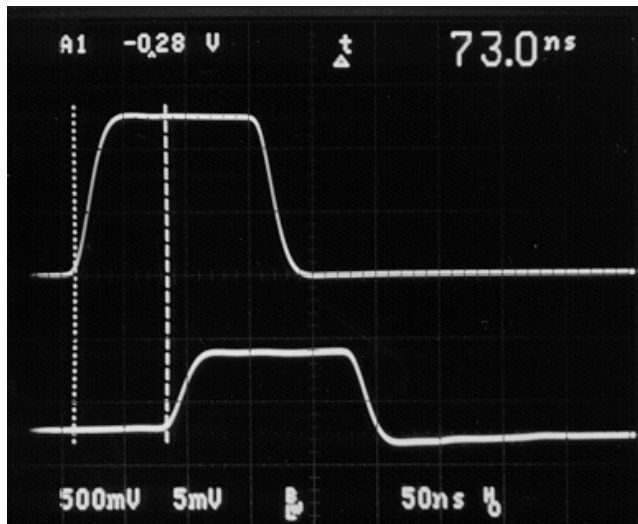
PBS: polarizing beamsplitter cube; **QWP:** quarter wave plate; **M:** mirror, **FR-M:** Faraday Rotator-Mirror

Compact Fiber-Optic Delay Line Module Using LC Polarization Switching

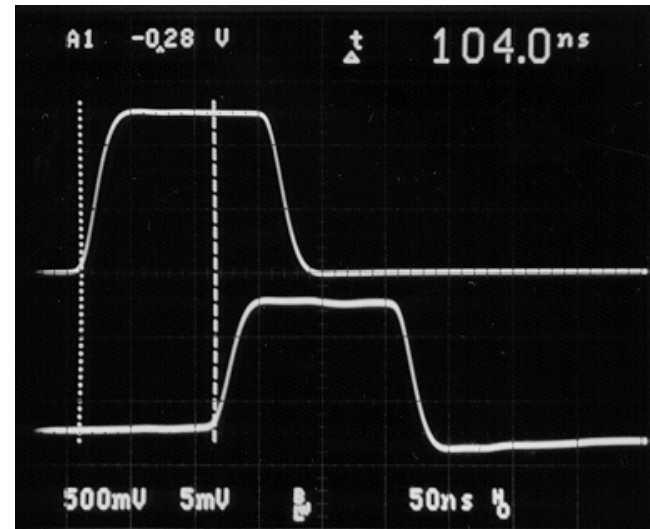


Oscilloscope traces showing:

(a) the non-delayed and (b) the delayed signal



(a)



(b)

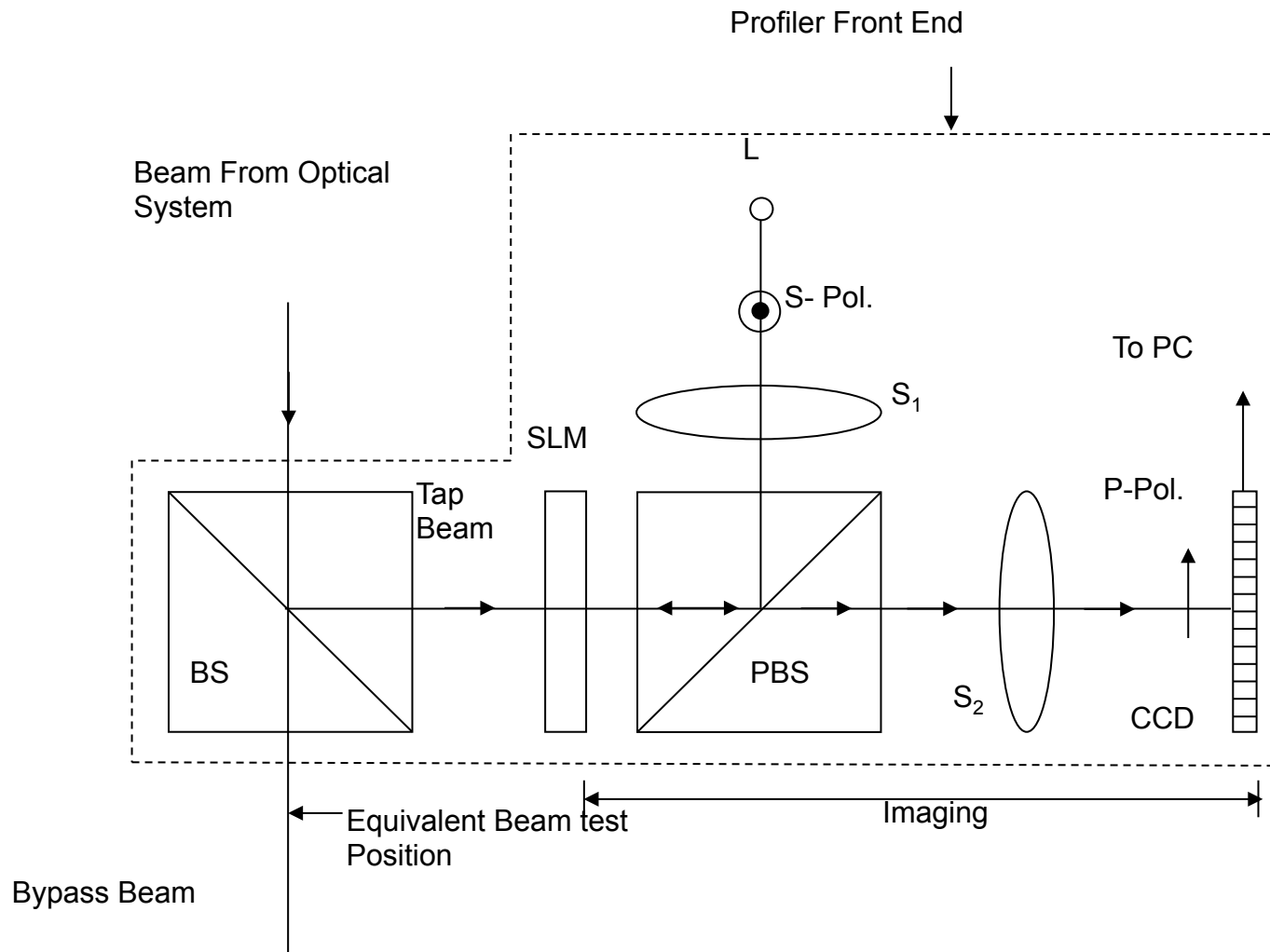
Non-PM fiber is 3.1 m. Since light travels twice through the fiber, it goes through 6.2 m long fiber, with index of refraction of 1.5, the expected time delay is 31 ns.

Top traces: signal driving the semiconductor laser.

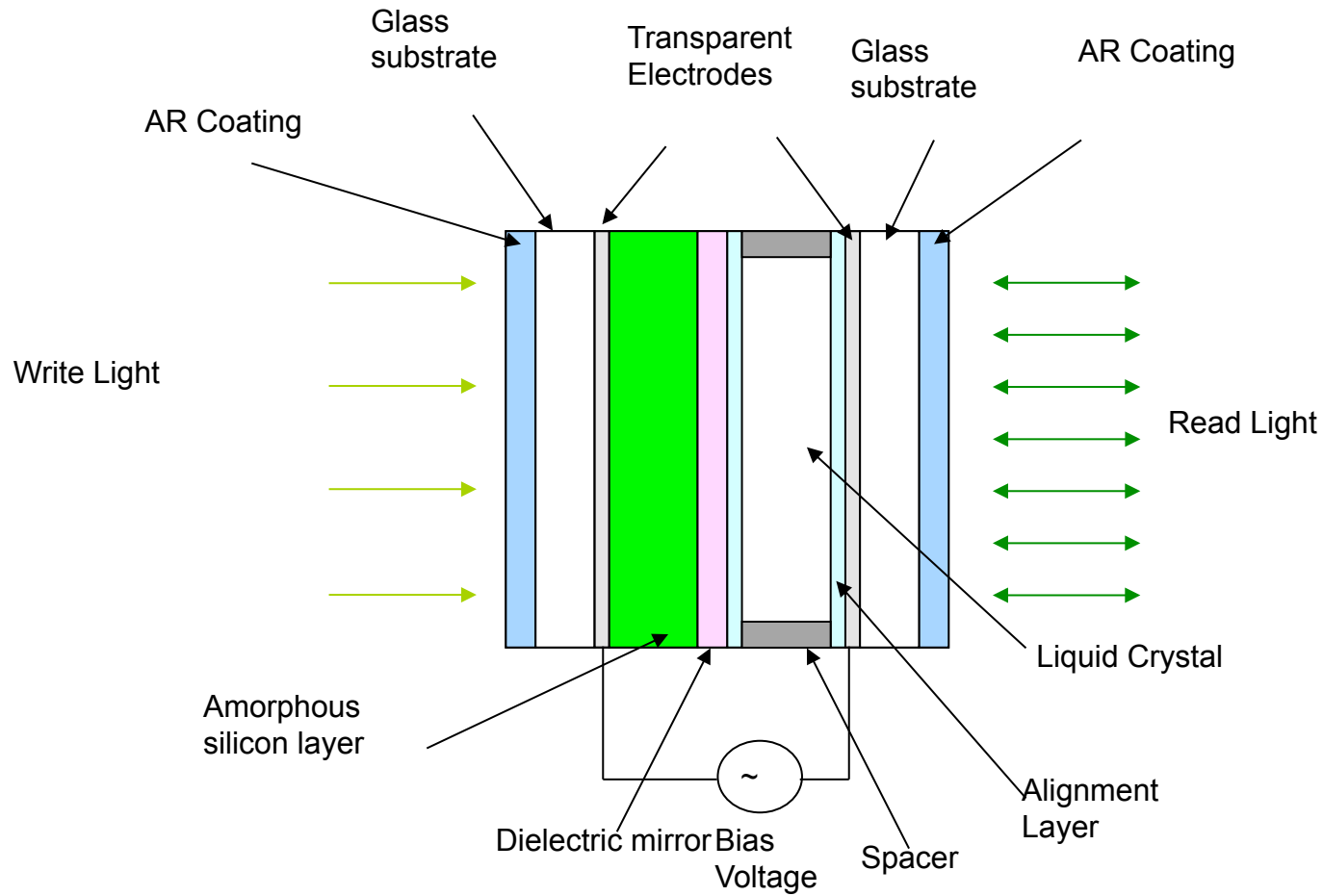
Bottom traces: Photodetected signal at the output of the PDL module.

Liquid Crystal Agile Photonics
for Non-Destructive Testing and Analysis
of Laser Beams

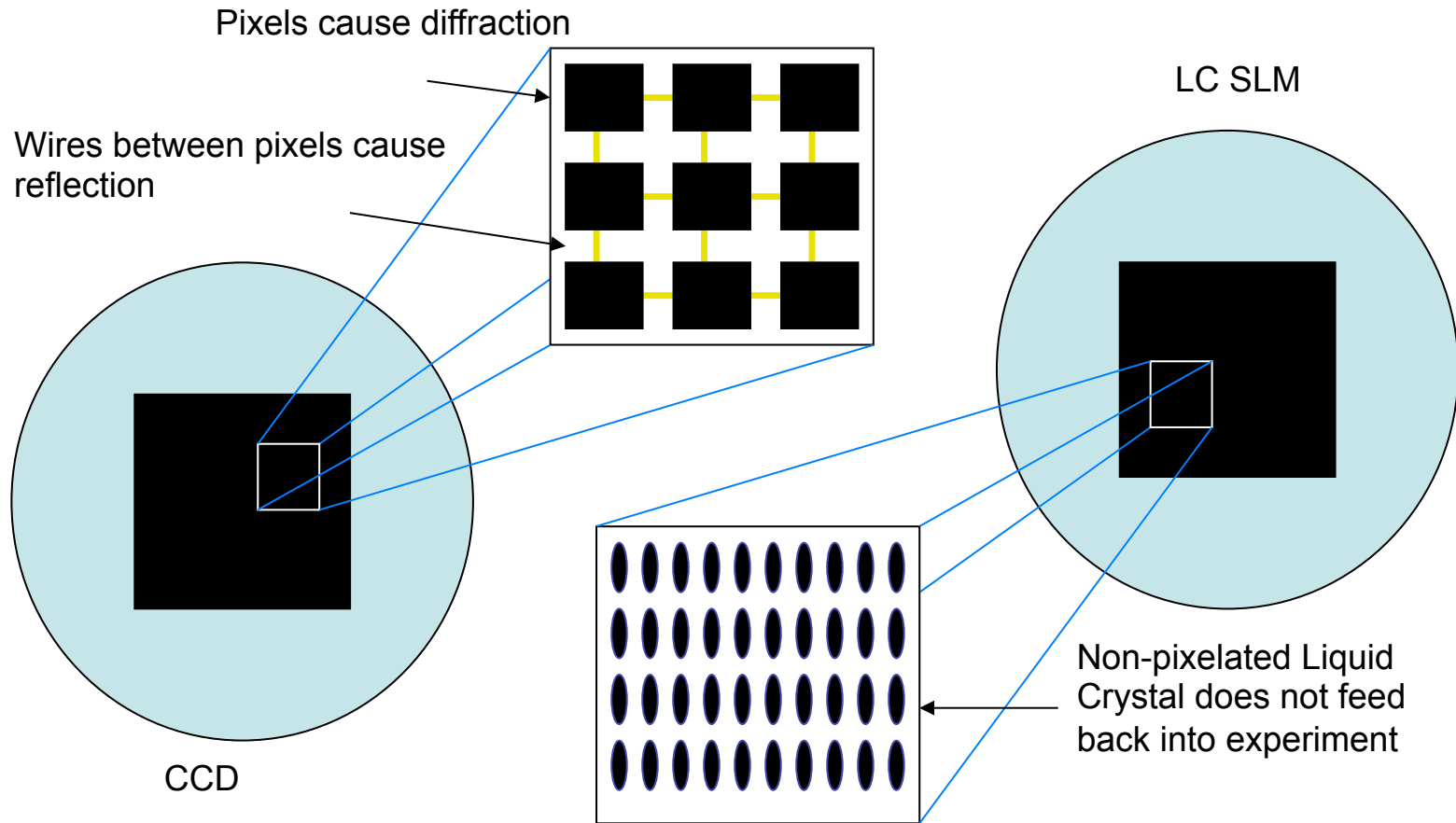
MINIMALLY INVASIVE BEAM PROFILER/IMAGER DESIGN USING AN OPTICALLY ADDRESSED LC SLM



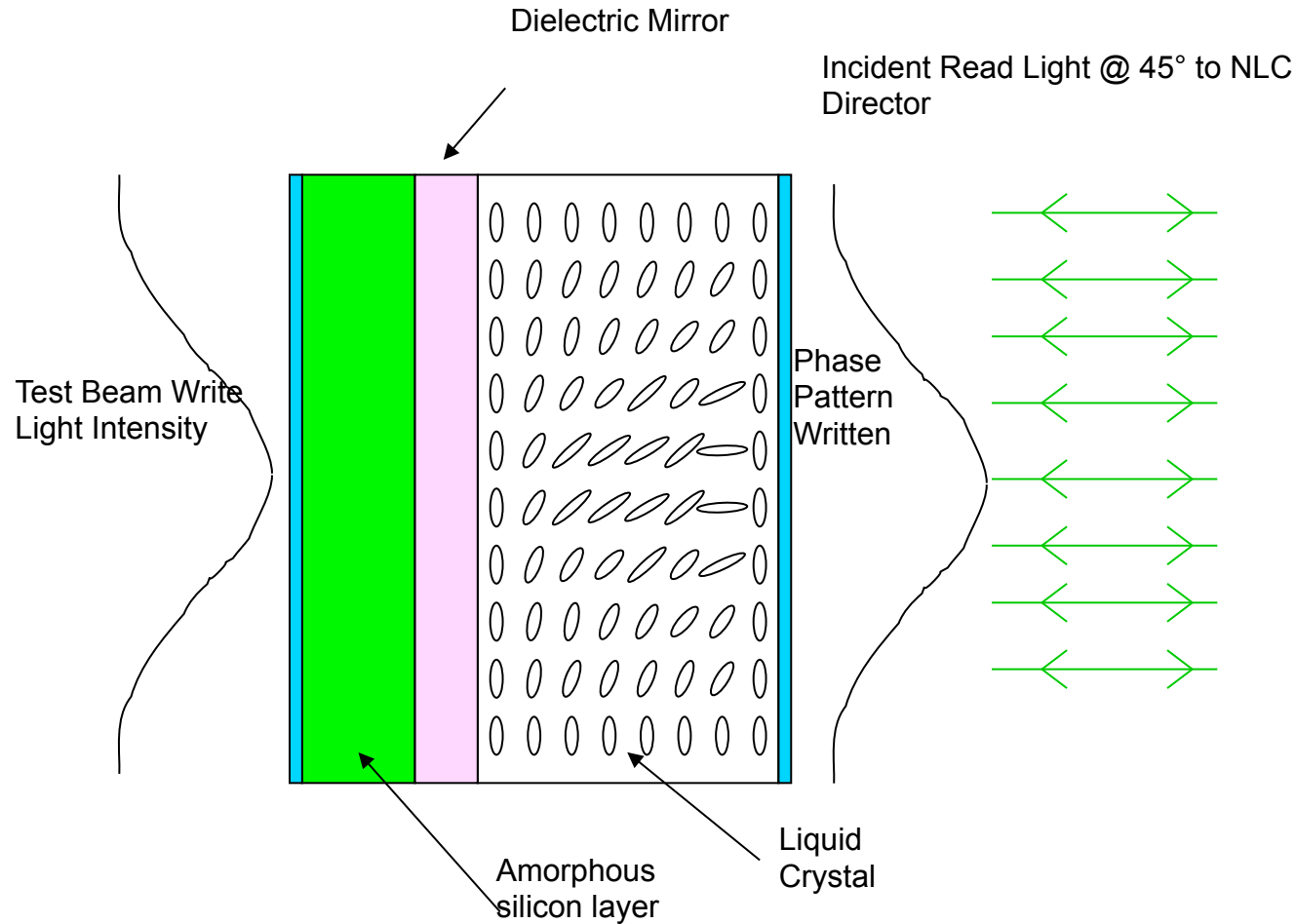
Schematic of the Hamamatsu PAL-SLM



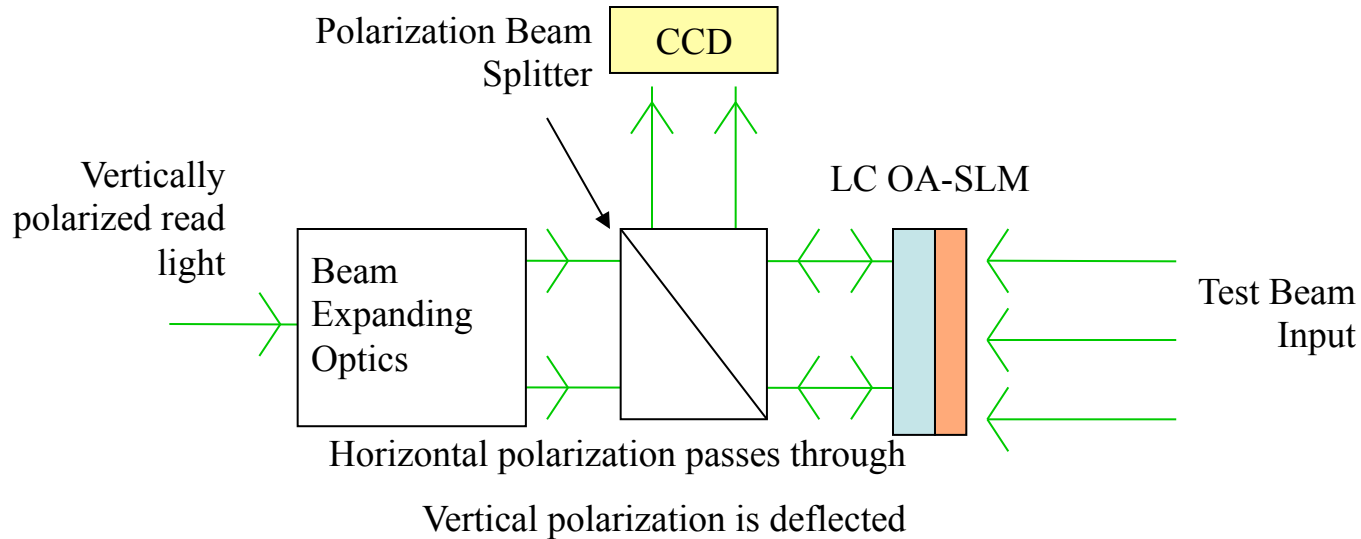
Non-Invasive Beam Profiler/Imager Advantages



Liquid Crystal Operation within the PAL LC-SLM for the Proposed Profiler



Beam Analyzer Operation

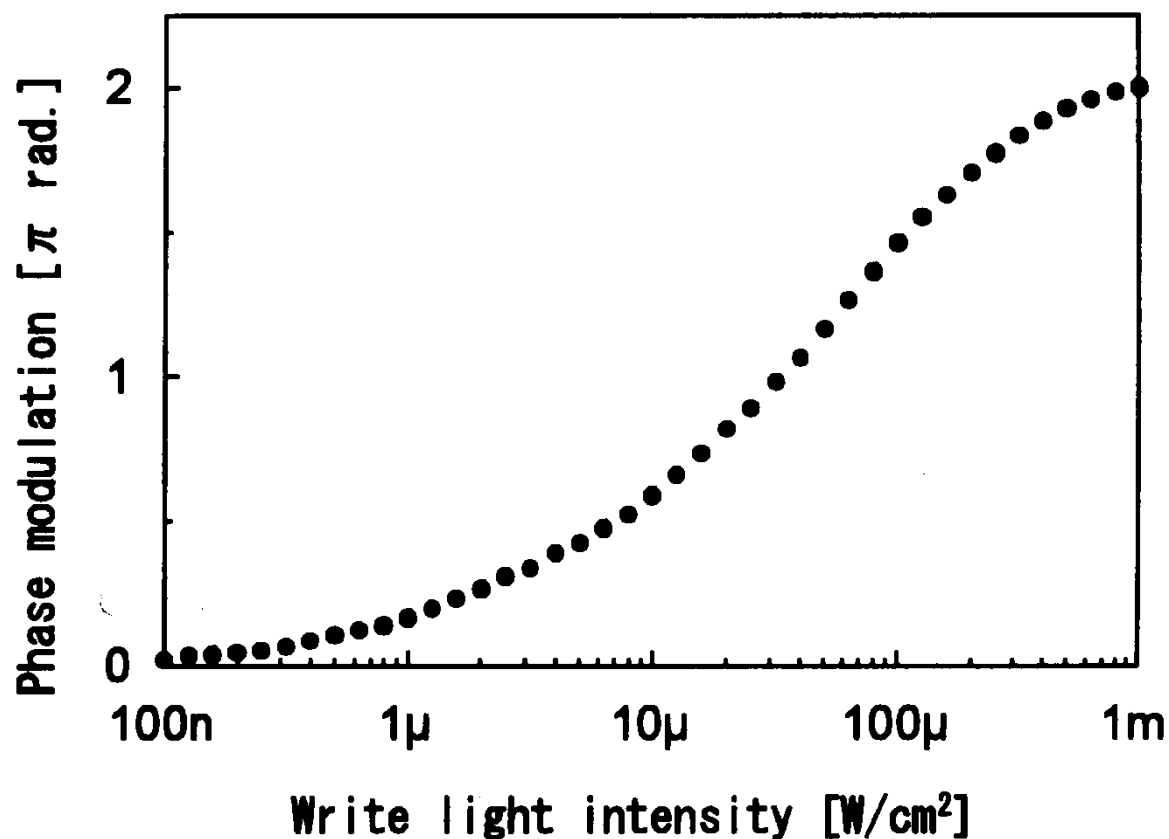


**SLM converts Input Intensity Pattern
into Output Polarization-coded Intensity Pattern**

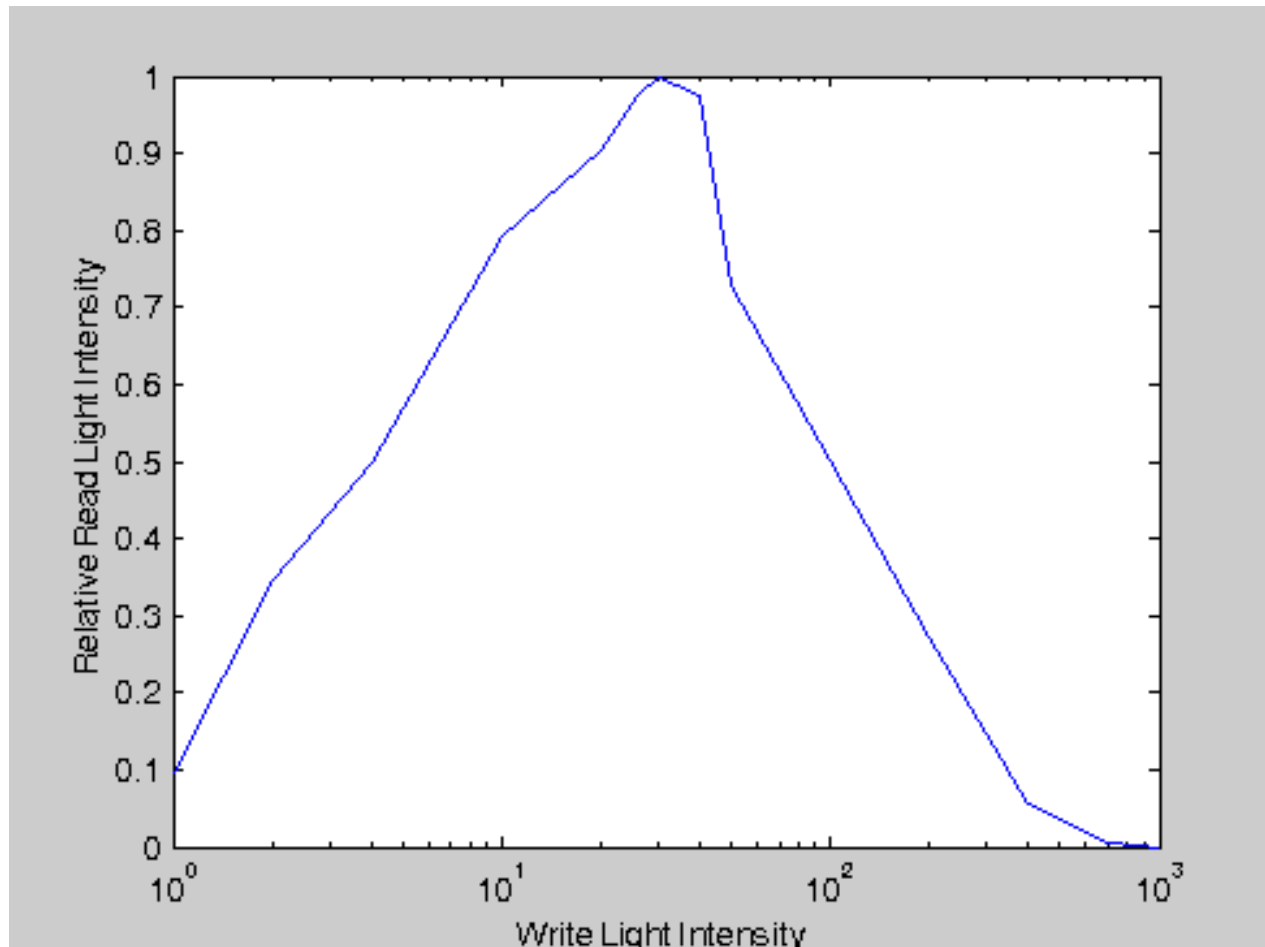
$$I = \frac{A^2}{4} [2 + 2 \cos(\phi)] = A^2 \sin^2\left(\frac{\phi}{2}\right)$$

Output intensity is a function of LC SLM phase

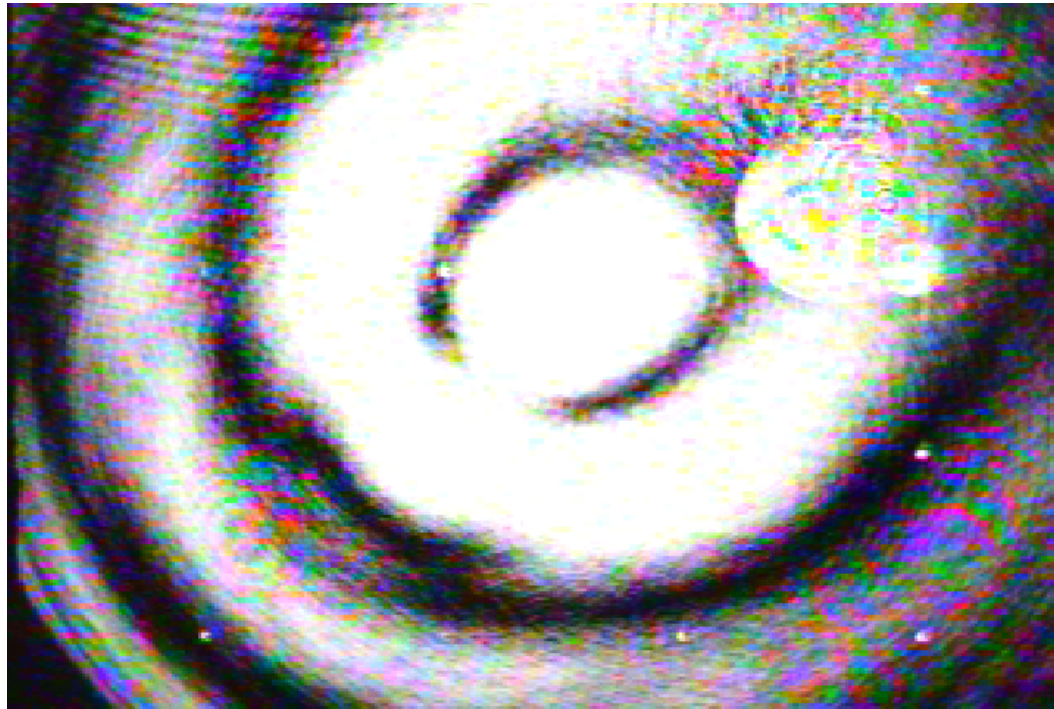
Manufacturer Provided Experimental Phase Response at 633 nm Read Light versus Write Light Intensity for Hamamatsu PAL LC SLM



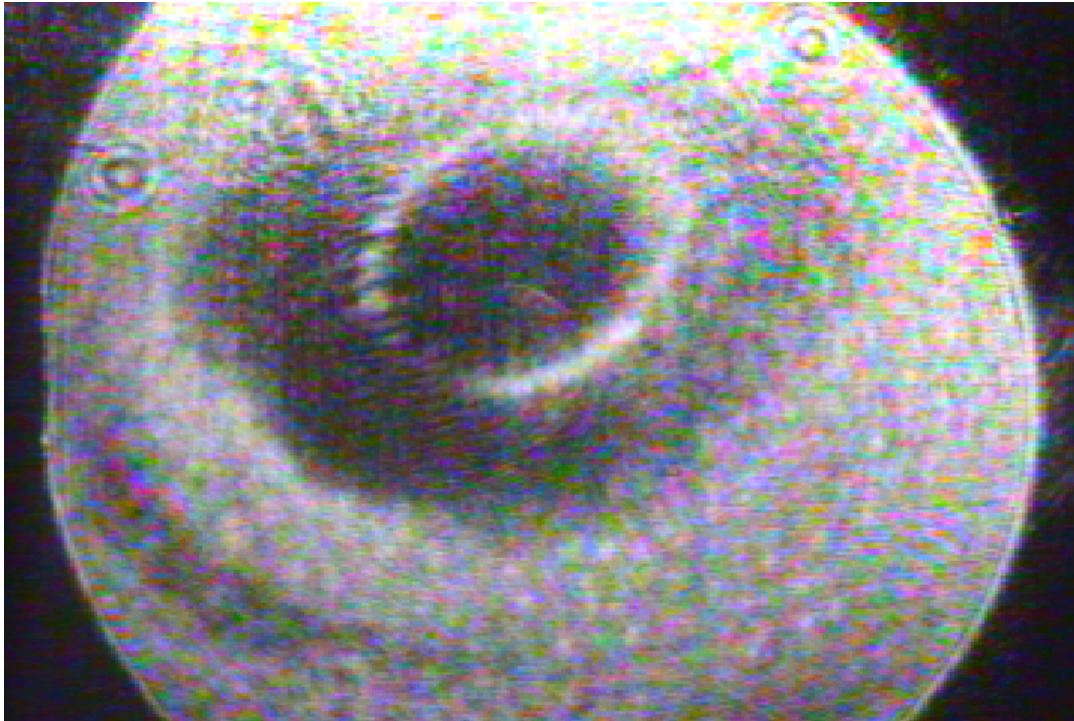
Calculated Logarithmic 633 nm Read Light Relative Intensity vs. Write Light Intensity Plot for the PAL LC SLM. The write light axis units are in $\mu\text{W}/\text{cm}^2$ while the read light axis units are relative units scaled to 1.



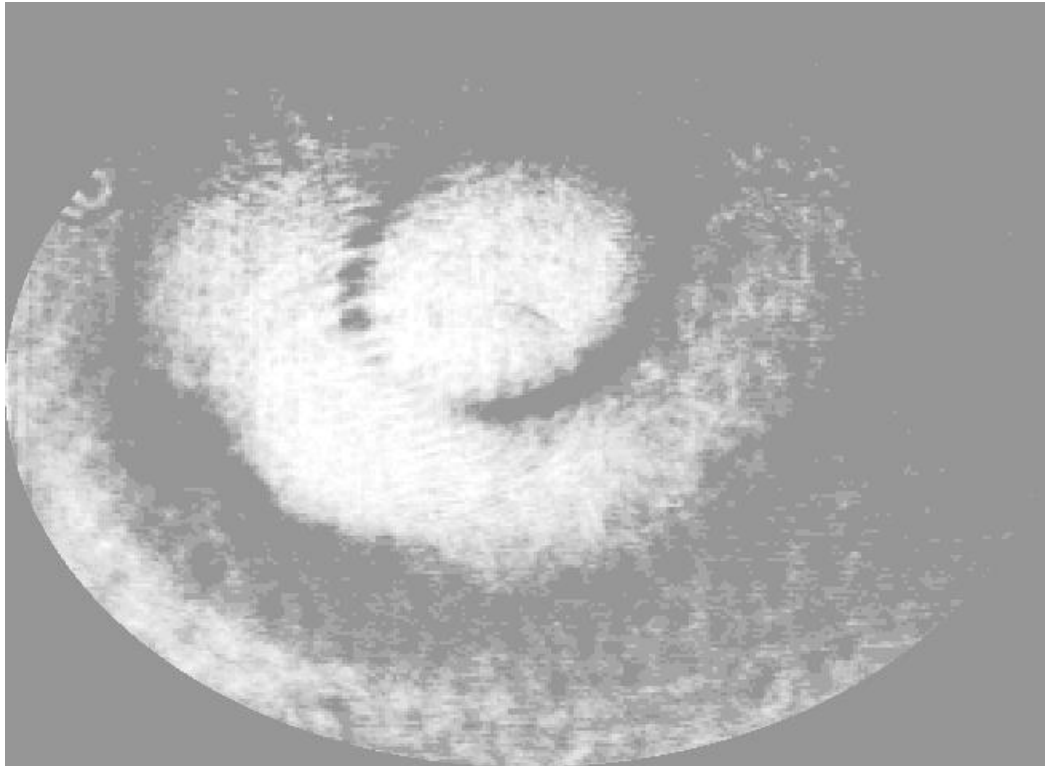
Original Beam Intensity Pattern Measured by a CCD on the Write Side location of the SLM. Due to back-reflections, this image also contains two unwanted smaller versions of the original beam towards the top left corner of the image.



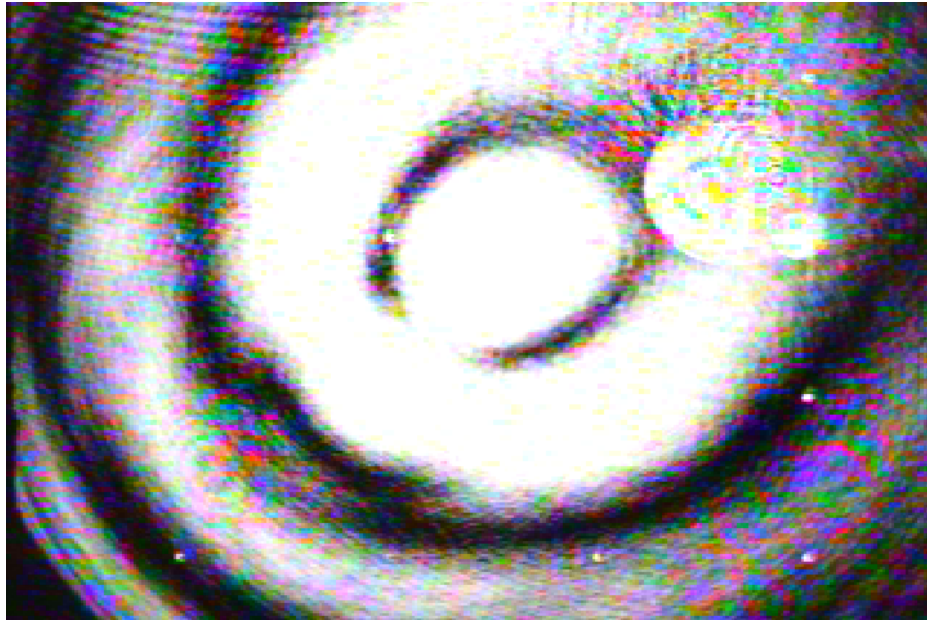
Read Light Direct Image from the Beam Profiler CCD



Experimentally produced and the post-processed power profile image of the test beam generated via the minimally invasive beam profiler instrument



Experimental Results



Original Intensity Pattern via
CCD

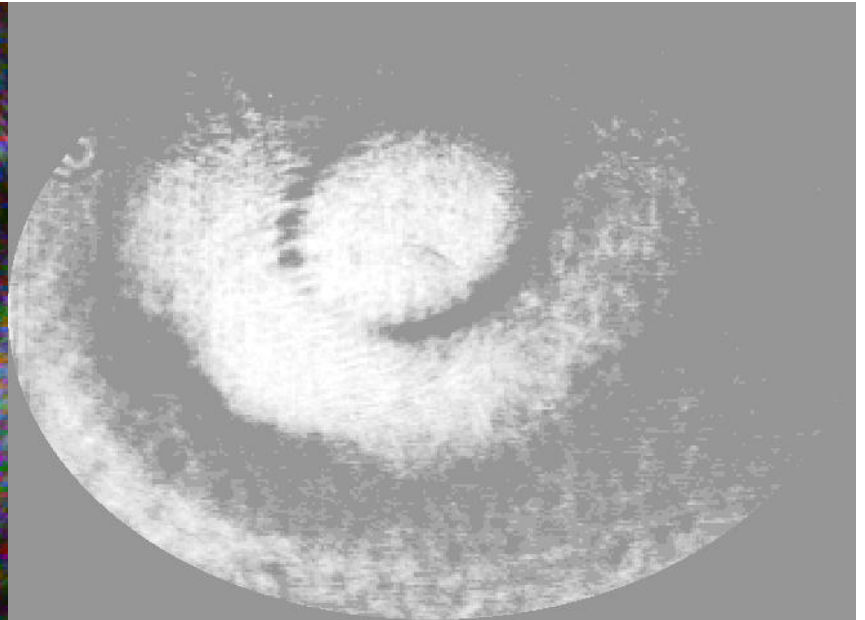
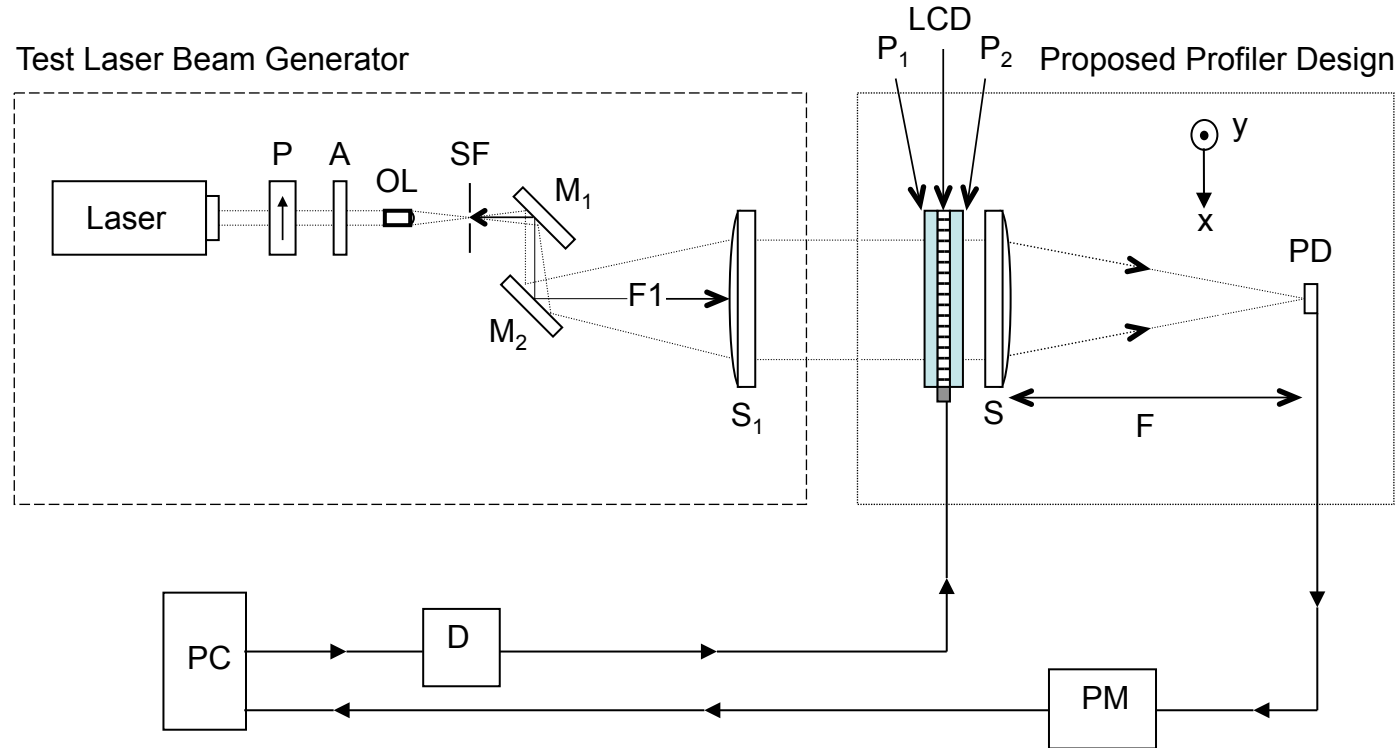


Image Processed Intensity
Pattern via Instrument

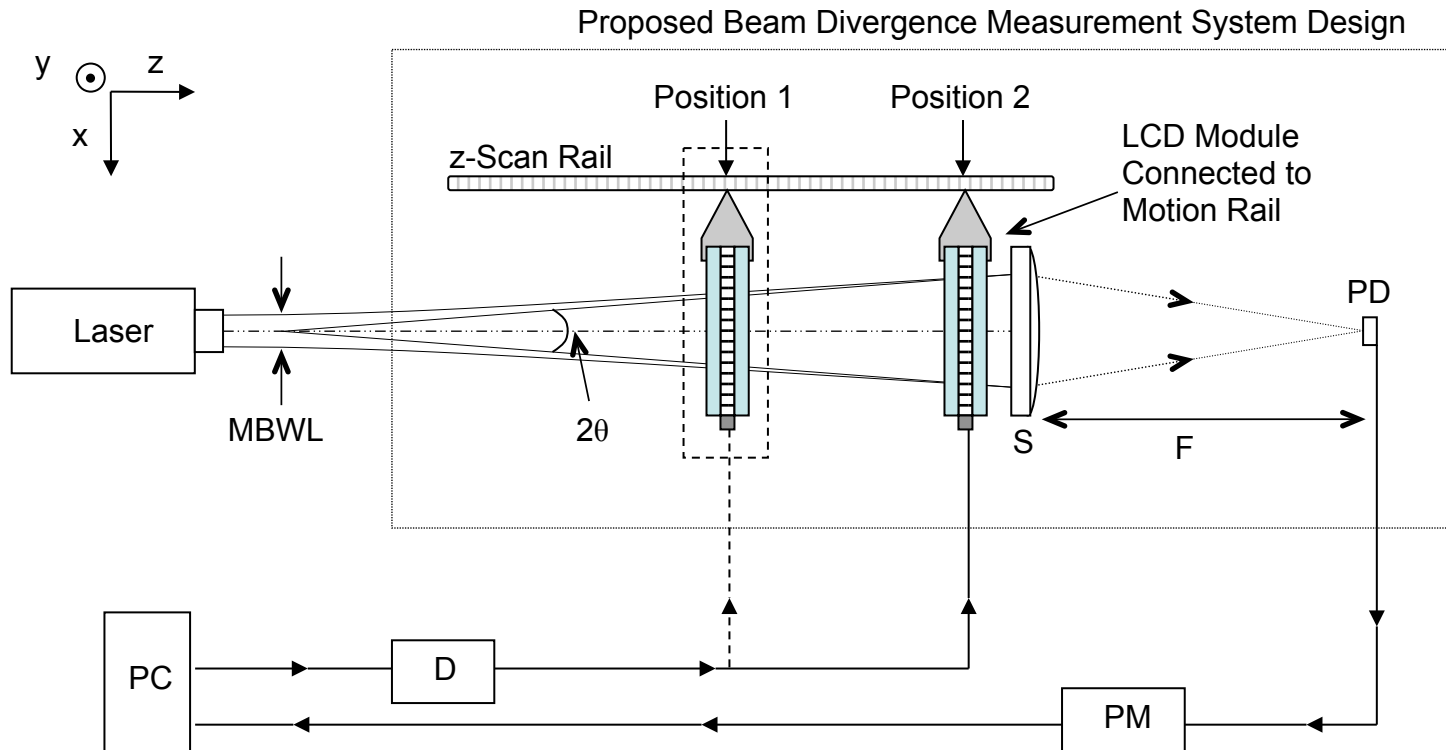
LCD-based No-Moving Parts Beam Profiler/Imager



P: Polarizer; A: Attenuator; OL: Objective Lens; SF: Spatial Filter; M1, M2: Mirrors; S, S1: Lenses; LCD: Liquid Crystal Display Panel; P1, P2: Orthogonal Linear Polarizers; PD: Photodiode; PM: Power Meter; D: LCD Driver; PC: Computer Unit.

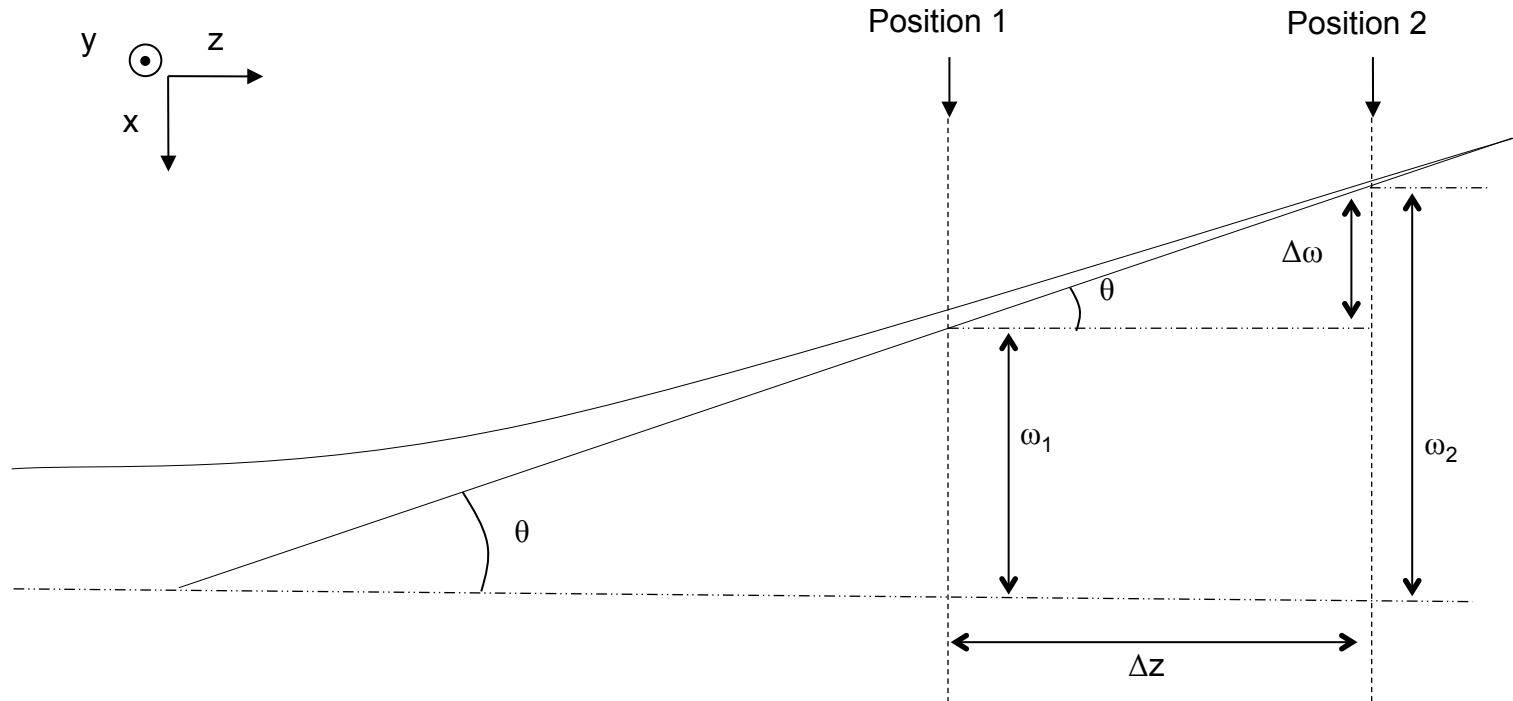
M. Gentili and N. A. Riza, "Wide Aperture No Moving Parts Optical Beam Profiler Using Liquid Crystal Displays," Applied Optics, Vol.46, pp.506-512, 2007.

Beam Divergence Measurement System using the LCD Profiler

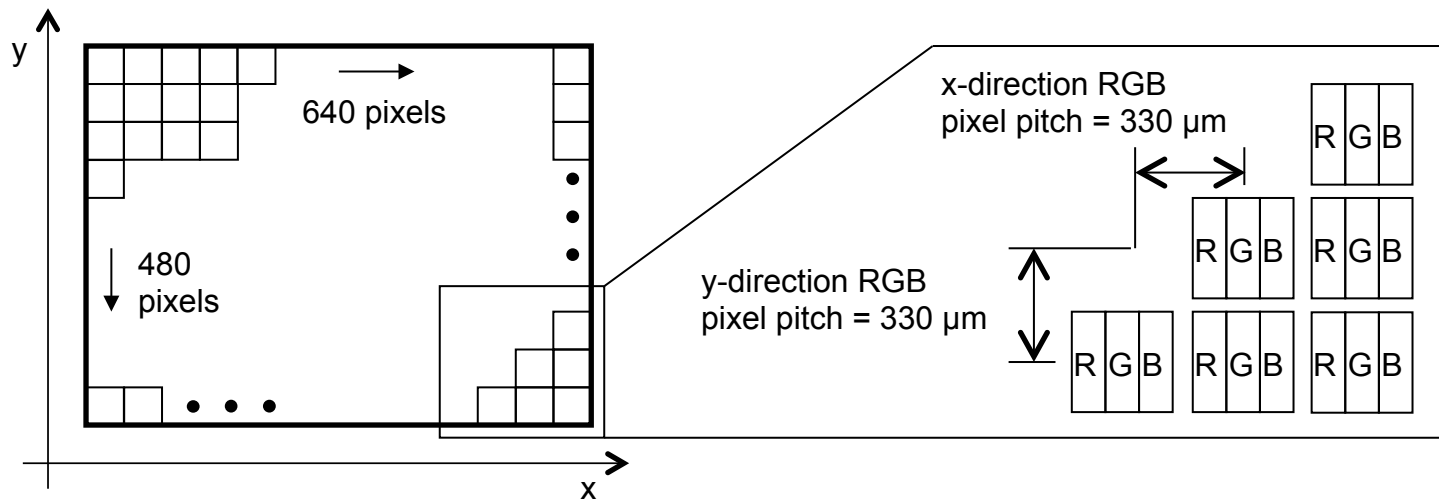
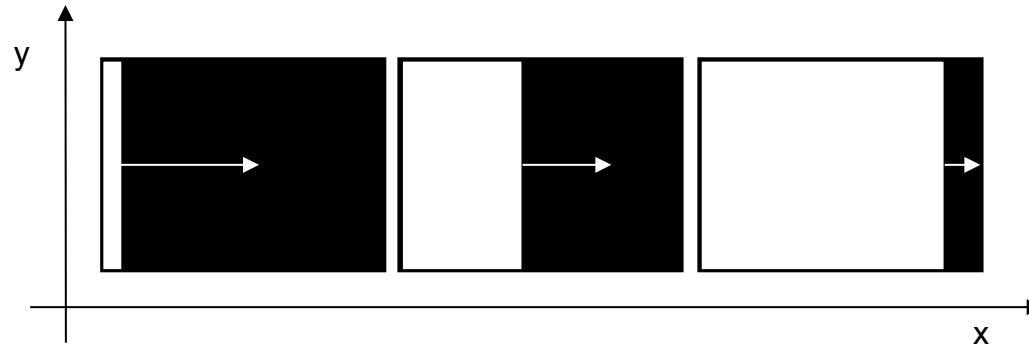


MBWL: Minimum Beam Waist Location.

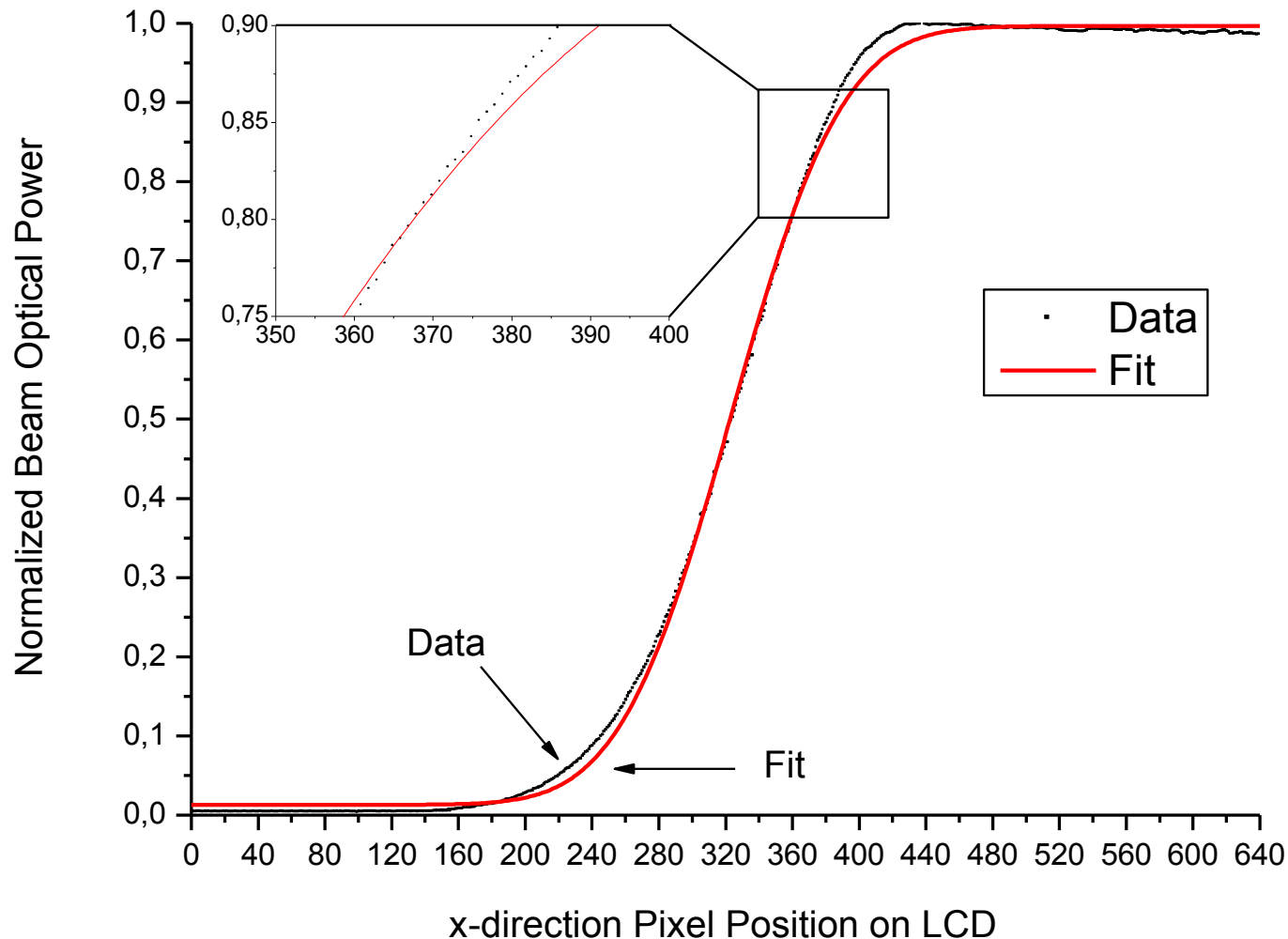
Laser Beam Divergence Angle θ Computation From The Gaussian Beam Waist Differences Along The Optical Axis



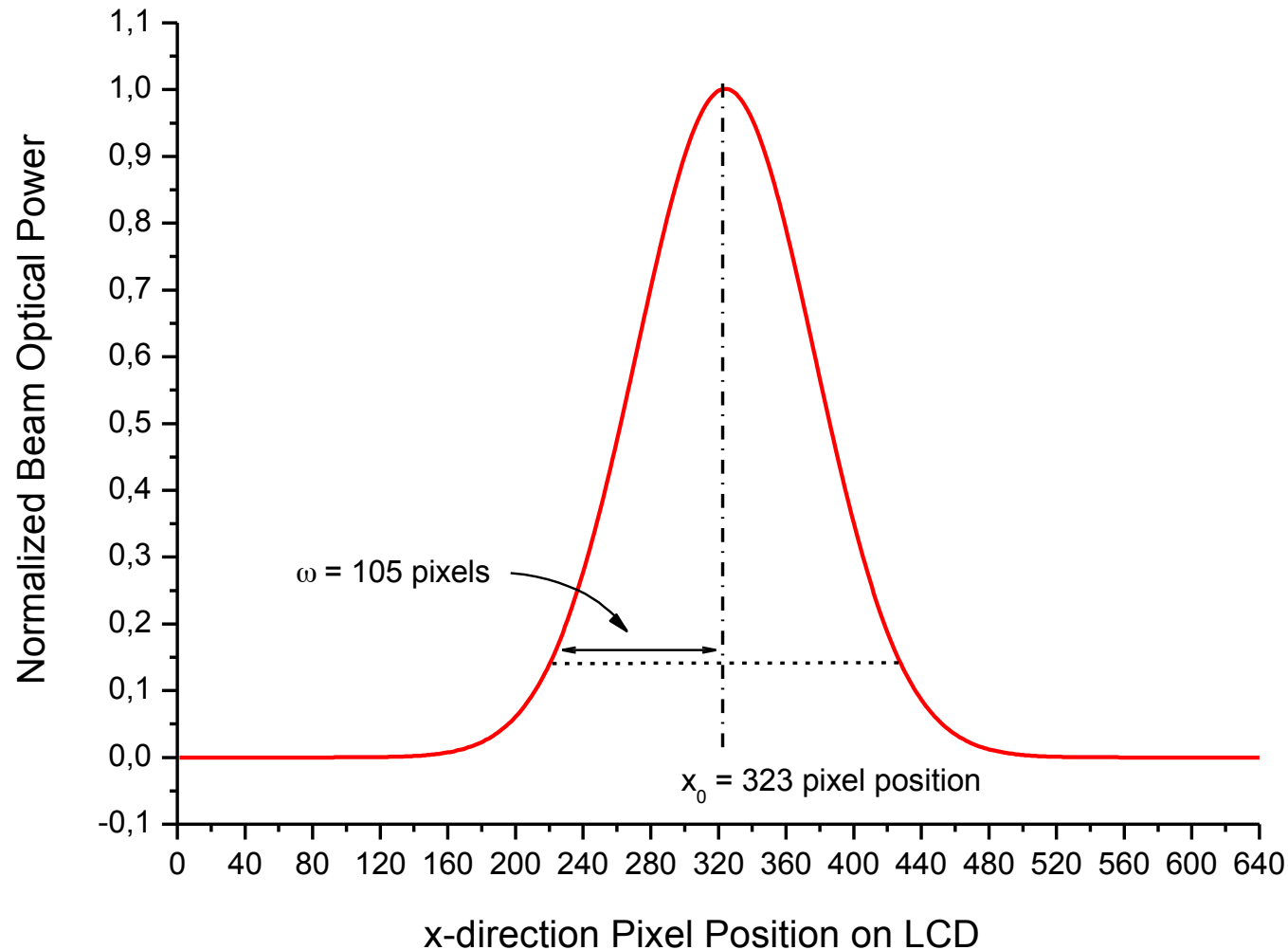
1-D Knife-edge Profiling Implemented Along the x-direction Using the Computer Programmed LCD



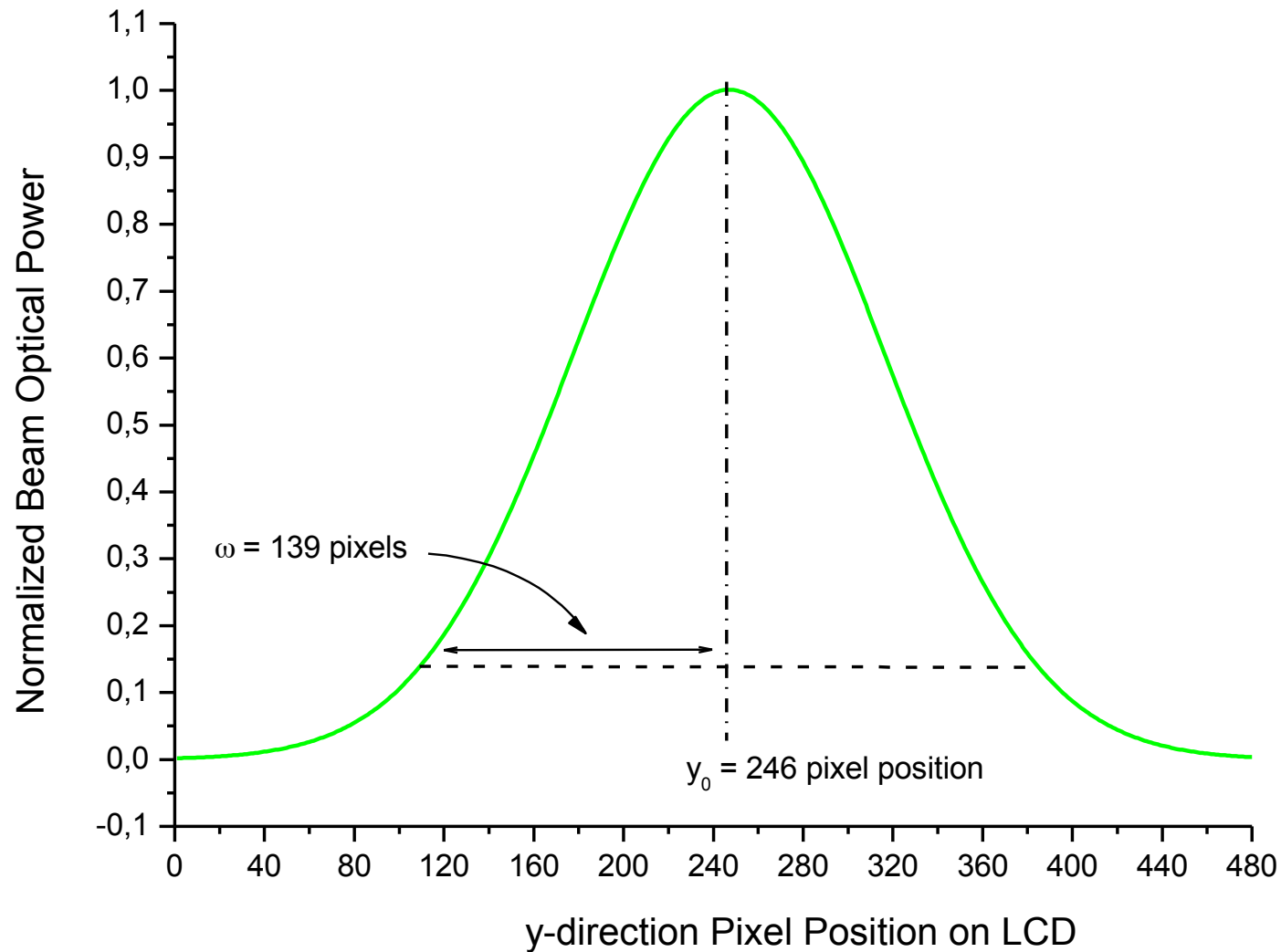
**Data acquired when performing Knife-Edge experiment in the x-direction
(dotted) and using the best fitting error function (line)**



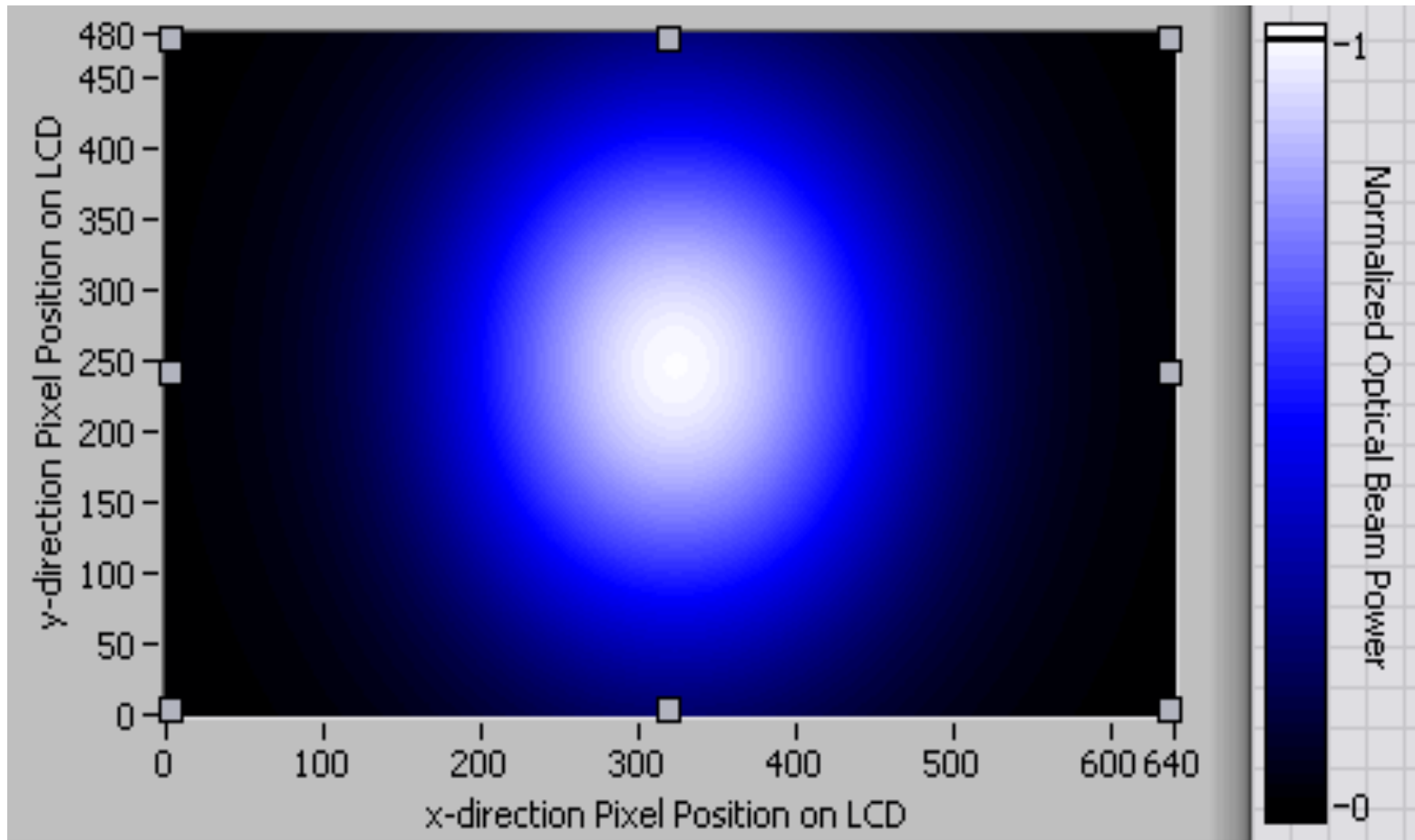
x-direction Gaussian intensity distribution computed using parameters from the best fitting error function from Experiment



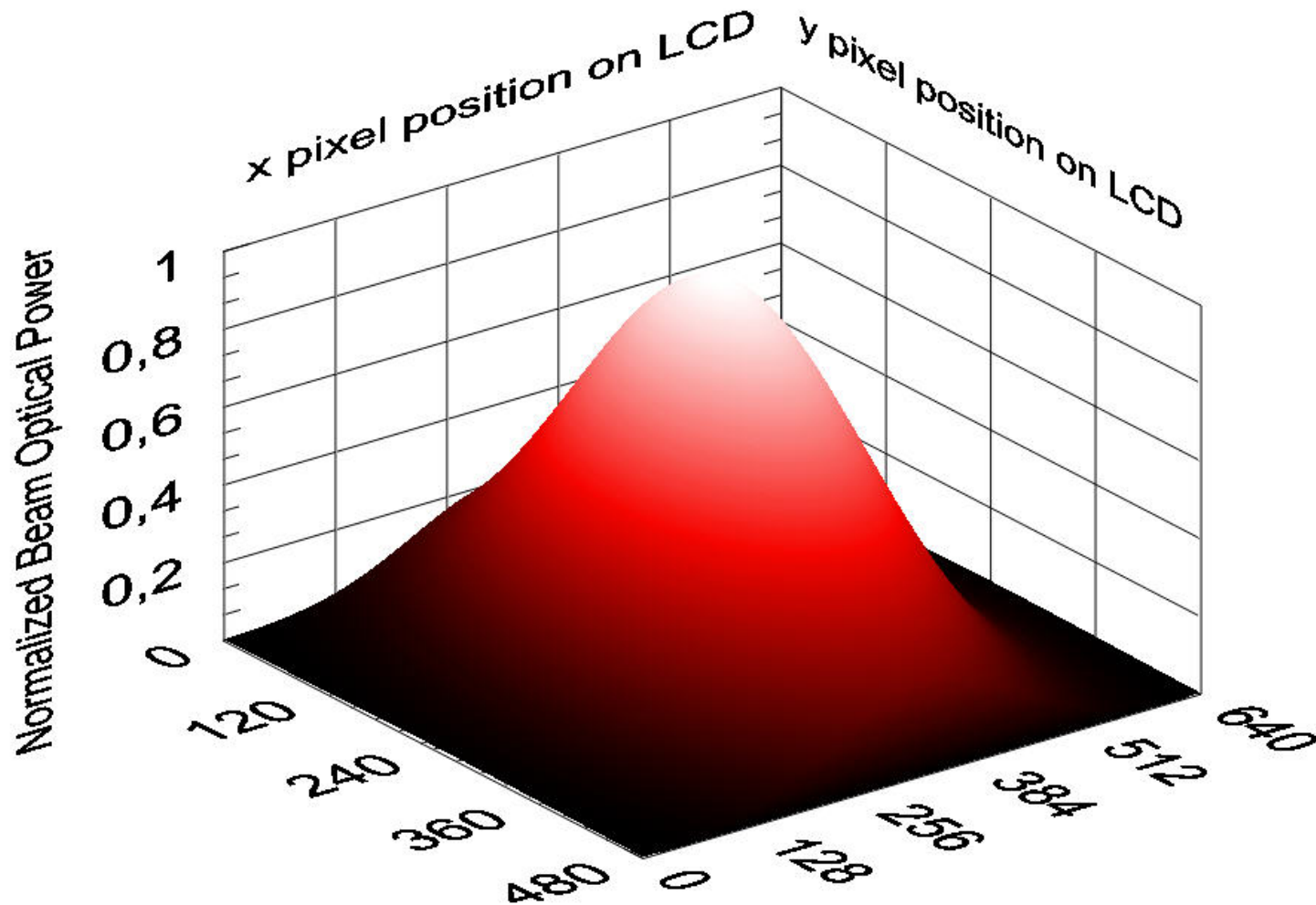
y-direction Gaussian intensity distribution computed using parameters from the best fitting error function from Experiment



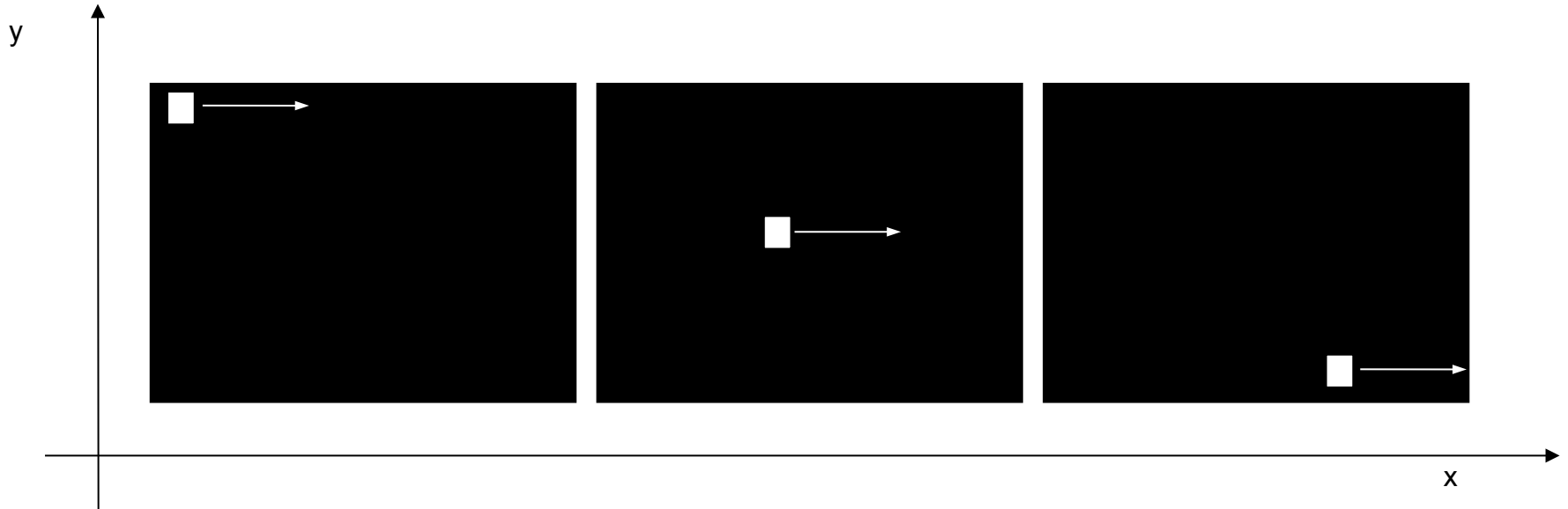
2-D Profile obtained from the x and y-direction 1-D fitted profiles (Gradient View)



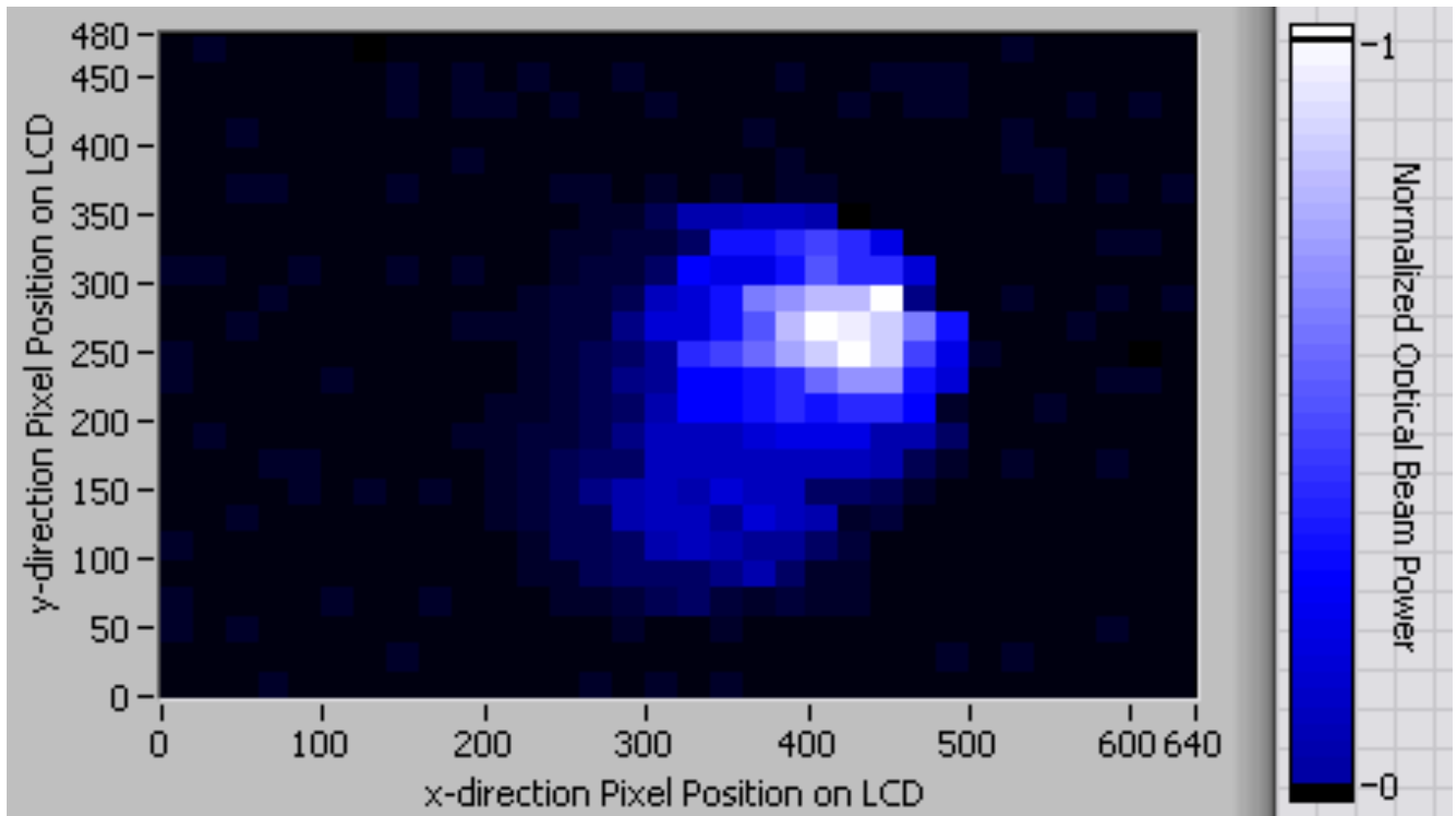
**2-D Profile obtained from the x and y-direction 1-D fitted profiles
– Spatial view**



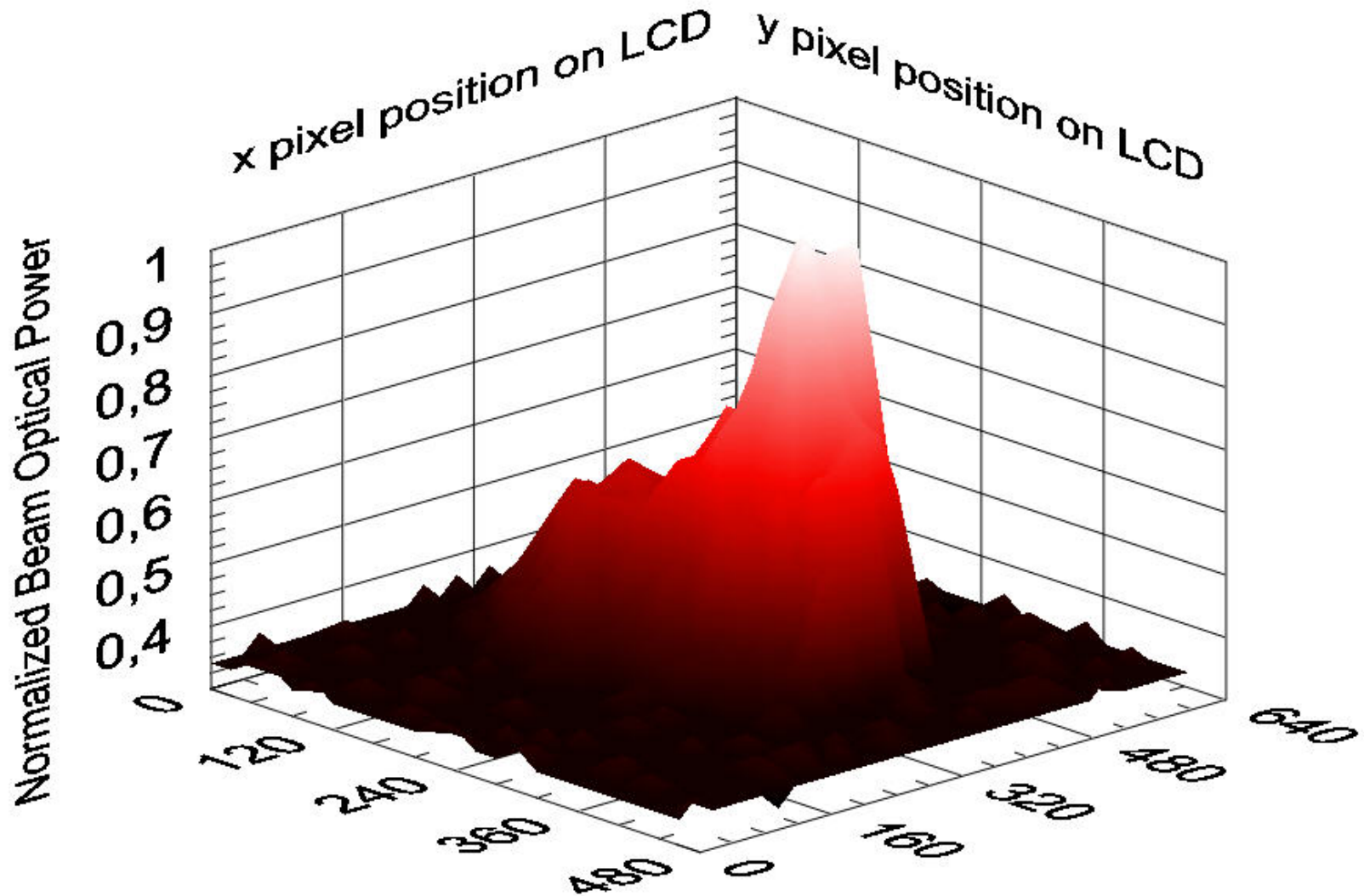
Pin-hole profiling steps using LCD profiler showing three typical LCD images during profiling



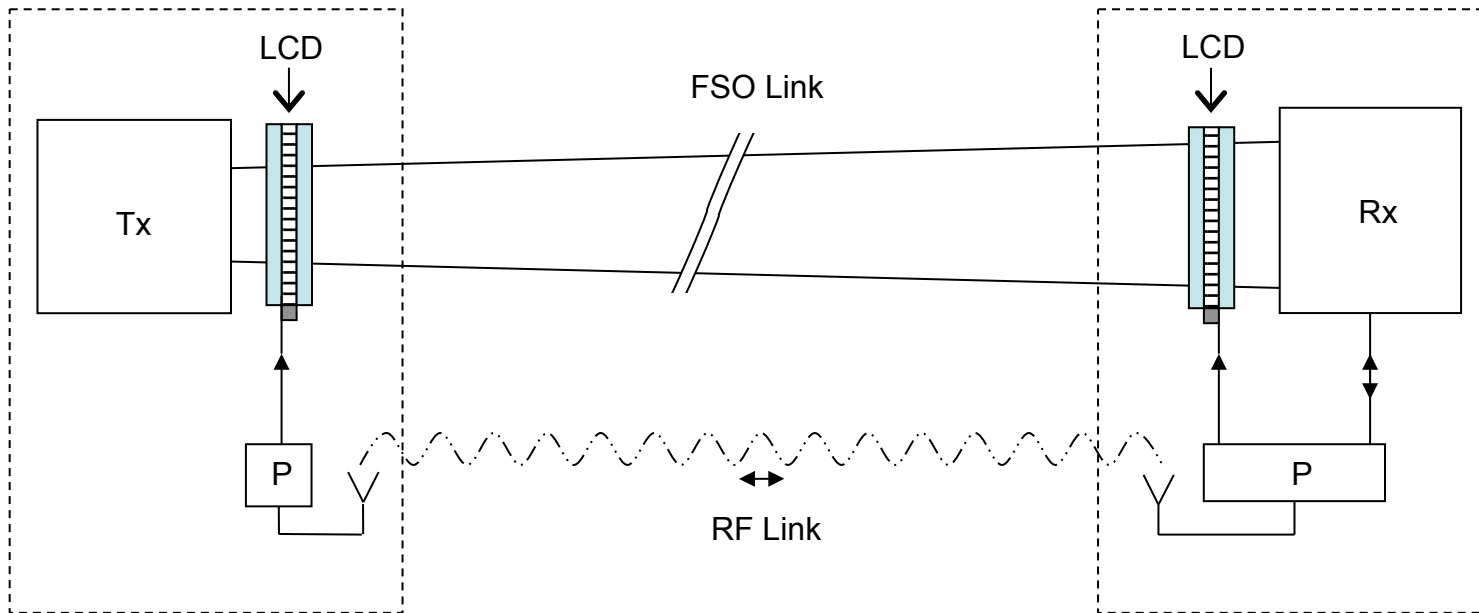
2-D Profile obtained from the Pin-hole experiment – Gradient view



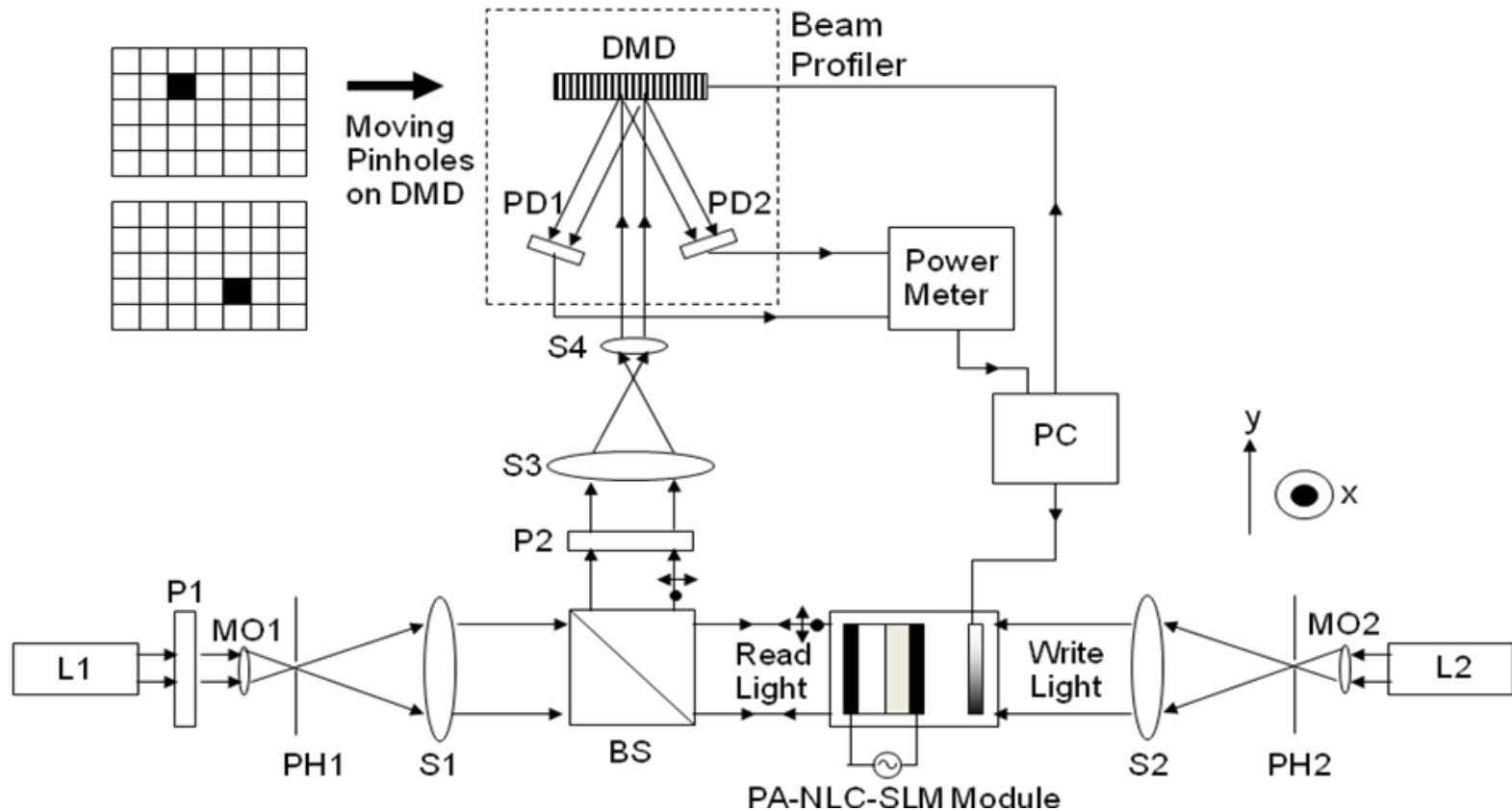
2-D Profile obtained from the Pin-hole experiment – Spatial view



Free-space Optics (FSO) laser communication link using built-in LCD based profilers that enable inherent link beam alignment and divergence measurements. P: processor

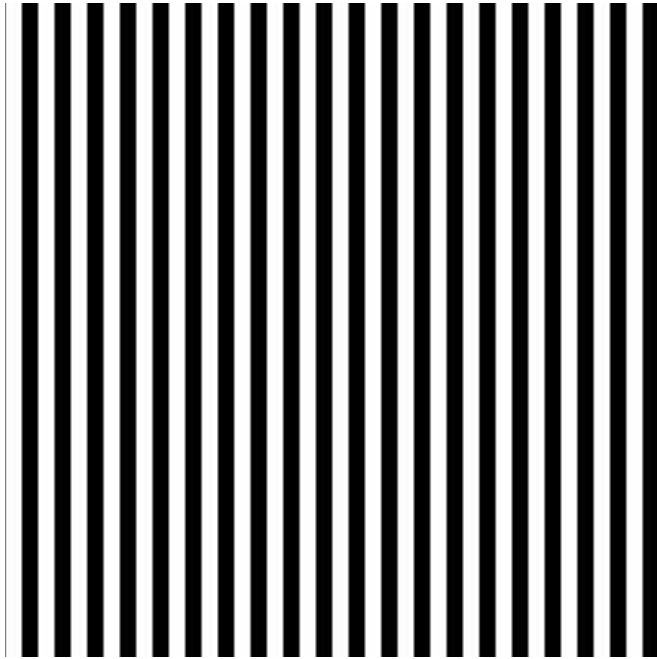


DMD-based Pinhole Laser Beam Imaging System With Liquid Crystal-based Arbitrary Test Beam Generator

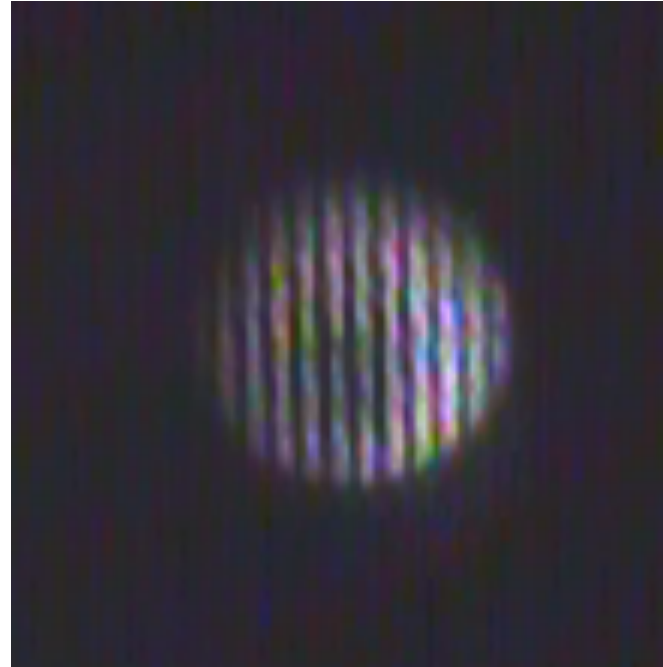


M. Sheikh and N. A. Riza, "Demonstration of Pinhole Laser Beam Profiling using a Digital Micromirror Device," IEEE Photon. Tech. Lett, May 15, 2009.

- (a) 480 x 480 pixels parallel lines pattern loaded onto the PANLC-SLM**
(b) Generated test beam as observed on a CCD camera placed at DMD plane



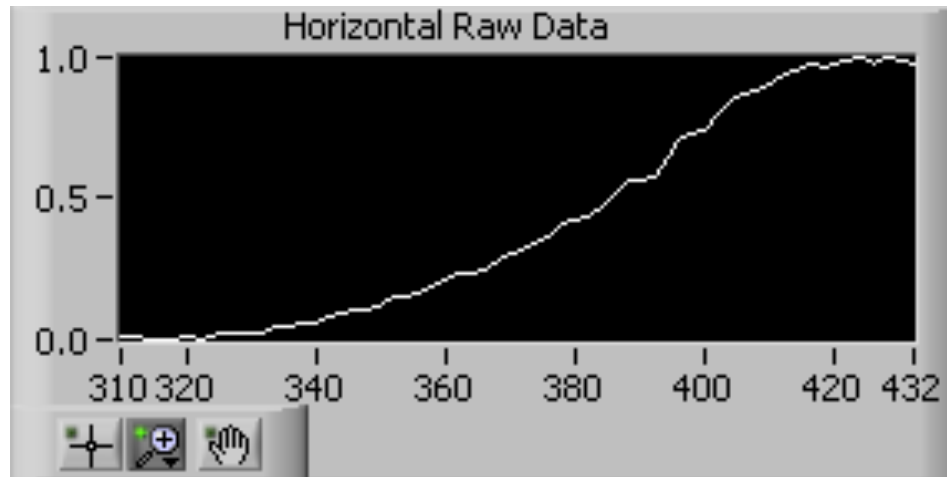
(a)



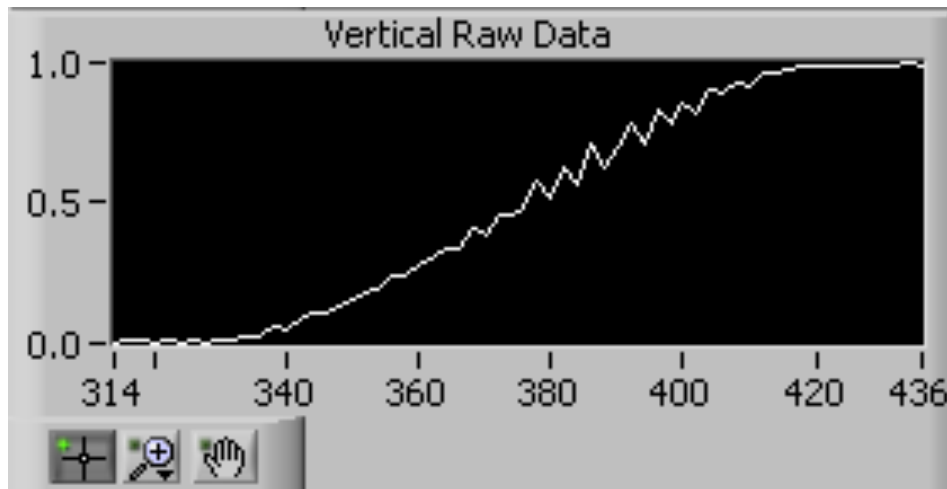
(b)

- (c) Horizontal knife-edge raw data along the test beam
(d) Vertical knife-edge raw data along the test beam

(c)

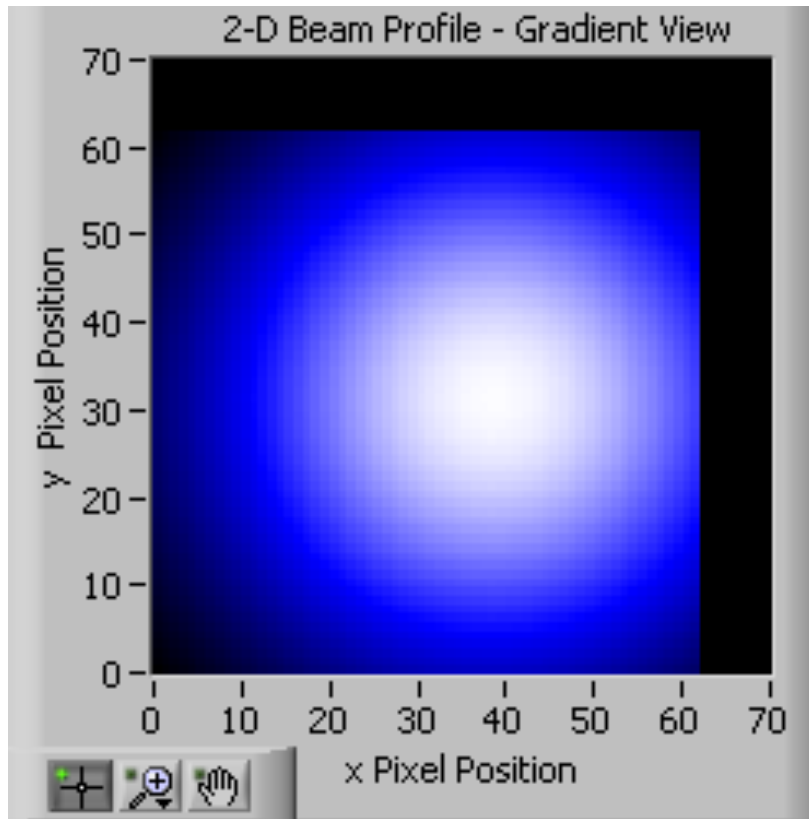


(d)

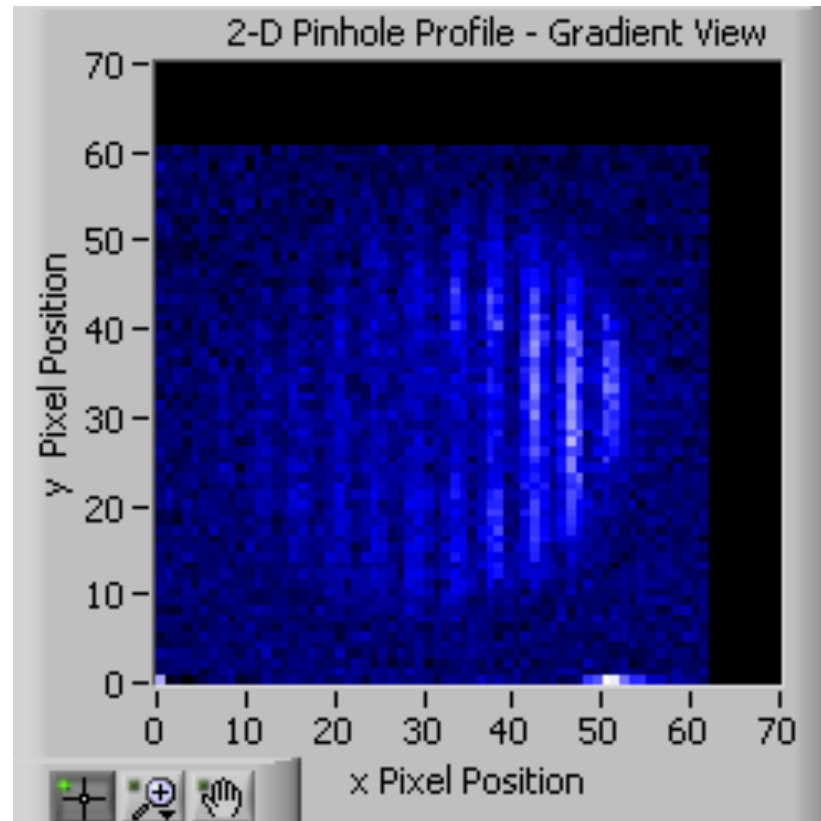


(e) 2-D beam profile obtained using knife-edge profiling

(f) 2-D beam profile obtained using DMD-based pinhole profiling



(e)



(f)

Presentation Conclusion

LC Devices + Free-Space/Solid Optics and/or Fiber-Optics

Powerful Solutions for Both

FreeSpace and Fiber-Optic

Applications

Relevant Prior Art References on LC Optical Switching

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- [2] J. P. Sheridan, J. M. Schnur, and T. G. Giallorenzi, Applied Phys. Lett., 22, 560, 1973.
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R. A. Soref, Applied Optics, 21,8, 1982.
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- [13] R. A. Soref, US Patent 4,948,229, 1990.
- [14] M. R. Meadows, US Patent 5,381,250, 1995.
- [15] N. A. Riza, SPIE Vol.2026, 1993; N. A. Riza, IEEE JLT, 12,8, 1994.
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