# Agile Single Pixel Imager *
# - A Review

**By**
**Nabeel A. Riza**

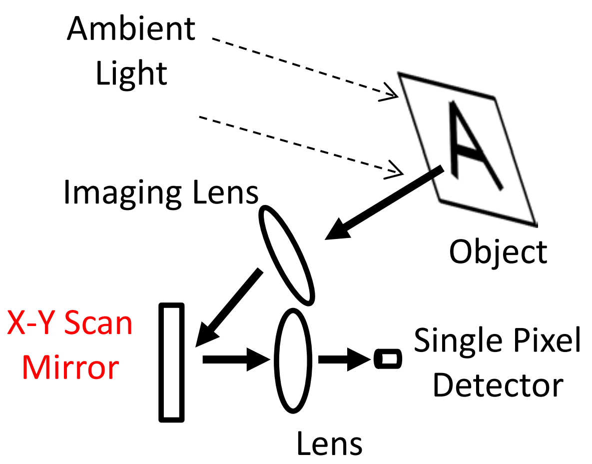
*** In passive imaging, "Single Pixel"  in the literature commonly refers to using a Single Detector, i.e., a Point Photo-Detector, to design the Imager.**

**Note: Common Imaging Systems are called Cameras, Imagers, Scanners, Profilers, Sensors**

# Conventional Passive and Active Single Pixel Imaging Around for a Long Time (50+ years)
# Passive versus Active

## Passive

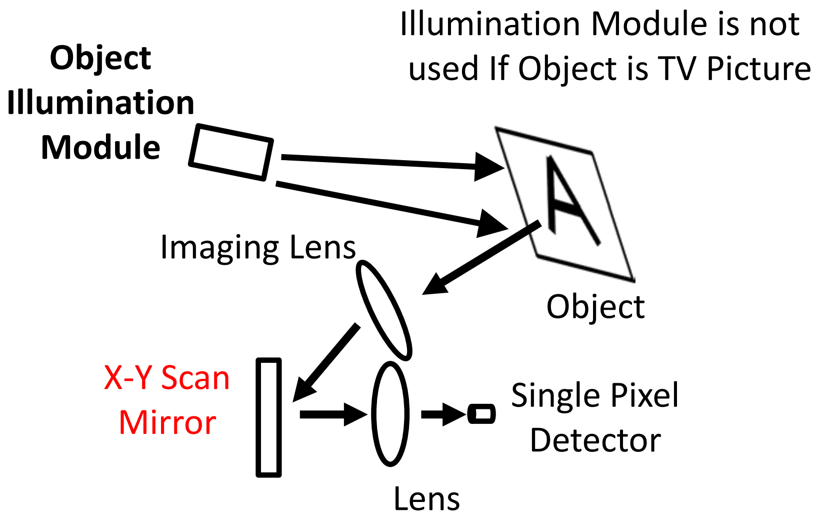
- Object illuminated by ambient light is imaged onto X-Y scan mirror which sequentially directs the shifted image irradiance onto a point detector.
- Pixel basis irradiance sampling is enabled by the point photo-detector that forms the sampling pin-hole (pixel).
- Image reconstruction is sequential (pixel by pixel).




## Active

- Object illuminated by custom light source or object itself is generating light, e.g., Television Display
- Imaging operations same as Passive Imager.

*** Alternative Design replaces X-Y scan Mirror & Lens by object X-Y motion stage**

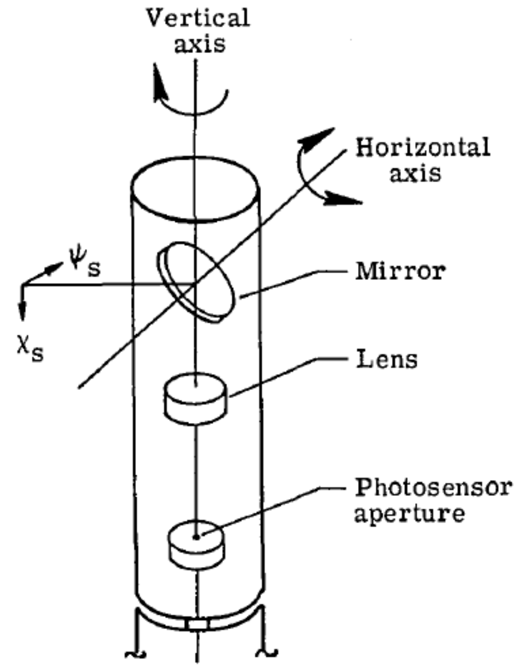


# Example Passive Single Pixel Imaging – NASA Scanning Mirror-based Single Pixel Imager

- Use of <u>single pixel</u> for imaging by **F. O. Huck** [1-2] **in 1969.** Also used by the USSR in **1968** [3].

Application:
NASA Planetary
Lander Imager

- Robust Optomechanical Design for Spacecraft Platform giving Spectral Flexibility




Single Pixel Imager called a facsimile camera [2]


[1] F. O. Huck and J. J. Lambiotte, "A Performance Analysis of the Optical-Mechanical Scanner as an Imaging System for Planetary Landers," NASA TN D-5552 (Dec.1969).
[2] S.J. Katzberg, F.O. Huck and S.D. Wall, "Photosensor Aperture Shaping to Reduce Aliasing in Optical-Mechanical Line-Scan Imaging Systems," Appl. Opt., vol. 12, pp. 1054-1060 (1973).
[3] A. S. Selivanov, V. N. Govorov, A. S. Titov, and V. P. Chemodanov, "Lunar Station Television Camera," (Reilly Translations, transl.): NASA CR-97884 (1968).
[4] L. Li, V. Stankovic, L. Stankovic, L. Li, S. Cheng and D. Uttamchandani, "Single pixel optical imaging using a scanning MEMS mirror," IOP Journal of Micromechanics and Microengineering, vol. 21, no. 2, 2011.

# Moving Digital Mask Coding of Spatially Dispersed Optical Radiation Detected By <u>One Point Photo-Detector</u> has been Around for a Long Time (50+ years)

## For Making Spectrometers – M. Golay 1949

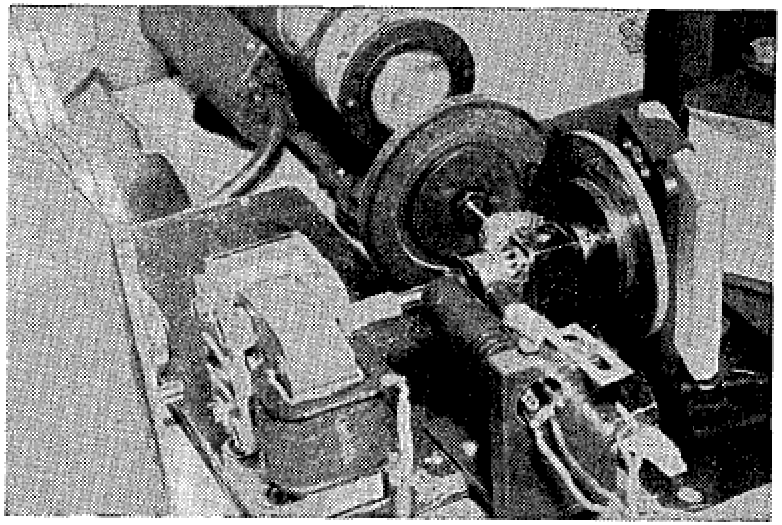


FIG. 3. Rotating two-dimensionally patterned gratings mounted on infra-red spectrometer.

**Approach - Wavelengths in Space Encoded by Moving Spatial Code Masks Driven by Motors and Total Light Caught by one Photo-Detector**

M. J. E. Golay, "Multi-slit spectrometry," J. Opt. Soc. Am. 39, 437–444 (1949).

# Moving Digital Mask Coding of Spatially Dispersed Optical Radiation Detected By One Photo-Detector has been Around for a Long Time (50+ years)

## For Television Display – P. Gottlieb 1968

GOTTLIEB: TELEVISION SCANNING SCHEME

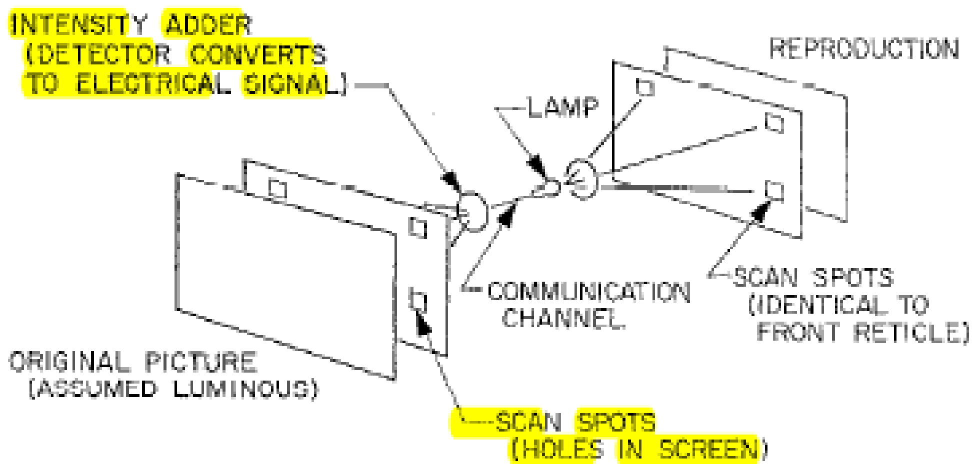



Fig. 1. Conceptual arrangement of a reticle scanning system.

Approach –
Luminous Picture (TV)
in Space Encoded by
Moving Spatial Code Masks

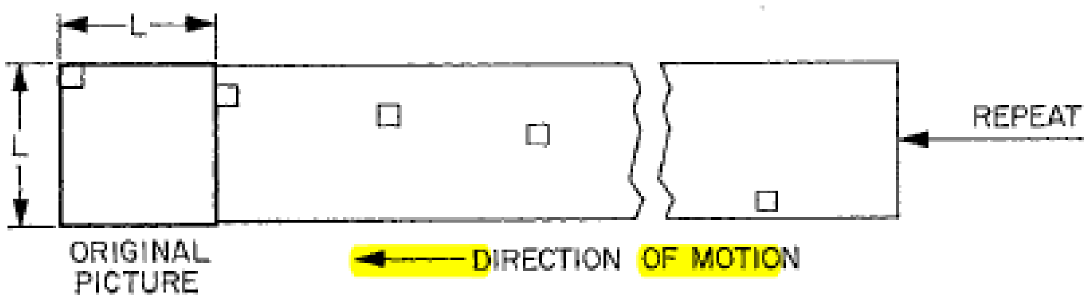


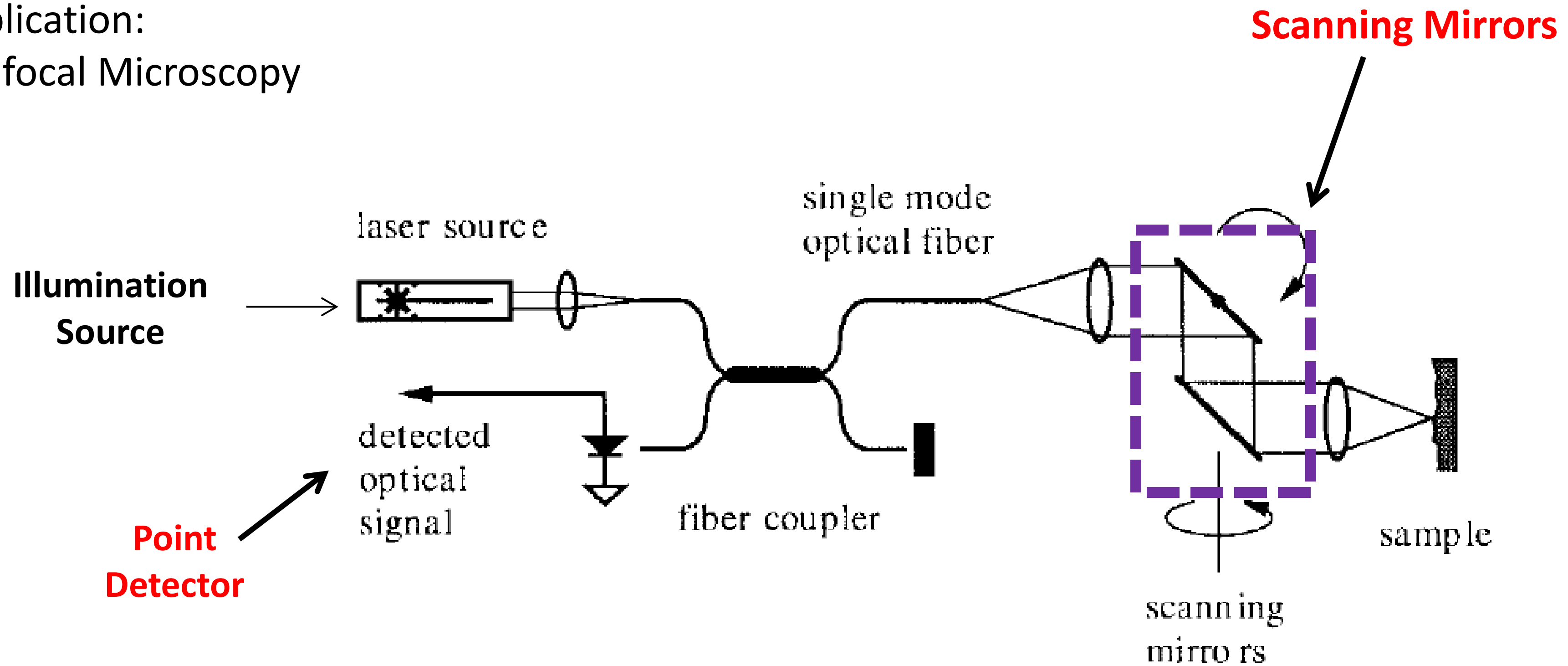

Fig. 2. Reticle for ordinary spot-scan system.


P. Gottlieb, "A television scanning scheme for a detector-noise limited system," IEEE Trans. Infom. Theory 14, 428–433 (1968).

## Example Active Single Pixel Imaging
## The Fiber-Coupled Scanning Mirror-based Single Pixel Imager

- Use of single pixel for active imaging by **Kino Lab[1] in 1998.**

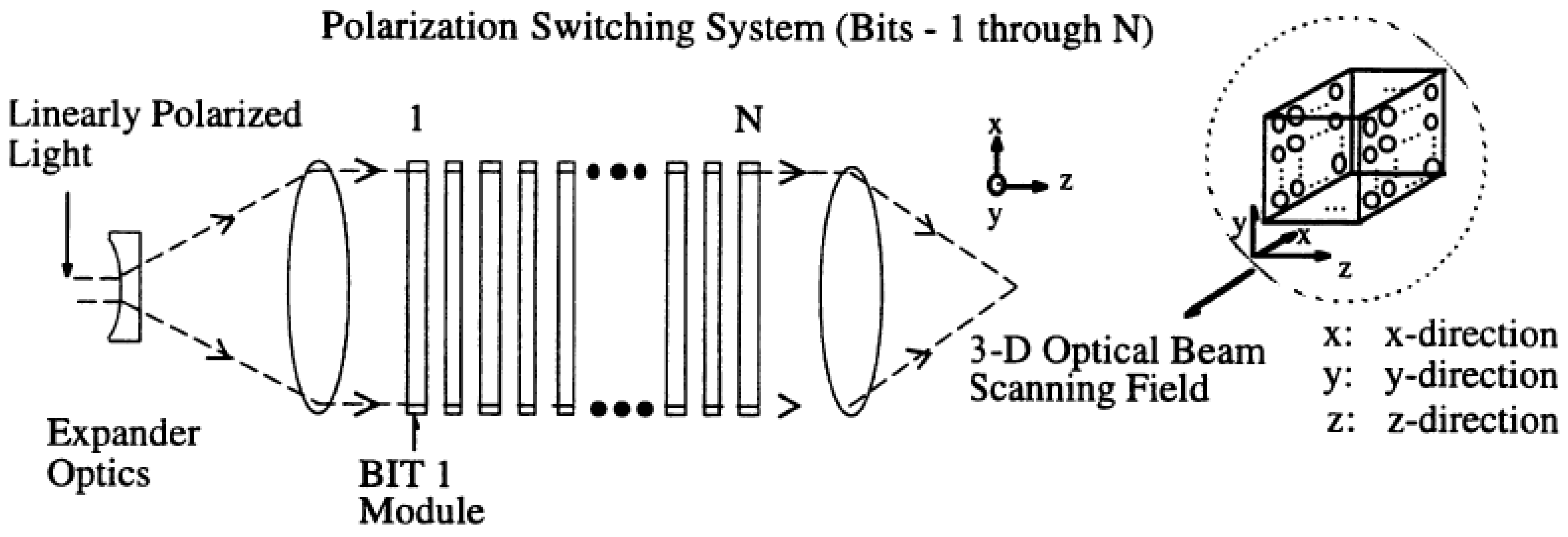
Application:
Confocal Microscopy




[1] D. L. Dickensheets and G. S. Kino, "Silicon-micromachined scanning confocal optical microscope," Journal of Microelectromechanical Systems, vol.7, no.1, pp.38-47, (1998).

*Imagers are also Called Scanners, Profilers, Mappers in Industry & Technical Literature*

# 1998 –Riza
# Single Pixel Active 3-D Imager using the PMOS
# P-MOS: Polarization Multiplexed Optical Scanner




**PMOS-Single Pixel Active 3-D Imager [1]**


[1] N. A. Riza , "BOPSCAN Technology: A methodology and implementation of the billion point optical scanner," International Optical Design Conference (IODC), SPIE Proc. 3482, (1998).

[2] N. A. Riza, "Digital control polarization based optical scanner," US Patent 6031658, (2000).

[3] N. A. Riza and S. A. Khan, "Programmable high-speed polarization multiplexed optical scanner," OSA Opt. Letters, vol. 28, no. 7, (2003).

[4] S. A. Khan and N. A. Riza, "Demonstration of 3-dimensional wide angle laser beam scanner using liquid crystals," OSA Optics Express, vol. 12, no. 5, p.868, (2004).

## 1999 –Riza
## Introducing the Concept of an Agile Pixel Single Pixel (Detector) Active 3-D Imager

***-- Agile Pixel here Refers to:***
***Shape of Each Sampling Pixel***
***is Unique & Programmable By SLM***

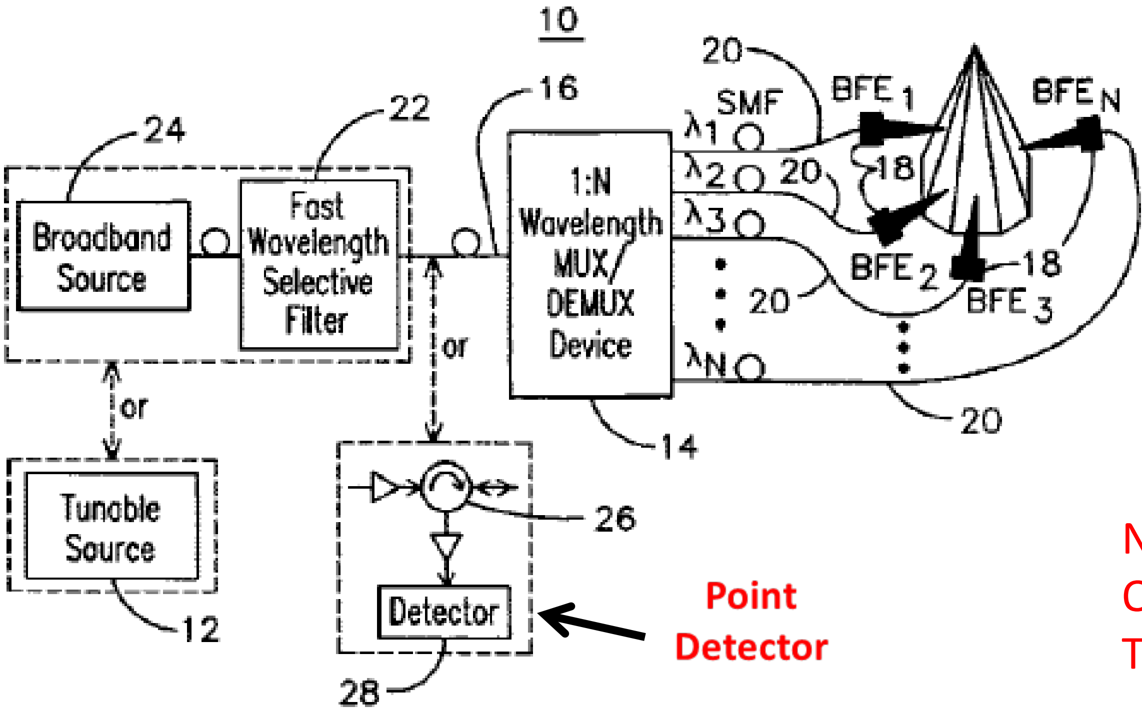
***-- Single Pixel here and Consistent with Prior-Art Refers to:***
***Using Single Point Detector***


- 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, “Reconfigurable Optical Wireless,” IEEE-LEOS Annual Meeting Proc., Nov. (1999).

# 1999 –Riza
# Single Pixel Active 3-D Imager using the WMOS
# W-MOS: Wavelength Multiplexed Optical Scanner

**This Fast Optical 3-D Scanner/Imager using Wavelength Coding**
**where 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***

**Point Detector**

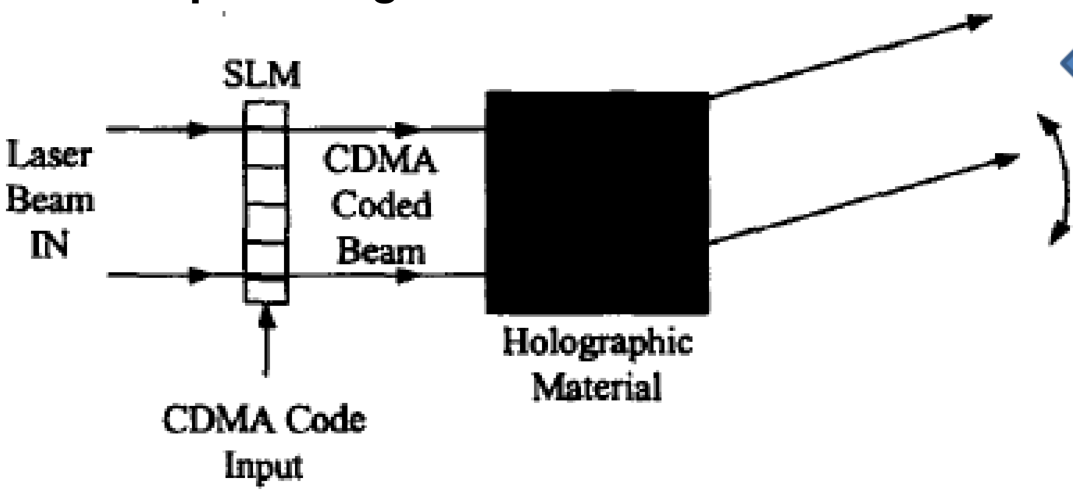
Note: Imager also uses Optical Amplification in Transmit & Receive Channels


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

# 1999 –Riza
# Single Pixel  Active 3-D Imager using the CMOS
# C-MOS: Code Multiplexed Optical Scanner

**This Fast Optical 3-D Scanner/Imager using Spatial Coding**
**where the Programmable SLM creates a Unique Agile Pixel to Sample the 3-D Object**

**SLM: Spatial Light Modulator**



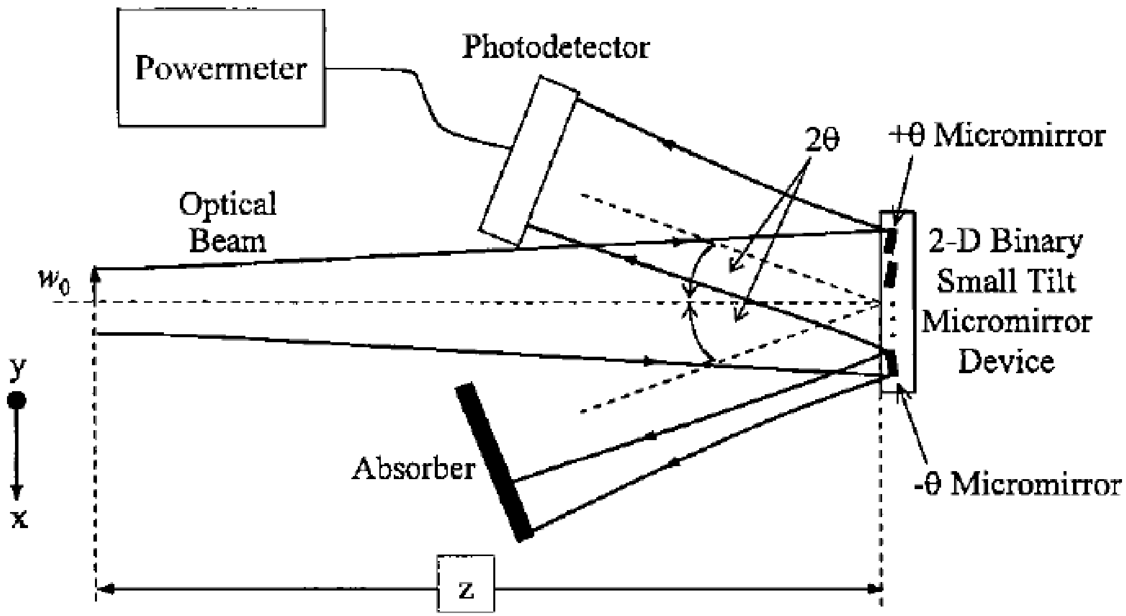

***Agile Pixel:***
***Shape and Location of Each Active Sampling Pixel is Unique & Programmable By SLM via CDMA code***

Fig.2 The proposed CDMA Scanner concept using a holographic storage material.

[1] N. A. Riza, "Reconfigurable Optical Wireless," IEEE-LEOS Annual Meeting Proc., Nov. (1999).
[2] N. A. Riza, "Multiplexed Optical Scanner Technology,"  USA Patent No. 6,687,036, Feb.3, (2004).
[3] N. A. Riza and M. A. Arain, " Code multiplexed optical scanner," Applied Optics, IP, vol. .42, no.8, March 10, (2003).

# 2001 – Riza
# SLM-based Single Pixel Passive 2-D Imager using Agile Pixel

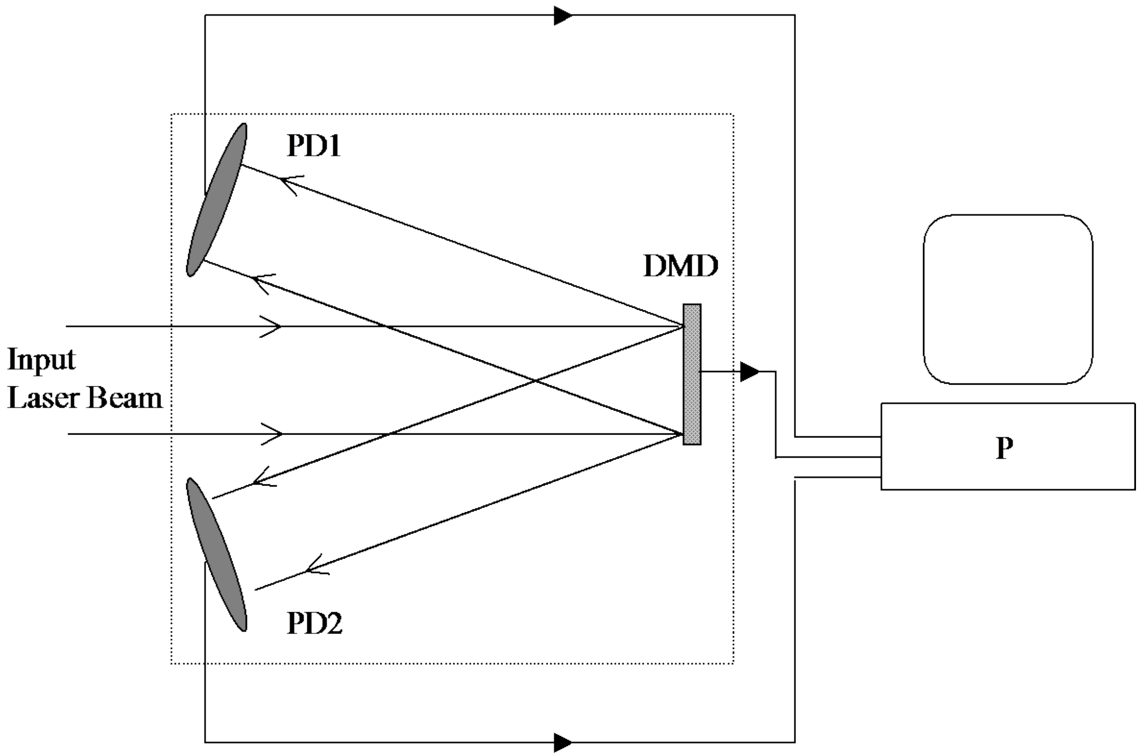
- Digital Micromirror Device (DMD) SLM deployed for single pixel-imaging, first proposed and demonstrated by **Riza[1] in 2001** for image reconstruction using an *agile pixel*.




***Agile Pixel:***
***Shape and Location of Each Irradiance Sampling Pixel is Unique & Programmable By SLM***
***- slit, pin-hole, etc***


[1] S. Sumriddetchkajorn, N.A. Riza, "Micro-electro-mechanical system-based digitally controlled optical beam profiler," Appl. Opt. 41, 3506-3510 (June 2002). (Received Oct.24, 2001).
[2] N. A. Riza, "Digital optical beam profiler," USA Patent No. US6922233 B2, filling date: 2003, publication date: 2005.

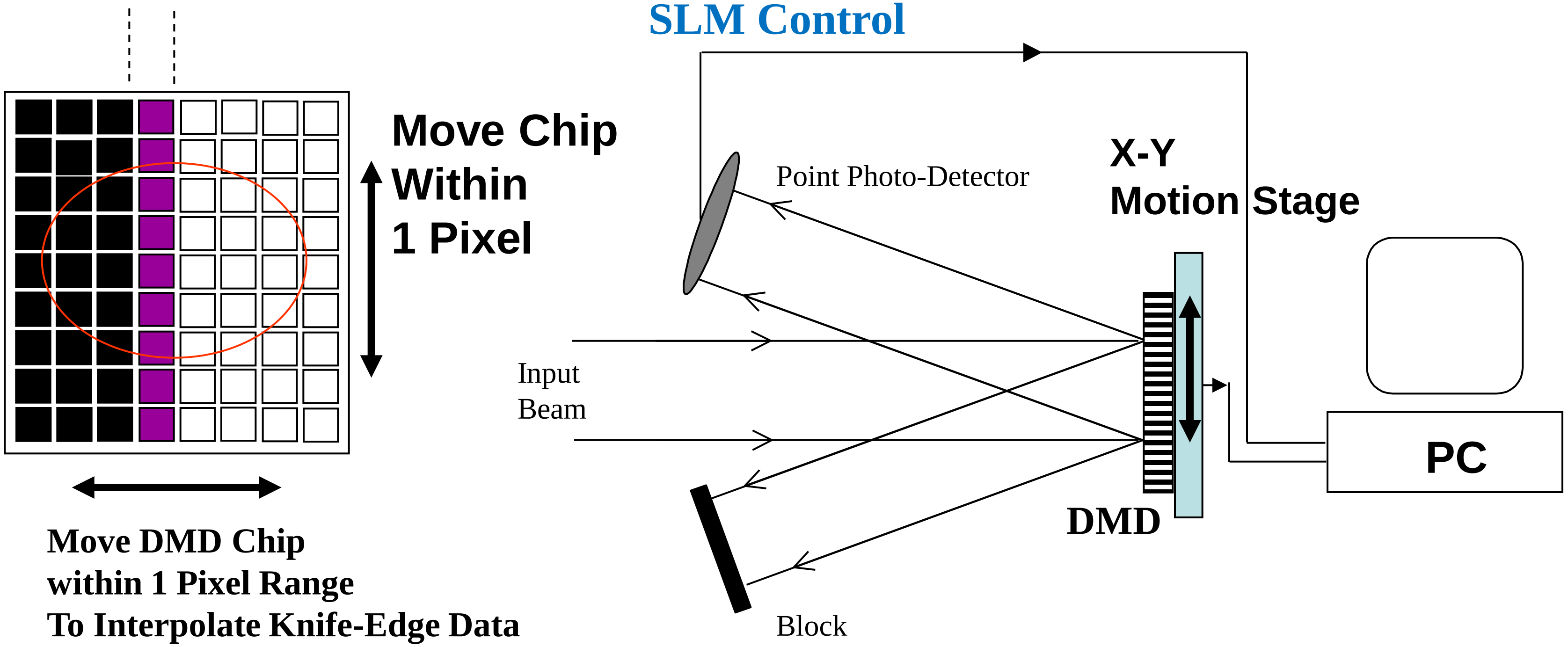
# 2003 – Riza
# SLM-based Dual Pixel (i.e. Dual Point Detector) 2-D Imager with Agile Pixel




-- Accurate Even when Input Optical Power Fluctuates during Pixel to pixel scanning operation implemented in DMD

[1] N. A. Riza and M. J. Mughal, “The NU-POWER All-Digital Beam Profiler: A Powerful New Tool for Spatially Characterizing Laser Beams,” SPIE Photonics North Conf. Paper 101-721, May 2003
[2] N. A. Riza and M. J. Mughal, "Optical Power Independent Optical Beam Profiler," Optical Engineering, 43, 4, April 2004..
[3] N. A. Riza and M. J. Mughal, “Digital optical beam profiler ,” USA Patent no. US7092079 B2, filling date: 2003, publication date: 2006.

# 2005 – Riza
# SLM-based Single Pixel 2-D Super Resolution Imager using Hybrid Analog-Digital SLM Control




- Move Entire DMD Chip by N Sub-Pixels in X and Y over a 1 Pixel Range
- Fast as Motion Range is Very Small

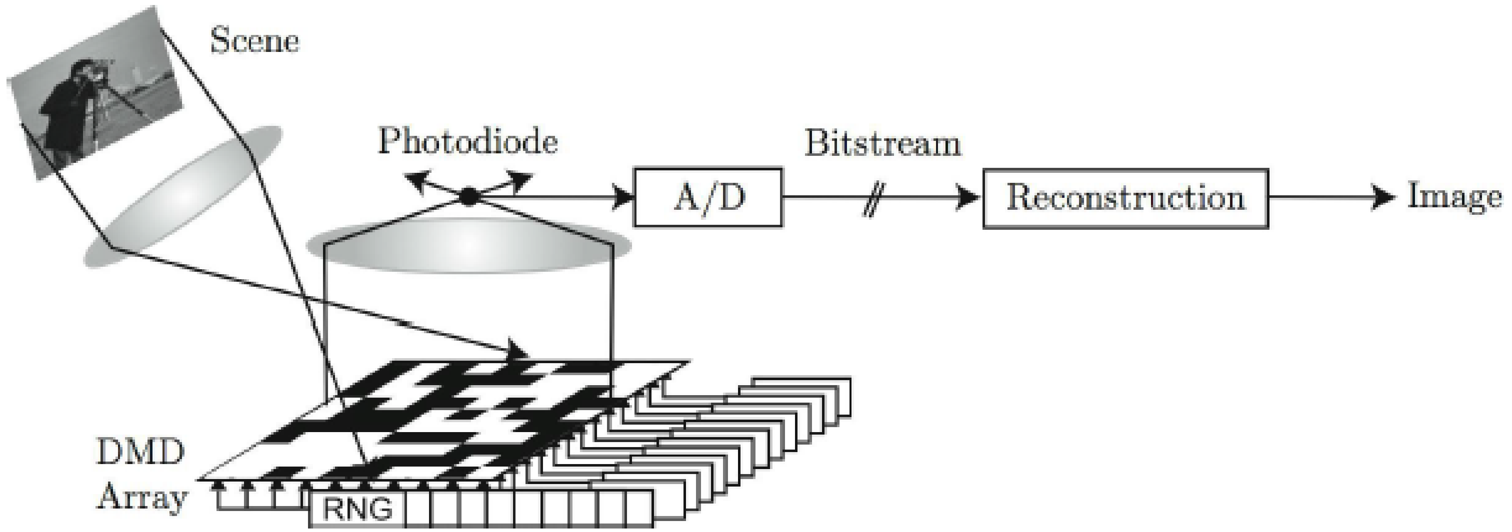
**Super Resolution Irradiance Mapper --- Resolution ~ Pixel/N**

- Use Data Interpolation Image Processing Algorithms

N. A. Riza and F. N. Ghauri, "Super Resolution Hybrid Analog–Digital Optical Beam Profiler Using Digital Micromirror Device," IEEE Photonics Technology Letters, vol. 17, no. 7, (2005).

## 2006 – R. Baranuik Group
## DMD-based Single Pixel 2-D Imager used for Implementing Compressive Sensing

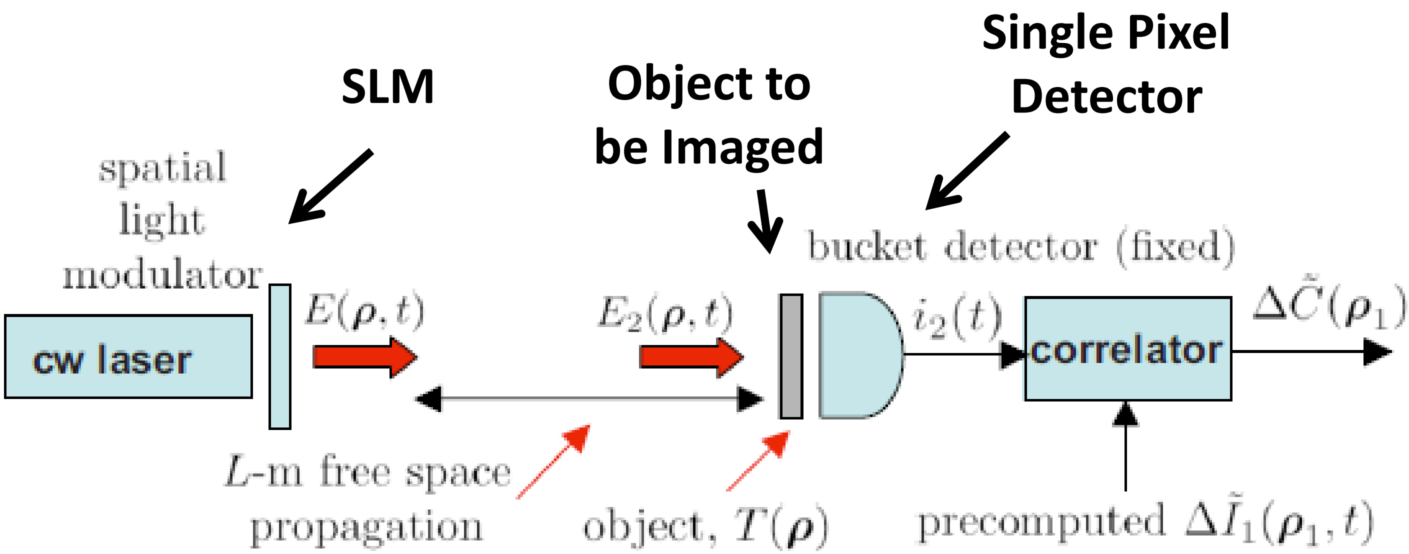
- **Takhar et al. at Rice University (USA)** implemented Compressive Sensing on Riza’s basic design **single pixel imager**.




D. Takhar, J. N. Laska, M. B. Wakin, M. F. Duarte, D. Baron, S. Sarvotham, K. F. Kelly, R. G. Baraniuk, “A new compressive imaging camera architecture using optical-domain compression ,” Proc. of Computational Imaging IV at SPIE Electronic Imaging, vol. 6065, 2006.

# 2008 – Shapiro
# Ghost Single Pixel Imager
## (Case of Active Imaging)

- **In 2008, Shapiro** demonstrated **Ghost Imaging** using a **single pixel detector**.

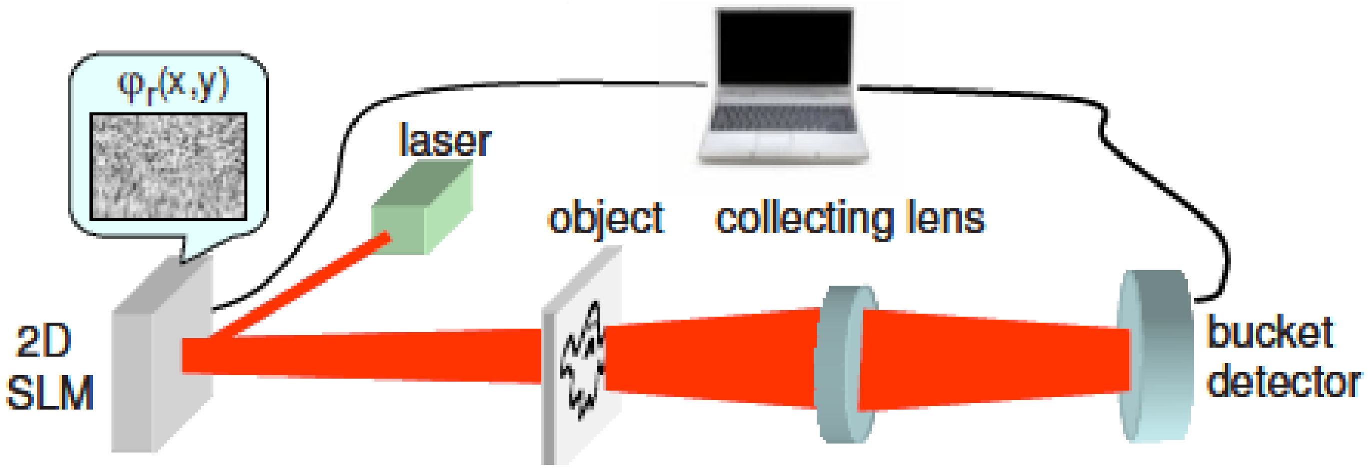



**Experimental setup in [1] uses a single pixel photodiode**

Jeffrey H. Shapiro, "Computational ghost imaging," Phys. Rev. A **78**, 061802(R), (2008).

# 2009 – Silberberg
# Ghost Single Pixel Compressive Imager
# (Case of Active Imaging)

- **Silberberg in 2009** implemented **compressive** sensing on **ghost imaging.**

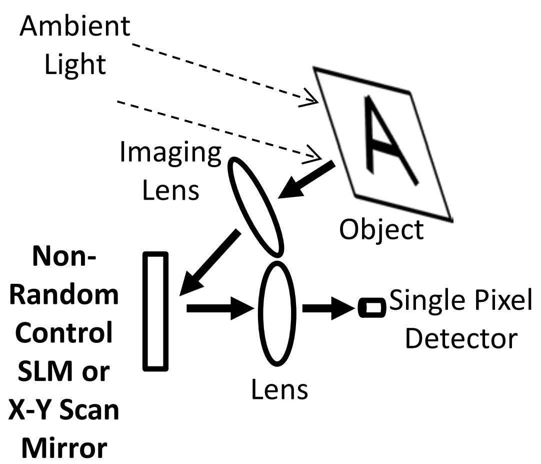



**Experimental setup in [1] uses a single pixel photodiode**


O. Katz, Y. Bromberg, Y. Silberberg, “Compressive ghost imaging,"  Applied Physics Letters 95, 131110, (2009).

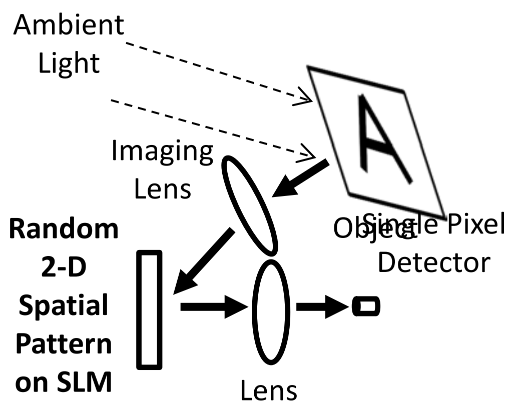
# Conventional vs Compressive vs Ghost

## X-Y Mirror-1969-F. O. Huck
## Code SLM-(active) 1999-N. A. Riza
## SLM (passive)-2001-N. A. Riza
## SLM (active +passive ) 2010 - Riza



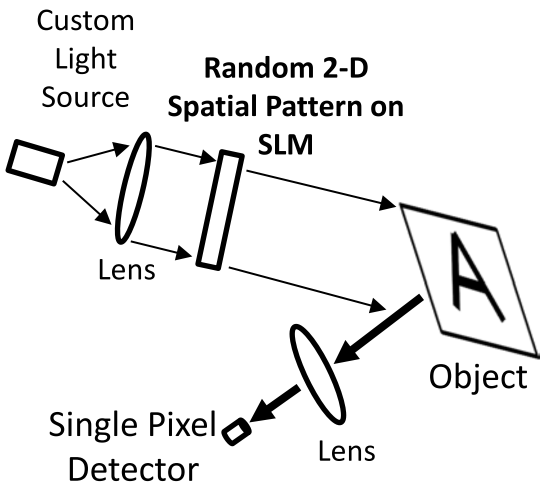

- **Passive, Active and Passive+Active Imaging**
- **Object is imaged onto Spatial Light Modulator (SLM) or X-Y scan mirror which sequentially directs the image irradiance onto a point detector.**
- **Image reconstruction is sequential (pixel by pixel) using non-random and smart (agile pixel) SLM/ Mirror control.**

## R. G. Baraniuk-2006
## Implemented Compressive Sensing on Riza's SLM Imager




- **Passive Imaging**
- **Object is imaged onto SLM, programmed with random sparse patterns, which directs the image irradiance onto a single pixel detector. Iterative processing between SLM coded patterns and corresponding detector values allows image reconstruction.**
- **Image reconstruction is not sequential (pixel by pixel). It is iterative.**

## J. H. Shapiro-2008
## Ghost




- **Active Imaging**
- **Object illuminating random SLM coded light is collected by a single pixel detector. Iterative processing between SLM coded patterns and corresponding detector values allows image reconstruction.**
- **Image reconstruction is not sequential (pixel by pixel). It is iterative.**

# CS: Compressive Sensing (or Compressed Sensing) based Image Reconstruction Principles via Agile Pixel Camera

Image Estimation Using:

- Measurement of N photo-detected Signals
  via Point Detector (PD) in Camera

- N Spatial Pattern Masks used for the N PD Measurements

- Compressed Sensing Reconstruction Algorithm
  via Numerical Optimization deployed on PD measurements
  and Spatial Mask Information to Estimate Image

- Change Image Processing Optimization Criteria and Repeat Image Acquisition and CS Processing Steps to Improve Image Quality

# Random Pattern-based Image Reconstruction

**[e.g., Apart from CS, also can use Classic Linear Reconstruction (non CS method)]**

$$\text{Image Reconstruction} = \underbrace{\sum_{i=1}^{M}}_{\text{Sum over M measurements}} \left( \underbrace{\text{Point PD detected intensity } I_i}_{i^{th}\text{ weight}} \times \underbrace{\text{SLM programmed random pattern } P_i}_{i^{th}\text{ measurement}} \right)$$

**M**: number of Random 2-D patterns

# Random Pattern-based Image Reconstruction

## (Linear Reconstruction used in Tera Hertz Sensing Imaging)

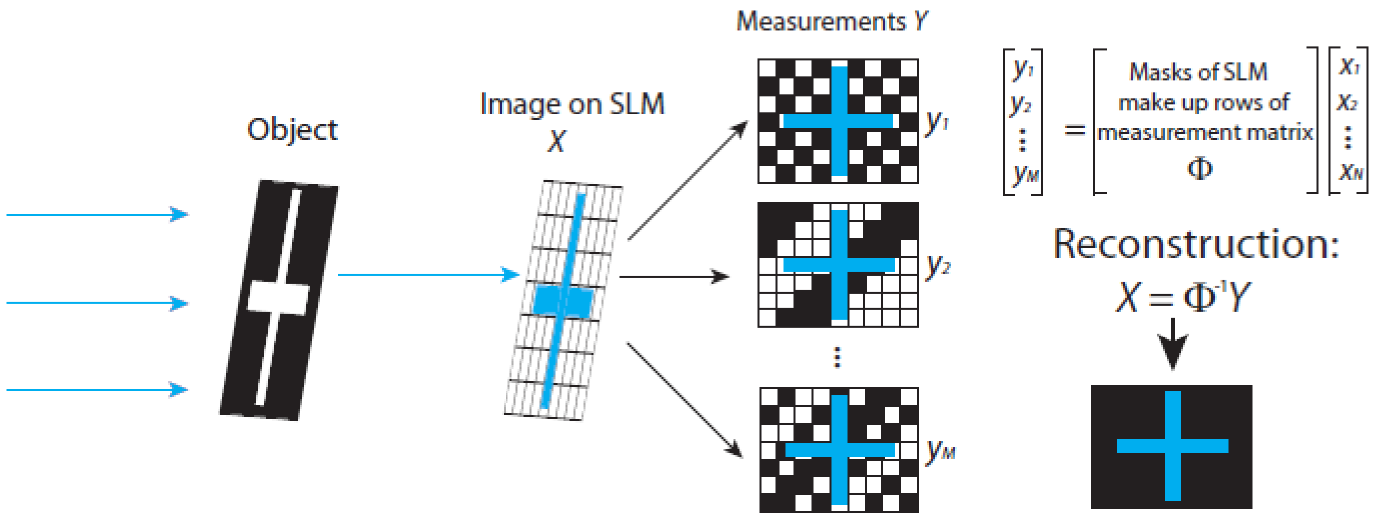



Fig. 1. Schematic depicting multiplex imaging process where the spatial modulation of a formed image allows for the reconstruction using a single pixel detector. Example $7 \times 9$ binary masks taken from rows of the $63 \times 63$ $S$-matrix are shown.

Shrekenhamer, David, Claire M. Watts, and Willie J. Padilla. "Terahertz single pixel imaging with an optically controlled dynamic spatial light modulator." Optics express 21.10 (2013): 12507-12518.

# Random Pattern-based Image reconstruction

## (used in TeraHertz Imaging)

#187520 - $15.00 USD    Received 21 Mar 2013; revised 5 May 2013; accepted 7 May 2013; published 14 May 2013
(C) 2013 OSA    20 May 2013 | Vol. 21, No. 10 | DOI:10.1364/OE.21.012507 | OPTICS EXPRESS 12507

eral different types of binary coded apertures that can be used to multiplex an image - though the field is dominated by random and Hadamard based masks. Random binary masks are comprised of 1's and 0's determined by standard probability distributions such as Gaussian or Bernoulli, among others. Hadamard matrices are square matrices composed of +1's and -1's in which each row is orthogonal to all other rows [25]. To create binary masks we can use an *S*-matrix, created by omitting the first row and column of the corresponding normalized Hadamard matrix, substituting all 1's with 0's, and all -1's with 1's. Each row of this matrix can then be used as a 1, 0 mask for successive measurements in a single pixel imaging system.

We define a one- or two- dimensional image by a vector $X$ with $N$-elements (this can be done by concatenating the rows into a single column). We represent a single measurement $y_j$ in a multiplexing scheme by the following expression:

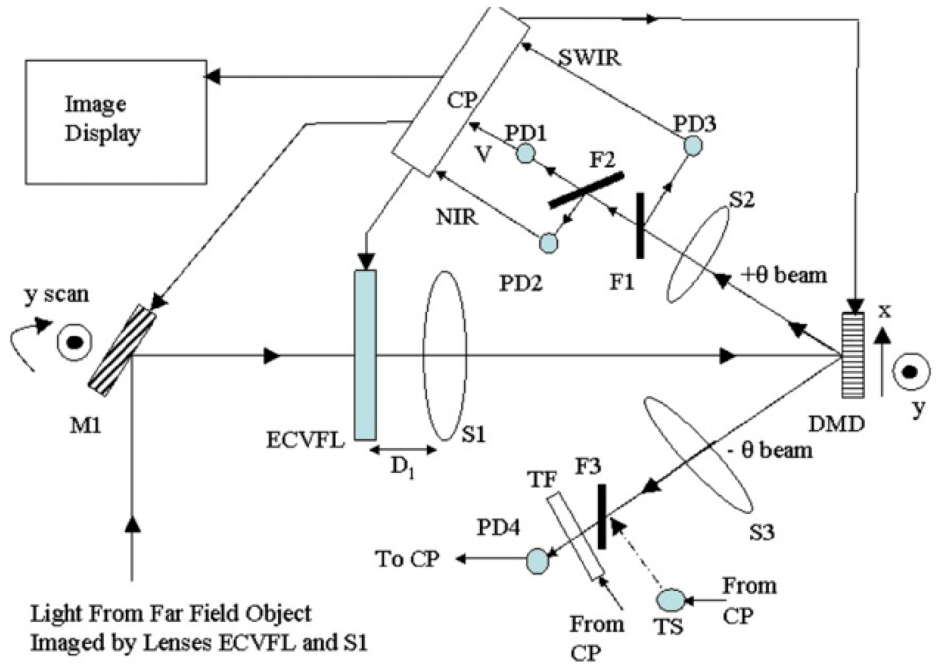
$$y_j = \sum_{i=1}^{N} \phi_{ji} x_i \tag{1}$$

or the matrix equation $Y = \Phi \times X$. In this equation, $Y$ is a column vector with $M$-elements representing the $M$ measurements taken and $\Phi$ is the $M \times N$ measurement matrix, in which each row represents a mask displayed on the SLM. For example, $\Phi$ that corresponds to a raster

Shrekenhamer, David, Claire M. Watts, and Willie J. Padilla. "Terahertz single pixel imaging with an optically controlled dynamic spatial light modulator." Optics express 21.10 (2013): 12507-12518.

# 2010 – Riza
# SLM-based Active and Passive Dual Pixel 3-D Imager

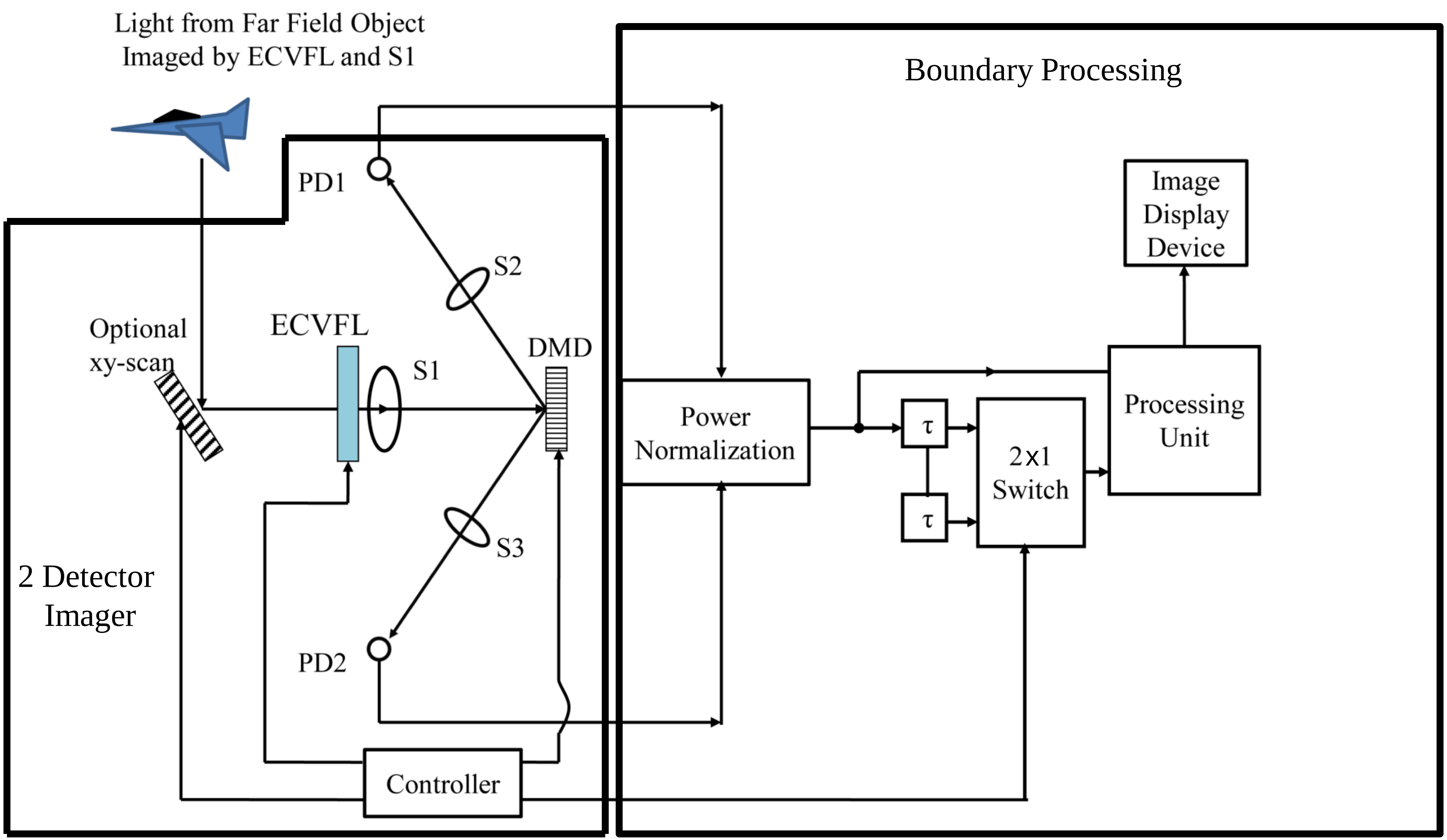
- DMD-based Single Pixel Imaging using Electronic Lens for 3-D Multi-Spectral Light Irradiance Capture (Passive) and Illumination (Active)




**DMD-based broadband optical image sensor for robust imaging[1]**

N. A. Riza, S. A. Reza, P. J. Marraccini, "Digital Micro-mirror Device-based broadband optical image sensor for robust imaging applications," Optics Communications, vol. 284, no. 1, pp. 103-111, (2011). On-line version 2010.

# 2012 – Riza
# SLM-based Dual Pixel Passive 3-D Imager for Boundary Detection

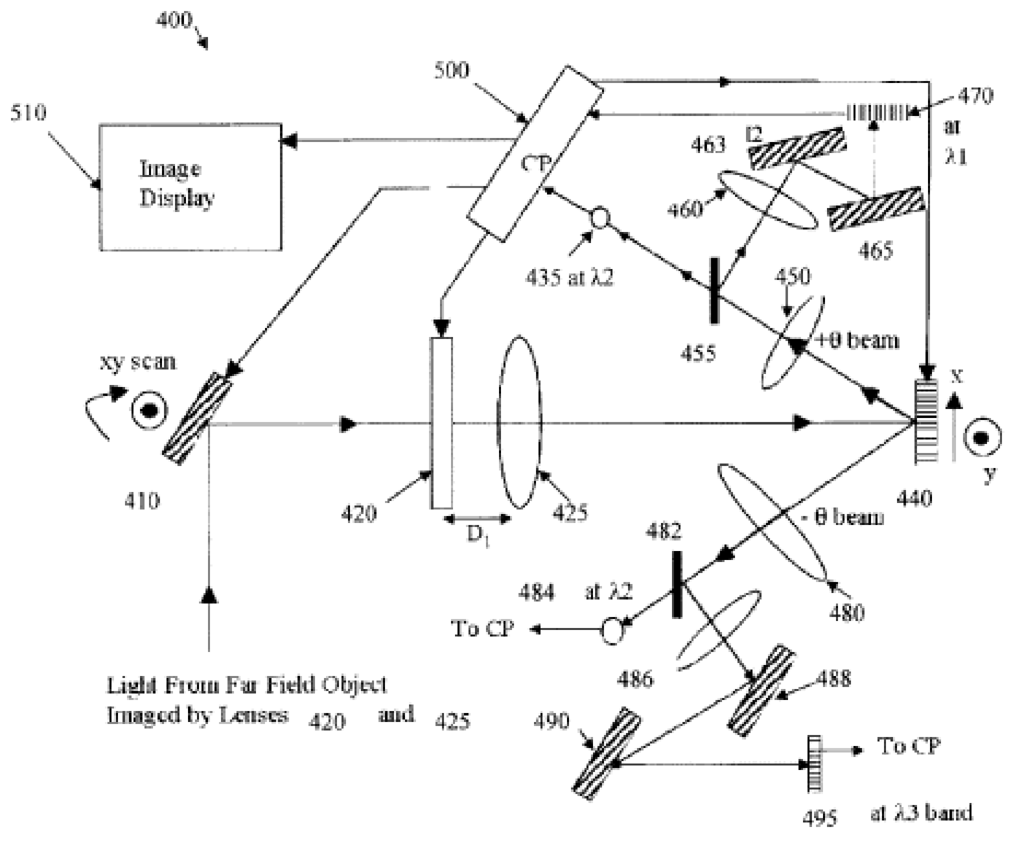



τ: Time delay of 1 pixel.


N.A. Riza, P. J. Marraccini, and C. Baxley, "Data Efficient Digital Micromirror Device-Based Image Edge Detection Sensor Using Space-Time Processing ," IEEE Sensors Journal ,2012.

# 2012 – Riza
# SLM-based Passive Parallel-Serial Scan 3-D Imager

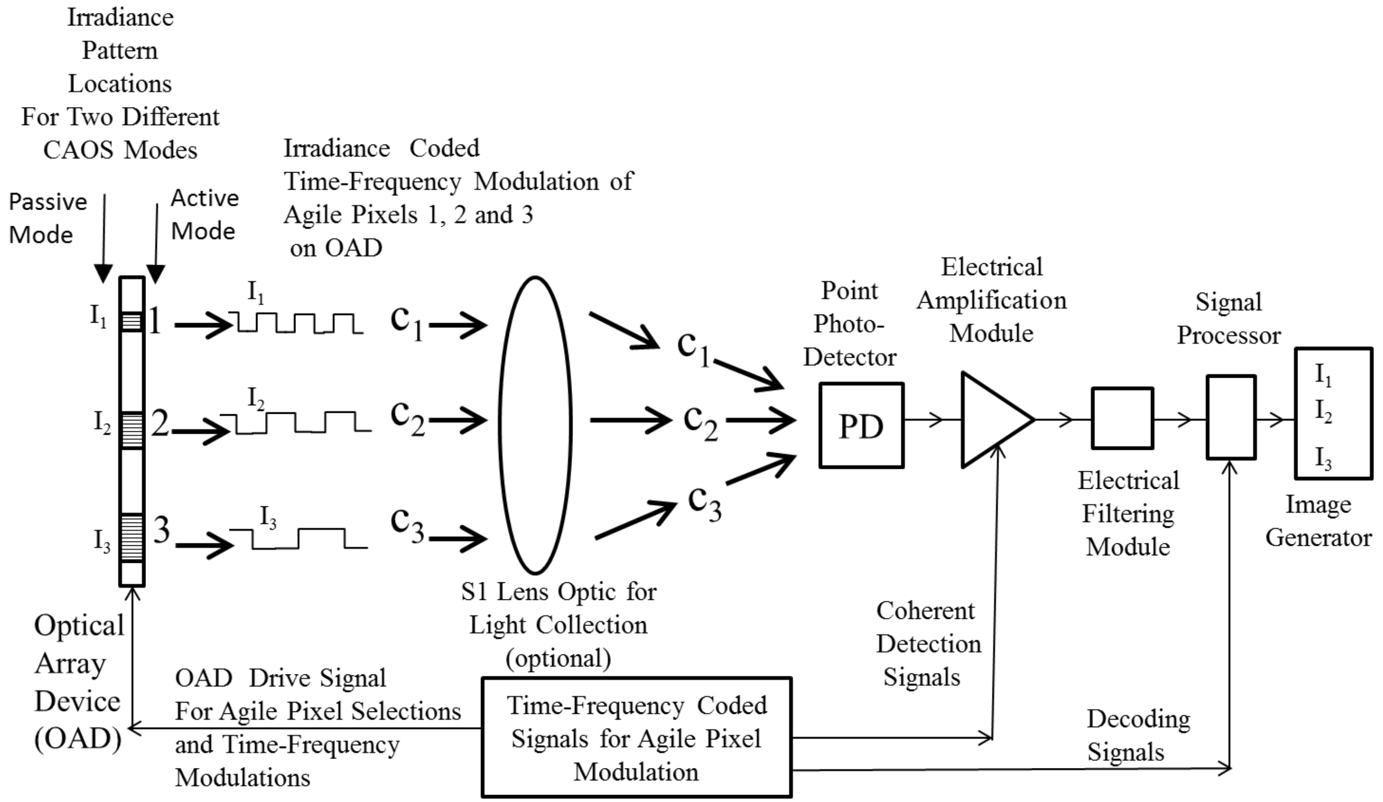
- DMD-based Single Pixel Imaging using Electronic Lens for 3-D Multi-Spectral Light Irradiance Capture (Passive) using both Point Detector (Serial Scan) and CCD/CMOS/2-D Detector Array (Parallel Scan of Image Irradiance)




N. A. Riza, Compressive optical display and imager, US Patent 8783874 B1, July 22, 2014 (filed 2012)

# 2014 – Riza
# Coded Access Optical Sensor (CAOS) Imager

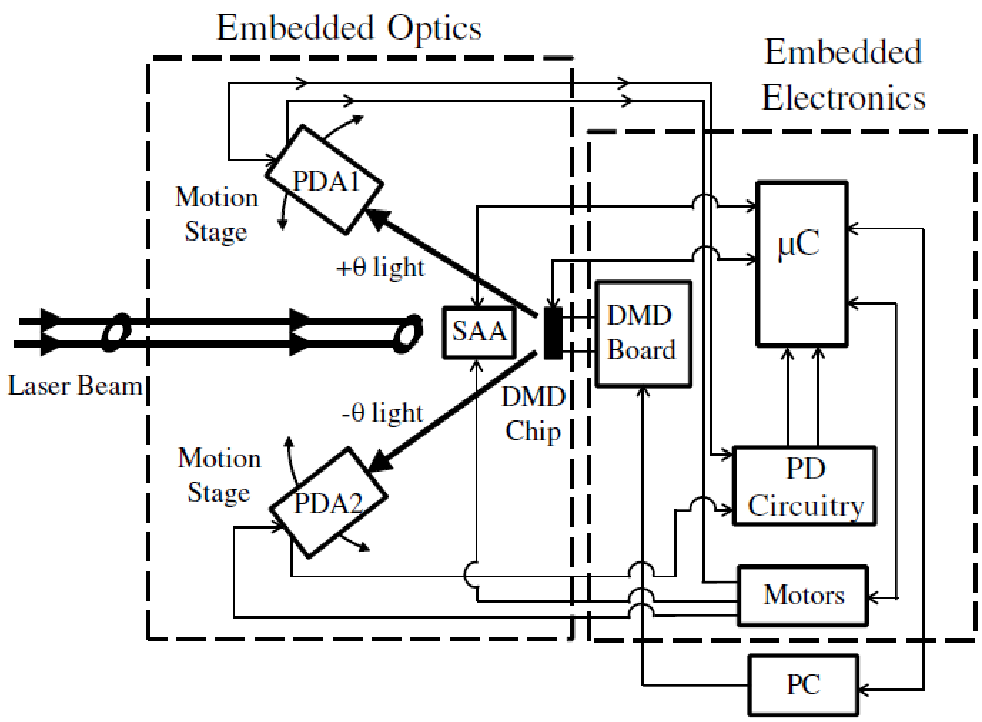
- **Active and Passive Illumination Designs**
- **Paradigm Shift from 2-D Spatial Domain Mask-type Coding (e.g., random masks for compressive imaging) to RF Wireless Communication Style Non-Random Time-Frequency Domain encoding/ decoding (e.g., CDMA, FDMA, TDMA and hybrid versions) of many programmed agile pixels**
- **Can deploy optical/electrical coherent detection.**




N. A. Riza , Patent Application .
N. A. Riza, M. J. Amin, J. P. La Torre, "Coded Access Optical Sensor (CAOS) Imager," Journal of the European Optical Society (JEOS) Rapid Publications, April 2015.

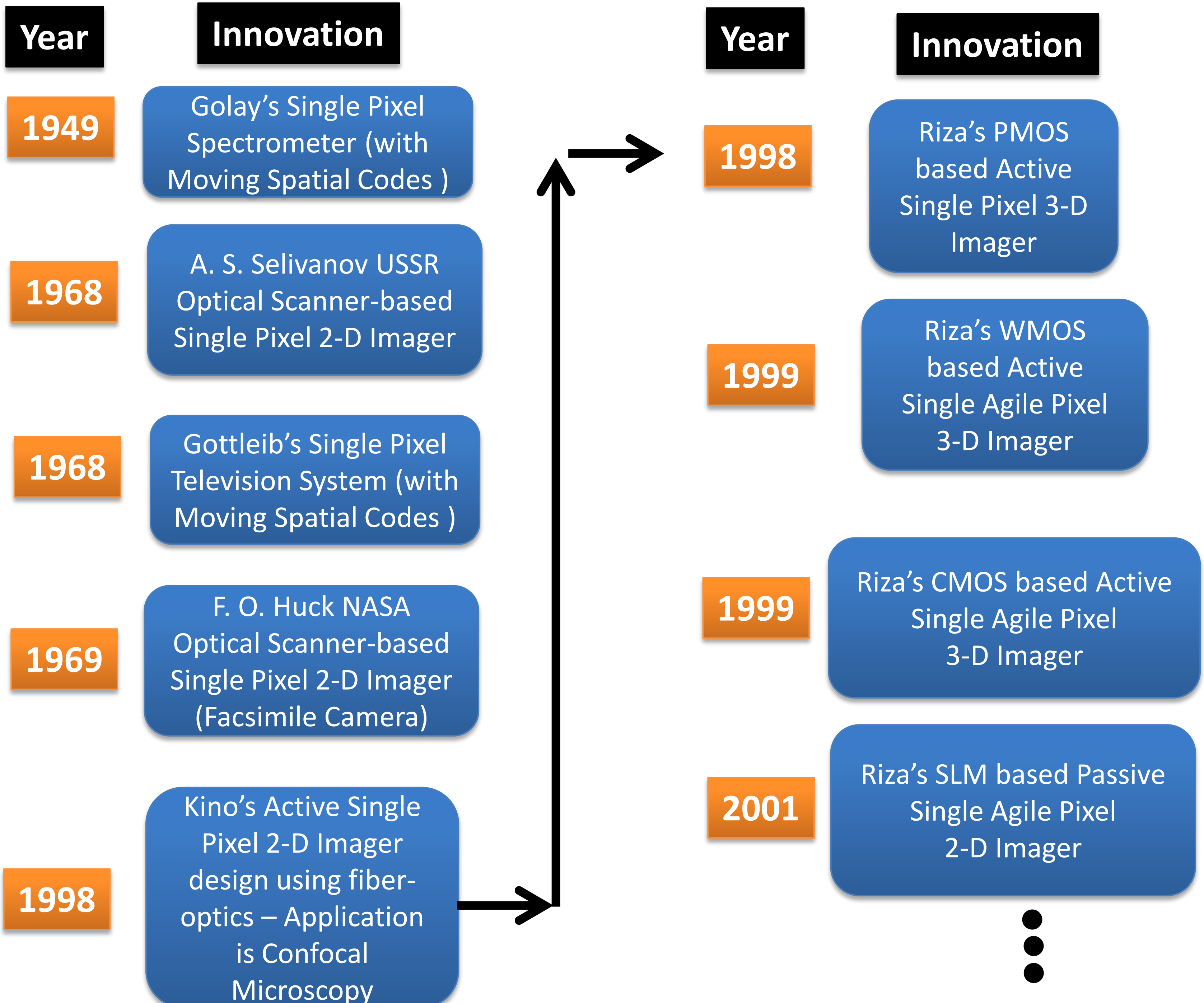
# 2015 – Riza
# Embedded Engineering Spatial Light Modulator (SLM)-based Dual Pixel Passive 2-D Imager and Spectrum Analyzer

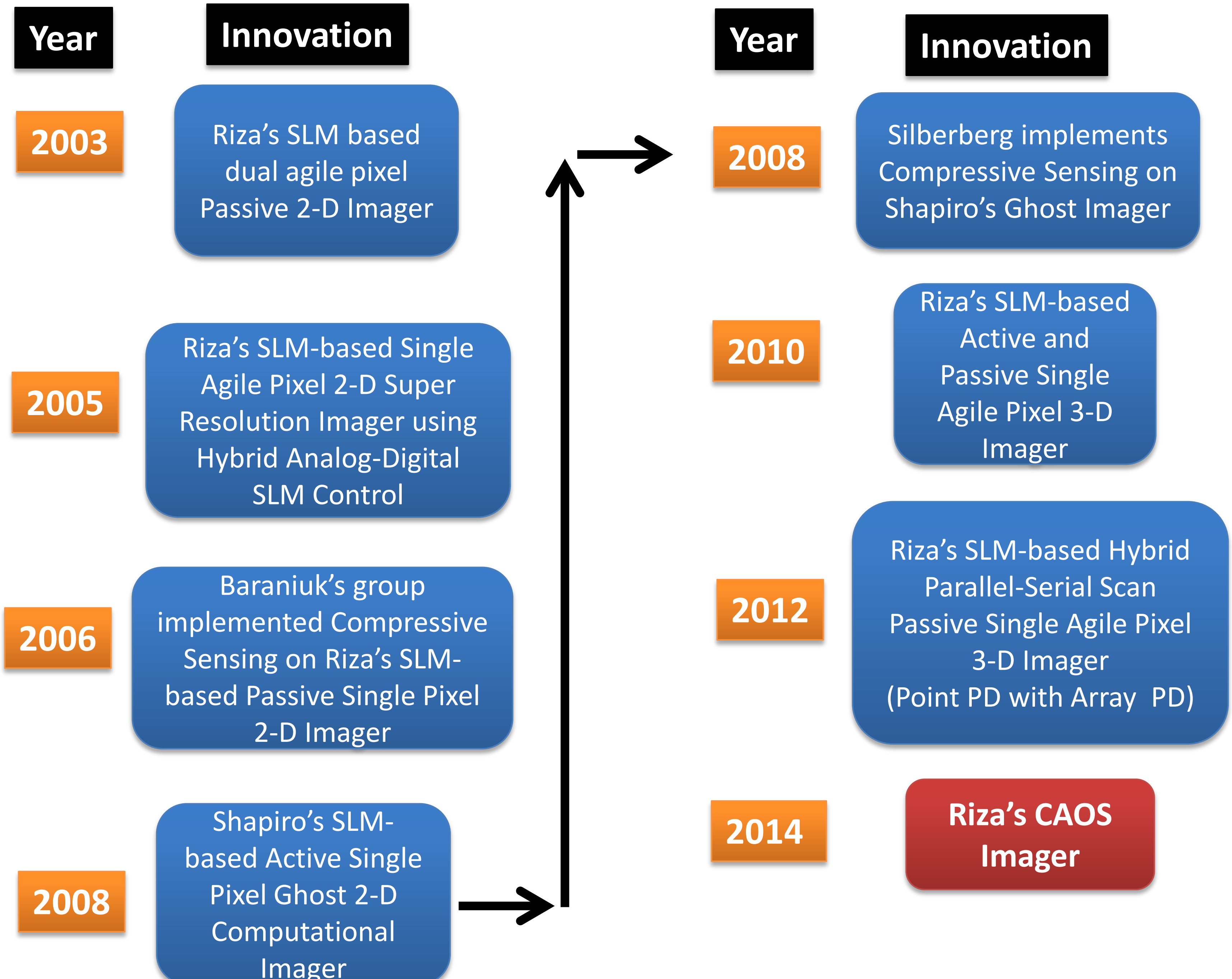
- And Embedded single pixel imaging system demonstrated by **Riza in 2015** for image reconstruction




**Embedded single pixel imaging system [1]**


M. J. Amin, J. P. La Torre and N. A. Riza, "Embedded Optics and Electronics Single Digital Micromirror Device-based Agile Pixel Broadband Imager and Spectrum Analyser for Laser Beam Hotspot Detection," Applied Optics, 54, 3547–3559, 2015.


Year
Innovation
1949
Golay’s Single Pixel Spectrometer (with Moving Spatial Codes )
1968
A. S. Selivanov USSR Optical Scanner-based Single Pixel 2-D Imager
1968
Gottleib’s Single Pixel Television System (with Moving Spatial Codes )
1969
F. O. Huck NASA Optical Scanner-based Single Pixel 2-D Imager (Facsimile Camera)
1998
Kino’s Active Single Pixel 2-D Imager design using fiber-optics – Application is Confocal Microscopy
Year
Innovation
1998
Riza’s PMOS based Active Single Pixel 3-D Imager
1999
Riza’s WMOS based Active Single Agile Pixel 3-D Imager
1999
Riza’s CMOS based Active Single Agile Pixel 3-D Imager
2001
Riza’s SLM based Passive Single Agile Pixel 2-D Imager


Year
Innovation
2003
Riza's SLM based dual agile pixel Passive 2-D Imager
2005
Riza's SLM-based Single Agile Pixel 2-D Super Resolution Imager using Hybrid Analog-Digital SLM Control
2006
Baraniuk's group implemented Compressive Sensing on Riza's SLM-based Passive Single Pixel 2-D Imager
2008
Shapiro's SLM-based Active Single Pixel Ghost 2-D Computational Imager
Year
Innovation
2008
Silberberg implements Compressive Sensing on Shapiro's Ghost Imager
2010
Riza's SLM-based Active and Passive Single Agile Pixel 3-D Imager
2012
Riza's SLM-based Hybrid Parallel-Serial Scan Passive Single Agile Pixel 3-D Imager (Point PD with Array PD)
2014
Riza's CAOS Imager