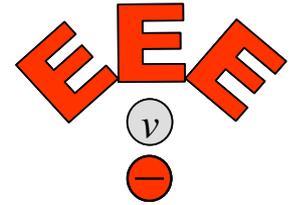




UCC

Coláiste na hOllscoile Corcaigh, Éire  
University College Cork, Ireland



# Wavelength Coded Imaging - A Review

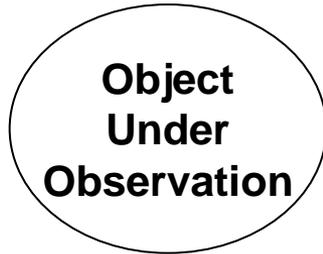
by  
Nabeel A. Riza

School of Engineering  
University College Cork (UCC), Ireland  
Email: [n.riza@ucc.ie](mailto:n.riza@ucc.ie)      <http://soe.ucc.ie>

**Note: The word *Scanner* , Profiler, Sensor and *Imager* are interchangeable.**

# Physical Scales for Wavelength-Coded Optical Imaging

## Example Objects:



**Macro-Scale: Aircrafts, Machine Parts, Human Body**

**Micro-scale: Blood Vessels, Cancer Cells**

**Nano-scale: DNA Structures**

**History of  
Frequency/Wavelength Coded  
Scanning/Imaging**

# 1964: Frequency Steered Microwave Radiation/ Radar

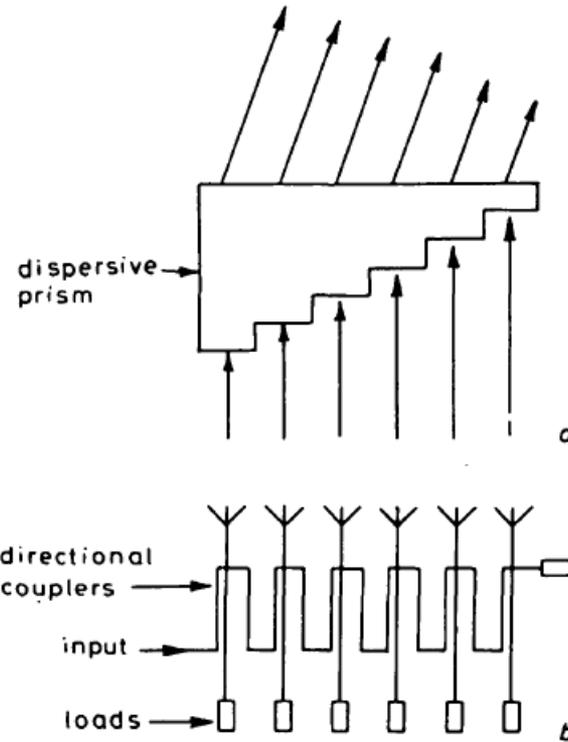


Fig. 22  
*Frequency-scanning configurations*

a Parallel-fed  
b Series-fed

- M. F. Radford, "Frequency scanning aeriels," *Electronic Engineering*, Vol 36, pp.222-226, April 1964.
- \* M. F. Radford, "Electronically scanned antenna systems," in *Proceedings of the Institution of Electrical Engineers (IEE)*, IEE Reviews, IET Digital Library, Vol. 125, No. 11R, pp. 1100-1112, Nov. 1978.
- I. W. Hammer, *Frequency scanned arrays*, Chapter 1 of *Radar Handbook*, M. I. Skolnik Editor, McGraw Hill, NY, 1970.

\* Figure Source

# 1971: Wavelength (i.e., Frequency) Steered Optical Radiation/Laser Radar

**United States Patent**

[11] **3,612,659**

[72] Inventor **Robert L. Forward**  
**Oxnard, Calif.**  
[21] Appl. No. **831,533**  
[22] Filed **June 9, 1969**  
[45] Patented **Oct. 12, 1971**  
[73] Assignee **Hughes Aircraft Company**  
**Culver City, Calif.**

## FOREIGN PATENTS

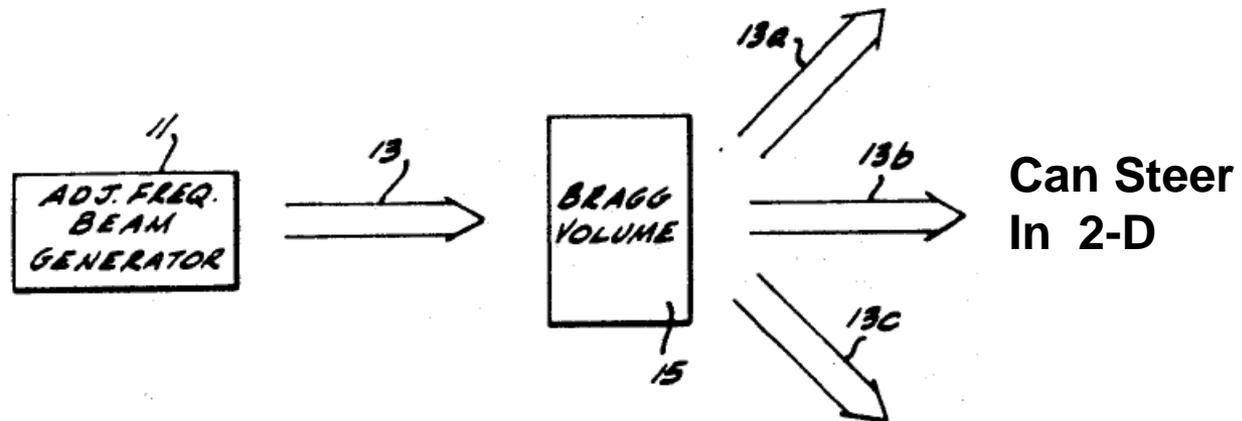
1,088,838 10/1967 Great Britain..... 350/162

## OTHER REFERENCES

Hoffman " Optical Information Storage in Three-Dimensional Media Using the Lippman Technique" Applied Optics Vol. 7, No. 10, Oct. 1968, pp. 1949- 1954. 350- 162.

Primary Examiner—John K. Corbin

Attorneys—James K. Haskell and Richard J. Rengel



- R. L. Forward, Passive Beam Deflecting Apparatus, US Patent 3612659, 1971.

# 1978: Wavelength coding used for Incoherent 1-D Optical Image (1-D Bar Code) Transmission via Single Fiber

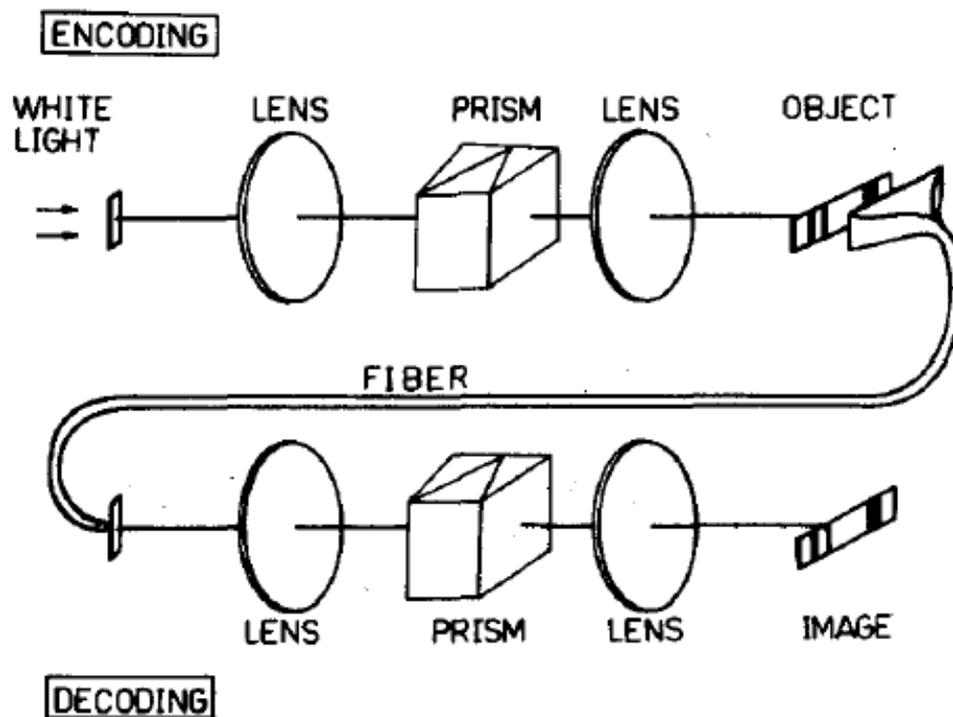
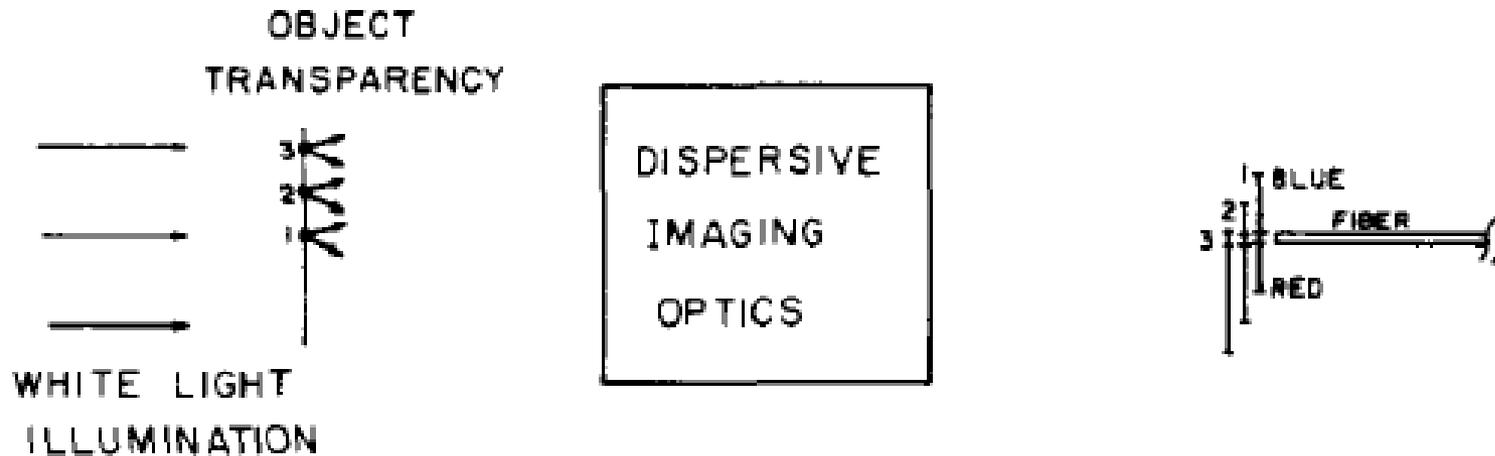


Fig. 1. Principle setup for wavelength coded transmission.

- H. O. Bartelt, "Wavelength multiplexing for information transmission," Optics Communications, Vol. 27, no. 3, pp. 365-368, 1978.

# 1983: Wavelength and Angle coding used for Incoherent Optical Image Transmission via Single Multi-Mode Fiber



**Fig. 17. Schematic arrangement for wavelength multiplexing.**

- A. A. Friesem, U. Levy, & Y. Silberberg, "Parallel transmission of images through single optical fibers," Proceedings of the IEEE, Vol.71(2), pp.208-221,1983.

# 1992: Wavelength coding used for Incoherent 2-D Optical Image Transmission via Single Mode Fiber (SMF)

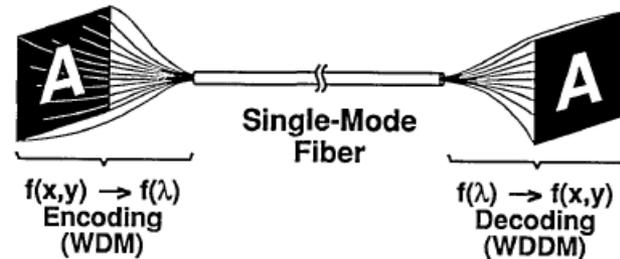


Fig. 1. 2D image transmission through a single-mode fiber. WDDM, wavelength-division demultiplexer.

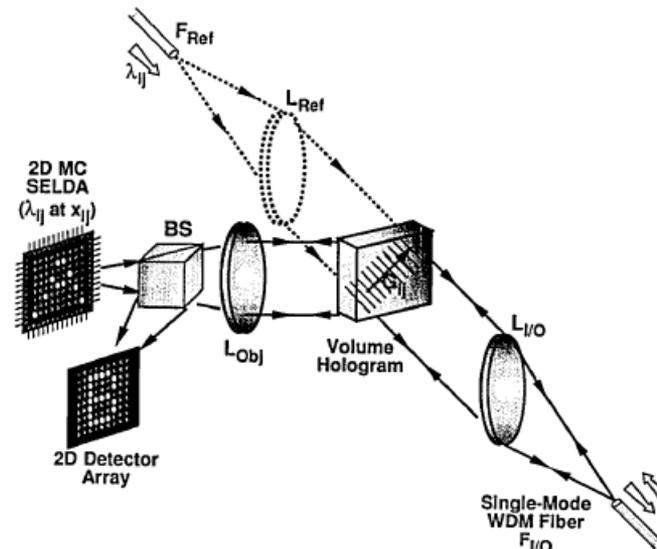


Fig. 2. Proposed 2D image transmission system through a single-mode fiber by using a 2D MC SELDA and a volume hologram.

- E. G. Paek, C. E. Zah, K. W. Cheung, & L. Curtis, "All-optical image transmission through a single-mode fiber," Optics letters, 17(8), pp.613-615, 1992.

# 1995 - RF-Wavelength Coding used for Coherent Optical Image transmission via SMF

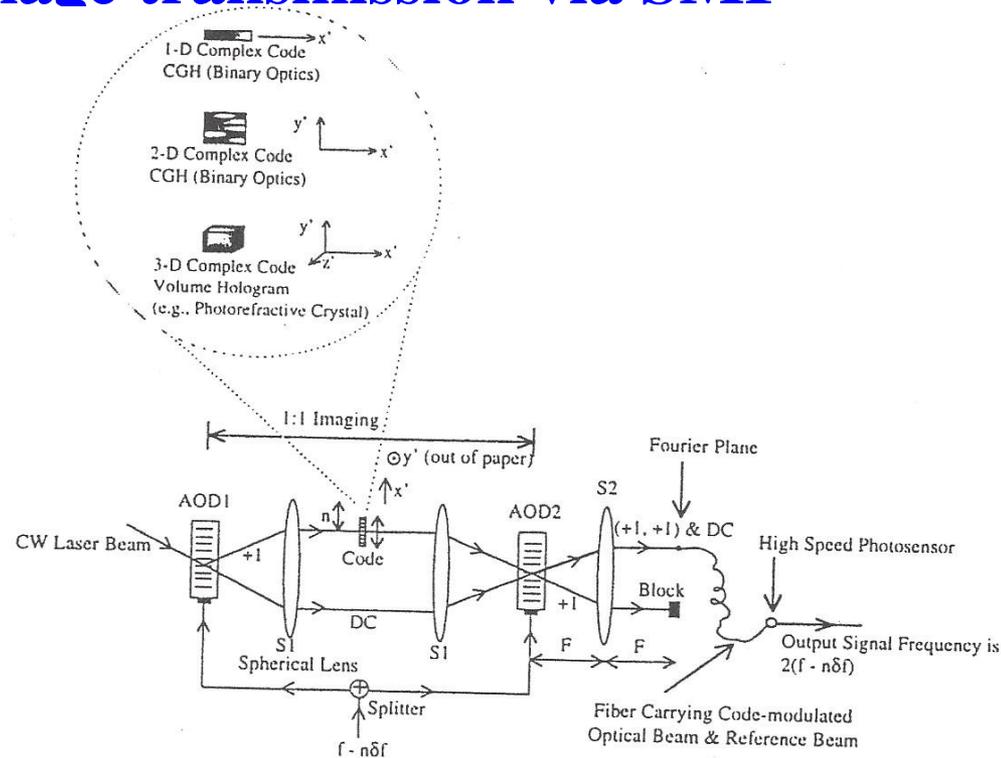
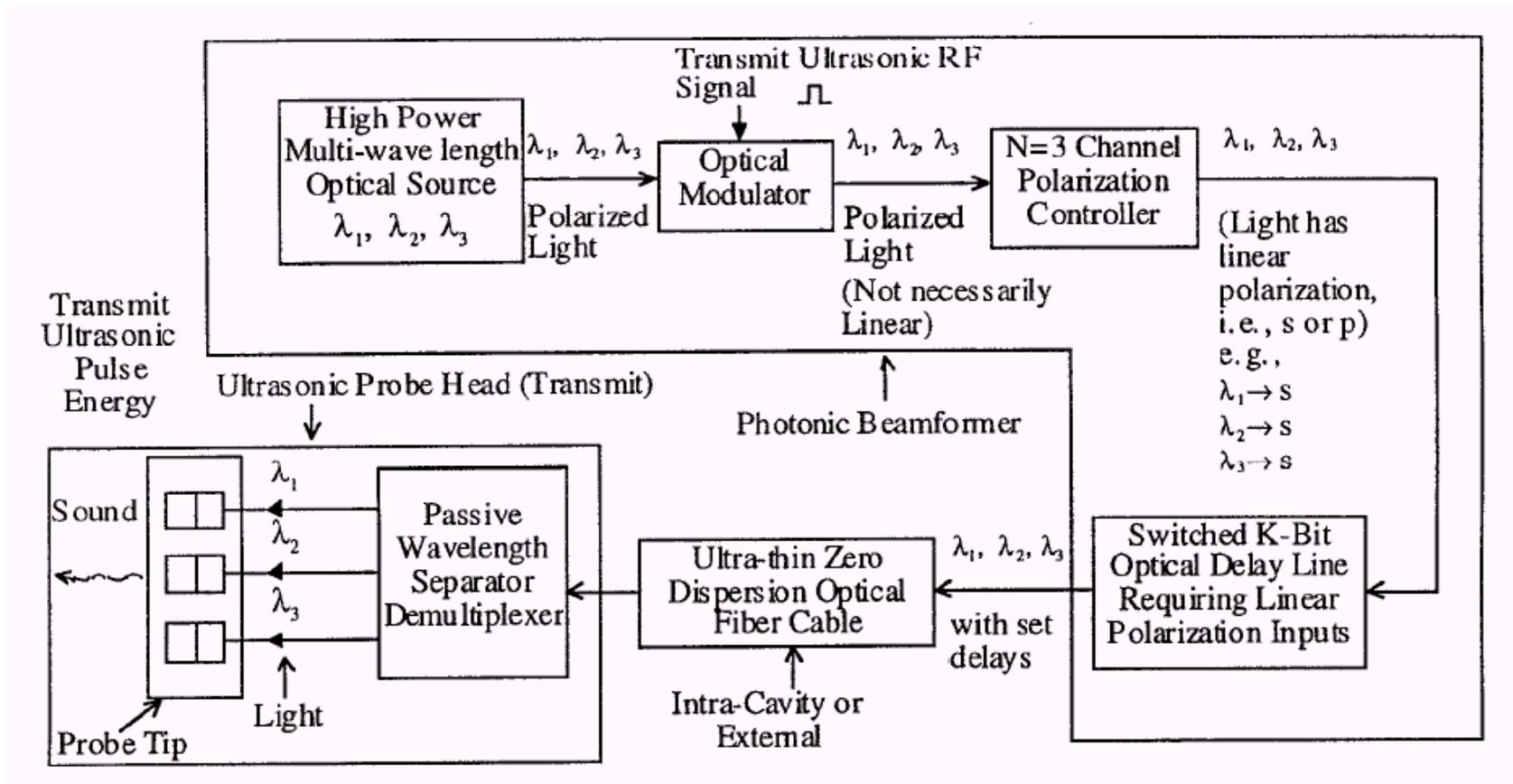


Fig. 4 Typical spatial code optical reading and encoding subsystem for 1-D scanned (e.g., along the  $x$ -direction) transmissive spatial codes. Note the possible user code and dynamic complex keycode storage options for other types of advanced optical encoders that can be formed by modifying the basic 1-D encoder shown in this figure.

- N. A. Riza, "High Speed Wide Bandwidth Optical Encryption and Decryption System using Spatial Codes," IEEE LEOS Annual Meeting Proceedings, OC 7.4, Nov., 1995.
- N. A. Riza, M. M. K. Howlader, and N. Madamopoulos, "Photonic security system using spatial codes and remote coded coherent optical communications," Opt. Eng. 35, 2487–2498 (1996).

# 1996: Wavelength Coded Endoscope for Ultrasonic/Optical Imaging



N. A. Riza, "Photonicly controlled ultrasonic arrays: scenarios and systems," *IEEE Ultrasonics Symposium*, IEEE Catalog No. 96CH35993, Vol. 2, pp. 1545-1550, Nov. 1996.

N. A. Riza, "Photonicly controlled ultrasonic probes," US Patent 5718226, Feb 17, 1998.

# 1998 - Wavelength Coded Endoscope for Optical Imaging

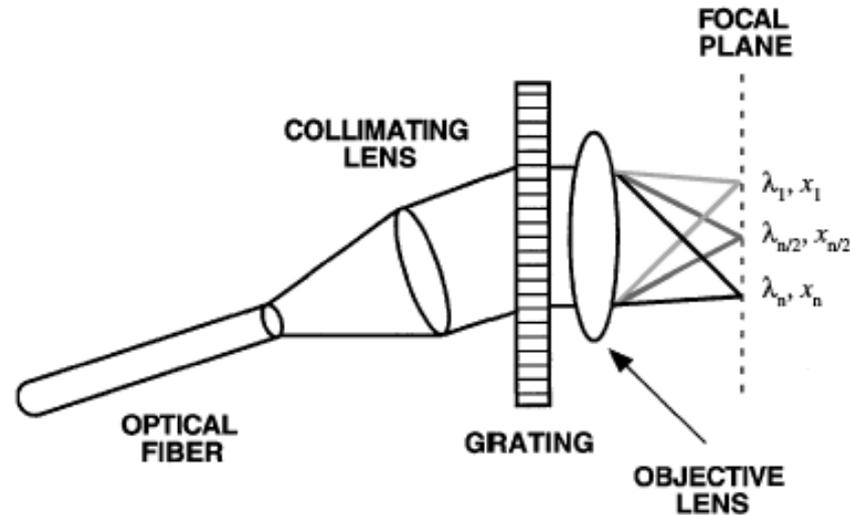


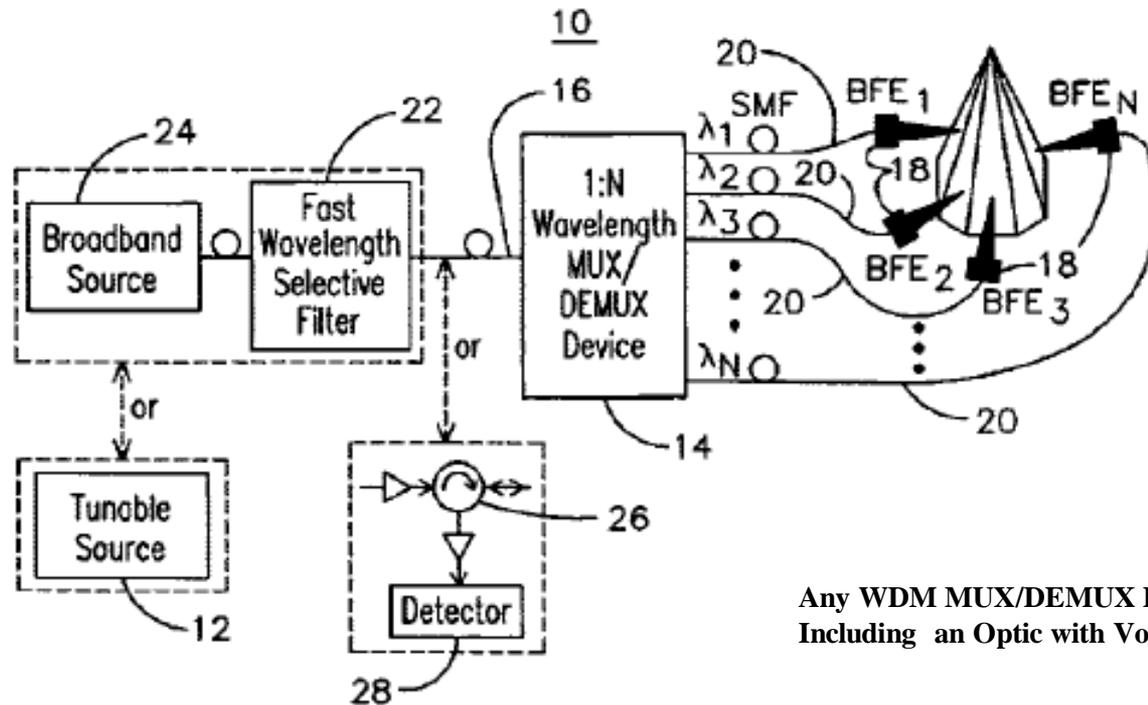
Fig. 1. Schematic of the SECM probe.

## SECM: Spectrally encoded confocal microscopy

- G.J. Tearney, R.H. Webb, B.E. Bouma, "Spectrally encoded confocal microscopy," *Optics letters*, 23(15), pp.1152-1154, 1998.

# 1999 - Wavelength Coded Fiber Remoted Optical 3-D Imager with T/R optical amplification & $\lambda$ gain & switching controls

Each Programmable BFE/SLM creates a Unique Agile Pixel to Sample the 3-D Object

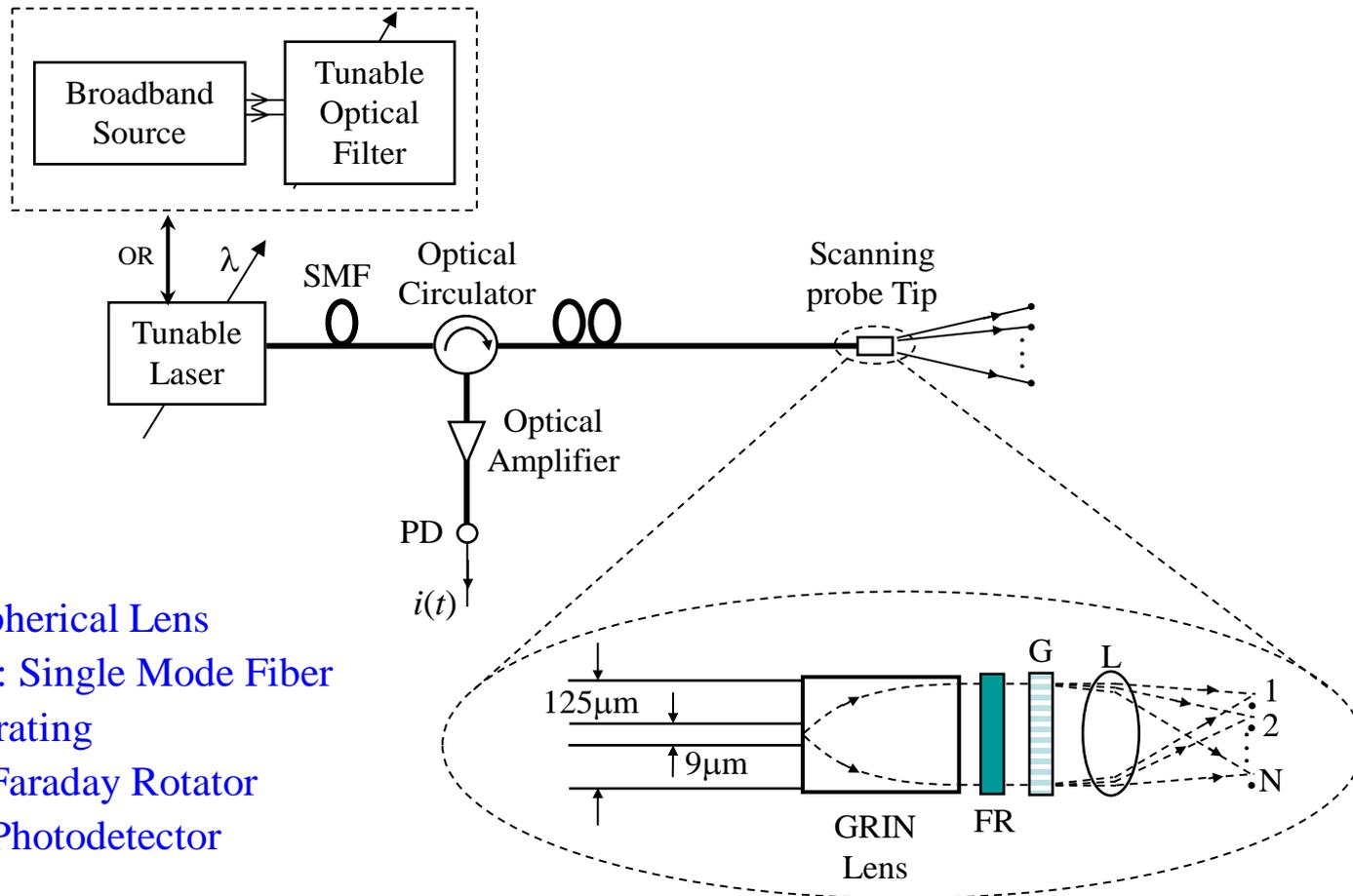


*Agile Pixel:  
Shape of Each  
Sampling Pixel  
is Unique &  
Programmable  
By SLM*

Any WDM MUX/DEMUX Device can be used  
Including an Optic with Volume Bragg Gratings

- N. A. Riza and Y. Huang, "High Speed Optical Scanner for Multi-Dimensional Beam Pointing and Acquisition," IEEE-LEOS Annual Meeting Proc., Nov. 1999.
- N. A. Riza, "MOST: Multiplexed Optical Scanner Technology," IEEE LEOS Annual Meeting Proc., November 2000.
- N. A. Riza, "Multiplexed Optical Scanner Technology," USA Patent No. 6,687,036, Feb.3, 2004.

# Non-Coherent Scanning Probe System for Internal and External Cavity Biomedicine using Agile Wavelength Manipulation



L: Spherical Lens

SMF: Single Mode Fiber

G: Grating

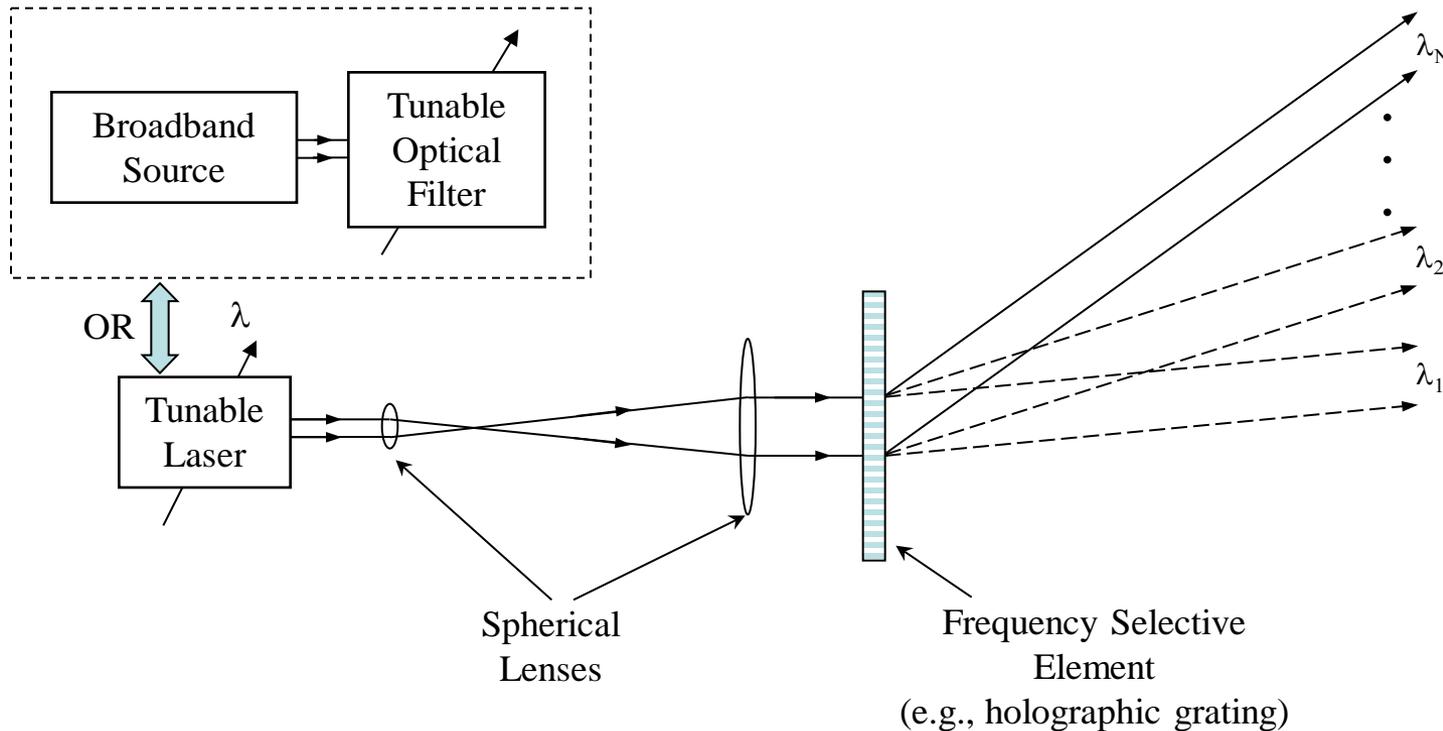
FR: Faraday Rotator

PD: Photodetector

N. A. Riza and Yu Huang, "High speed optical scanner for multi-dimensional beam pointing and acquisition," IEEE LEOS Annual Meeting, Vol. 1, pp. 184-185, 1999.

N. A. Riza and Z. Yaqoob, "High-speed fiber-optic probe for dynamic blood analysis measurements," SPIE Proc. Vol 4163, pp. 18-23, Aug. 2000.

# Free Space W-MOS Using Tunable Laser (1-D Scan Capability)



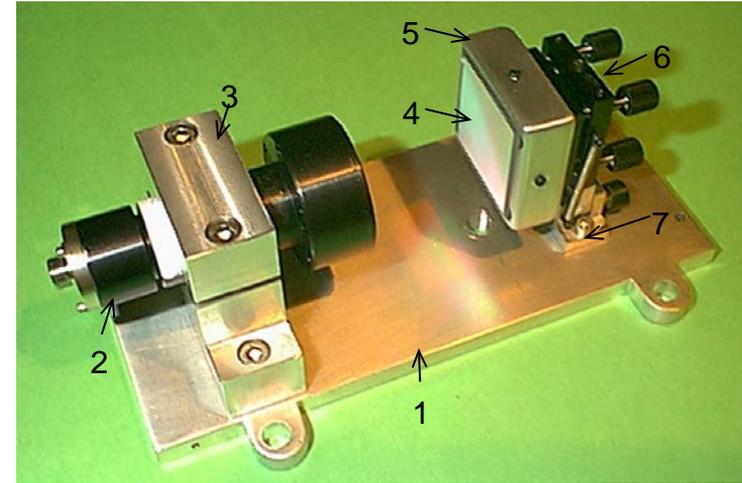
## Beam Scanning Options:

Single Beam High Speed 1-D Scanning

Multiple Simultaneous Beams High Speed 1-D Scanning

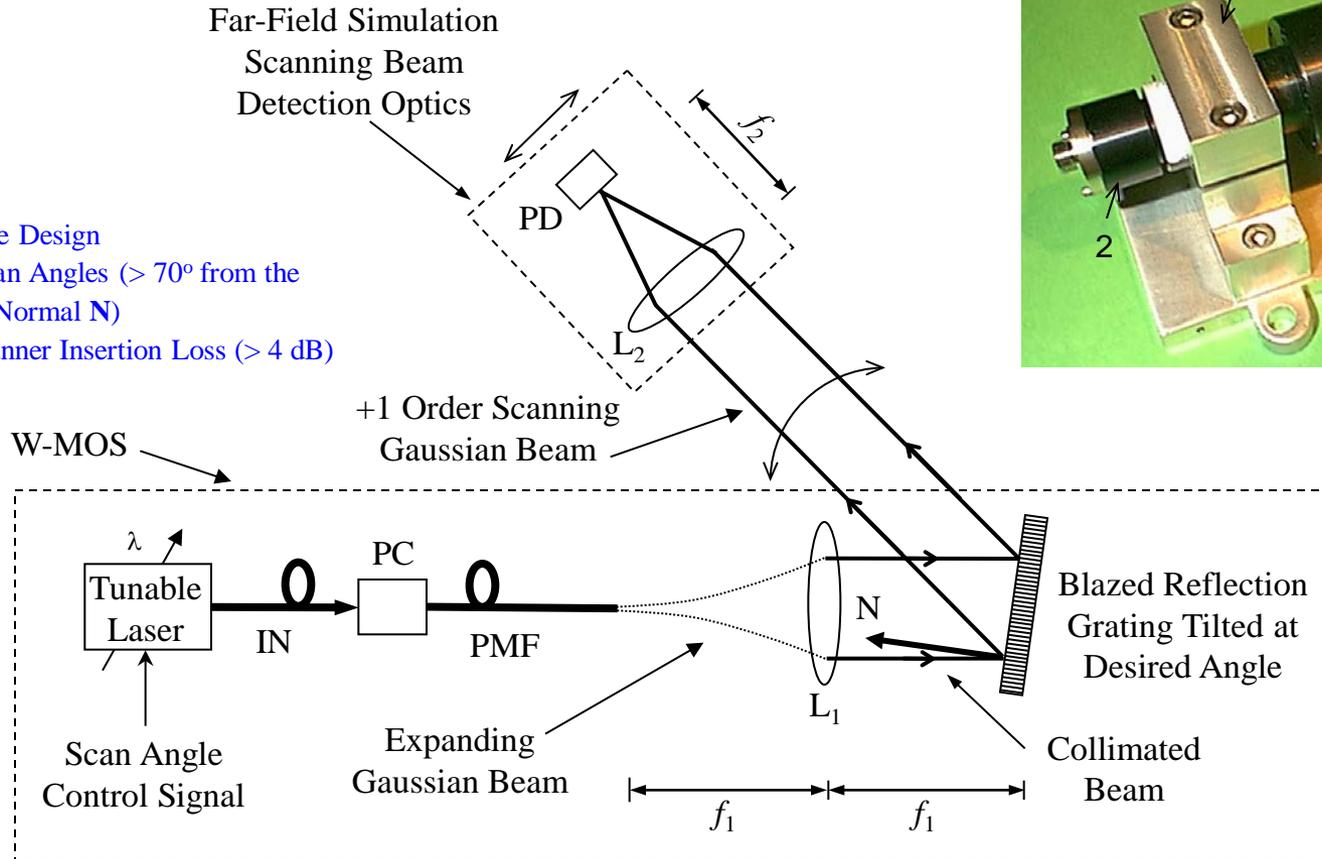
Z. Yaqoob, A. A. Rizvi, and N. A. Riza, "Free-space wavelength-multiplexed optical scanner,"  
Applied Optics, **40**(35), December 10, 2001.

# Hand-held Free-Space W-MOS Design Using Reflective Grating



## Features:

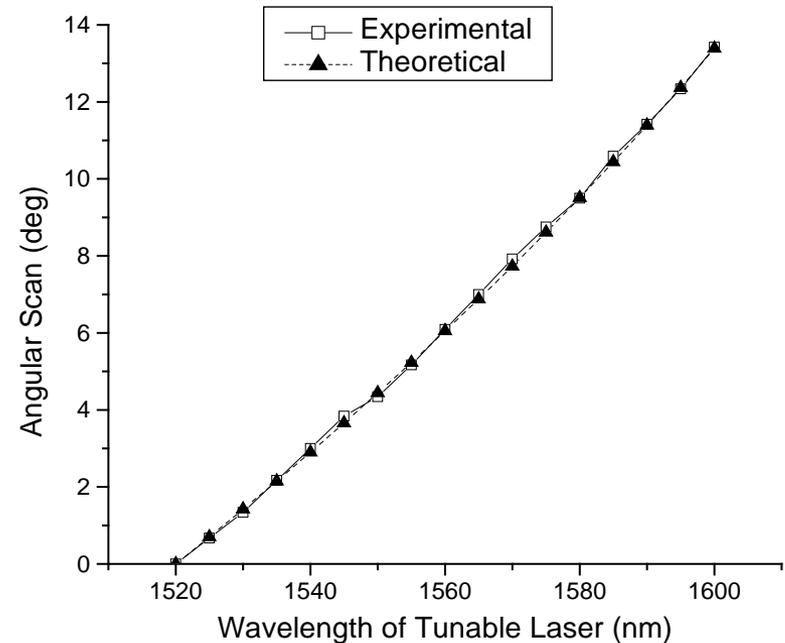
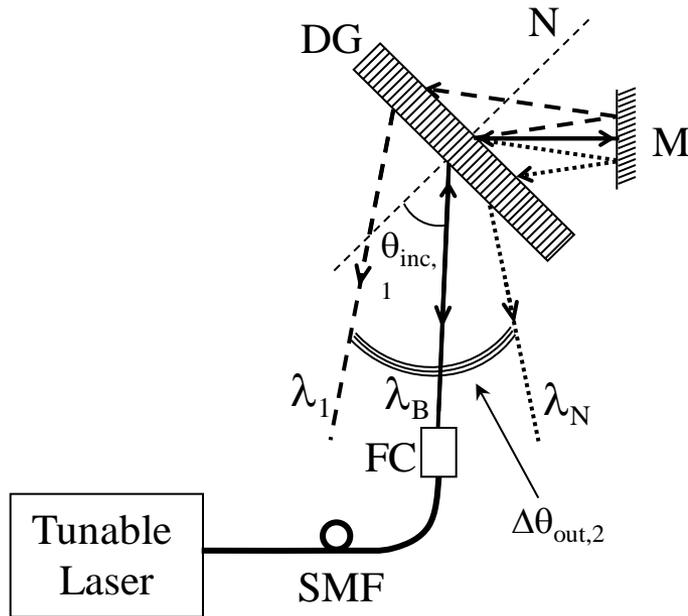
- Reflective Design
- Steep Scan Angles ( $> 70^\circ$  from the Grating Normal  $N$ )
- High Scanner Insertion Loss ( $> 4$  dB)



PD: Photodetector; GRIN Lens: Gradient index lens; PC: Polarization controller;  $L_i = i^{\text{th}}$  lens;  $f_i = \text{Focal length of } i^{\text{th}}$  lens.

Z. Yaqoob and N. A. Riza, "Free-space wavelength-multiplexed optical scanner demonstration,"  
Applied Optics, **41**(26), September 10, 2002.

# Angular Scan Range of an In-line Free-Space W-MOS Versus Wavelength of Tunable Laser



Estimated Total Angular Scan: 13.39°

Measured Total Angular Scan: 13.42°



Doubled the Scan Range

$$\Delta\theta_{out,2} = \sin^{-1} \left[ \frac{\lambda_N}{L} - \sin \left\{ \sin^{-1} \left( \frac{\lambda_N}{L} - \sin \theta_B \right) \right\} \right] - \sin^{-1} \left[ \frac{\lambda_1}{L} - \sin \left\{ \sin^{-1} \left( \frac{\lambda_1}{L} - \sin \theta_B \right) \right\} \right]$$

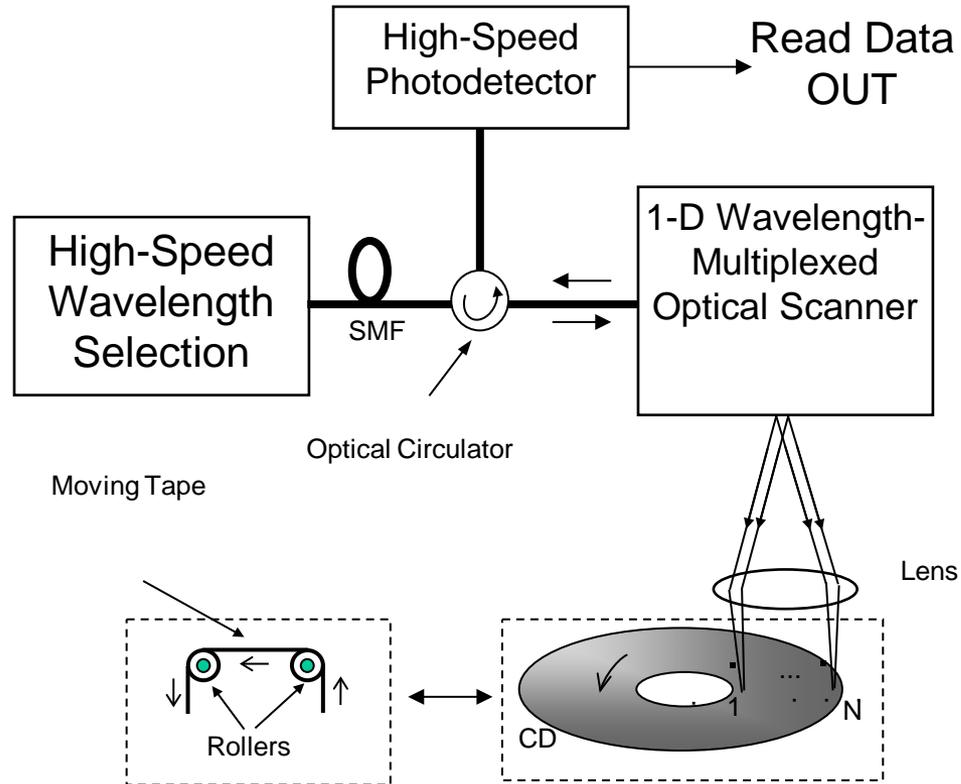
# Demonstration of Free-Space 1-D W-MOS

## Laboratory Free-Space W-MOS Parameters

## Specifications

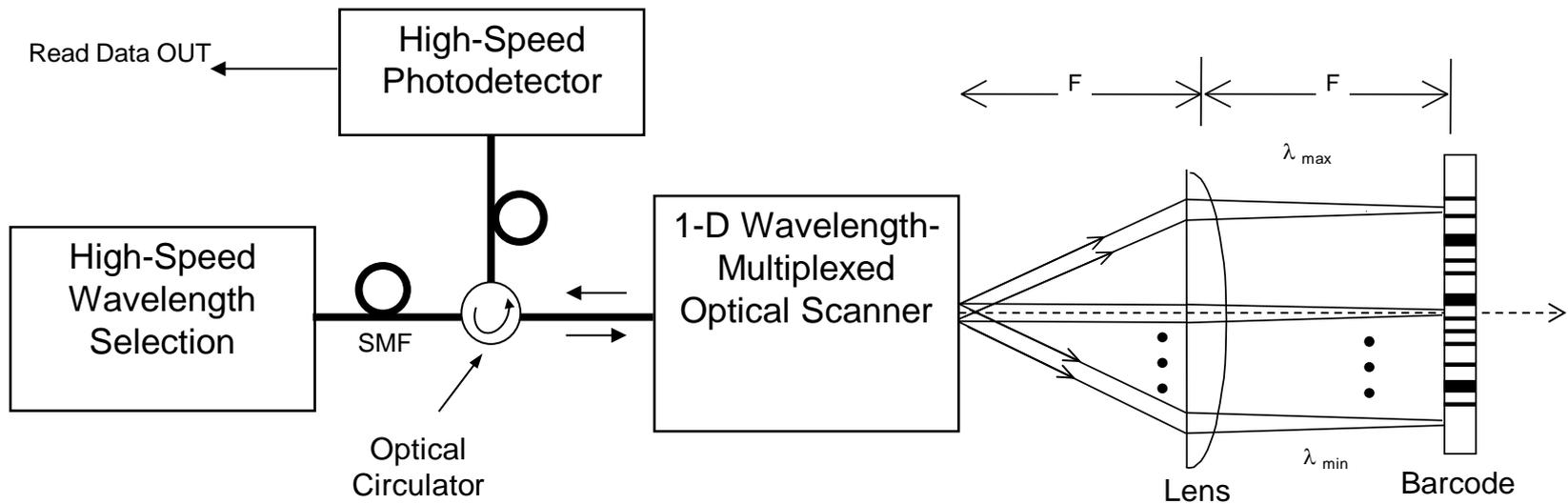
|  |   |                                      |
|--|---|--------------------------------------|
| Wavelength Dispersive Element          | <b>600 lines/mm Blazed Reflection Grating</b> | <b>940 lines/mm Dickson Gratings</b> |
| Scanner Design                         | Reflective                                    | Transmissive (In-line)               |
| Tunable Laser Bandwidth                | 1520 - 1600 nm                                | 1520 - 1600 nm                       |
| Scanner Aperture                       | 1.88 cm (1/e <sup>2</sup> Beam Size)          | 1.2 cm (grating size)                |
| Random Access Beam Switching Time      | 60 $\mu$ s Using MTX-TEML Tunable Laser       | SAME                                 |
| Scan Start Angle                       | 71° (from <b>N</b> to the grating)            | -4.44° (w.r.t. $\theta_{inc}$ )      |
| Scan Stop Angle                        | 84° (from <b>N</b> to the grating)            | 8.95° (w.r.t. $\theta_{inc}$ )       |
| Measured 1-D Scan Range                | 13°   | 13.42°                               |
| Maximum Beam Divergence                | 1.1 mrad                                      | 0.172 mrad                           |
| Beam Pointing Accuracy (No Modulation) | 0.06 mrad                                     | 0.0095 mrad                          |
| Beam Pointing Accuracy (2.5 GHz Mod.)  | 0.313 mrad                                    | 0.05 mrad                            |
| Number of Beam Spots                   | 206   | <b>1361</b> using In-line Design     |
| Average Scanner Insertion Loss (dB)    | 4.8   | <b>1.17</b> using Dickson Grating    |

# High-Speed Beam Scanning For 2-D Data Handling



Z. Yaqoob and N. A. Riza, "IEEE Photonics Technology Letters, March 2004.

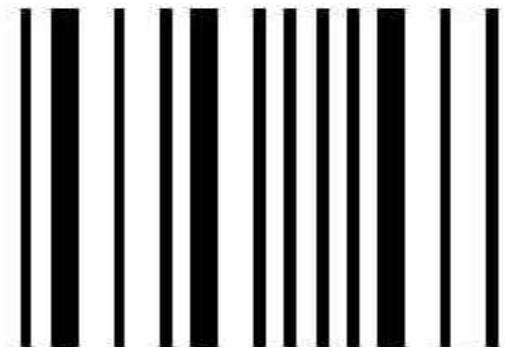
# Passive-Optics No-moving Parts Barcode Scanner



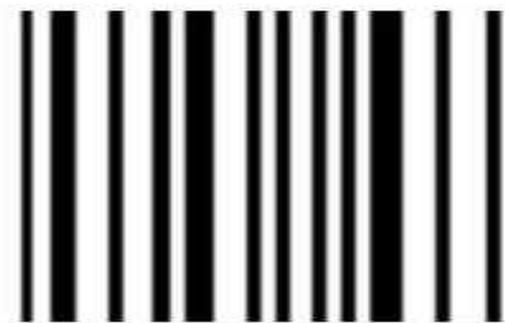
Z. Yaqoob and N. A. Riza, "IEEE Photonics Technology Letters, March 2004.

**(a) Digit '3' barcode image (in Codabar symbology) used to test in experimental barcode reader.**

**(b) The optically read and processed barcode, representing the correct digit '3' code recovered via the experimental system.**



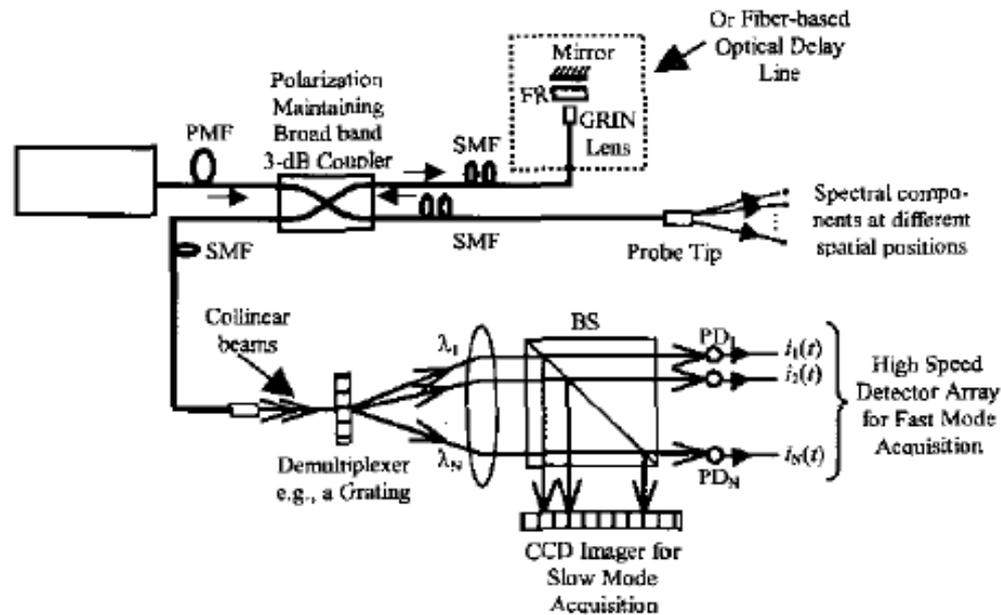
(a)



(b)



# 2004: Interferometric Wavelength Multiplexed Optical Scanner I-W-MOS



**Figure 1. Coherent probe system using a broadband source. PMF: Polarization Maintaining Fiber; SMF: Single Mode Fiber; FR: Faraday Rotator; GRIN: Gradient Index; BS: Beam Splitter; PD: Photodetector.**

Z. Yaqoob and N. A. Riza, "High-speed scanning wavelength-multiplexed fiber-optic sensors for biomedicine," The 1st IEEE International Conference on Sensors, IEEE Sensors 2002, Poster paper No. P1.36, June 12-14, 2002.

# 2004: Interferometric Wavelength Multiplexed Optical Scanner I-W-MOS

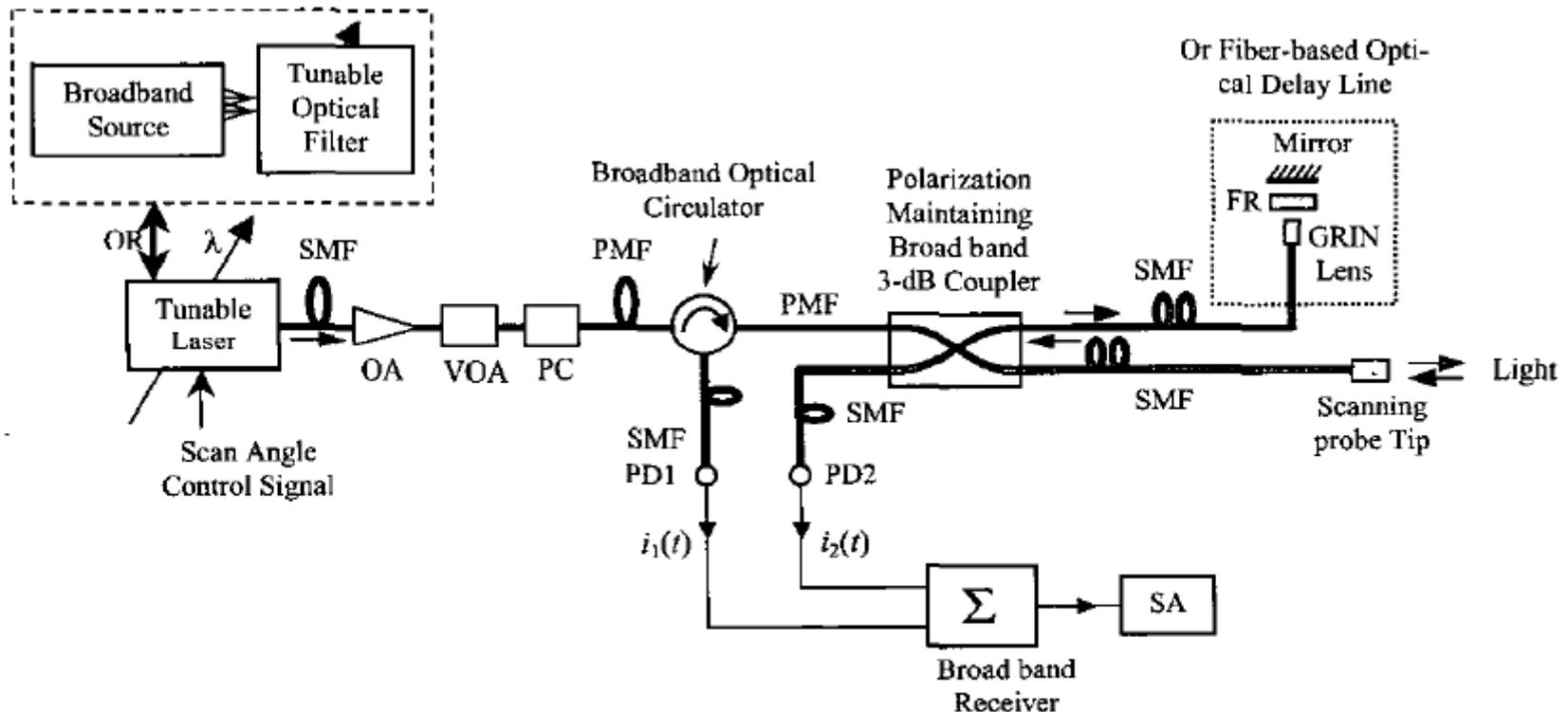


Figure 3. shows our advanced coherent scanning probe system with agile spectral shaping capability. SMF: Single Mode Fiber; PMF: Polarization Maintaining Fiber; OA: Optical Amplifier; PC: Polarization Controller; VOA: Variable Optical Attenuator; GRIN: Gradient Index; PD: Photodetector; SA: Spectrum Analyzer.

Z. Yaqoob and N. A. Riza, "High-speed scanning wavelength-multiplexed fiber-optic sensors for biomedicine," The 1st IEEE International Conference on Sensors, IEEE Sensors 2002, Poster paper No. P1.36, June 12-14, 2002.

# 2004: Interferometric Wavelength Multiplexed Optical Scanner I-W-MOS

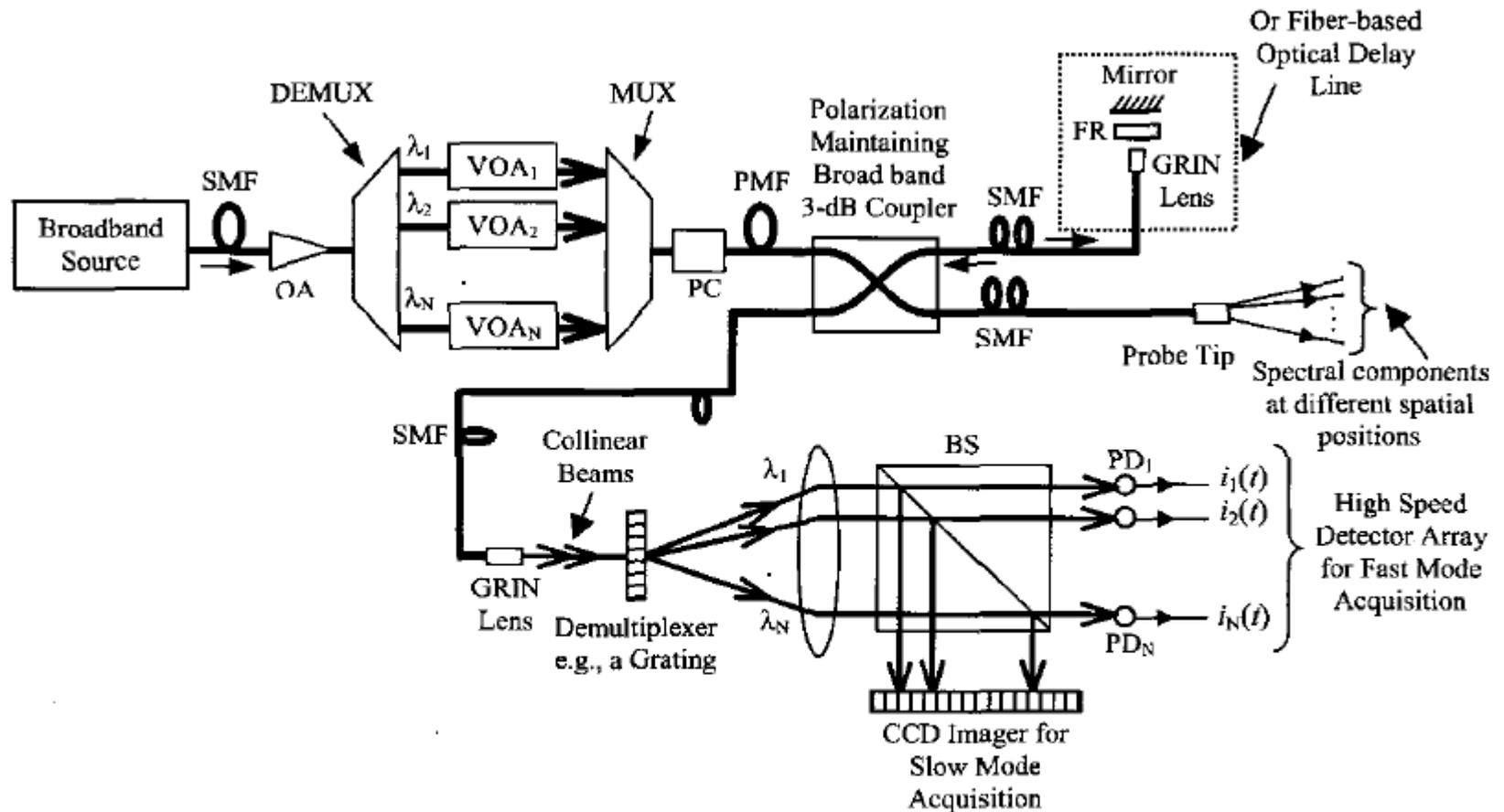
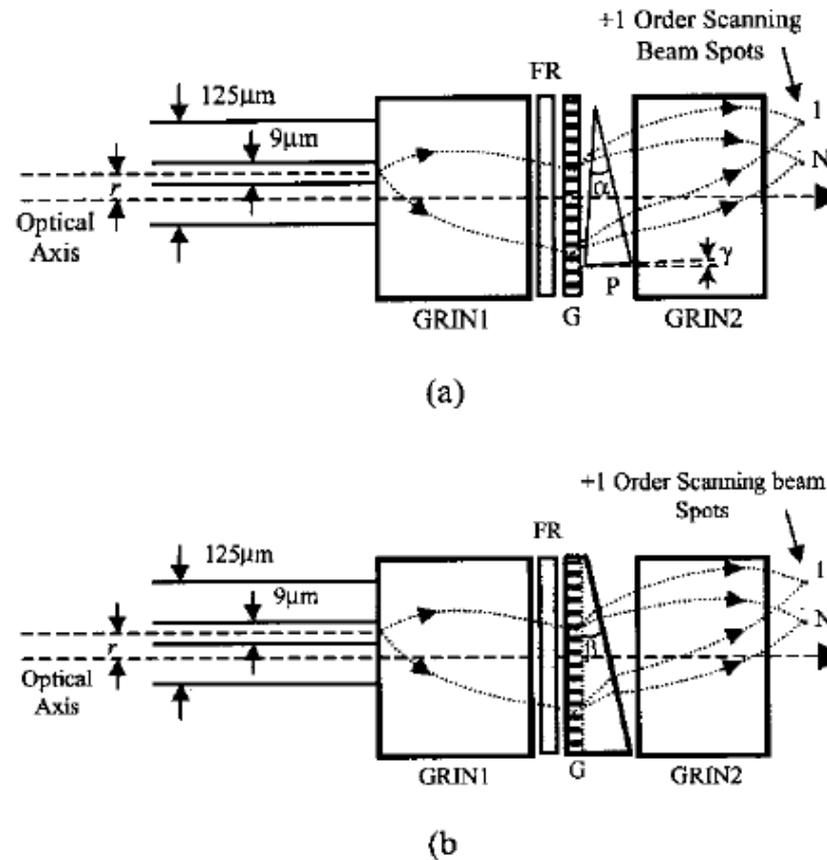


Figure 4. shows our Intelligent coherent probe system using a broadband source. MUX: Multiplexer; DEMUX: Demultiplexer; SMF: Single Mode Fiber; PMF: Polarization Maintaining Fiber; OA: Optical Amplifier; PC: Polarization Controller; VOA: Variable Optical Attenuator; GRIN: Gradient Index; PD: Photodetector; SA: Spectrum Analyzer.

# 2004: Interferometric Wavelength Multiplexed Optical Scanner I-W-MOS



**Figure 5. Miniaturized fiber-optic sensor heads. FR: Faraday Rotator; GRIN: Gradient Index; P: Prism; G: Grating.**

# 2005: Spectrally Encoded Interferometry $\longleftrightarrow$ (I-W-MOS)

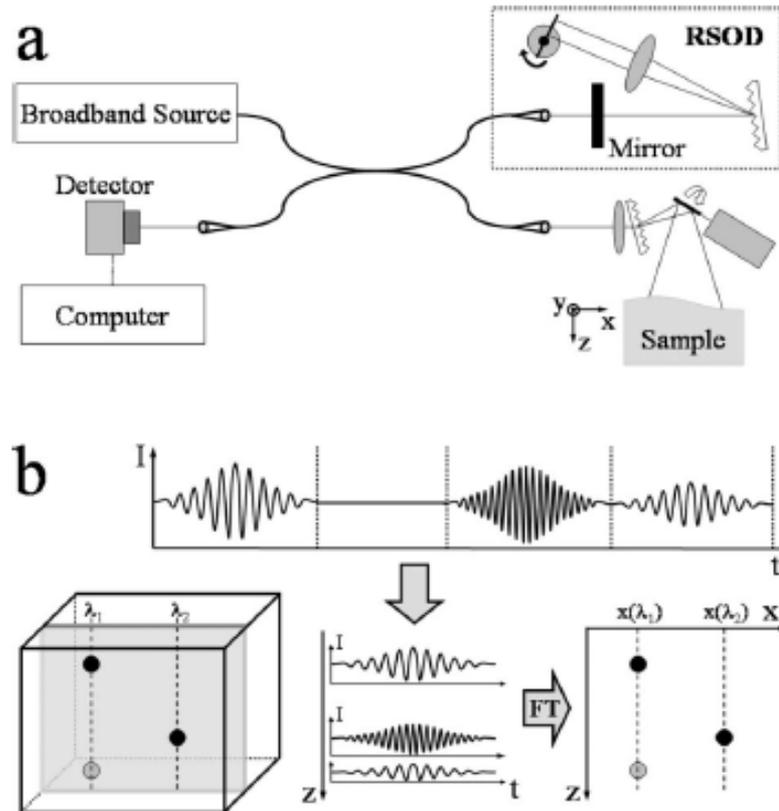
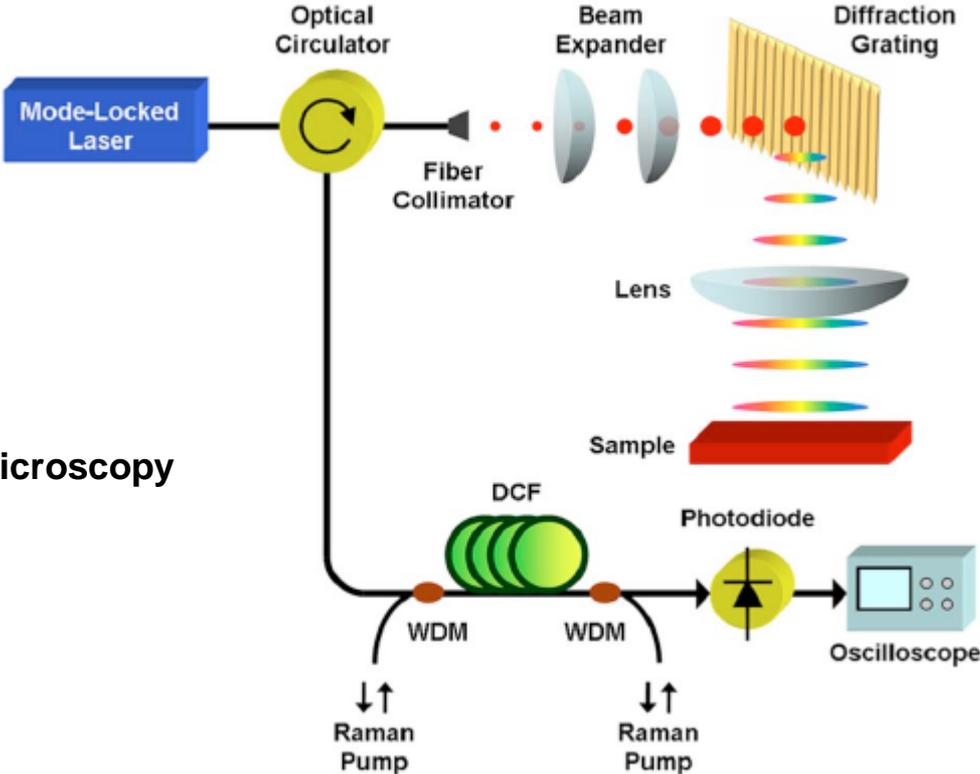


Fig. 1. a, Schematic of the time-domain spectrally encoded imaging system. b, Extraction of both transverse and depth information from the interference trace.

D. Yelin, S. H. Yun, B. E. Bouma, and G. J. Tearney, "Three-dimensional imaging using spectral encoding heterodyne interferometry," *Opt. Lett.* **30**, 1794-1796 (2005)

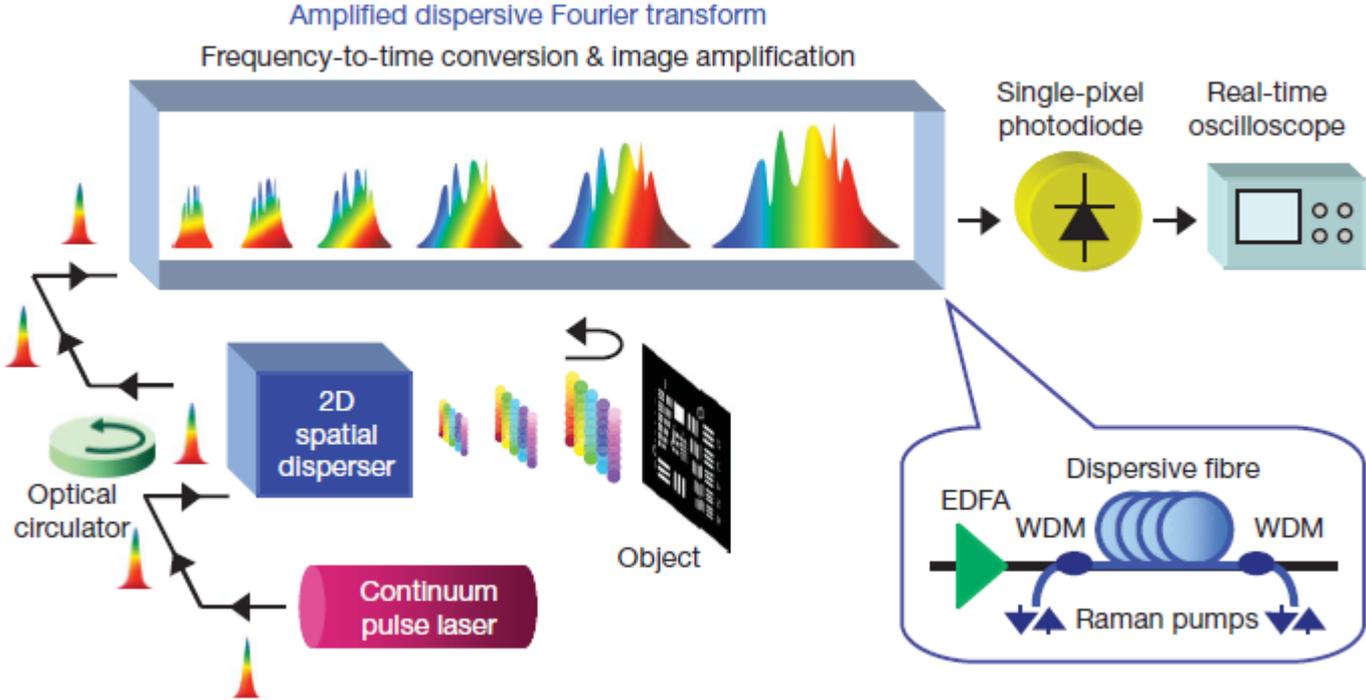
# 2008: Wavelength Coded Fiber Remoted Optical 2-D Imager using a Dispersion Shifted Fiber that maps wavelengths to time delays for high speed serial electronic decoding of optical image via Real-Time Oscilloscope ( using 1-D WMOS)

Technique is called STEAM  
for Serial time-encoded amplified microscopy



- K. Goda, K. K. Tsia, & B. Jalali, "Amplified dispersive Fourier-transform imaging for ultrafast displacement sensing and barcode reading," Applied Physics Letters, 93(13), 131109, 2008. (with 1-D motion of sample)

**2009: Wavelength Coded Fiber Remoted Optical 2-D Imager using a Dispersion Shifted Fiber that maps wavelengths to time delays for high speed serial electronic decoding of optical image via Real-Time Oscilloscope ( using 2-D WMOS)**



**Technique is called STEAM for Serial time-encoded amplified microscopy**

- K. Goda, K. K. Tsia, & B. Jalali, "Serial time-encoded amplified imaging for real-time observation of fast dynamic phenomena," Nature, 458(7242), 1145-1149, April 30, 2009. (2-D wavelength mapped imaging)