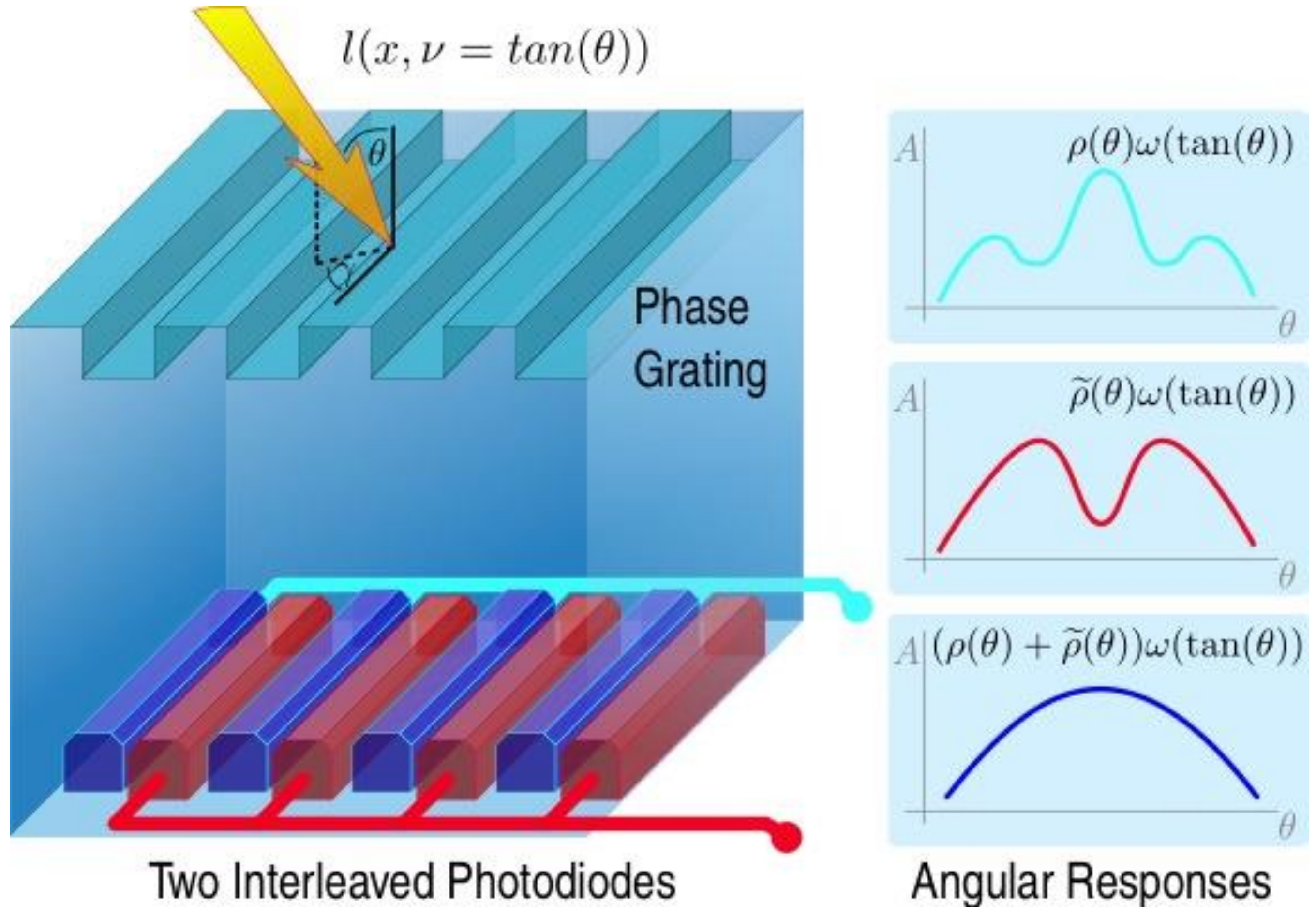


Computational Sensors

Suren Jayasuriya

Postdoctoral Fellow,

The Robotics Institute,

Carnegie Mellon University

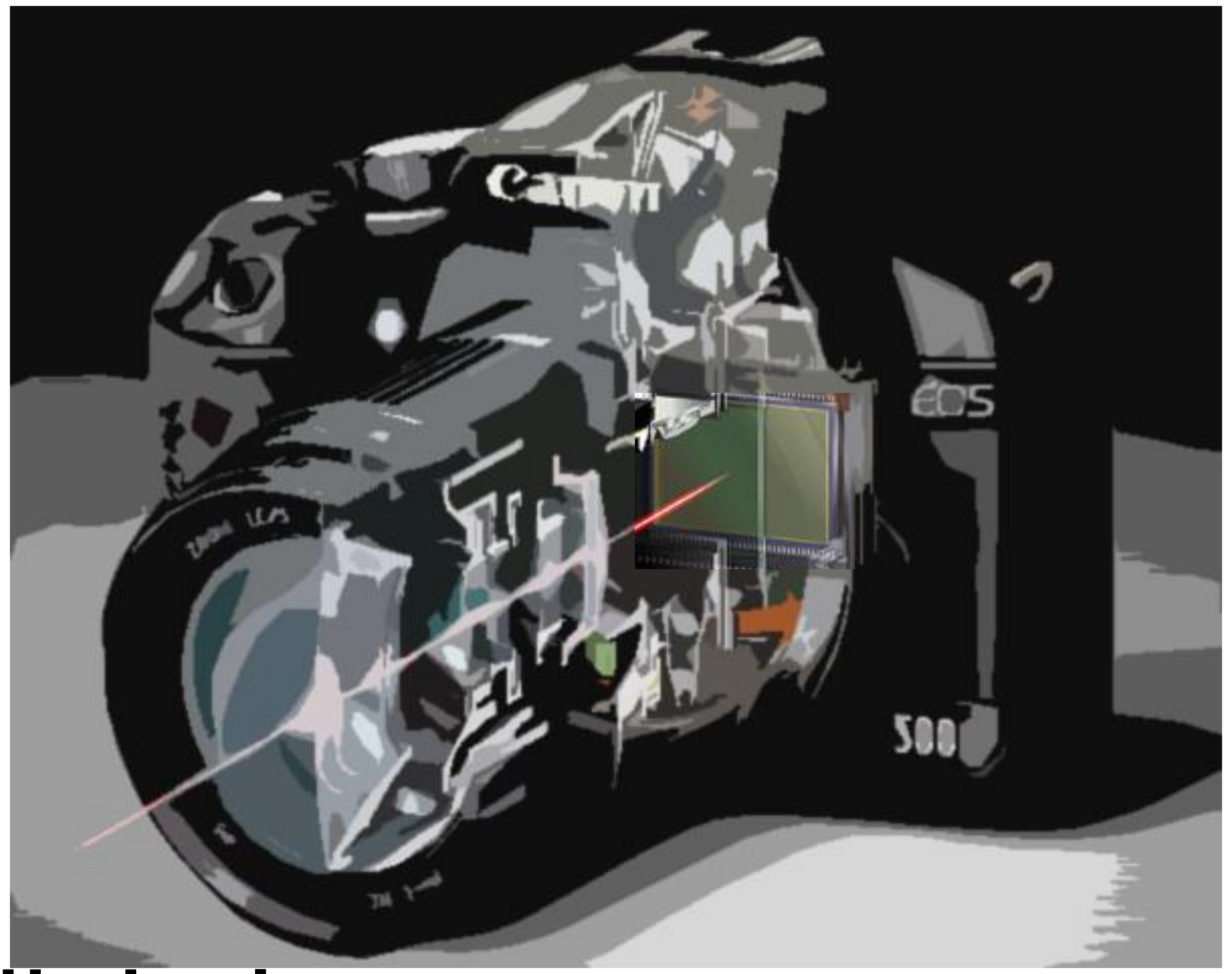
Class Announcements

1) Vote on this poll about project checkpoint date on Piazza: https://piazza.com/class/j6dobp76al46ao?cid=126

1) Reminder: Start HW5 this first week – if you haven't started by Wednesday, you should hurry up.

Computational Photography

optics to focus light on an image plane



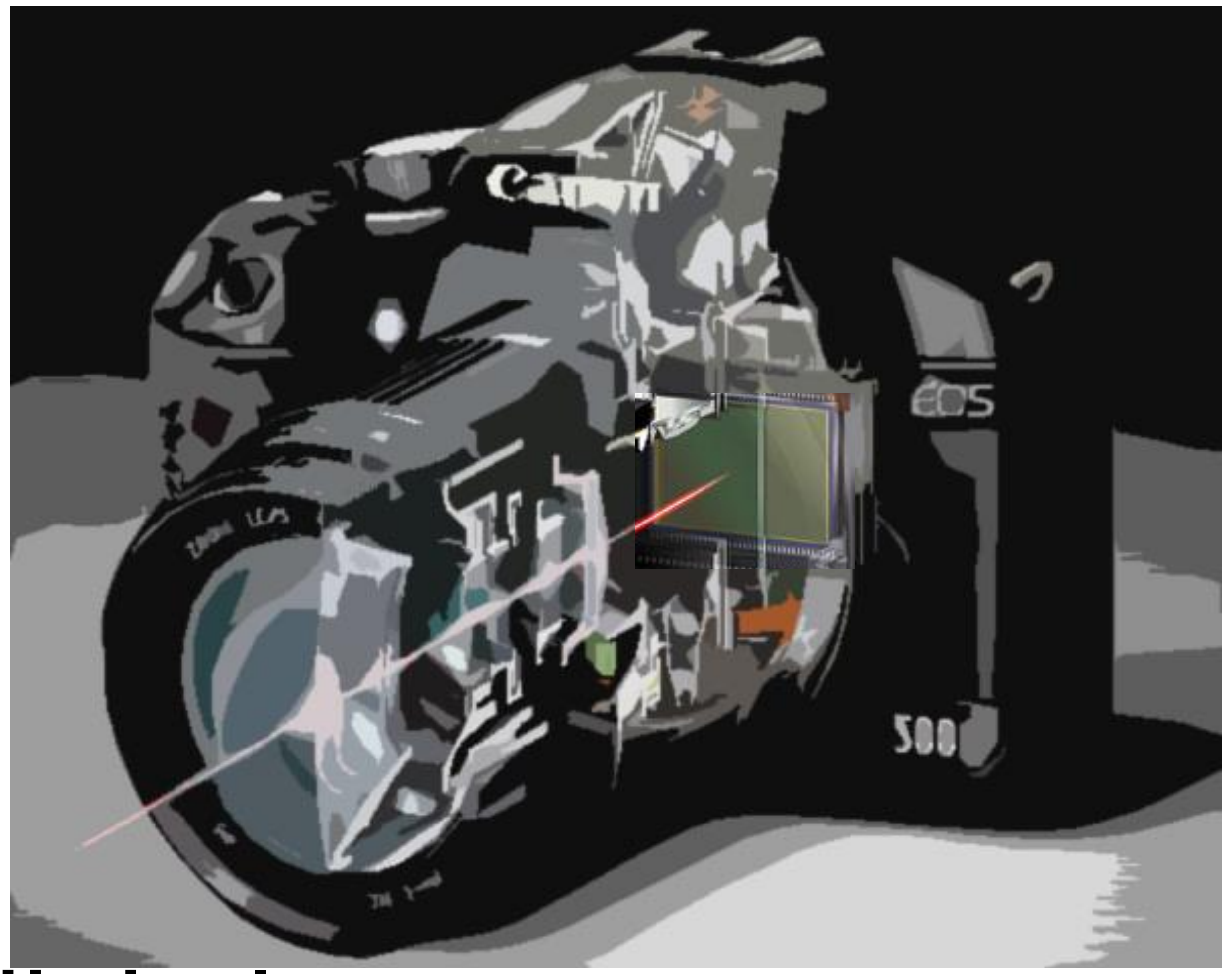
digital sensor to capture focused light (electrical process)

arbitrary computation between sensor and image

Slide courtesy of Ioannis Gkioulekas

Computational Photography

optics to focus light on an image plane

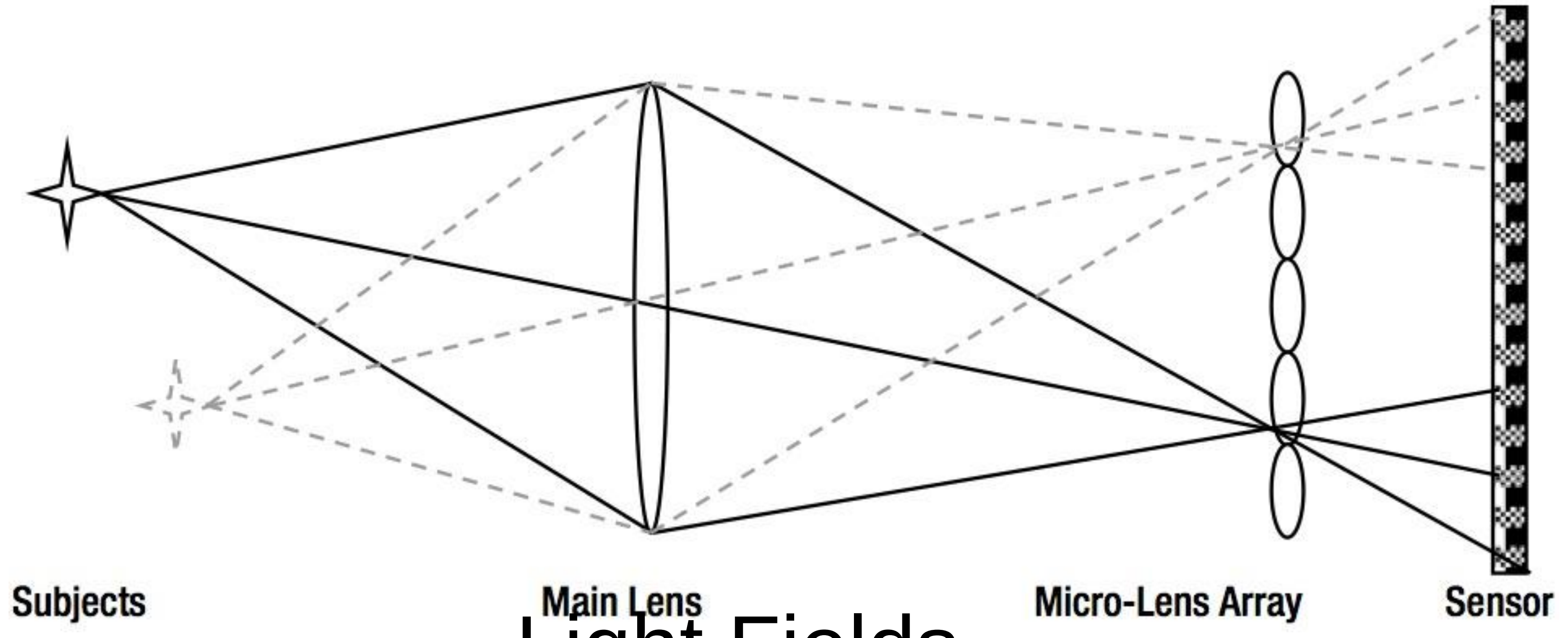


digital sensor to capture focused light (electrical process)

arbitrary computation between sensor and image

Examples include:

Coded Apertures

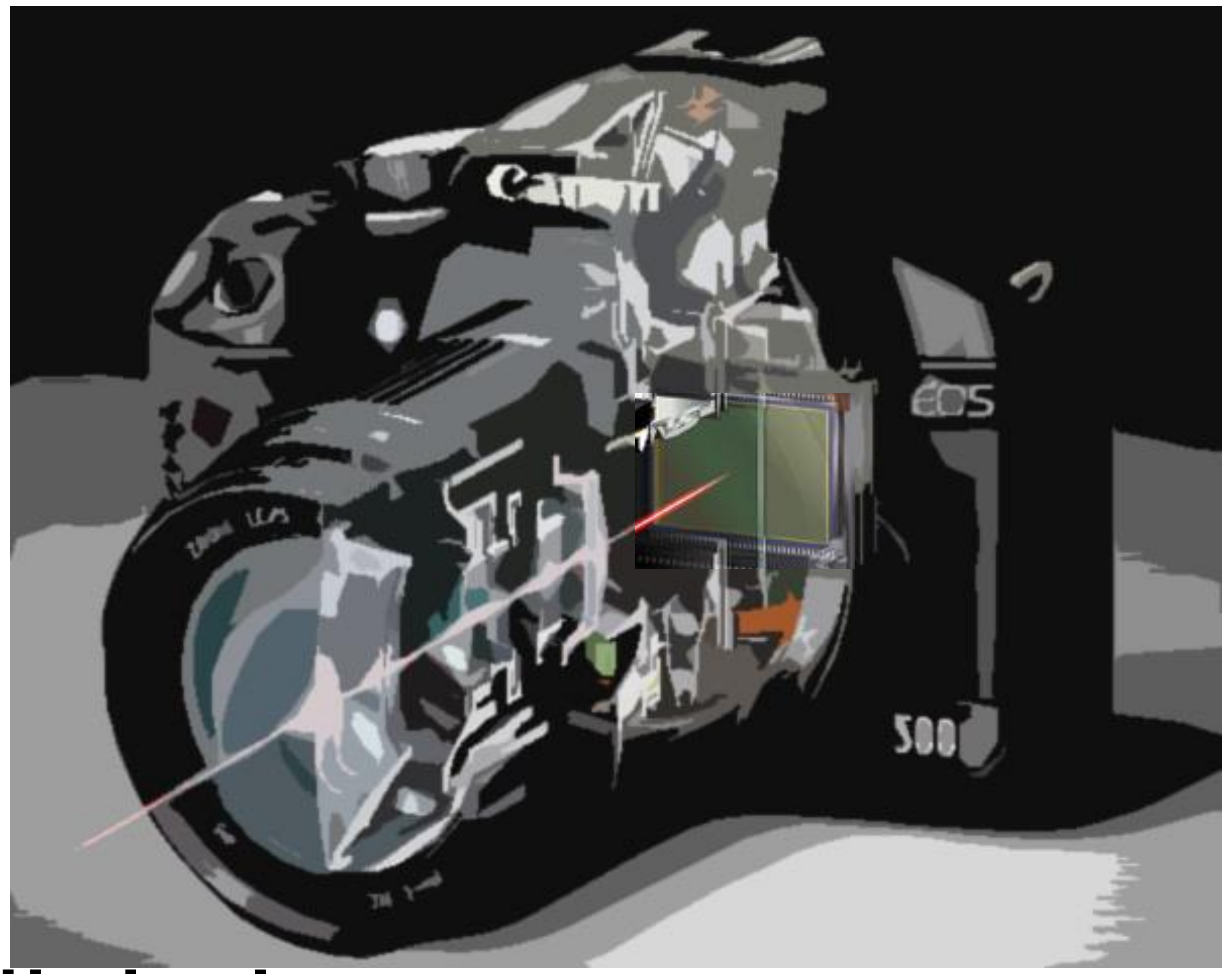


Light Fields

Slide courtesy of Ioannis Gkioulekas

Computational Photography

optics to focus light on an image plane



digital sensor to capture focused light (electrical process)

arbitrary computation between sensor and image

Examples include:

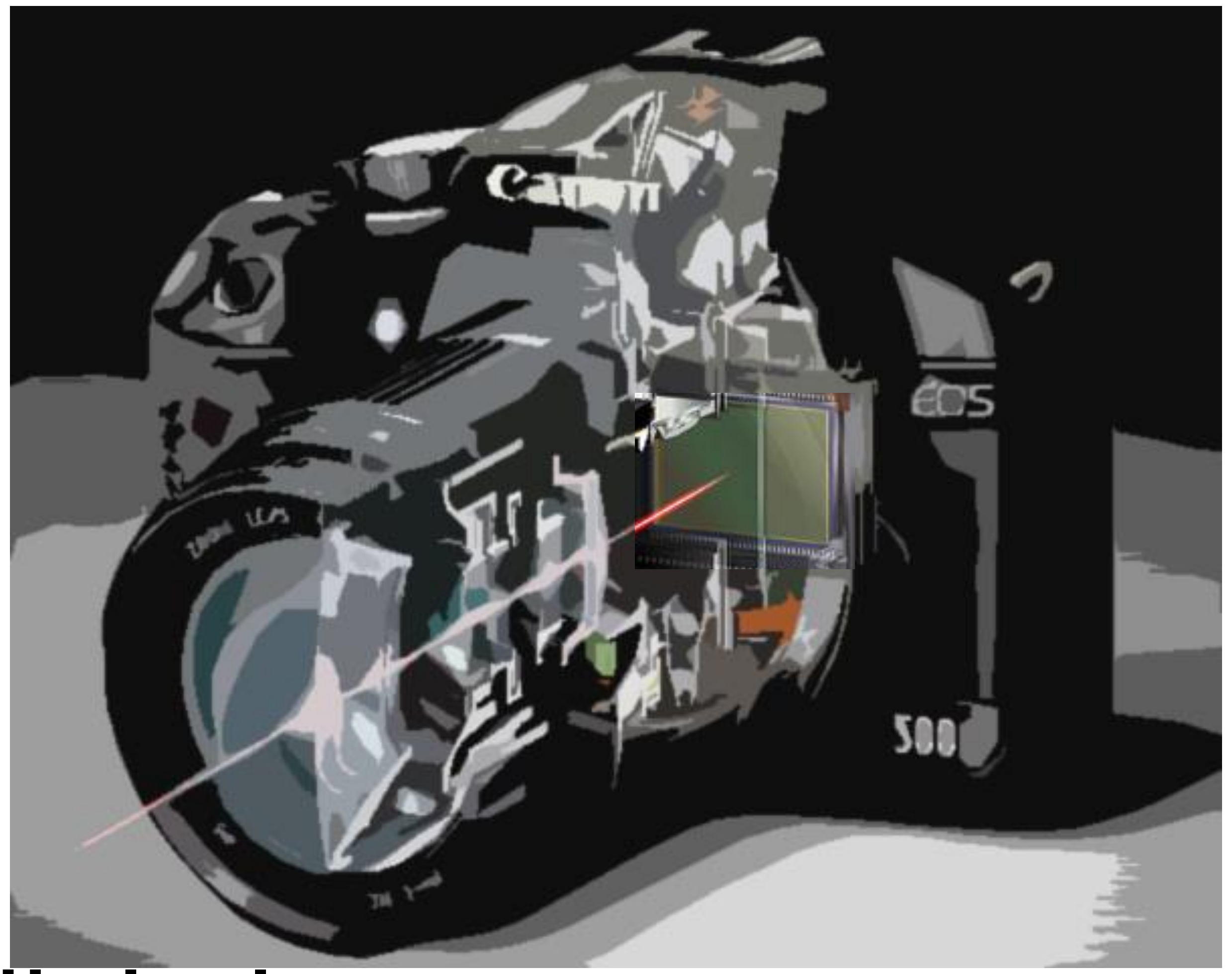
Panorama Stitching

HDR Imaging

Slide courtesy of Ioannis Gkioulekas

Computational Photography

optics to focus light on an image plane



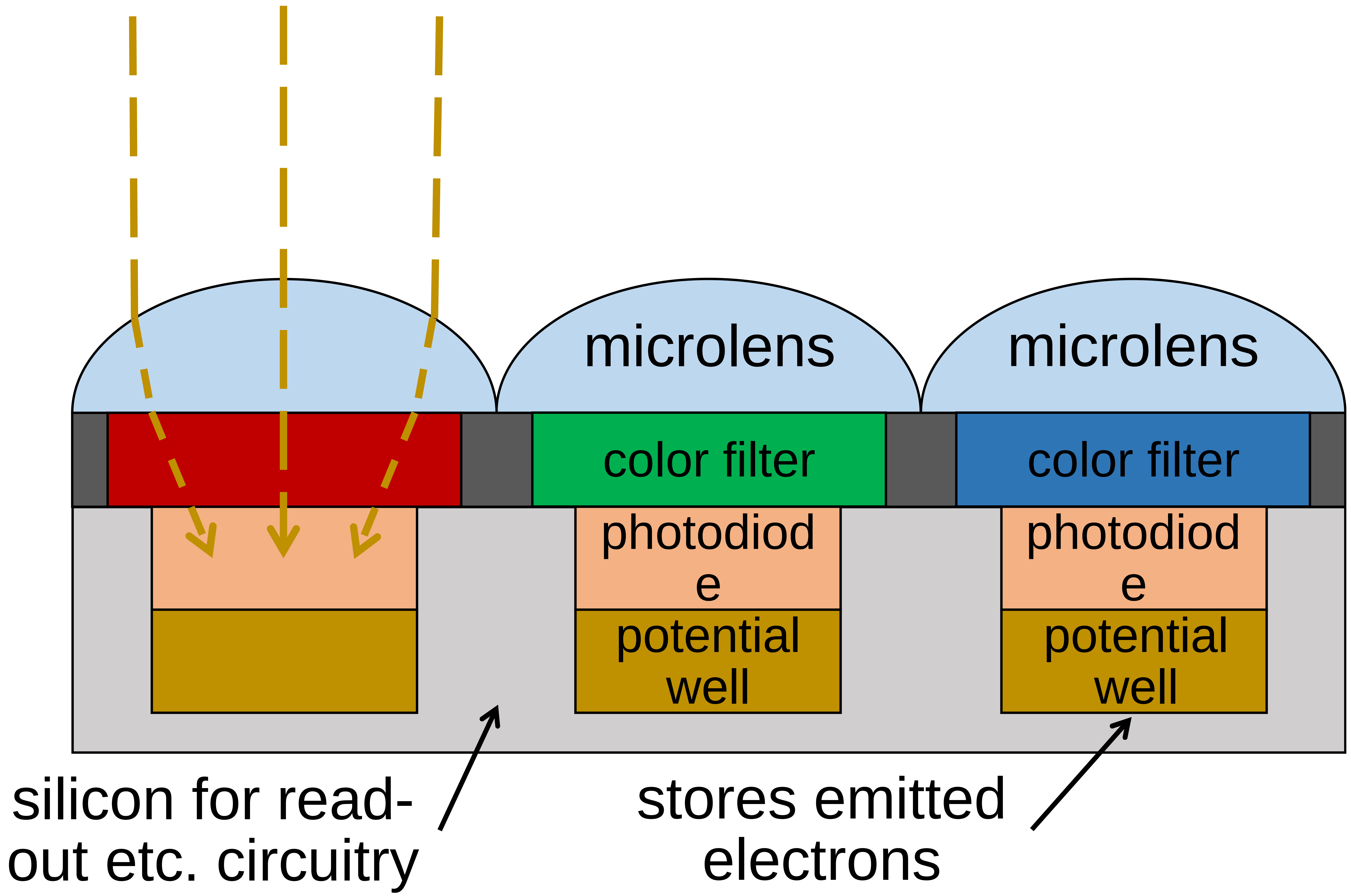
digital sensor to capture focused light (electrical process)

arbitrary computation between sensor and image

This lecture will cover recent developments in computational sensors

Slide courtesy of Ioannis Gkioulekas

Review: Traditional CMOS Image Sensors

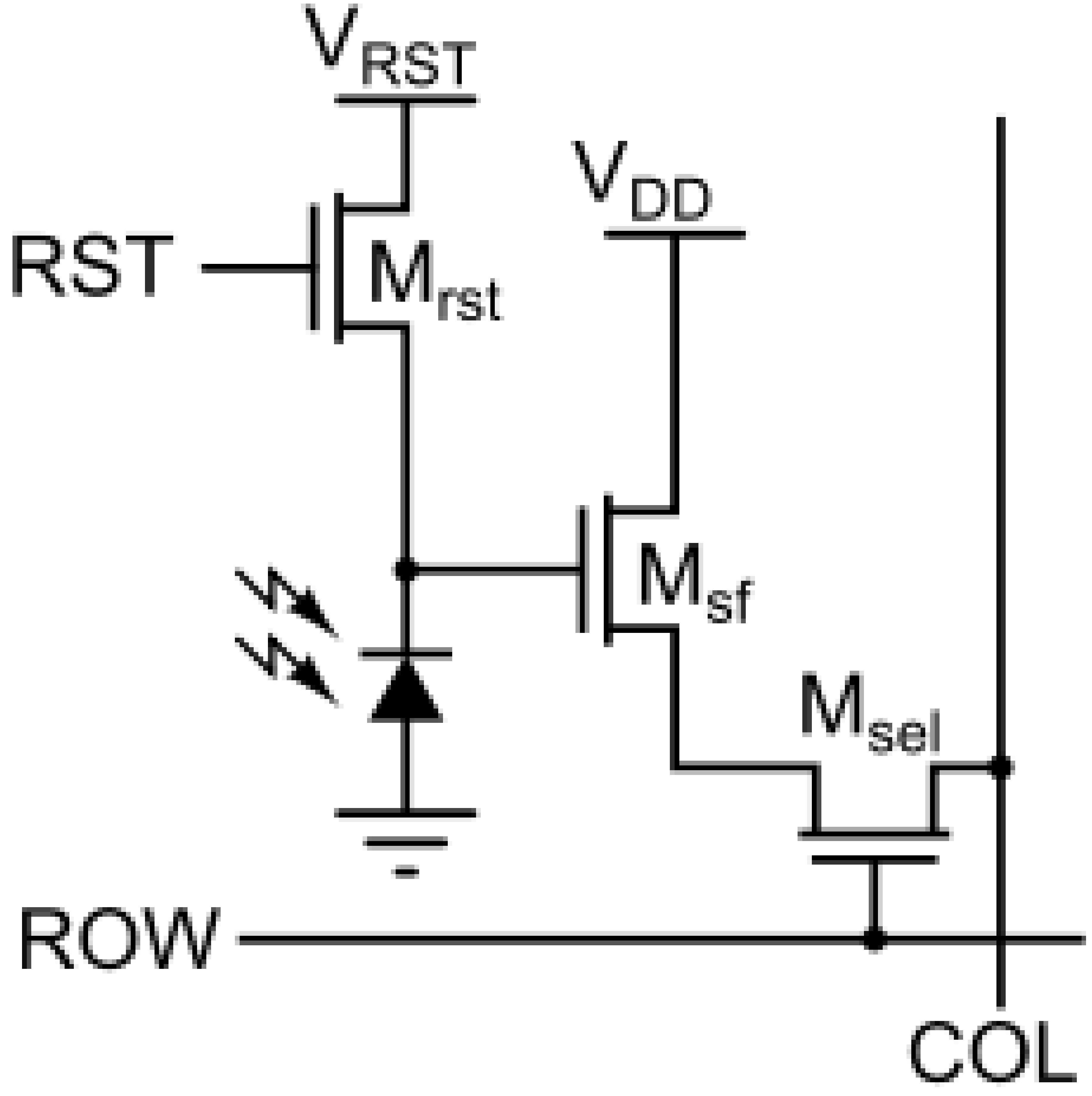


Pixel stack:

- Microlens
- Color Filter
- Photodiode
- Readout Circuitry

Slide courtesy of Ioannis Gkioulekas

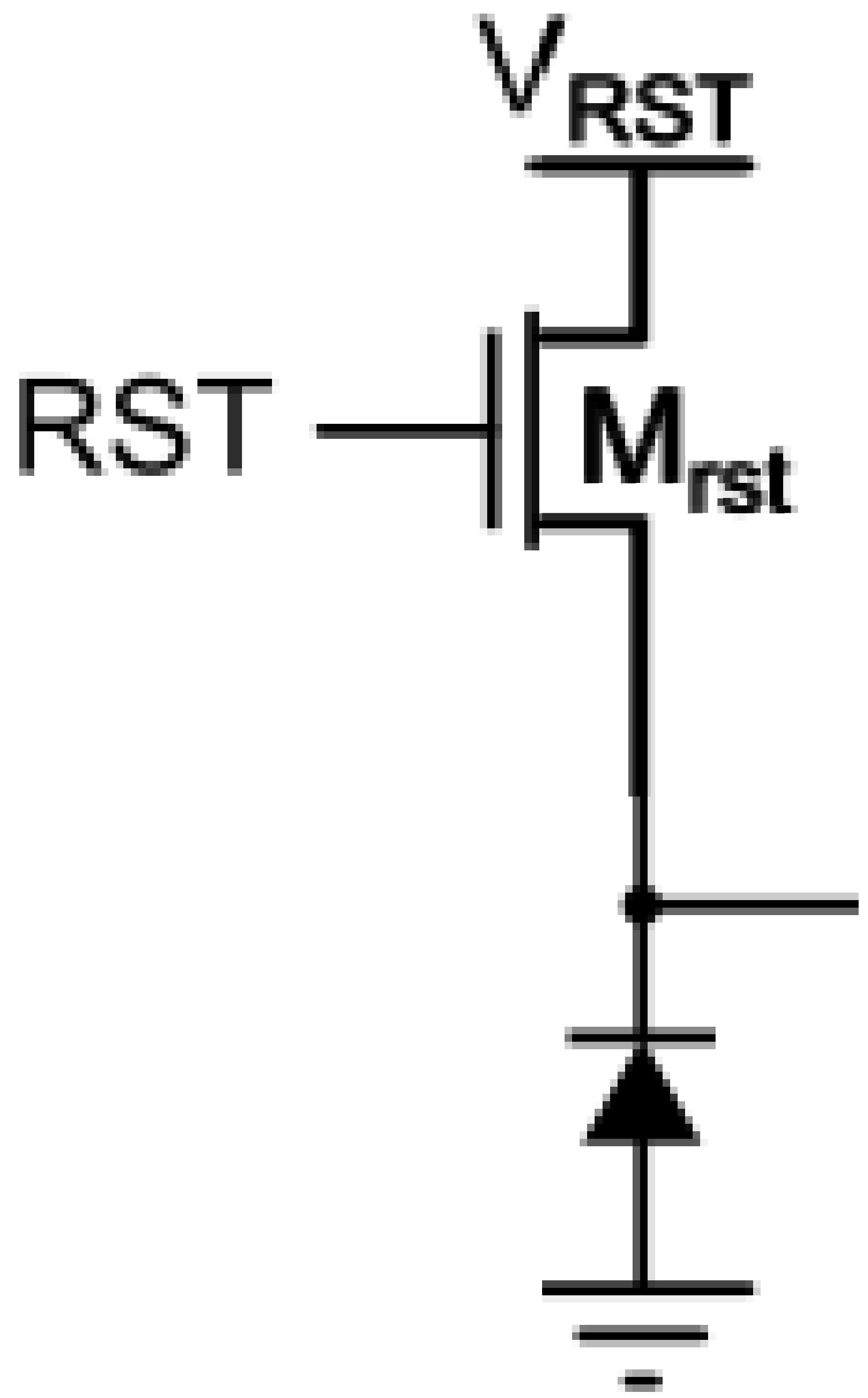
Pixel Diagram and Operation



3T (3 Transistors) Pixel:

- Each pixel has a reset, source follower (or amplifier) and row select transistor
- The relative timings between turning on/off the transistors = exposure and readout of the pixel

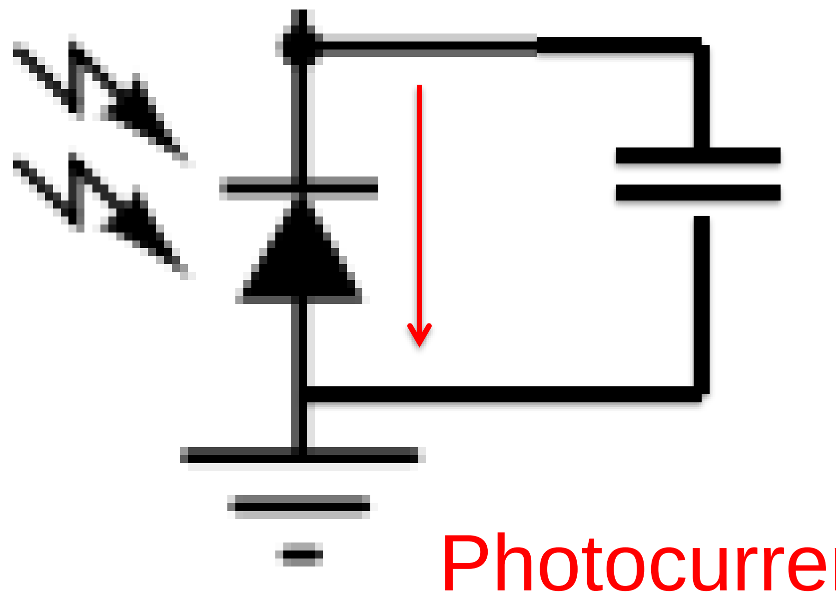
Pixel Diagram and Operation



RST = ON

- The photodiode is charged to a high voltage (between 1-3.3 volts for modern technologies)

Pixel Diagram and Operation



Photocurrent flows from cathode to anode

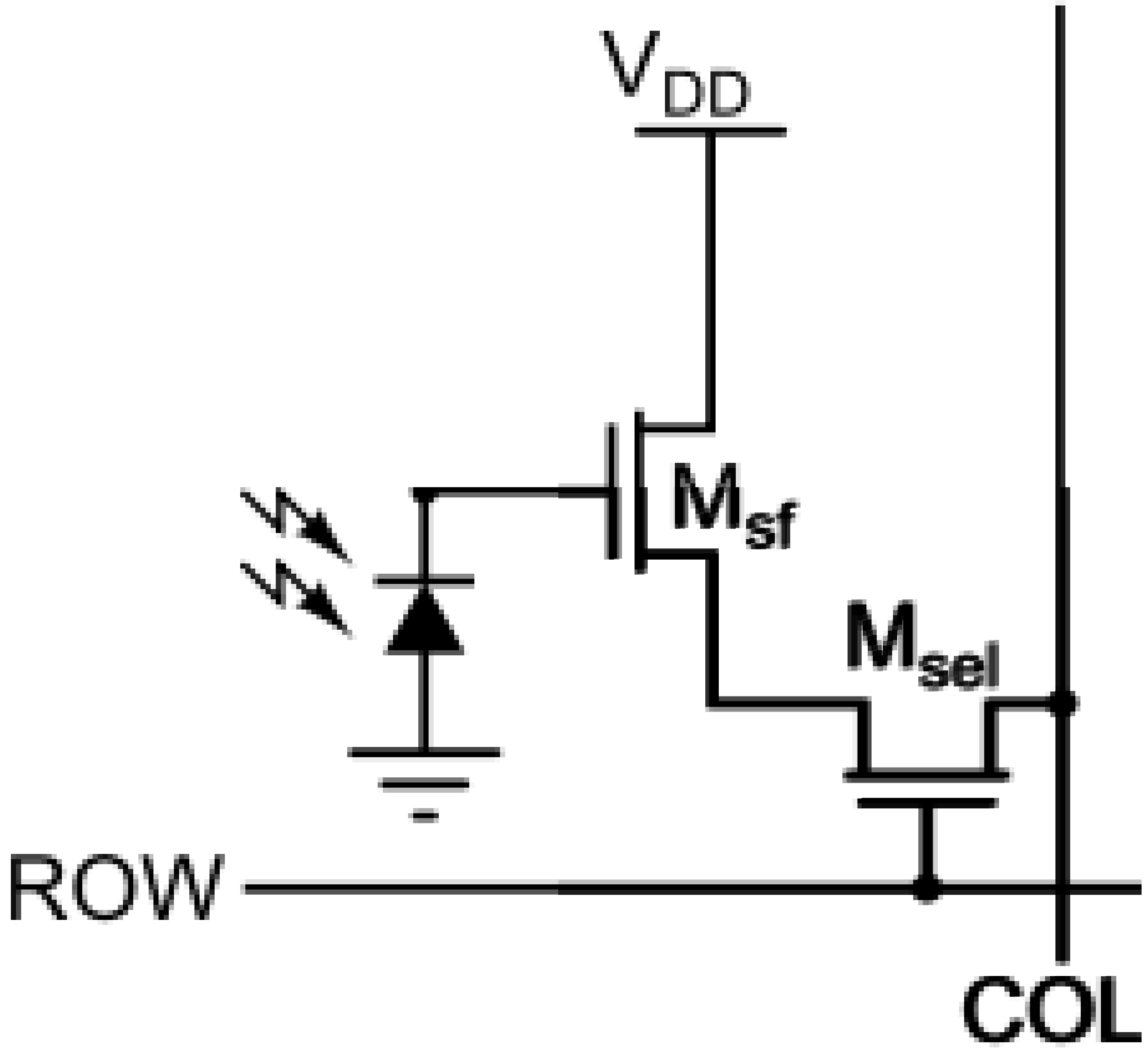
RST = OFF

- The photodiode is now integrated photocurrent onto its own (internal) capacitor

- Voltage is decreased across the capacitor as (negative) charge accumulates

- Eventually, the pixel will saturate or voltage = 0

Pixel Diagram and Operation

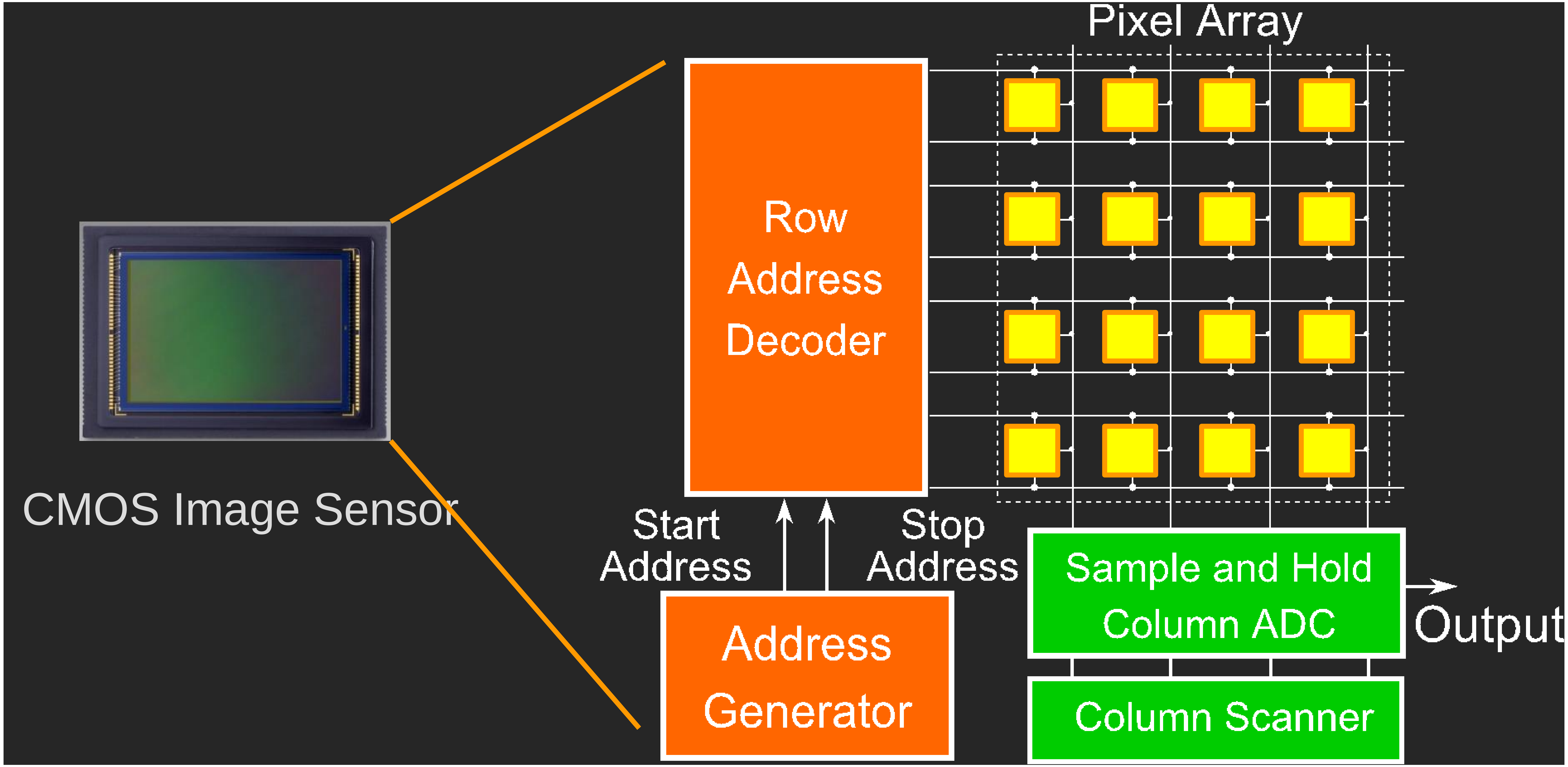


ROW = ON

- Transistors Msf and Msel are turned on

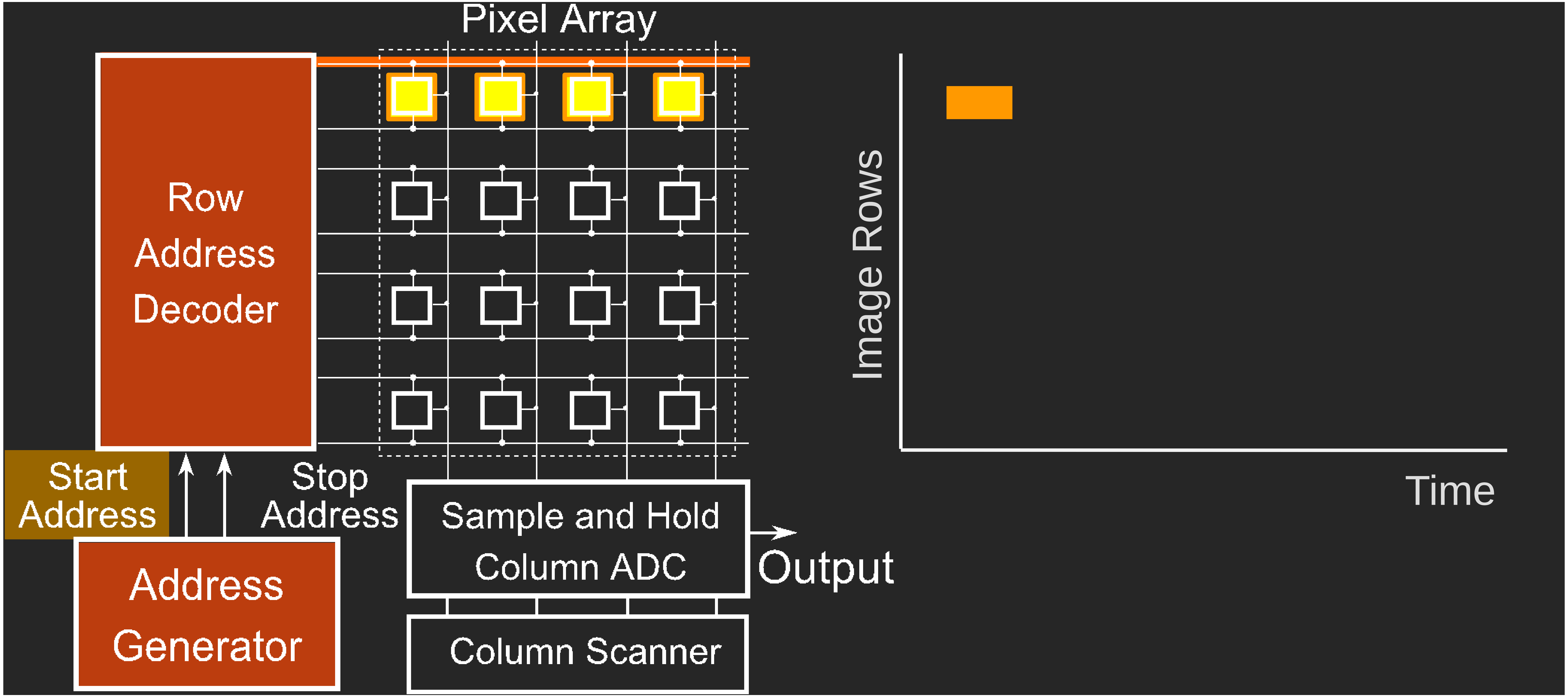
- The voltage is read out to the column, where it is sent to a column amplifier, then an ADC to be digitized

Rolling Shutter



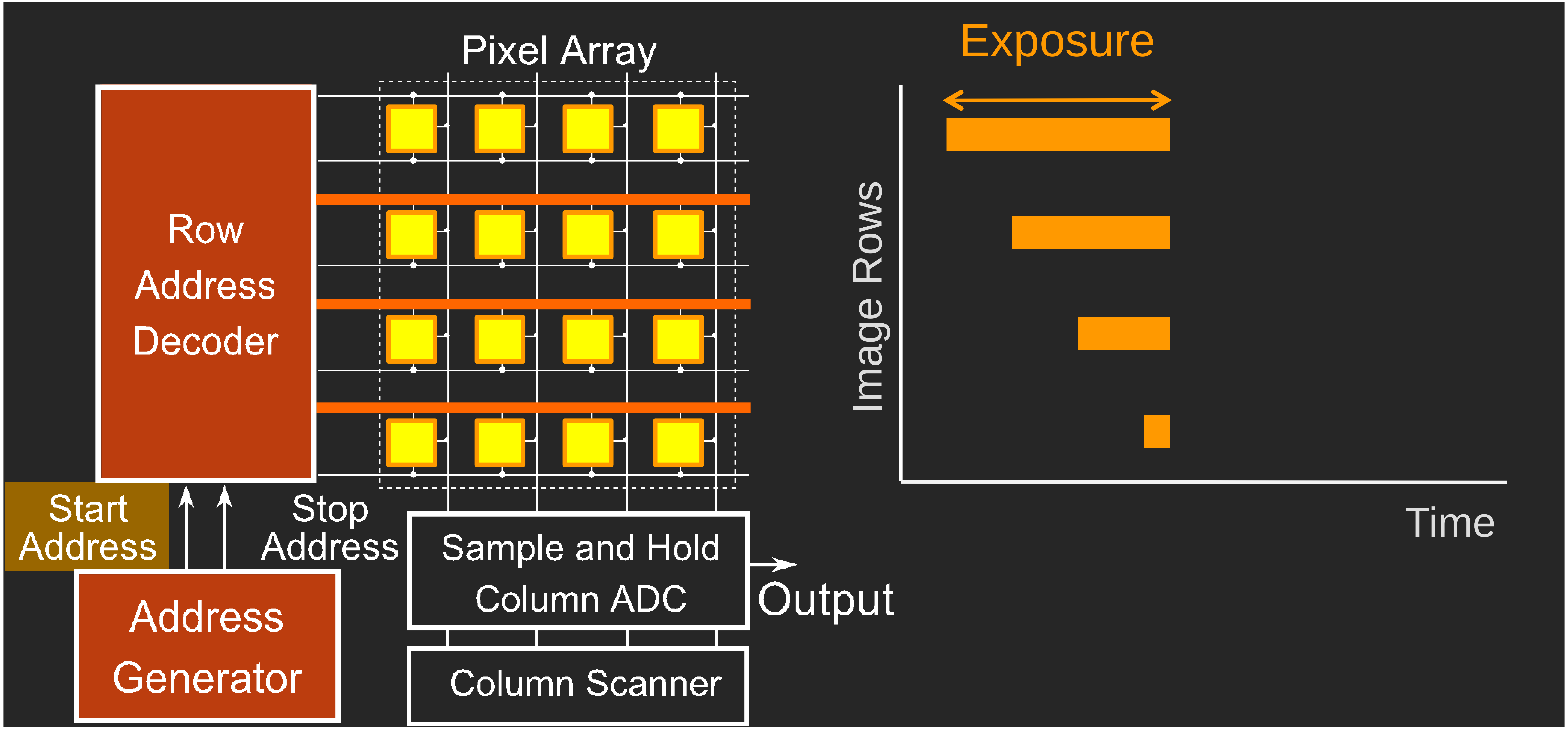
Slide courtesy of Jinwei Gu

Rolling Shutter



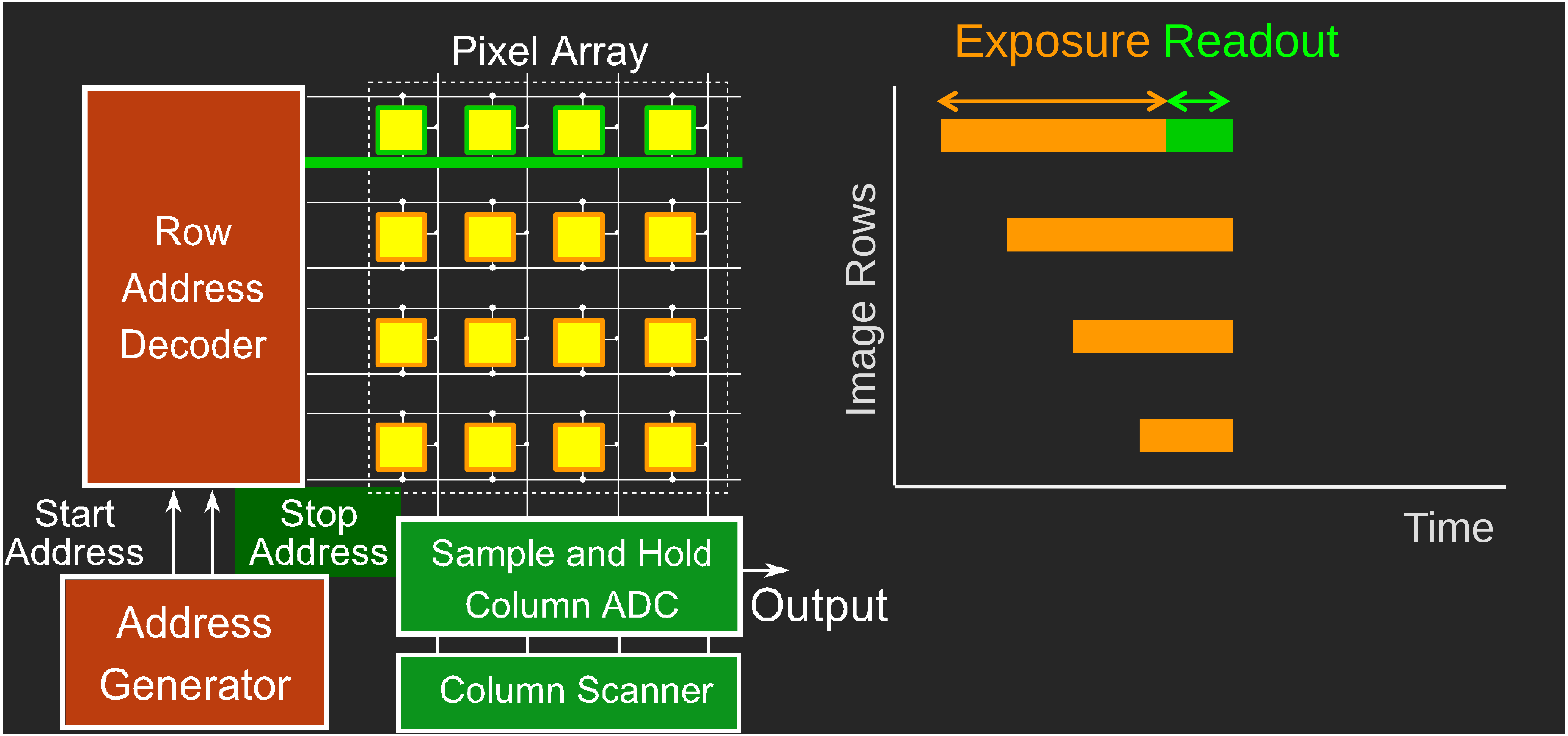
Slide courtesy of Jinwei Gu

Rolling Shutter



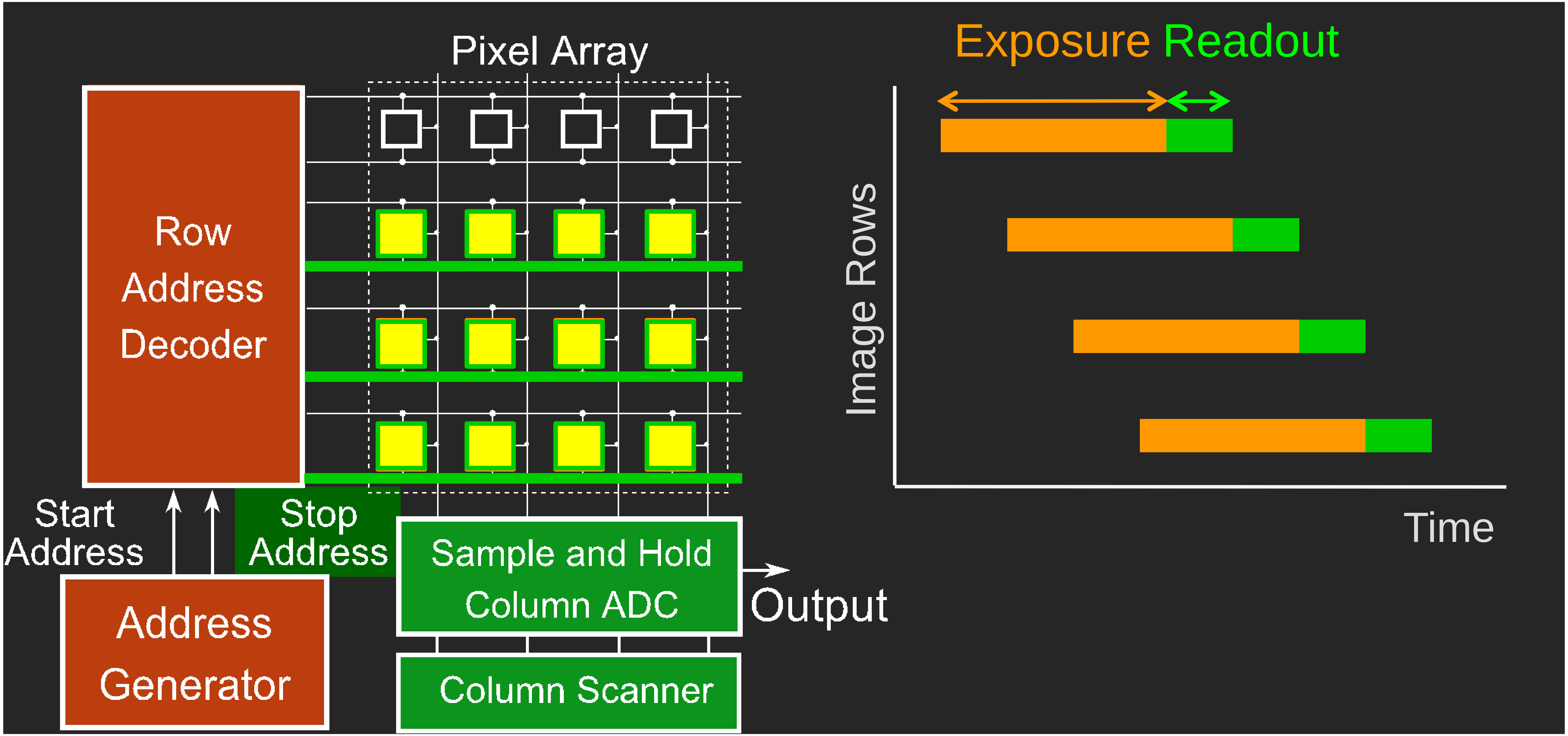
Slide courtesy of Jinwei Gu

Rolling Shutter



Slide courtesy of Jinwei Gu

Rolling Shutter



Slide courtesy of Jinwei Gu

Advantages and Disadvantages of Rolling Shutter

Advantages:

- Easy to read out the image sensor, space-efficient in column parallel readout
- No need for extra memory to store pixel voltage (unlike global shutter)

Disadvantages:

- Rolling shutter effect
- Can effect performance of computer vision algorithms such as structure-from-motion, SLAM, and stereo if not careful

Computational Sensors

But what is different about computational sensors vs. regular sensors?

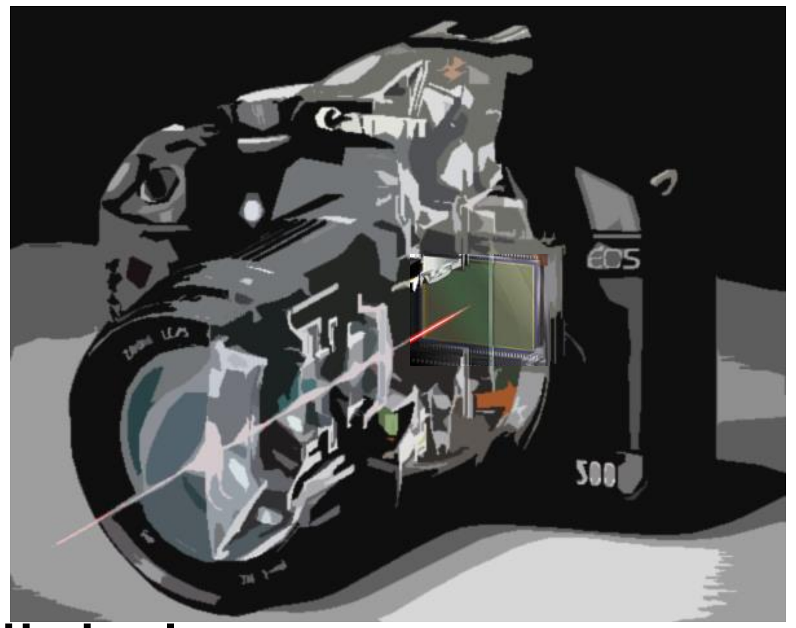
Some options:

(1) Change the readout/timing

(2) Change the pixel design itself

(3) Change the on-chip processing

optics to focus light on an image plane



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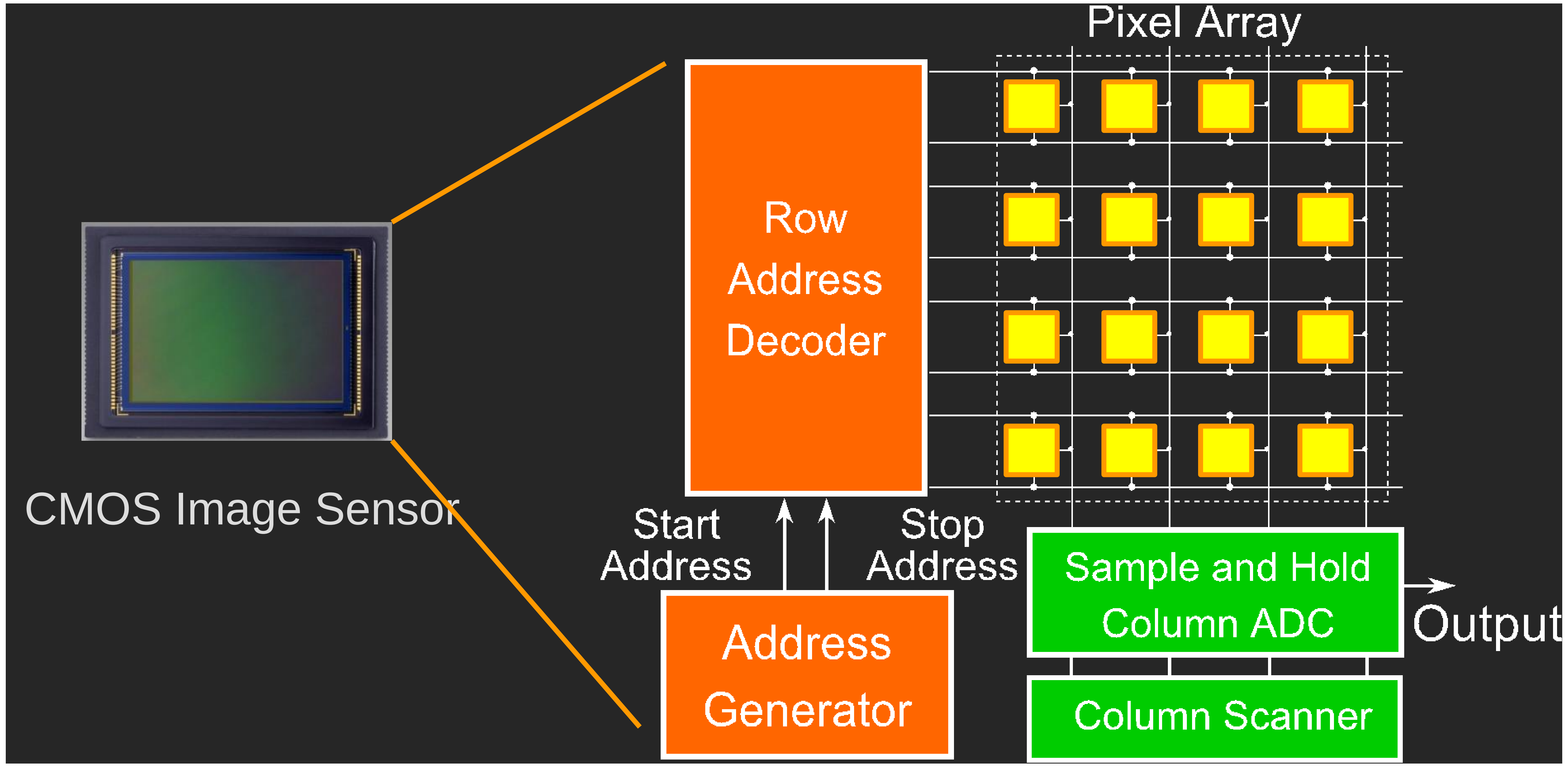
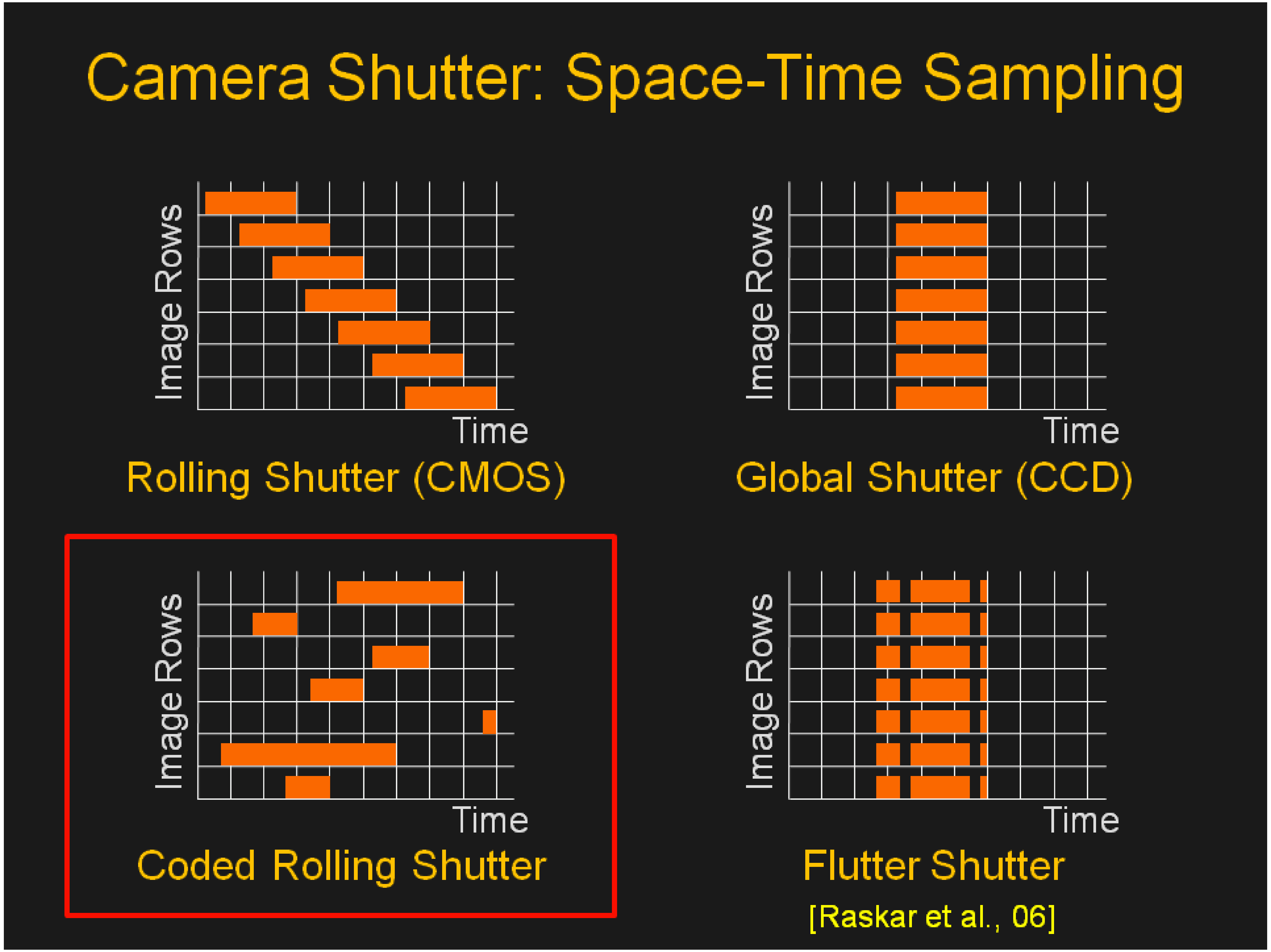
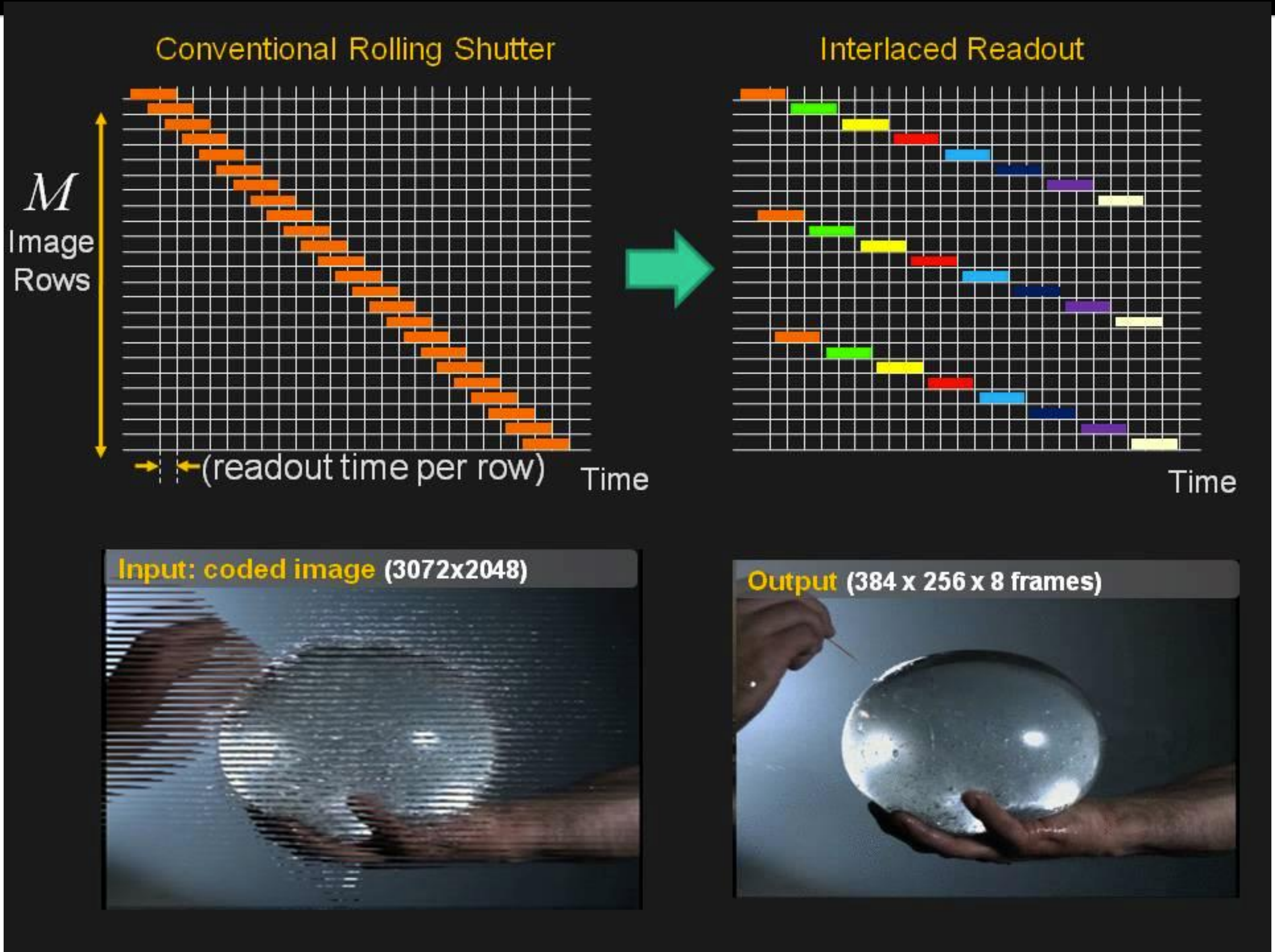


Change the Readout and Timing



Gu et al, "Coded Rolling Shutter Photography: Flexible Space-Time Sampling" ICCP 2010

Change the Readout and Timing



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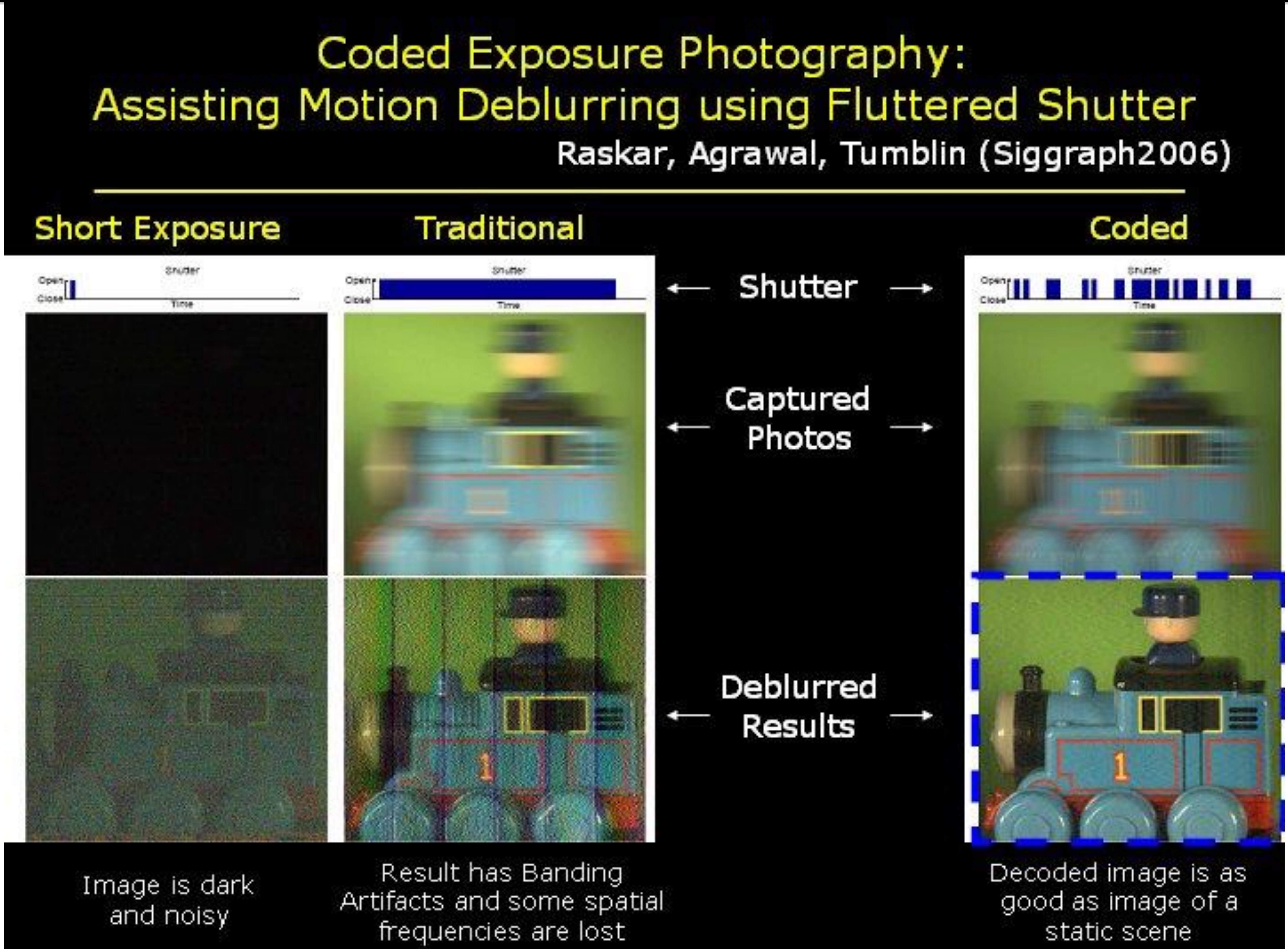
Change the Readout and Timing



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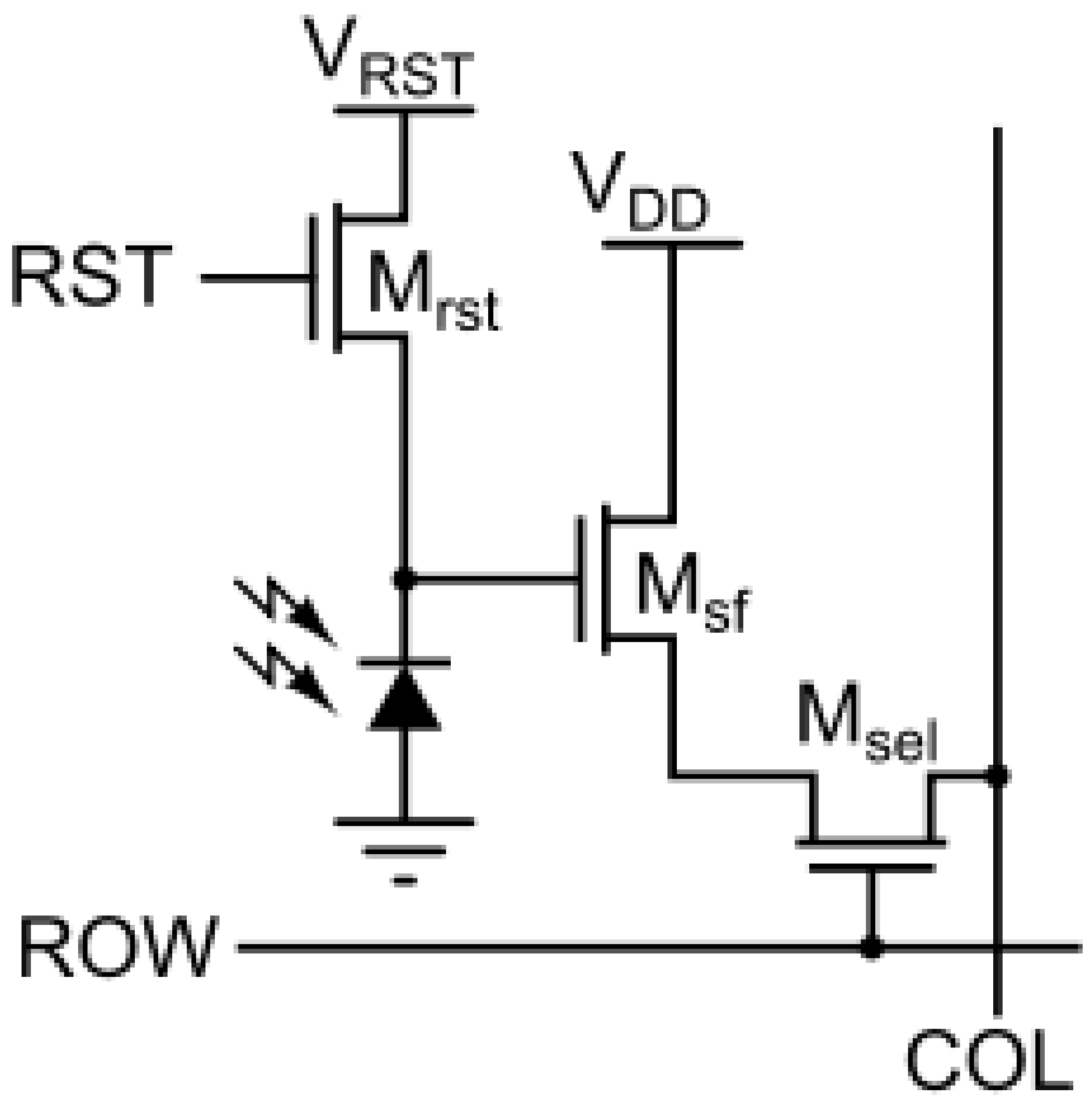
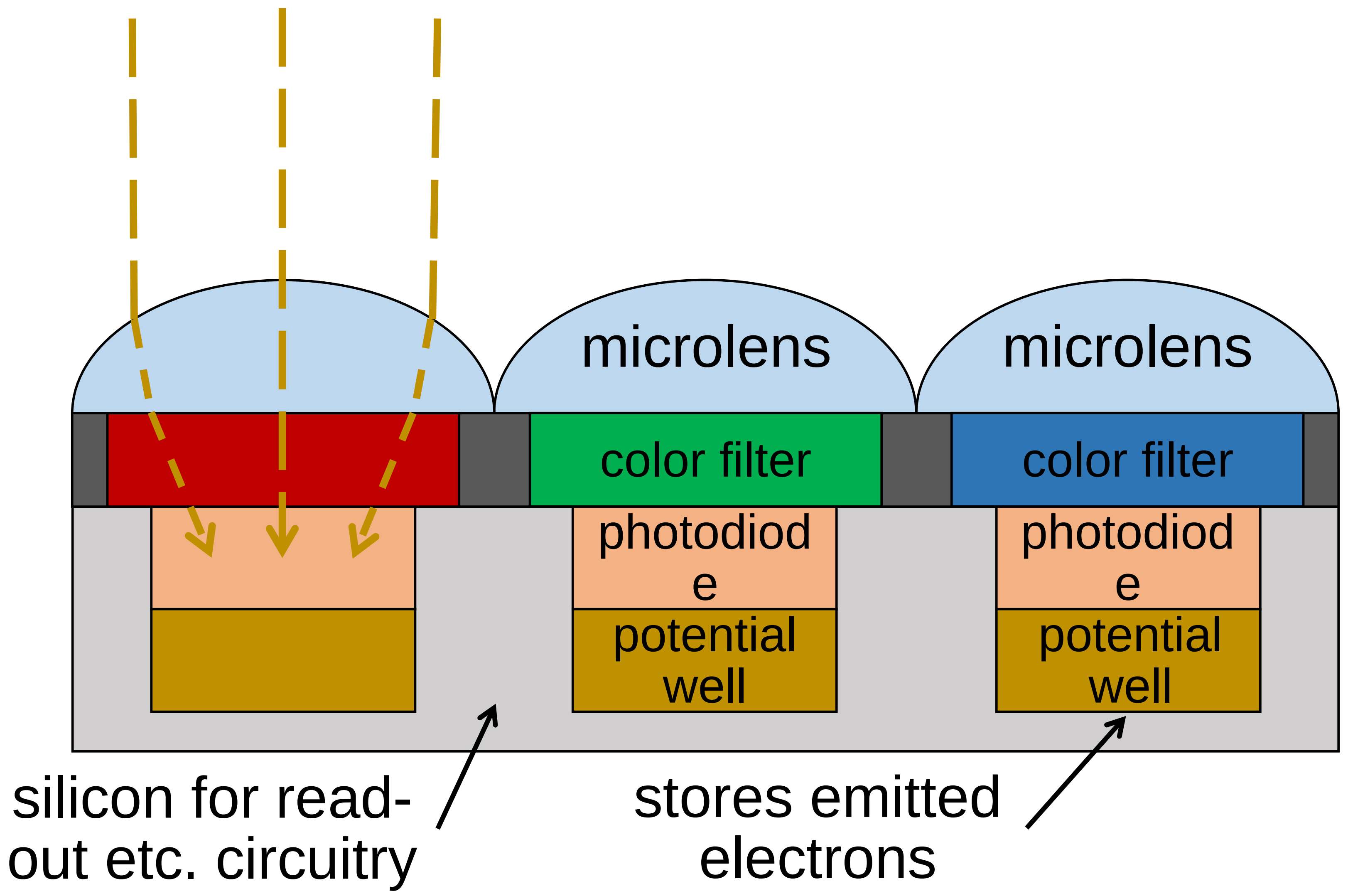
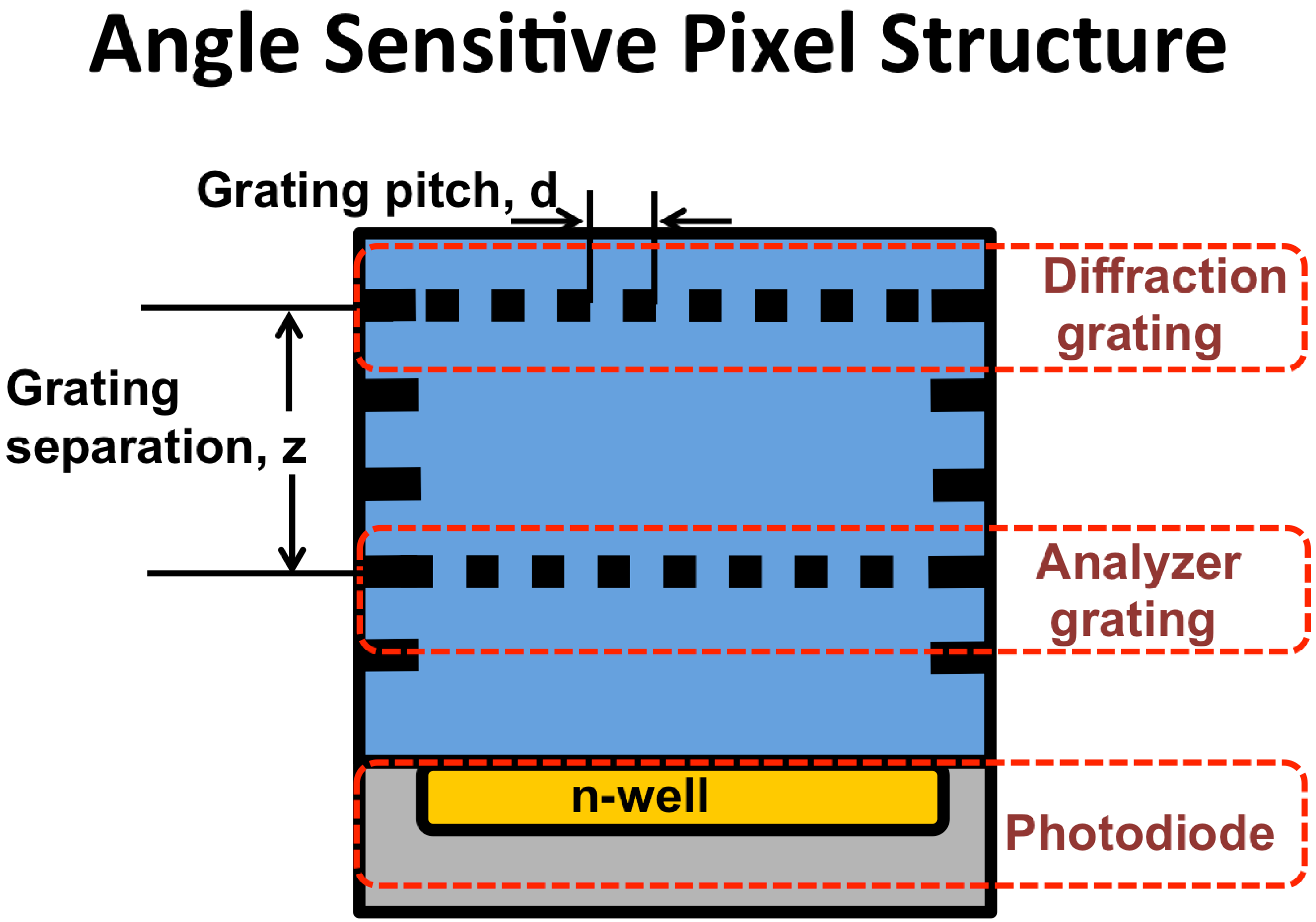


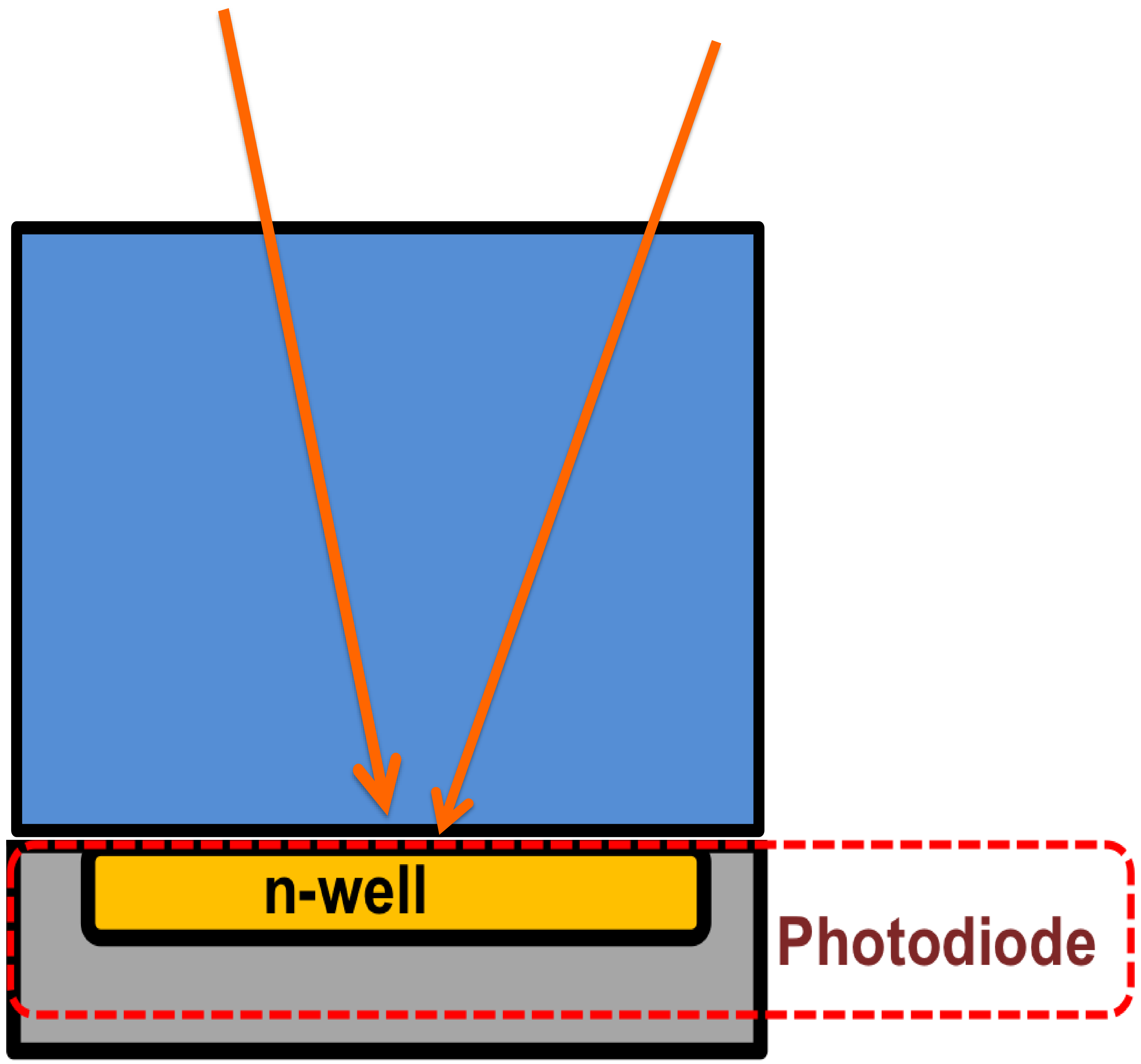


ASPs: A New Type of Pixel



A. Wang and A. Molnar, “A Light Field Image Sensor in 180nm CMOS”, JSSC 2012

Capturing Light Fields using ASPs



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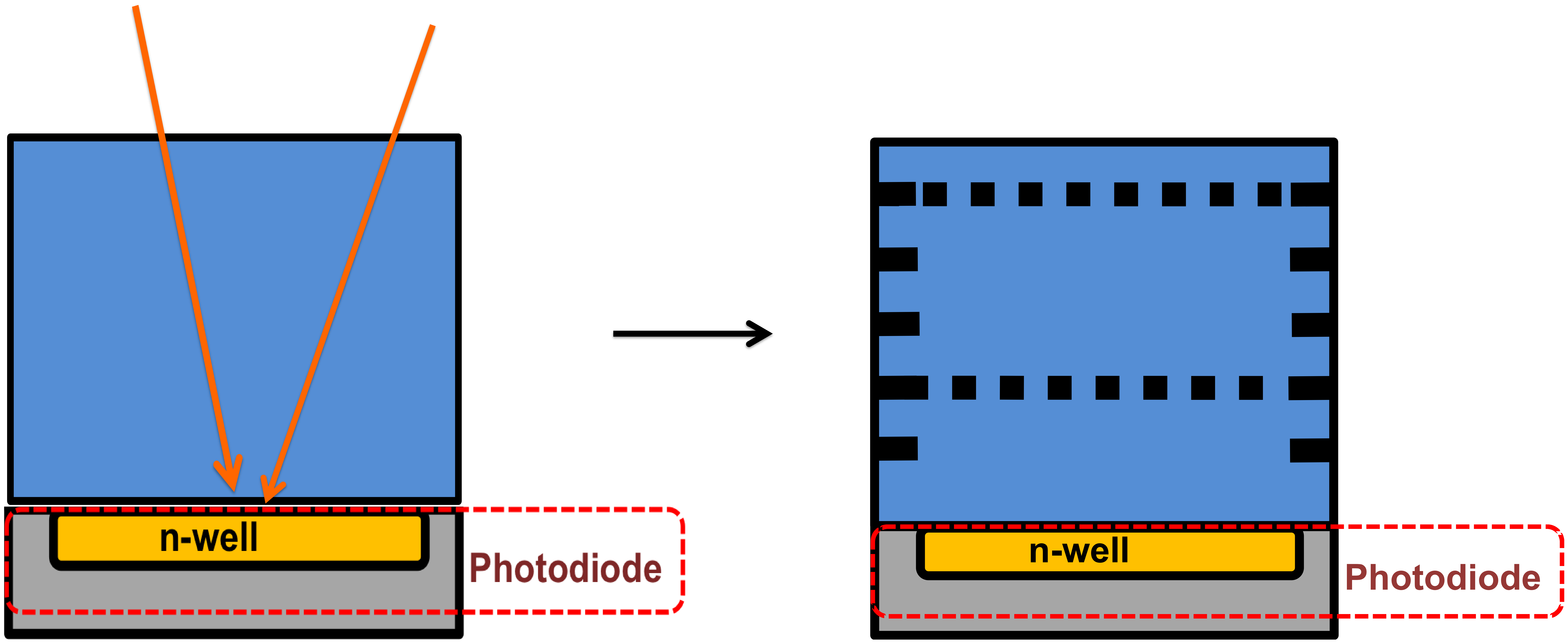
Capturing Light Fields using ASPs



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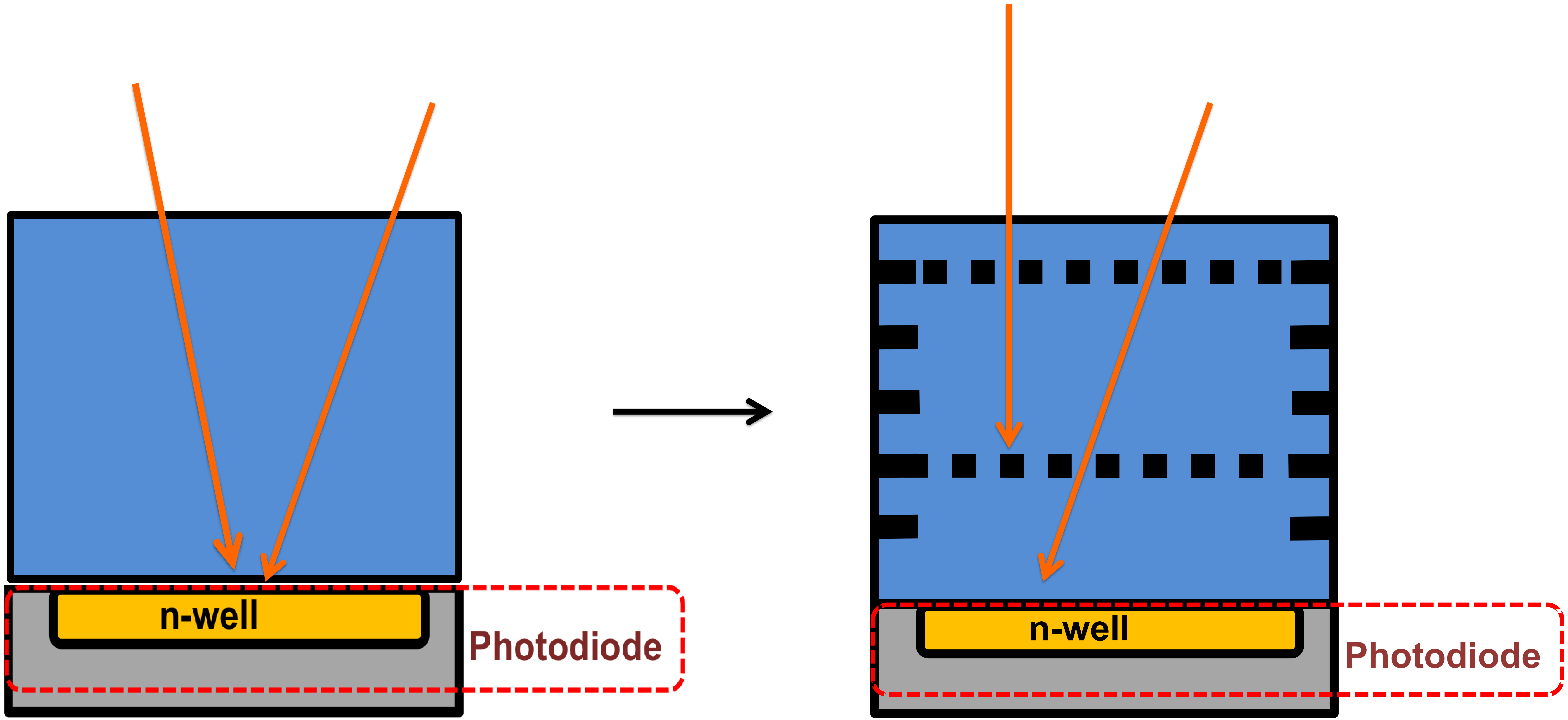
Capturing Light Fields using ASPs



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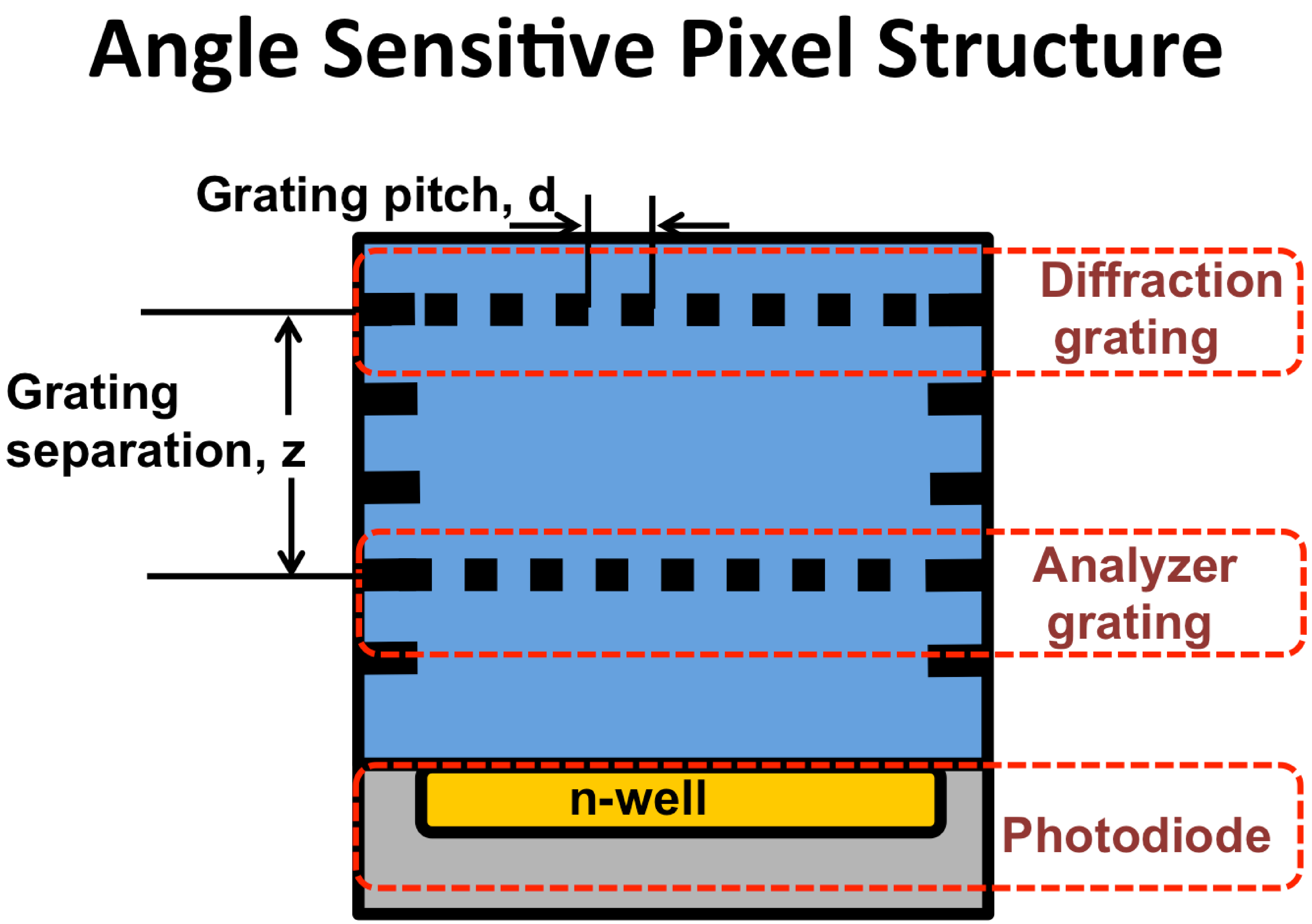
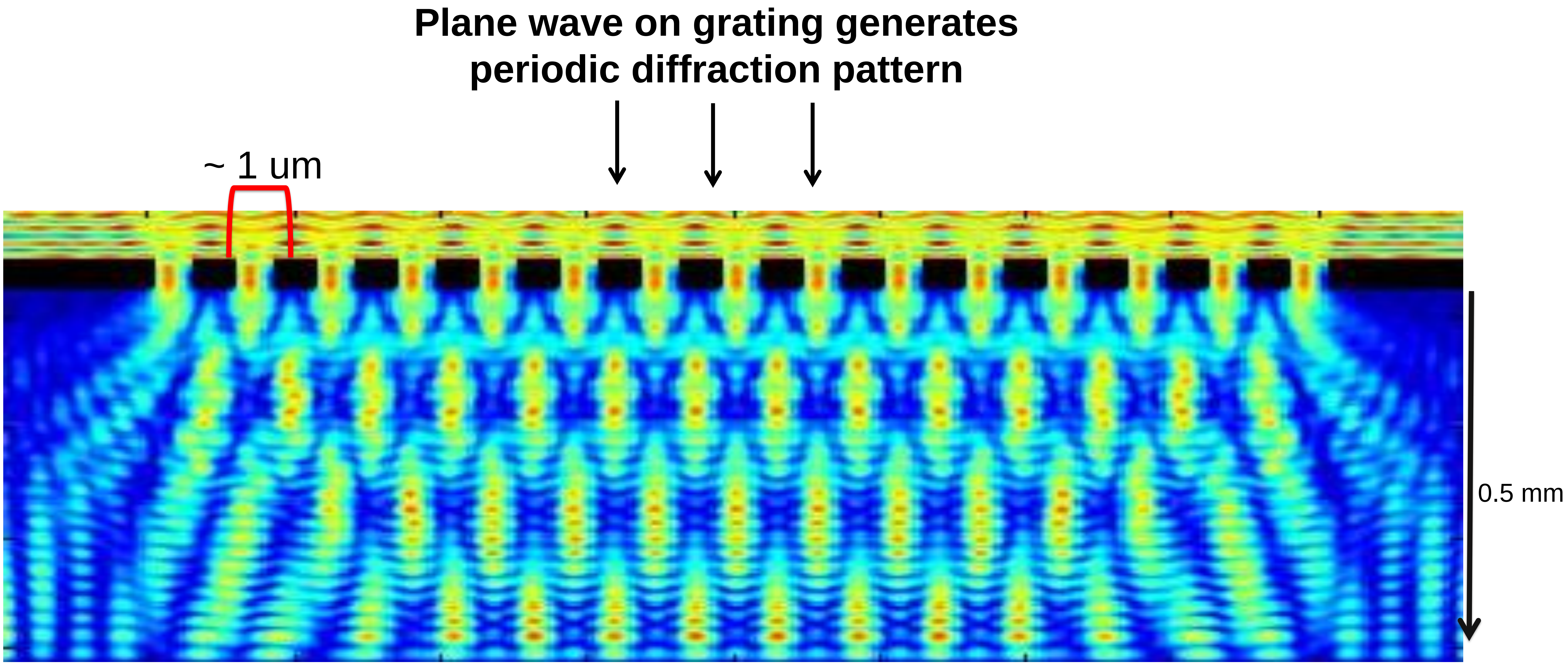
ASPs

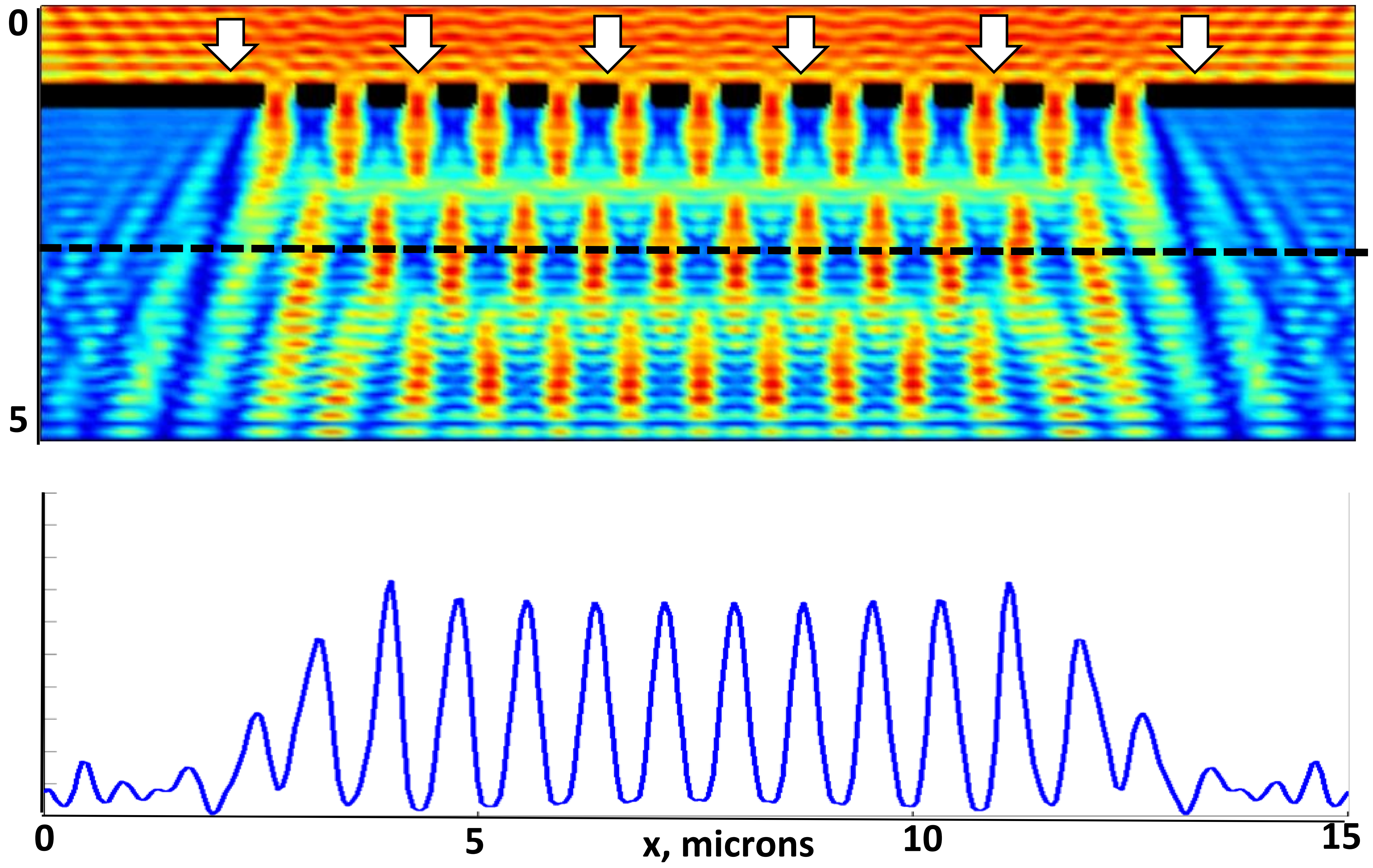


A. Wang and A. Molnar, “A Light Field Image Sensor in 180nm CMOS”, JSSC 2012

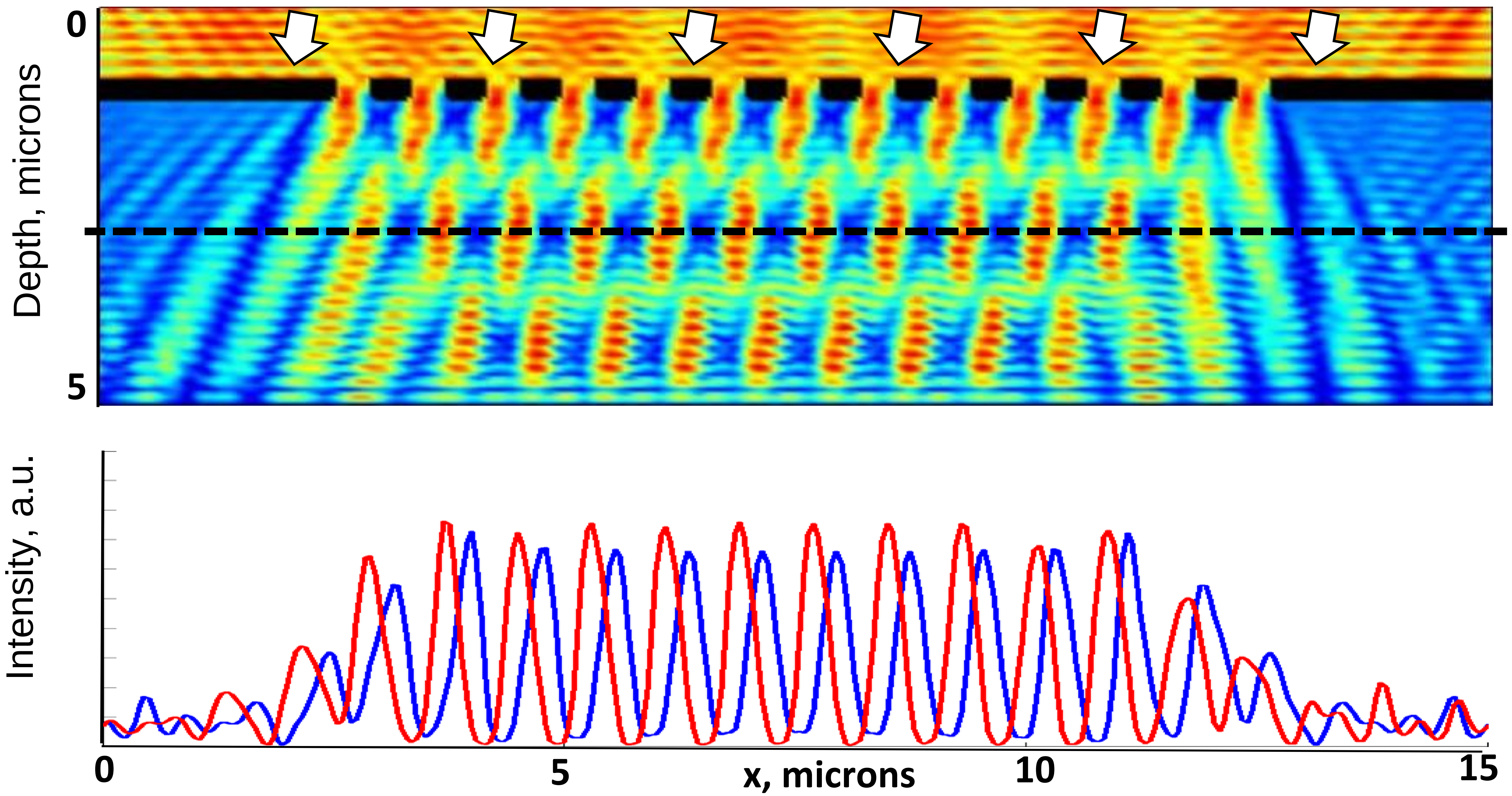
Operating Principle: Talbot Effect



Incident Angle

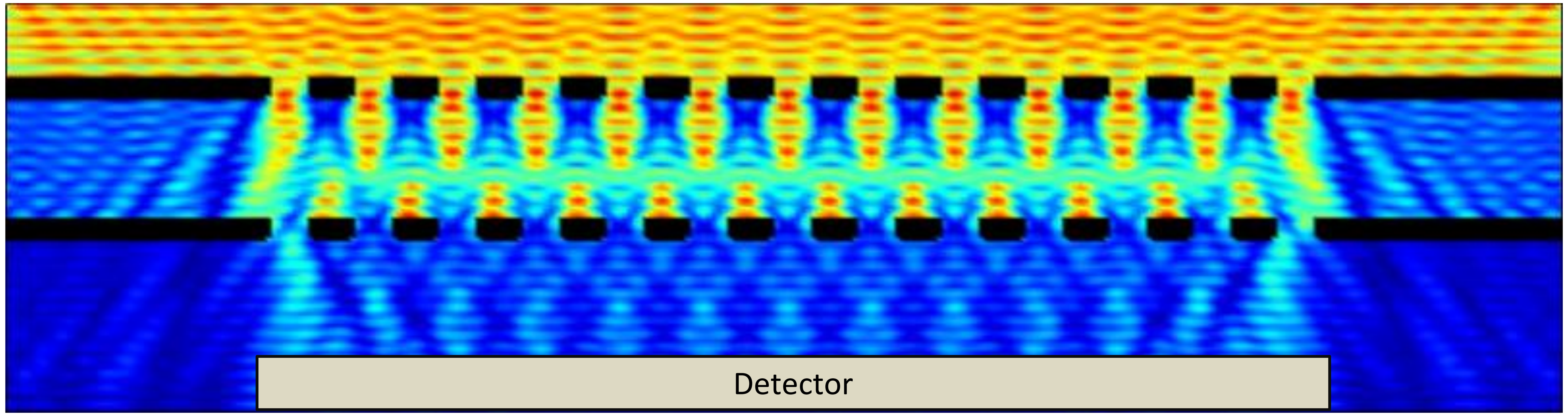


Incident Angle shifts

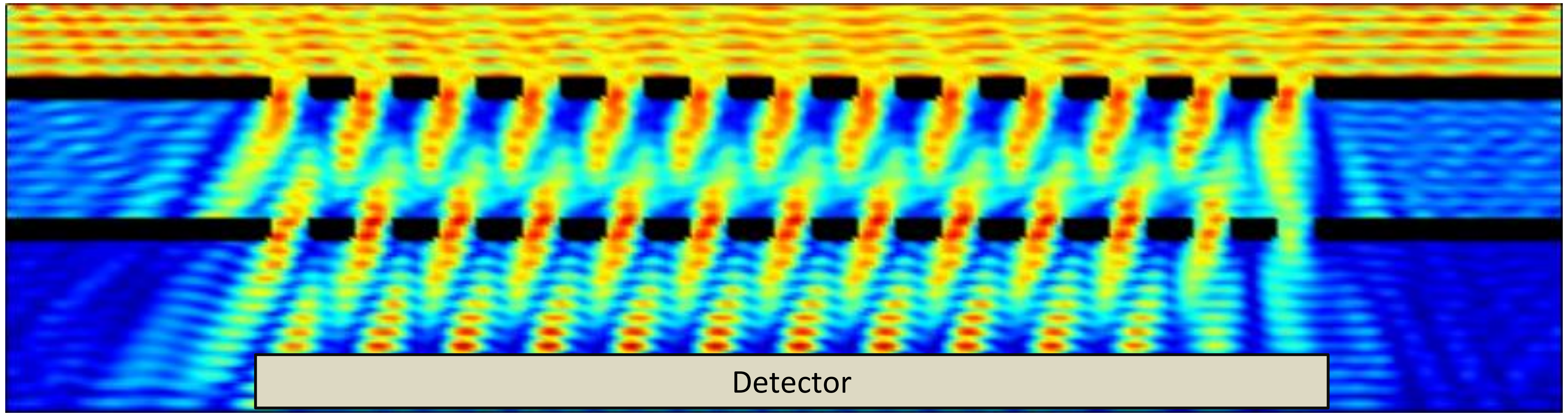


Add an Analyzer Grating

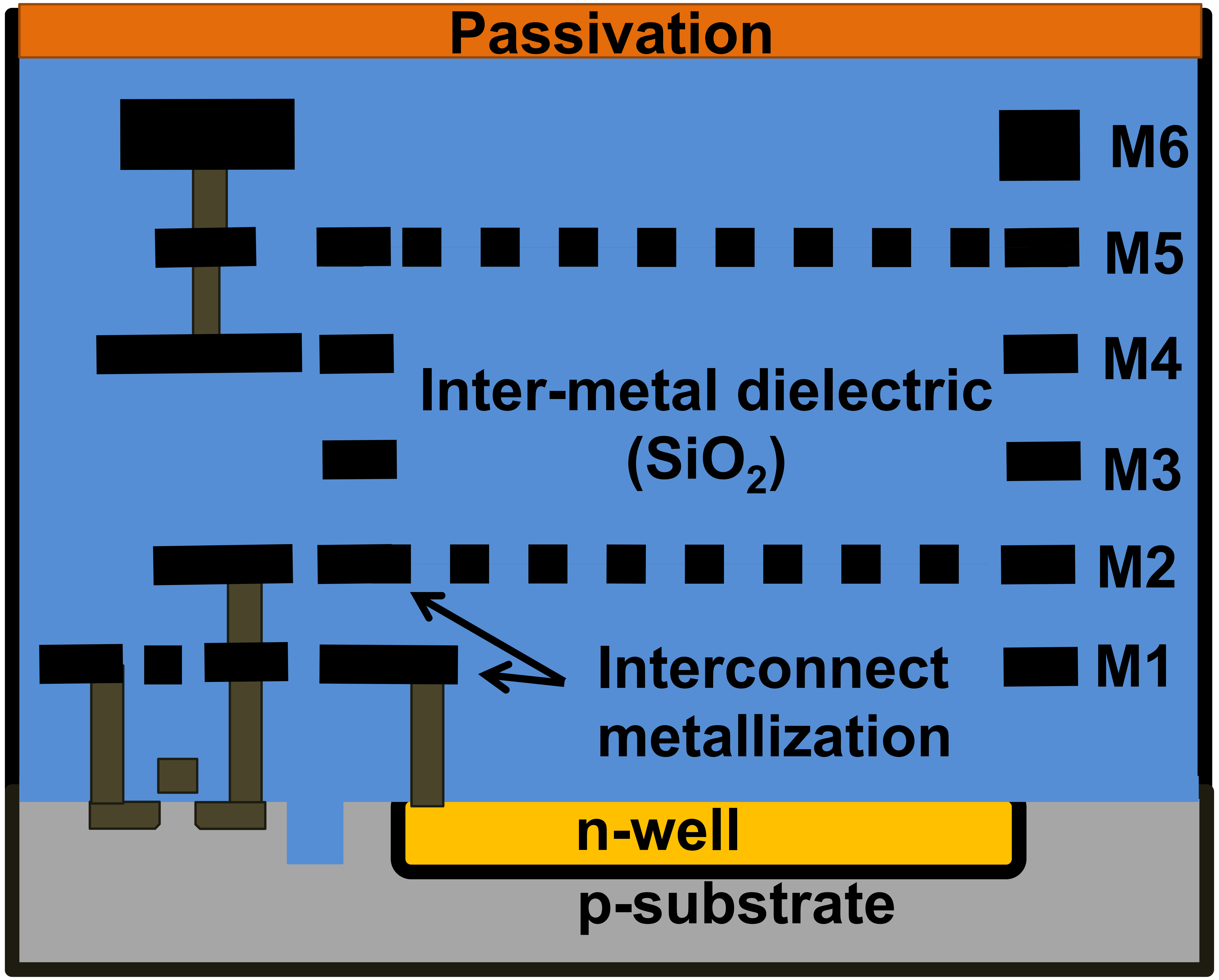
0 degrees



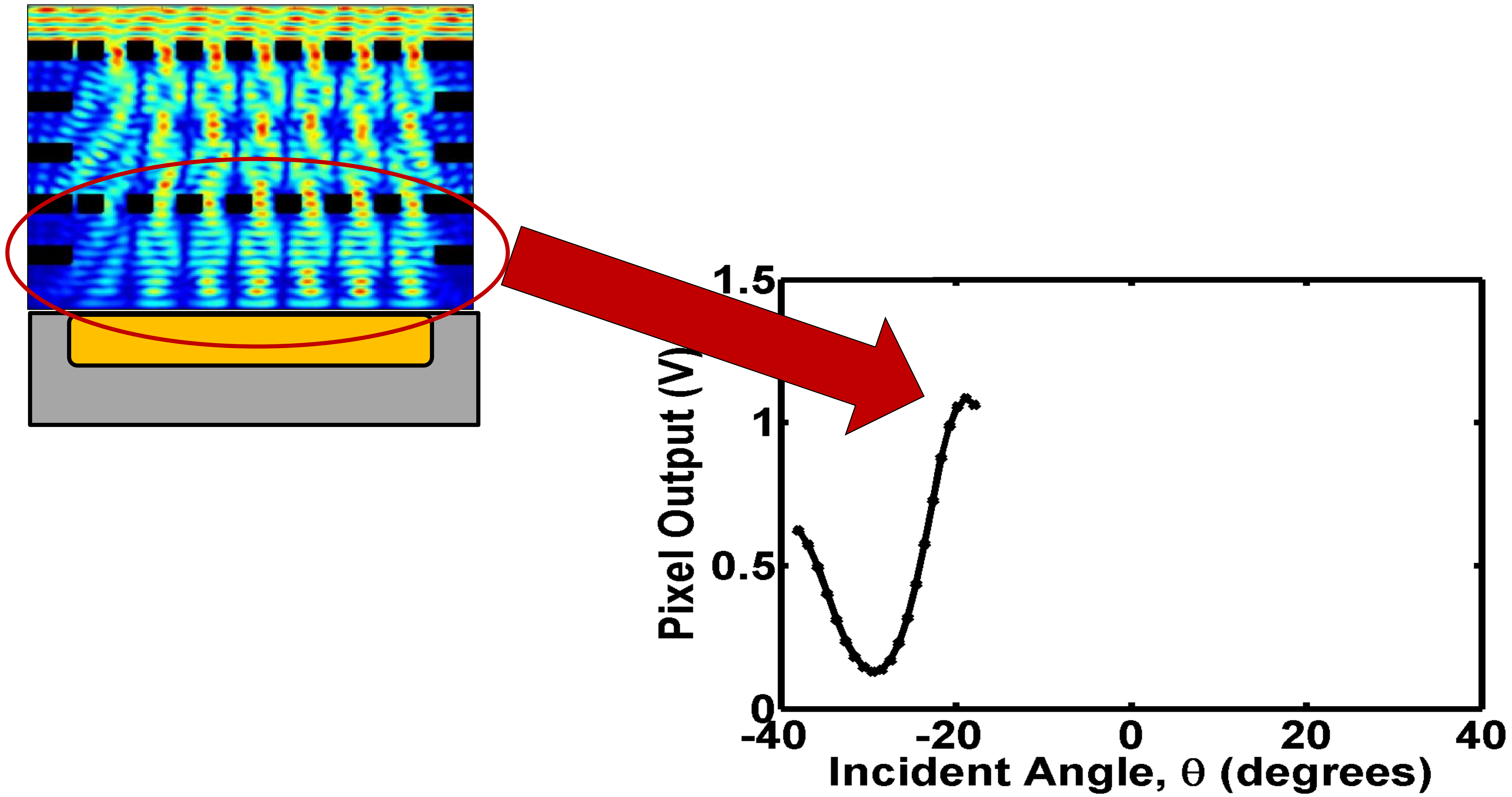
10 degrees



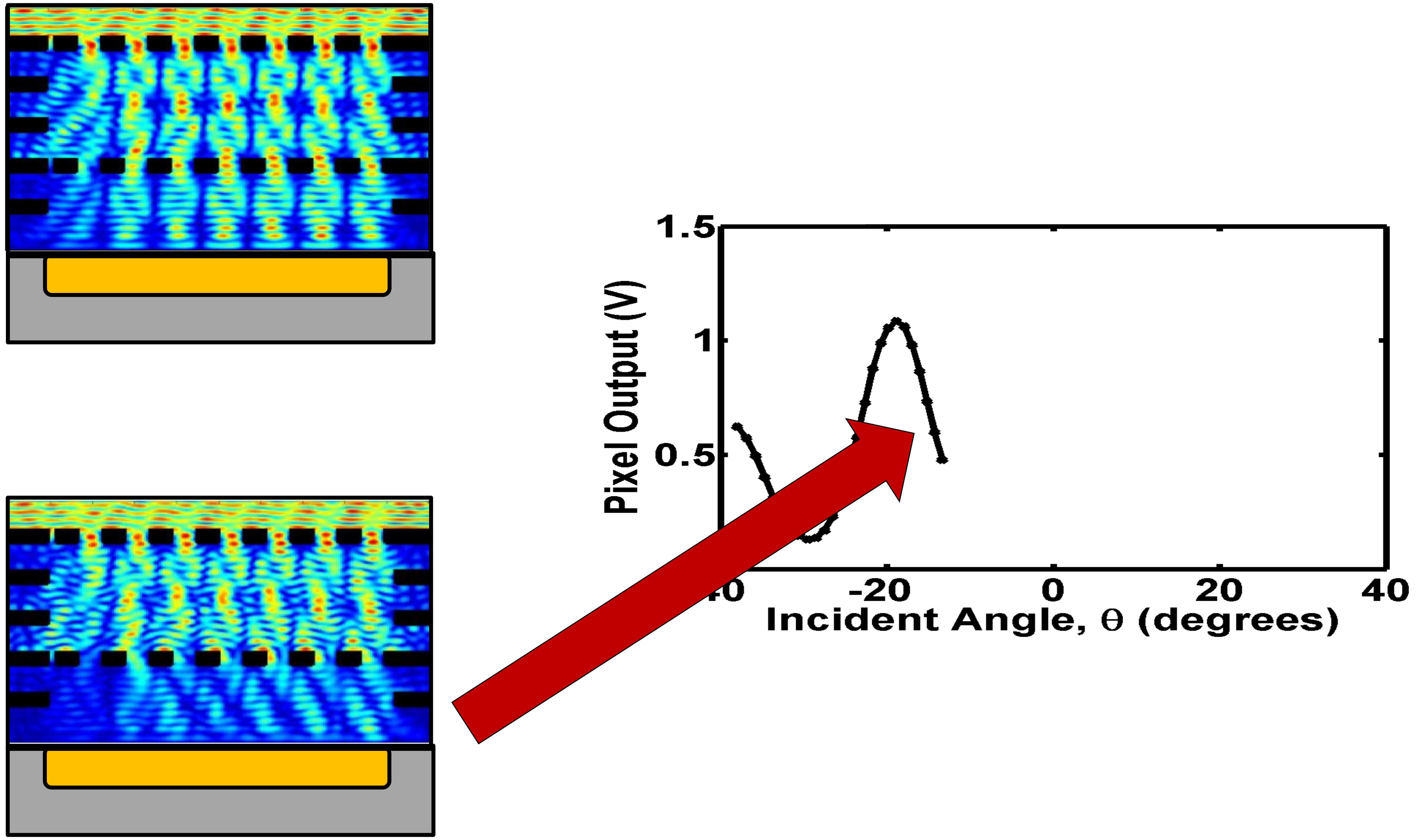
CMOS Implementation



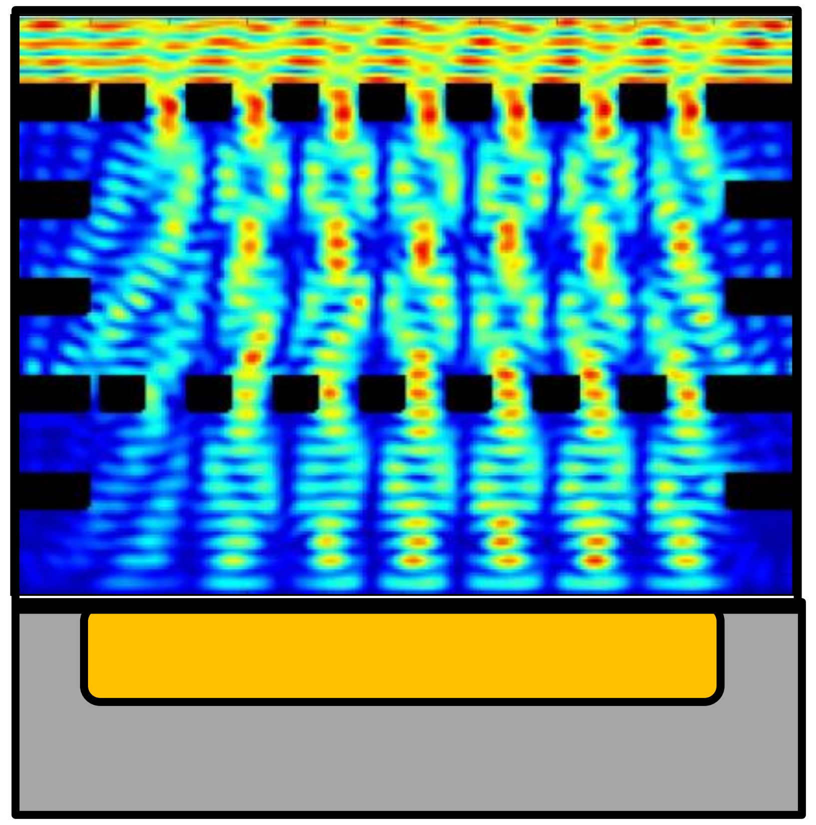
Angle Response

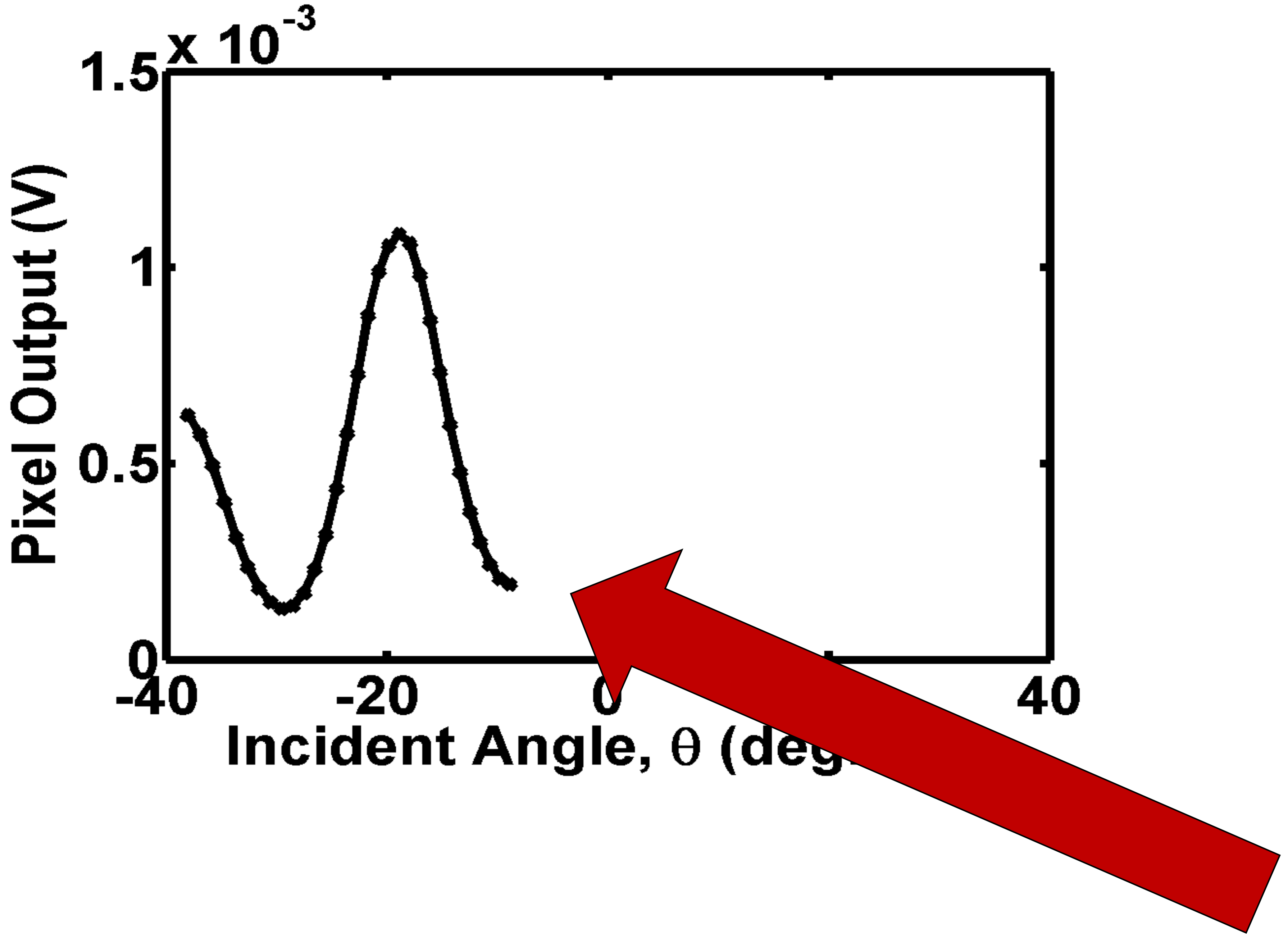


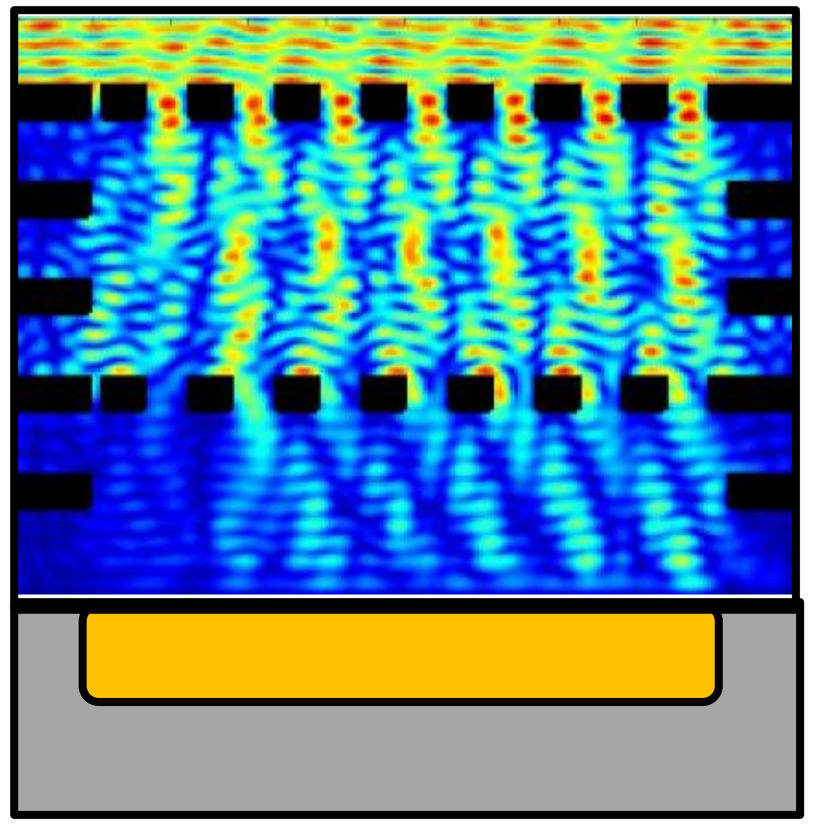
Angle Response

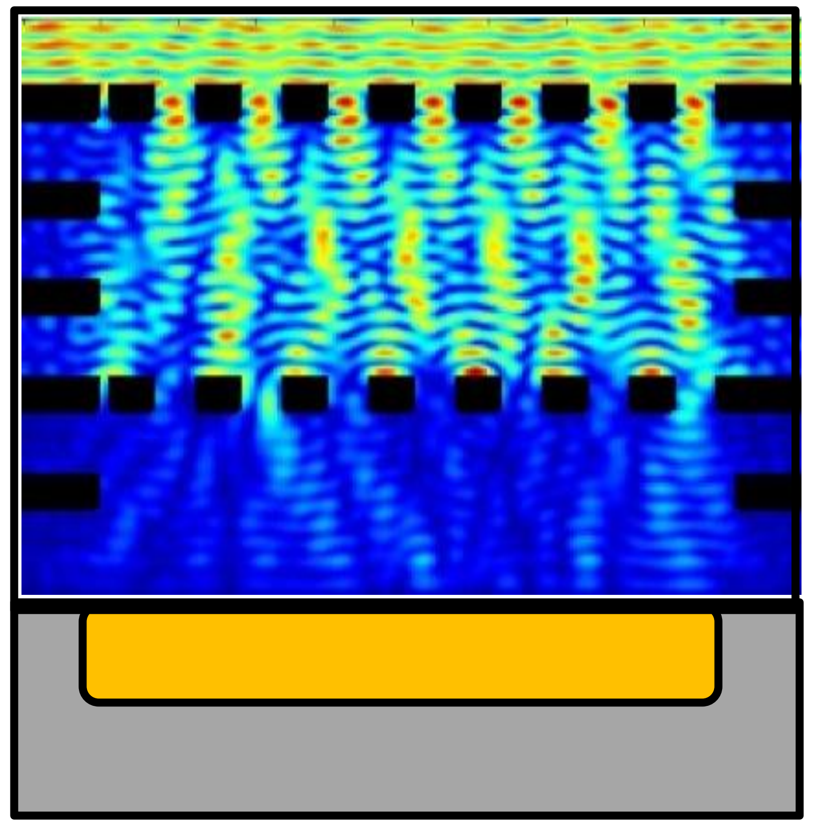


Angle Response

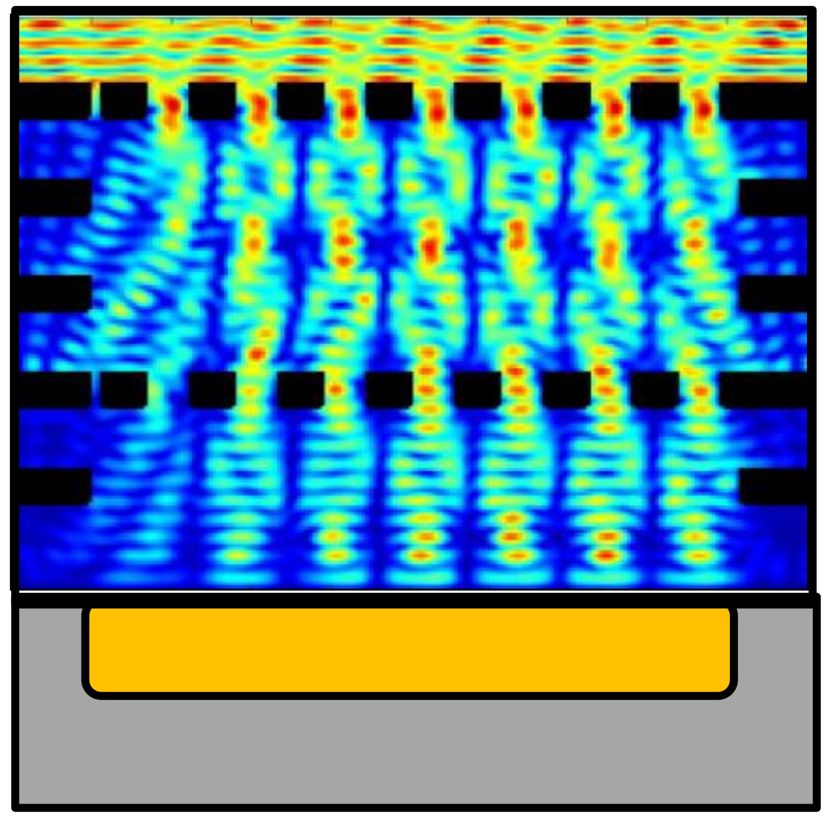


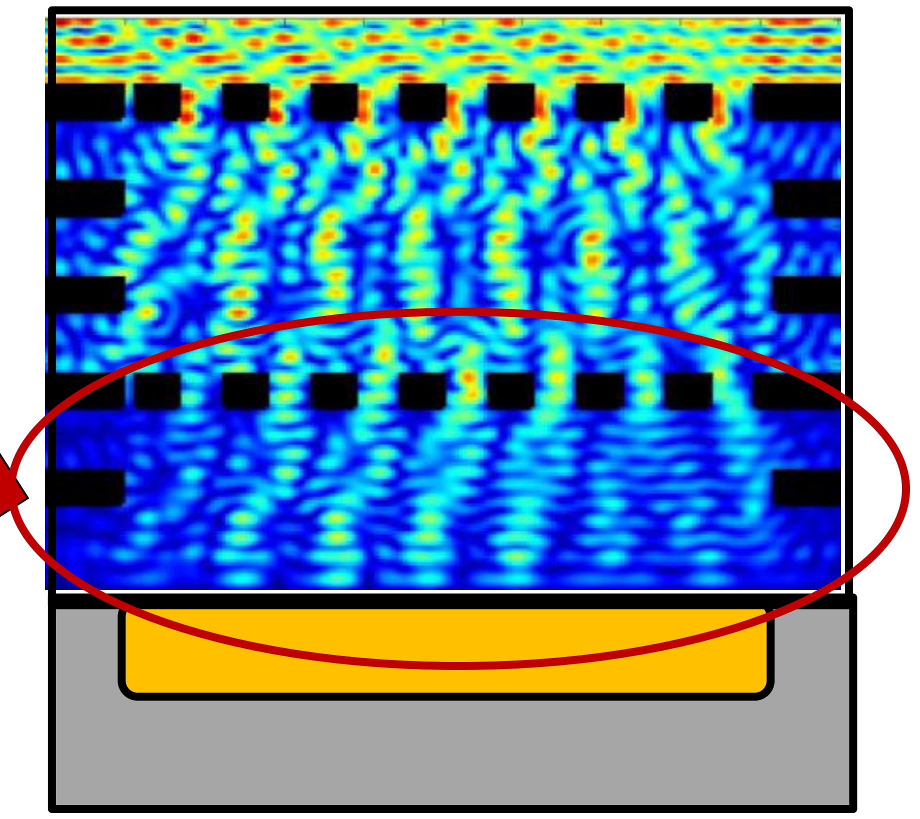


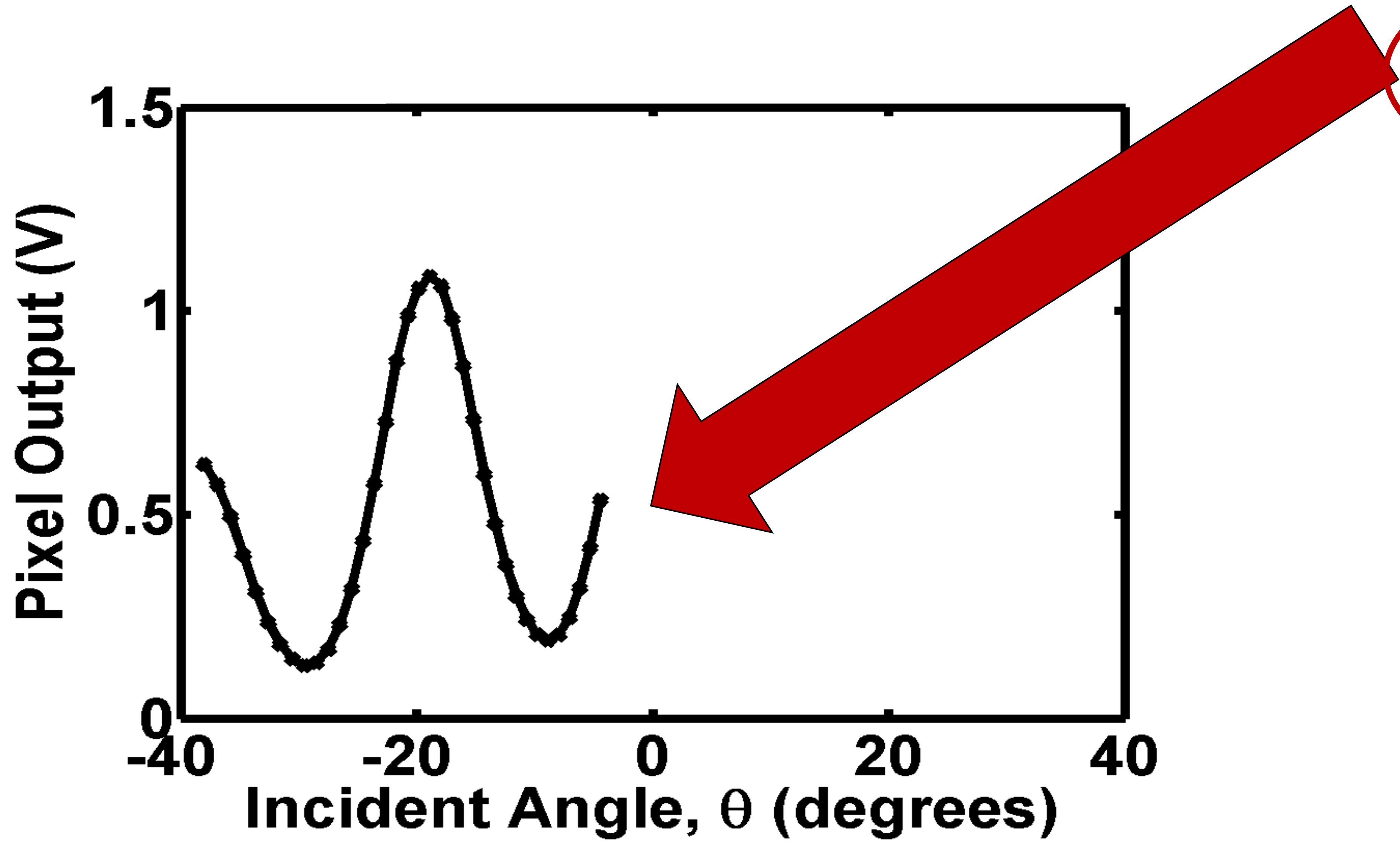


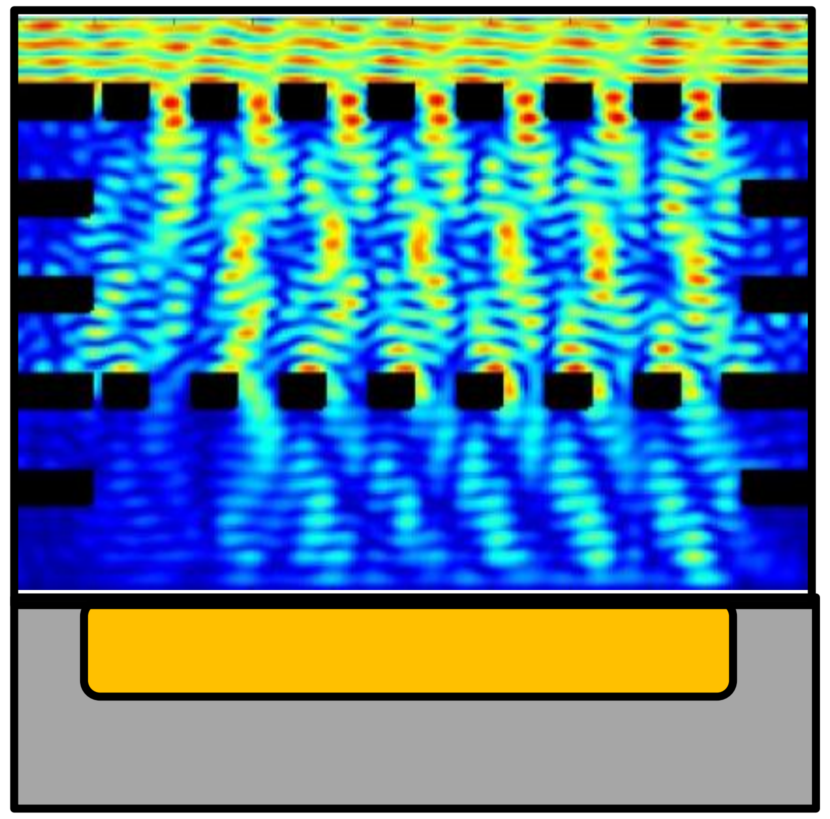


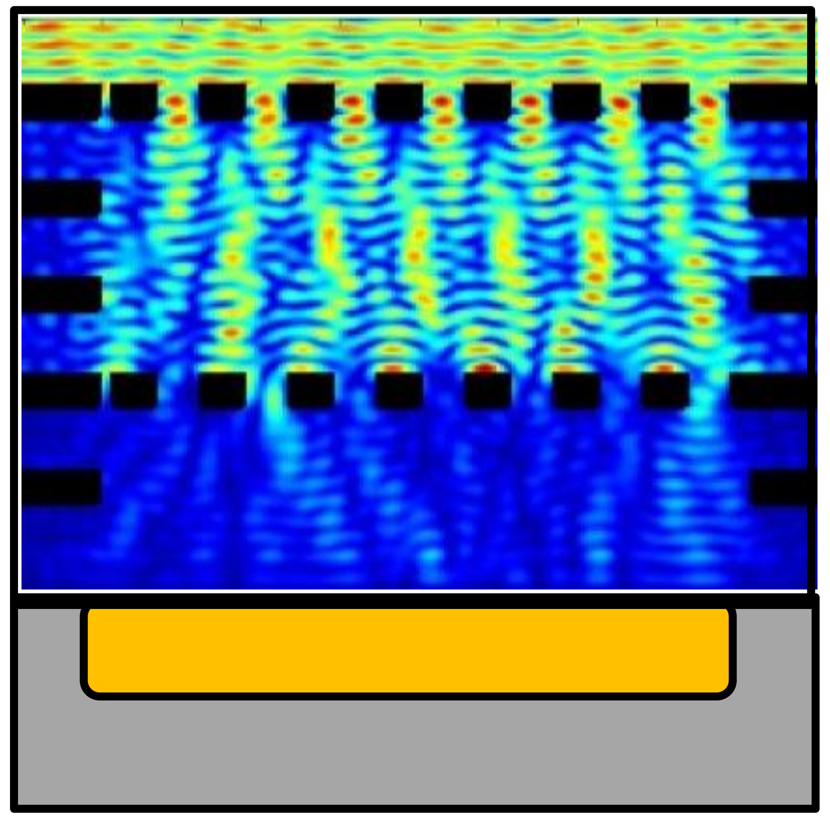
Angle Response











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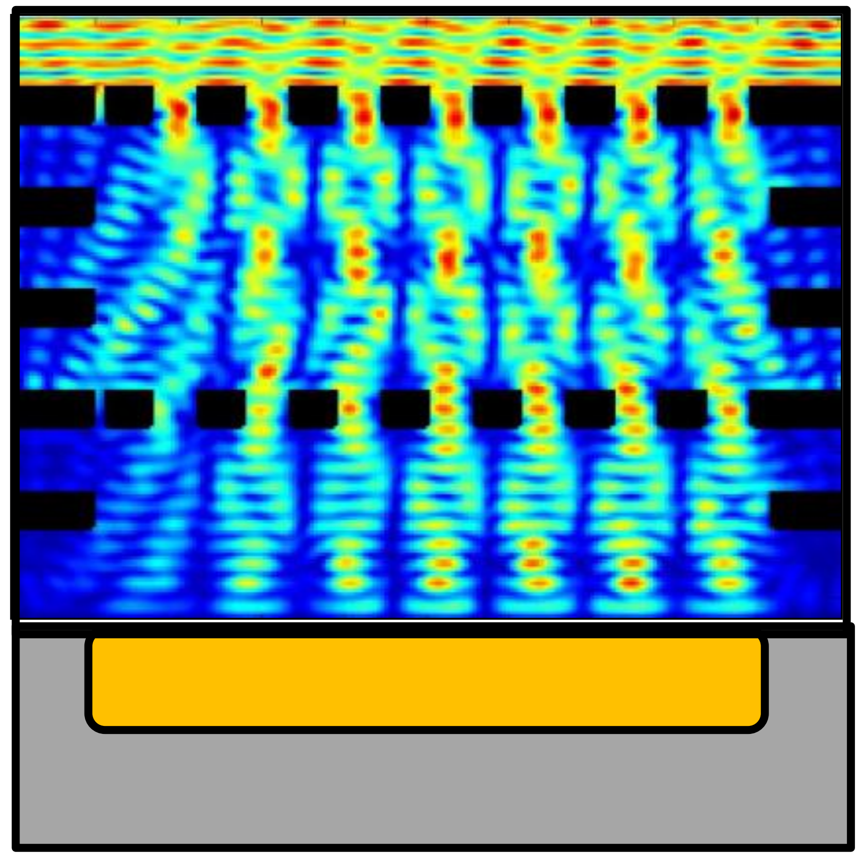
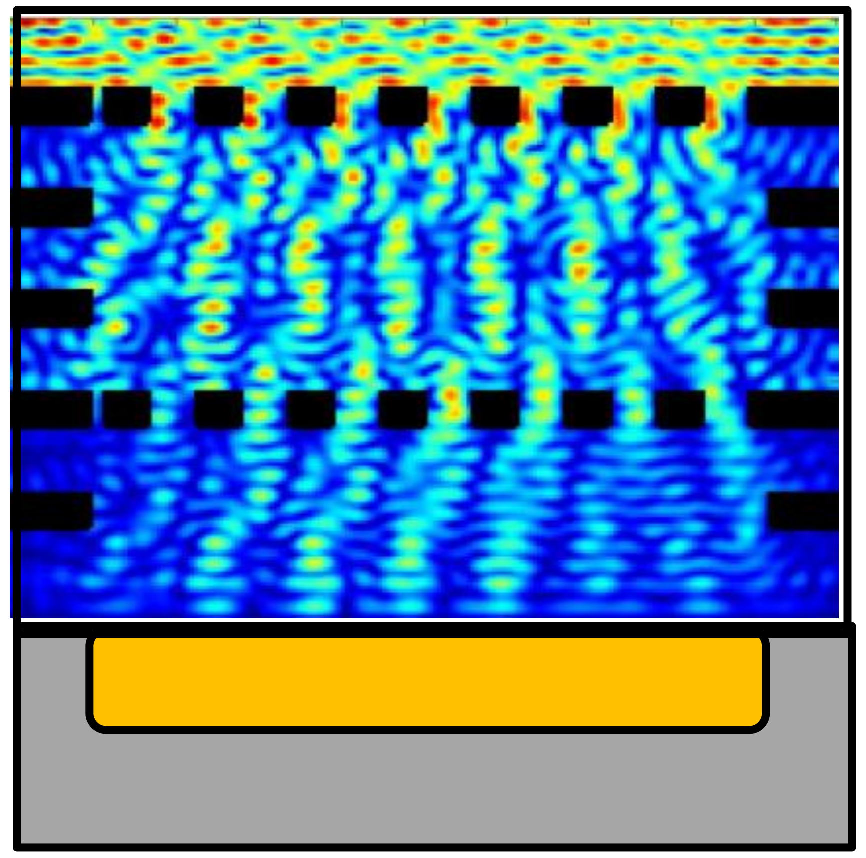
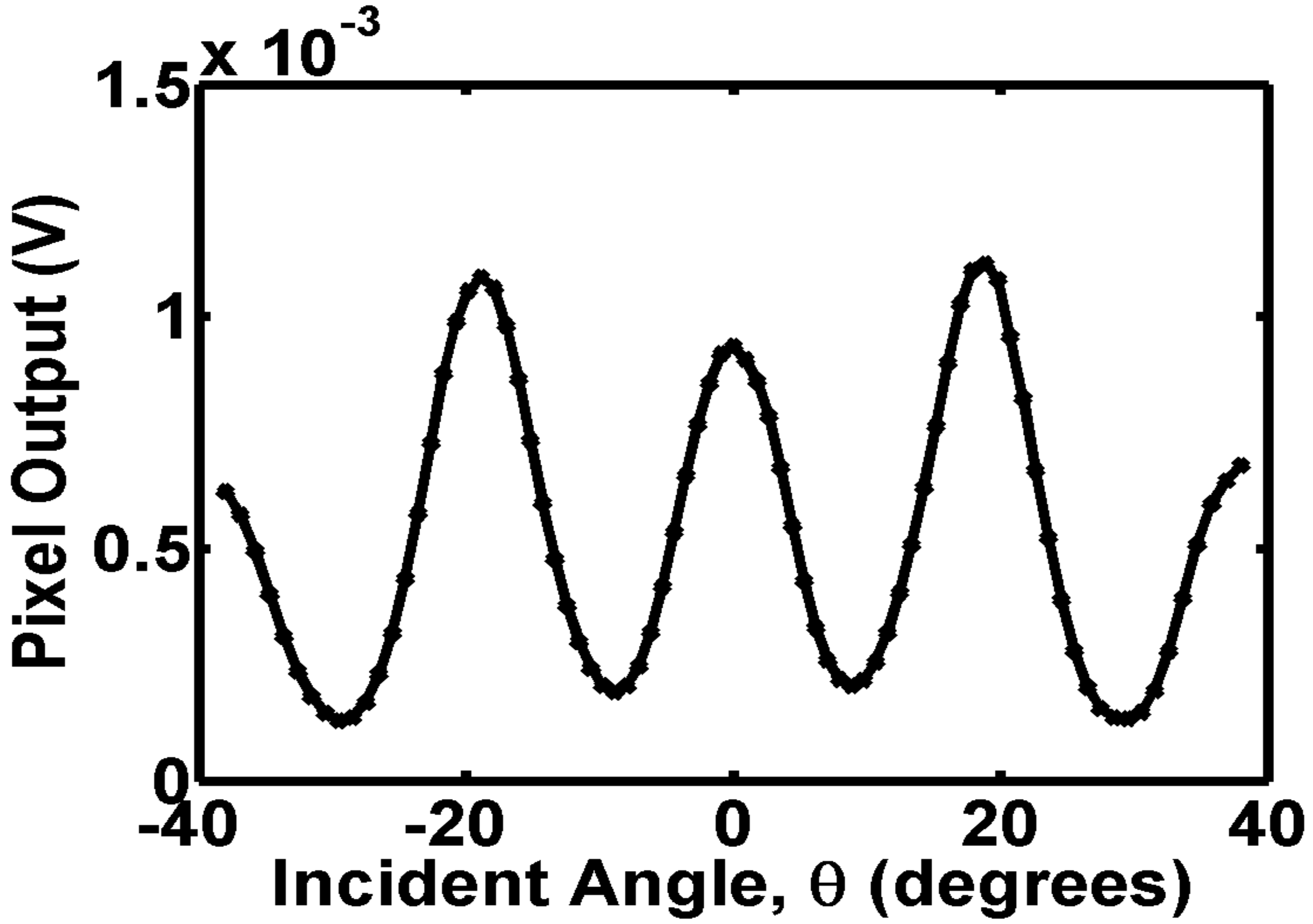
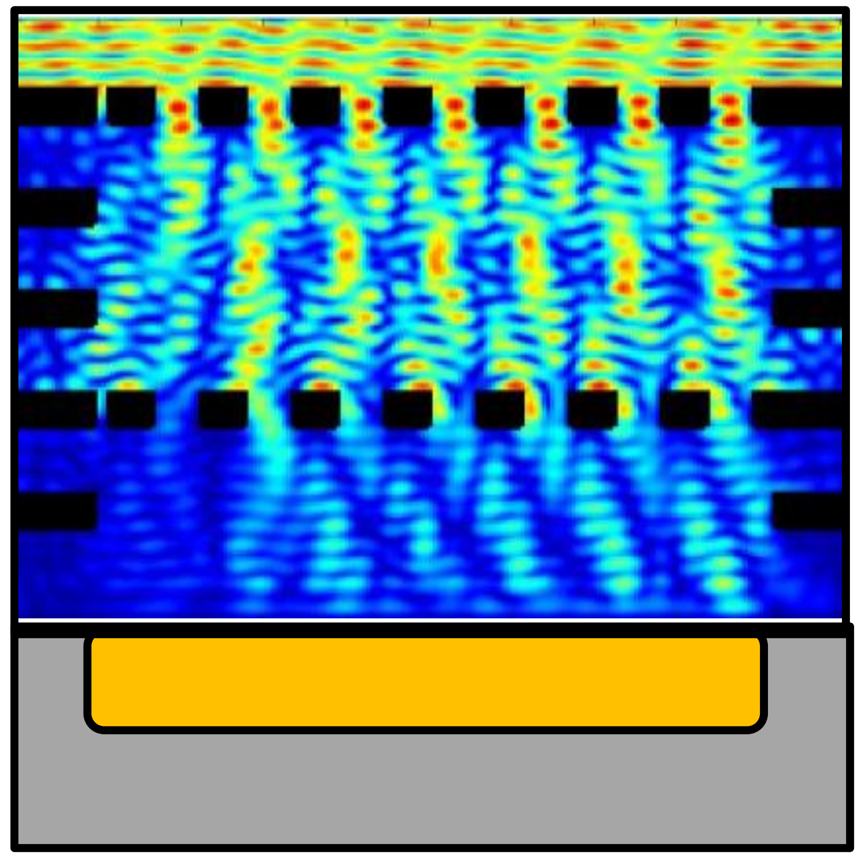
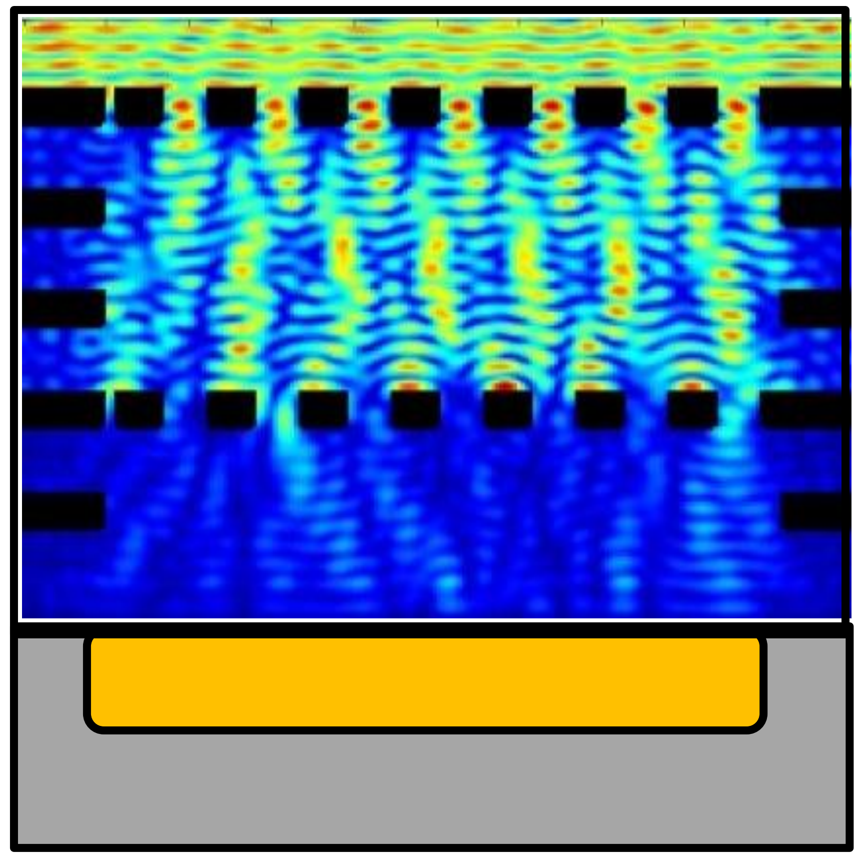




$$V_{out} = I_0 A(\theta)(1 + m\cos(\beta\theta + \alpha))$$

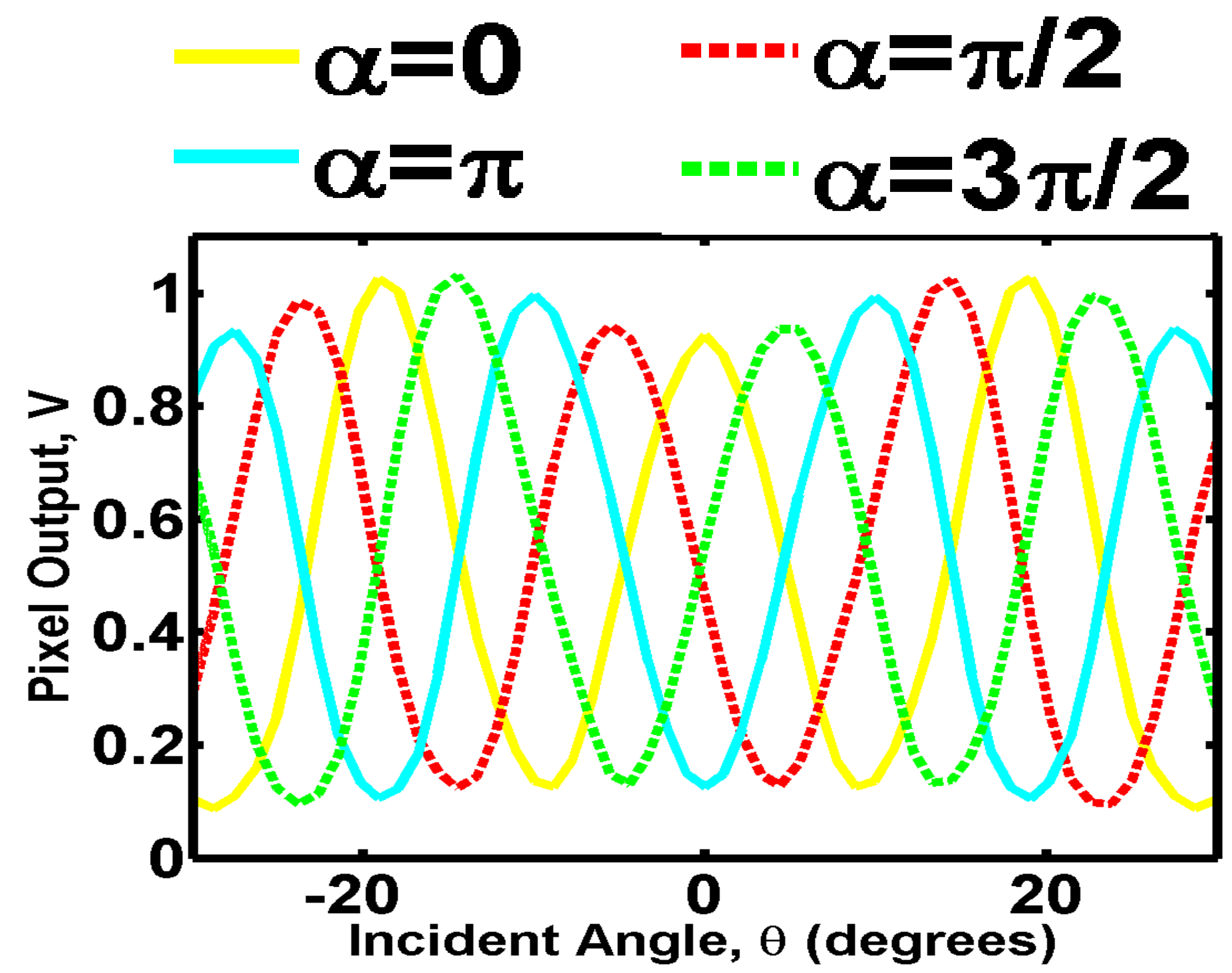


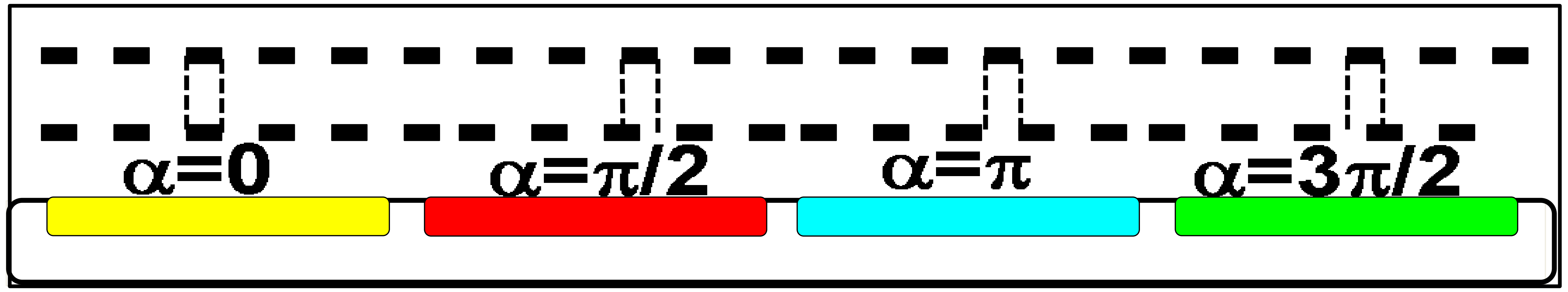




Quadrature Inversion

$$\begin{aligned} V_0 &= I_0 A(\theta)(1 + m\cos(\beta\theta)) \\ V_{\pi/2} &= I_0 A(\theta)(1 - m\sin(\beta\theta)) \\ V_{\pi} &= I_0 A(\theta)(1 - m\cos(\beta\theta)) \\ V_{3\pi/2} &= I_0 A(\theta)(1 + m\sin(\beta\theta)) \end{aligned}$$





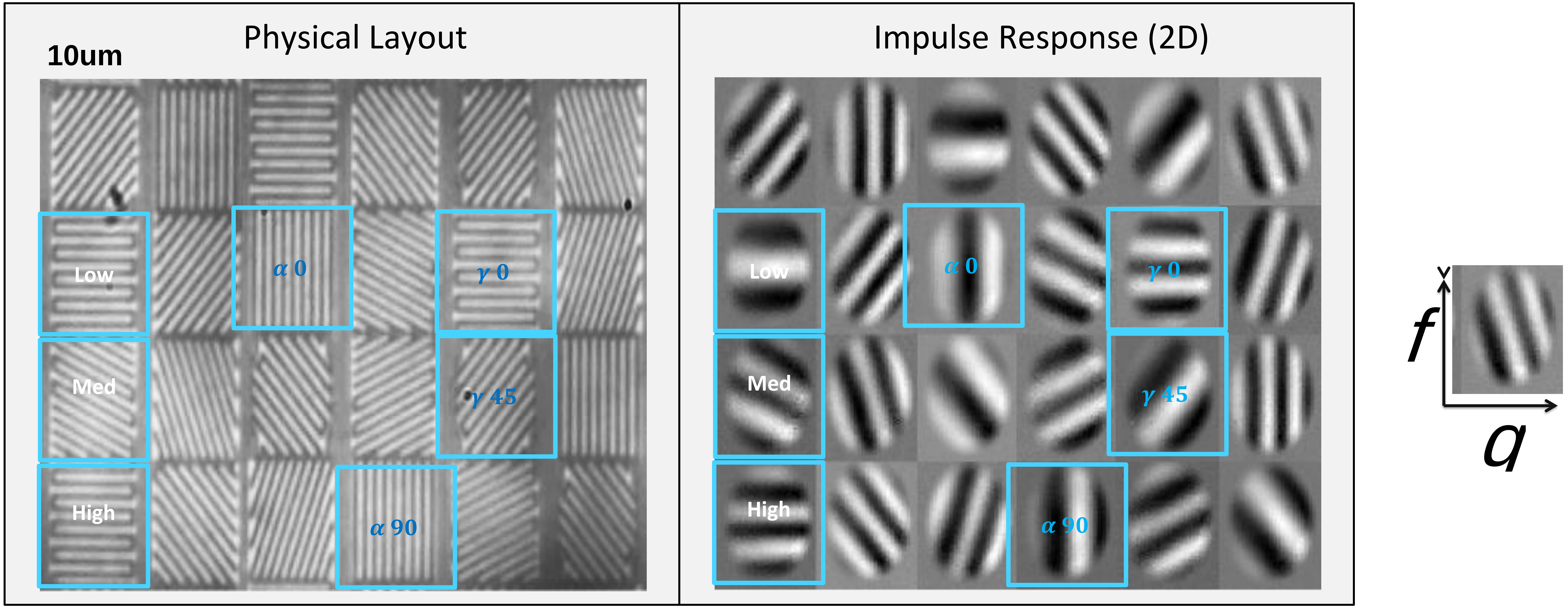
Intensity

$$I_0 A(\theta) = \frac{V_0 + V_\pi}{2} = \frac{V_{\pi/2} + V_{3\pi/2}}{2}$$

Incident angle

$$\theta = \frac{1}{\beta}\tan^{-1}\left(\frac{V_0 - V_\pi}{V_{3\pi/2} - V_{\pi/2}}\right)$$

2D ASP Tile

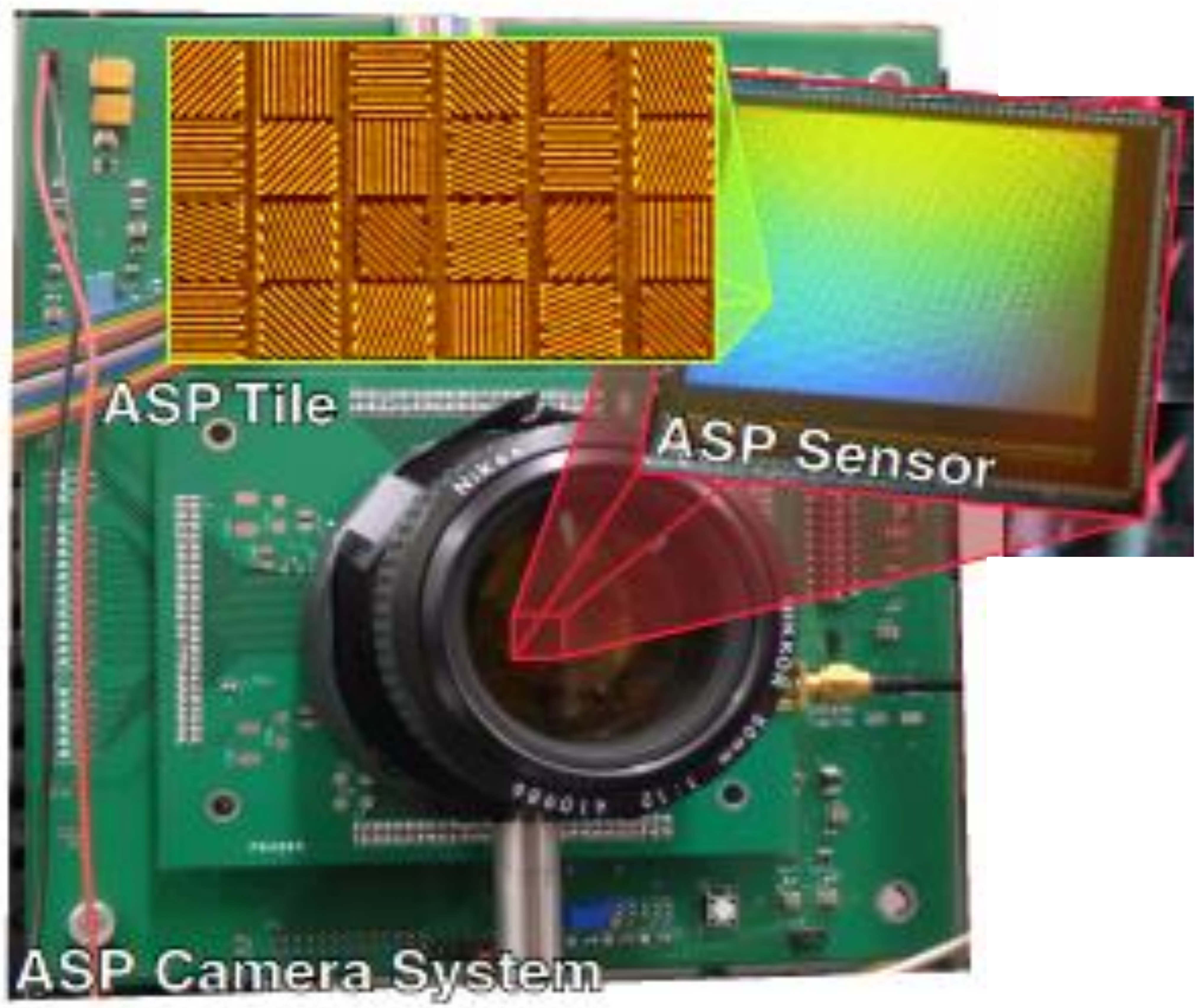


$$\rho^{(\alpha,\beta,\gamma)}(\theta) = \frac{1}{2} + \frac{m}{2}\cos\left(\beta\cos\gamma\,\theta_x + \beta\sin\gamma\,\theta_y + \alpha\right)$$

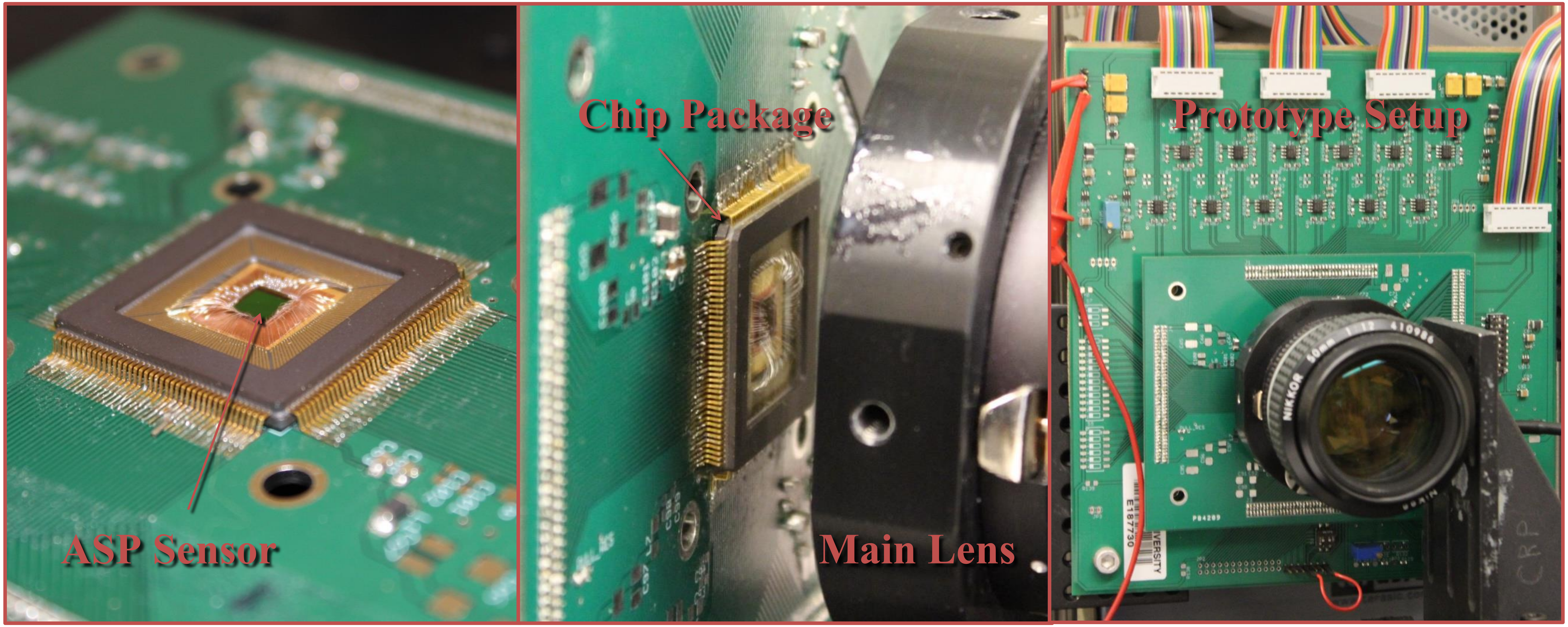
ASP Camera

We tile the entire image sensor with this repeated pattern of different ASP pixels

The sensor is fabricated in an unmodified CMOS process

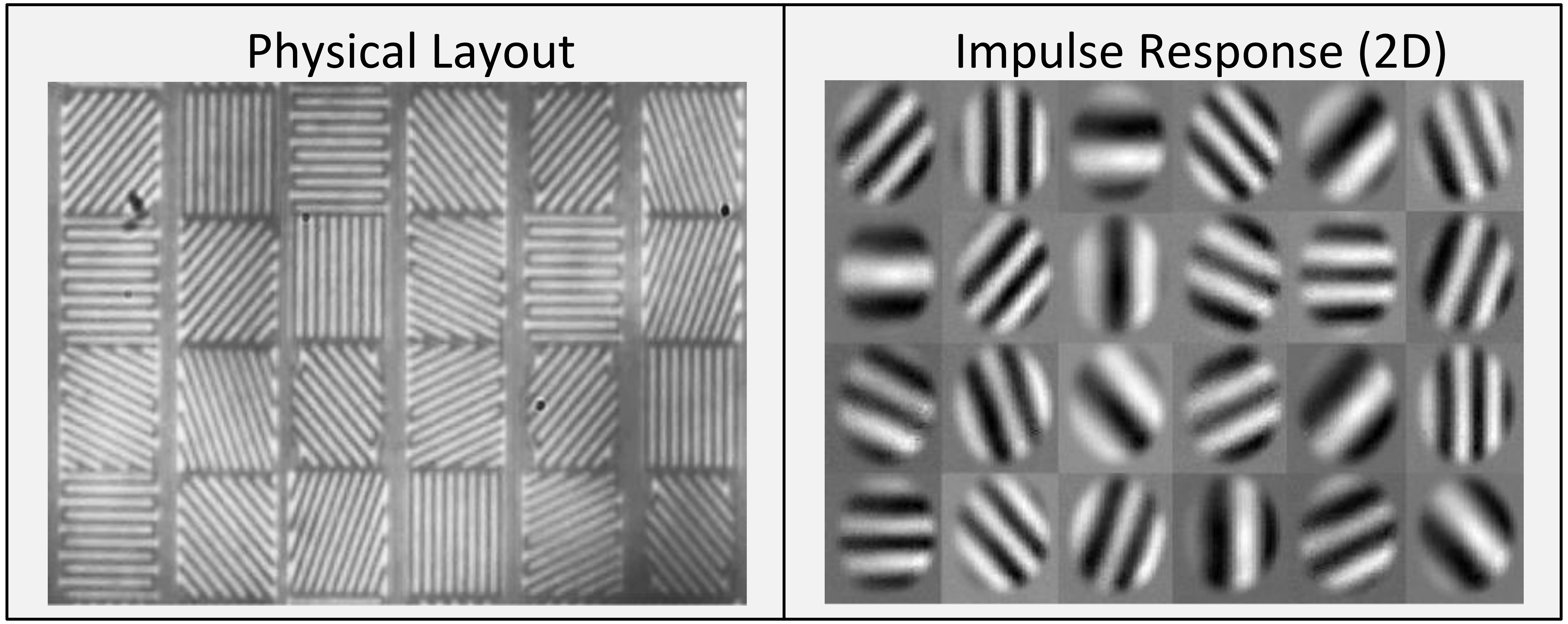


Experimental Setup



ASP Light Field Capture

$$i(x,y) = \iint \rho^{(\alpha,\beta,\gamma)} l(x,y,\theta,\phi)\, d\theta\, d\phi$$

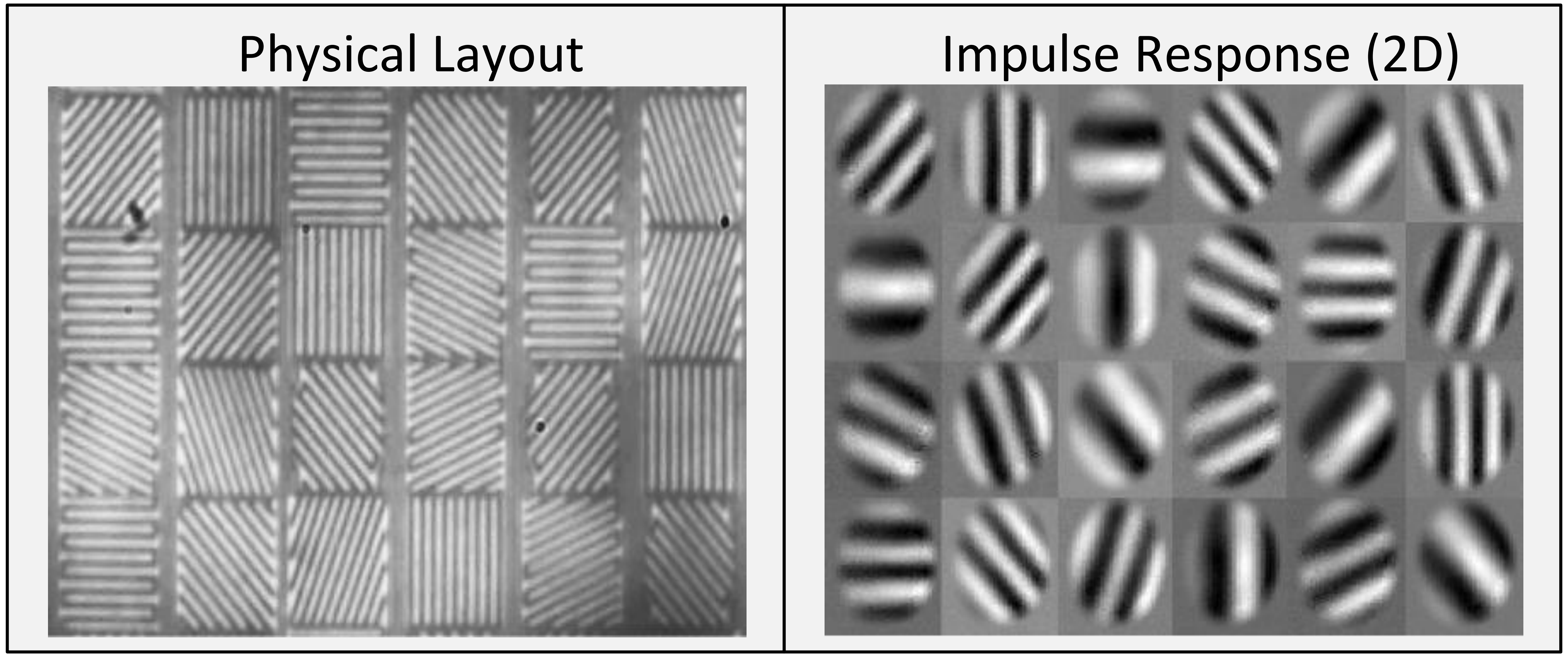


$$\rho^{(\alpha,\beta,\gamma)}(\theta) = \frac{1}{2} + \frac{m}{2}\cos\left(\beta\cos\gamma\,\theta_x + \beta\sin\gamma\,\theta_y + \alpha\right)$$

- Each pixel modulates the light field with a different angular response function

ASP Light Field Capture

- Model the image capture process: $i = \mathrm{F}\, l$



$$\rho^{(\alpha,\beta,\gamma)}(\theta) = \frac{1}{2} + \frac{m}{2}\cos\left(\beta\cos\gamma\,\theta_x + \beta\sin\gamma\,\theta_y + \alpha\right)$$

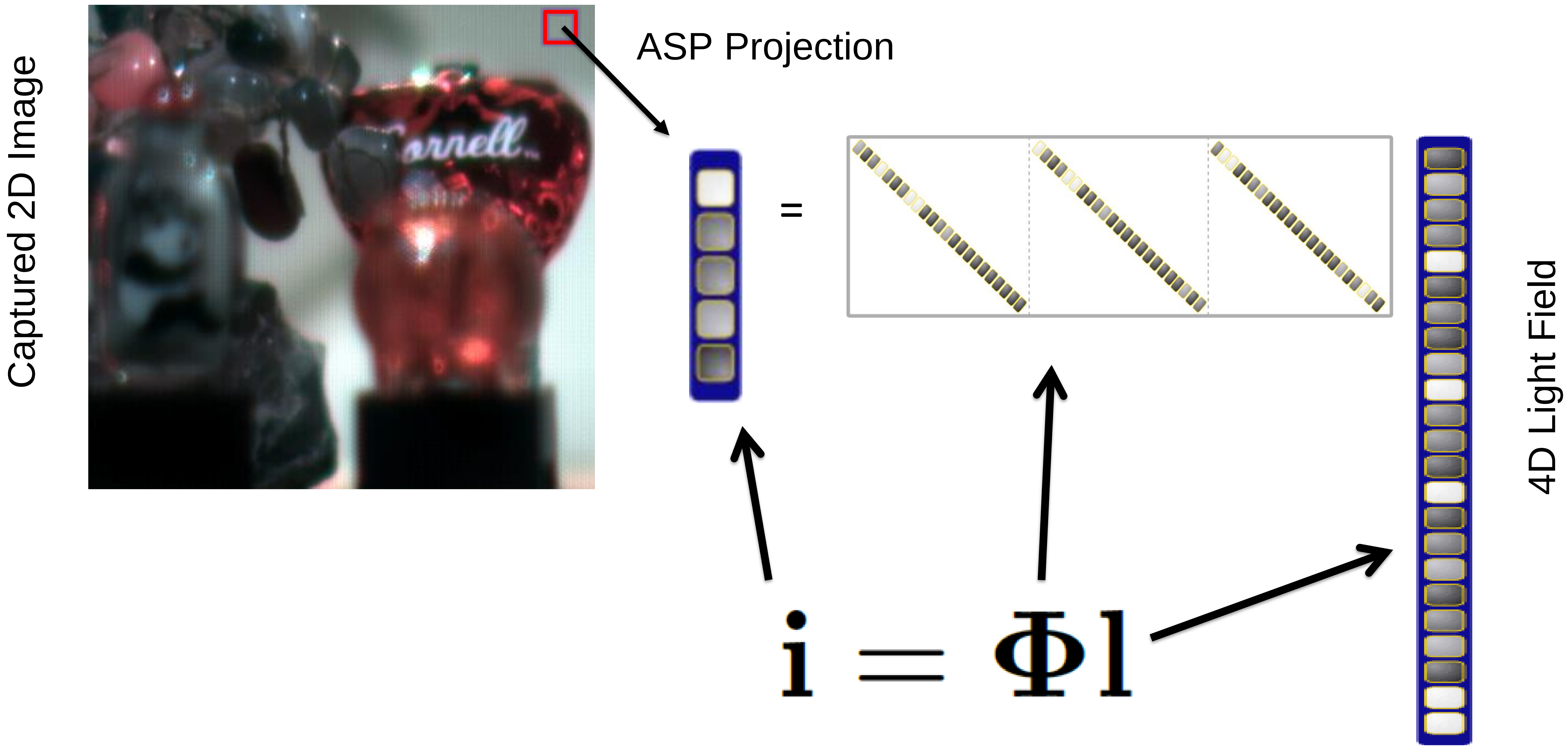
→ F

ASP Light Field Capture

- Linear Reconstruction: $l_{downsampled} = \mathrm{F}^{-1} i$

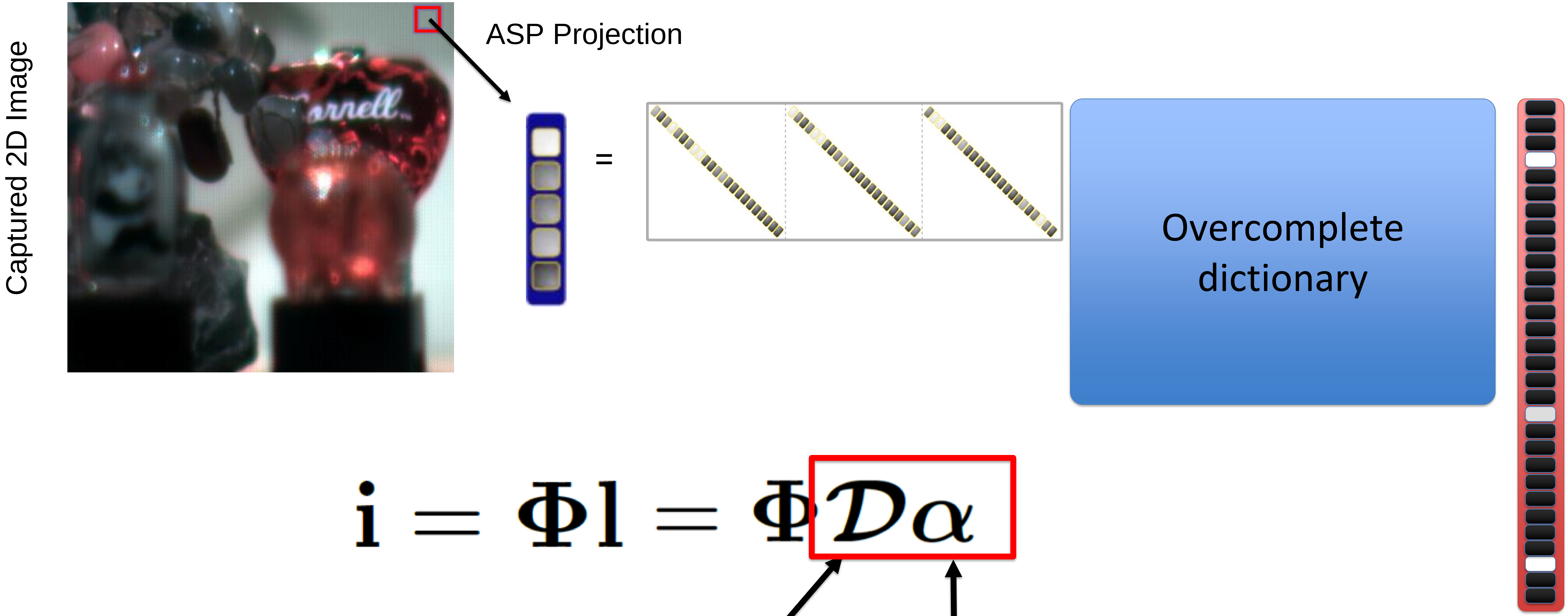
- We can invert this equation using linear methods by reducing the resolution of the 4D light field
- The resulting reconstruction is low resolution due to the **spatio-angular tradeoff**

Compressive Light Field Photography



$$\mathbf{i} = \mathbf{\Phi} \mathbf{l}$$

Compressive Light Field Photography



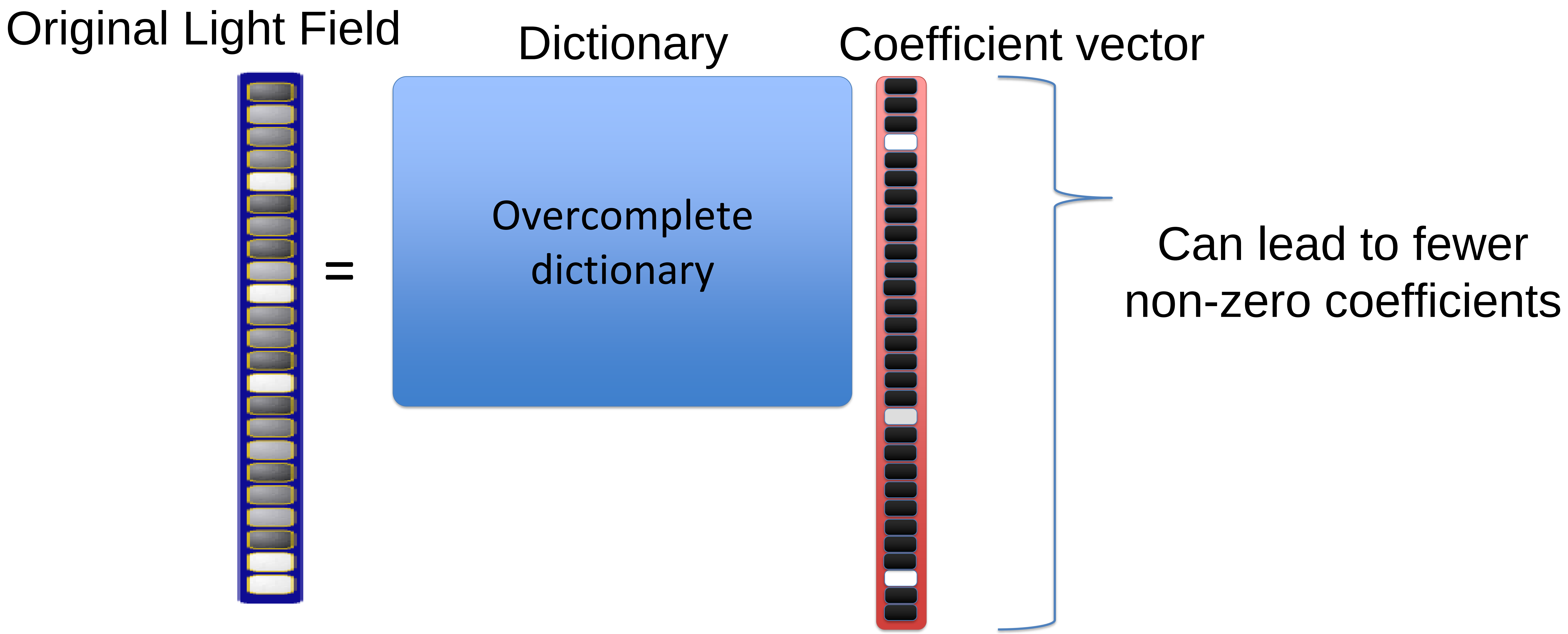
$$\mathbf{i} = \Phi \mathbf{l} = \Phi \mathcal{D} \alpha$$

Dictionary

Sparse Coefficients

Decomposing light fields into sparse representations

$$\mathbf{l} = \mathcal{D}\alpha \quad \text{s.t.} \quad \alpha \quad \text{is } \textit{sparse}$$



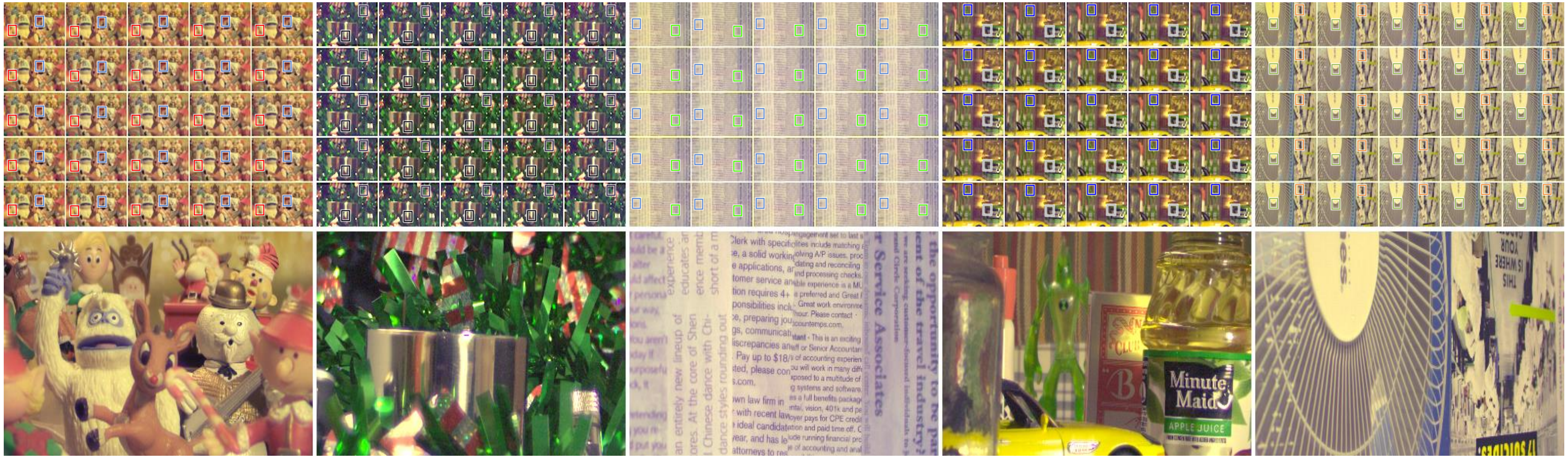
Dictionary Learning

$$\mathbf{l} = \mathcal{D}\alpha \quad \text{s.t.} \quad \alpha \text{ is } \textit{sparse}$$

Training light fields

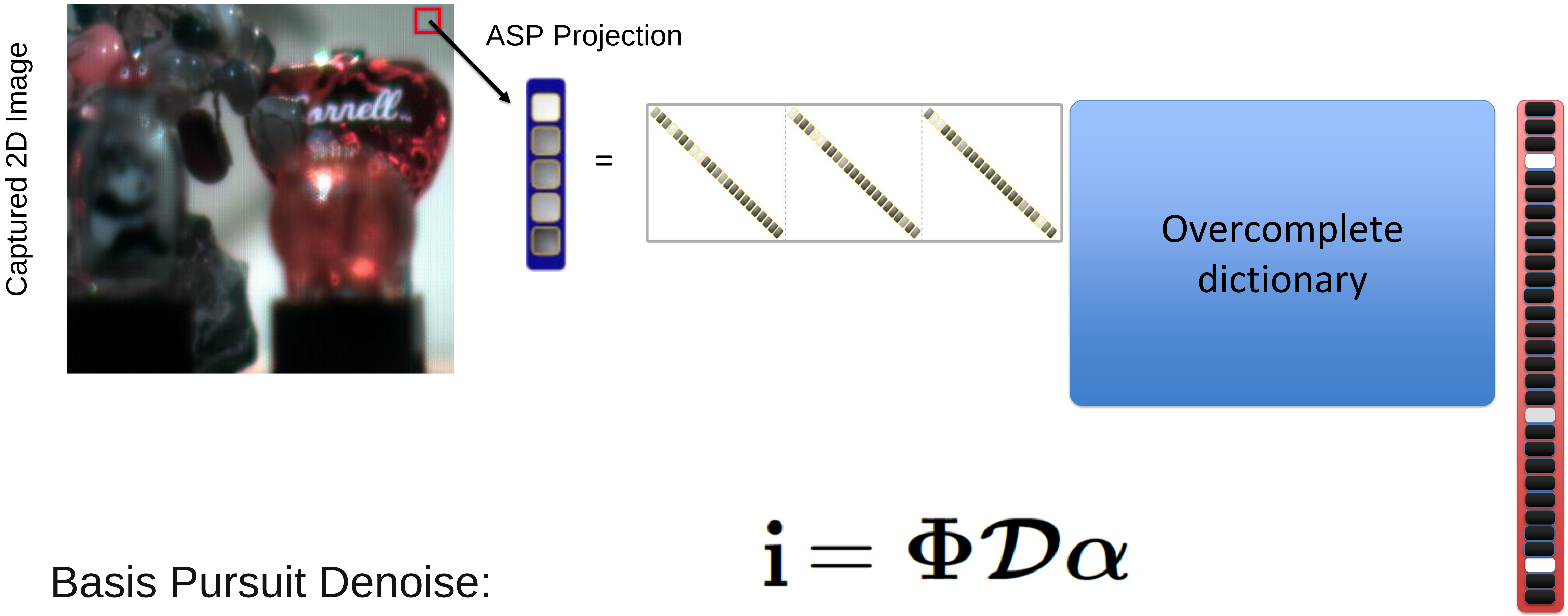
Use K-SVD algorithm to solve this problem

Sample 1,000,000 random 4D patches from training light fields



[Marwah et al. 2013]

Compressive Light Field Reconstruction

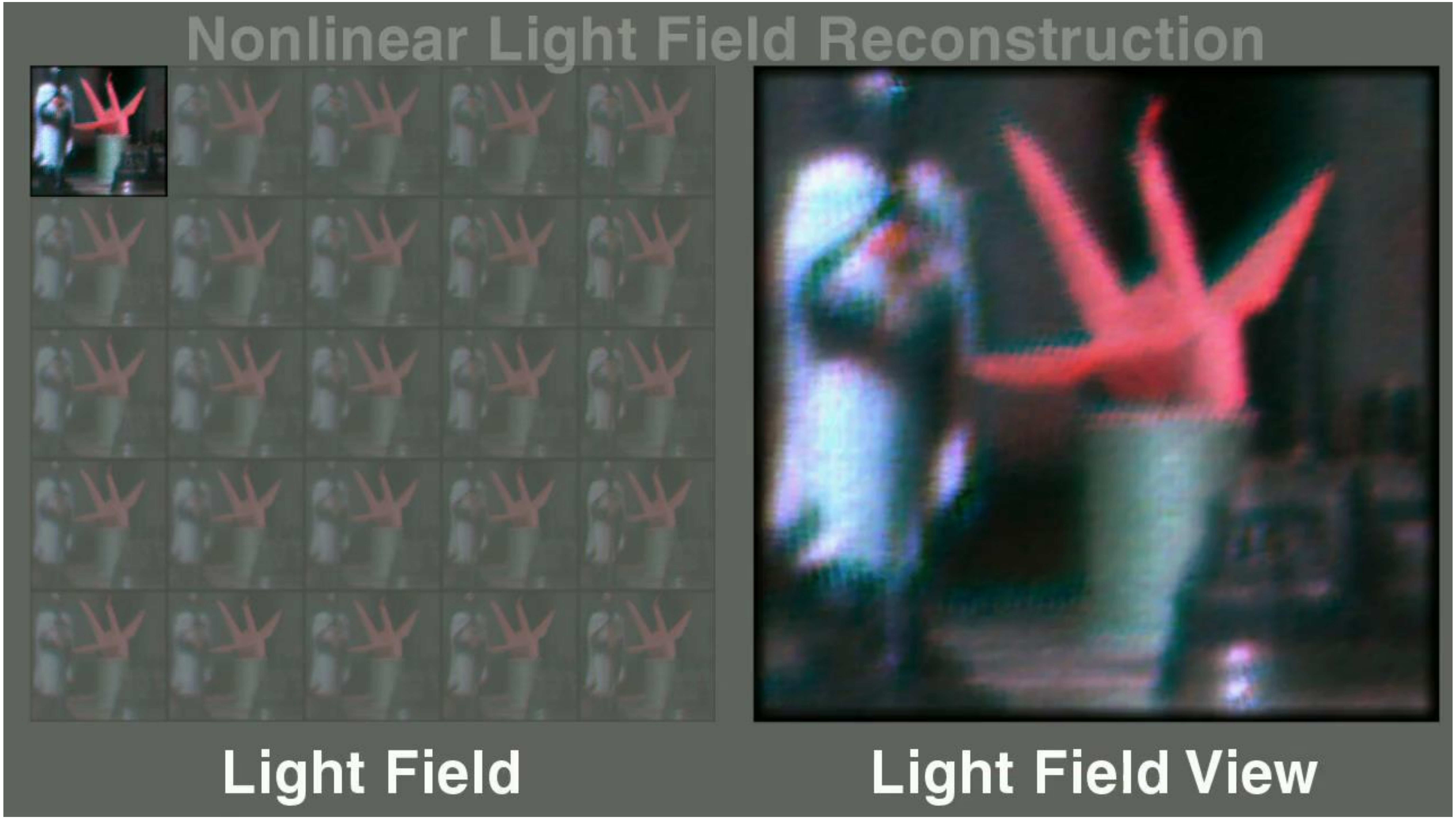


$$\mathbf{i} = \mathbf{\Phi} \mathcal{D} \boldsymbol{\alpha}$$

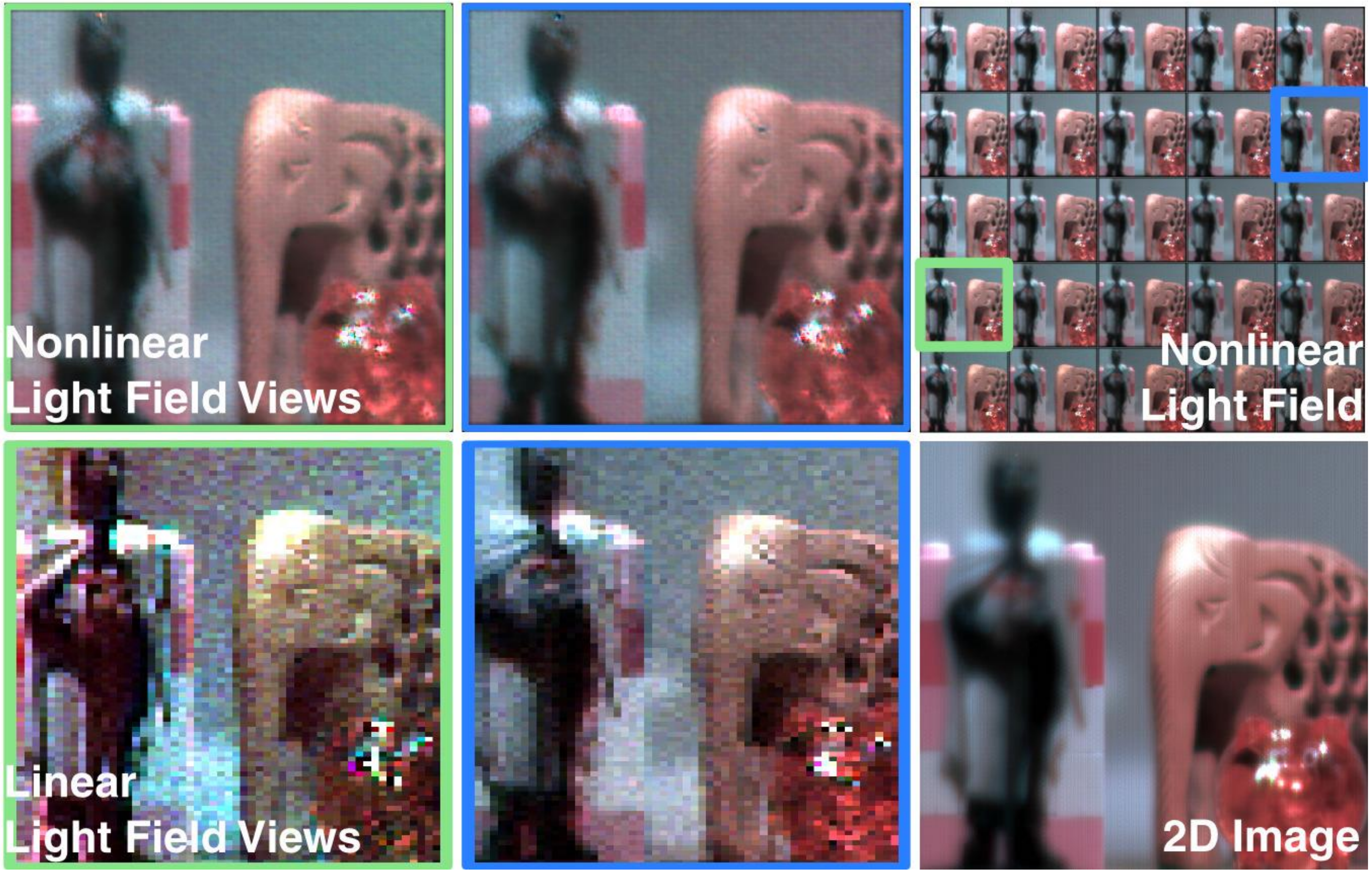
Basis Pursuit Denoise:

$$\underset{\{\boldsymbol{\alpha}\}}{\text{minimize}} \quad \|\boldsymbol{\alpha}\|_1$$
$$\text{subject to} \quad \|\mathbf{i} - \mathbf{\Phi} \mathcal{D} \boldsymbol{\alpha}\|_2 \leq \epsilon$$

Experimental results



Comparison of reconstruction methods



Digital refocusing after the picture has been taken

Focused on Swan

Focused on Knight

Computational Sensors

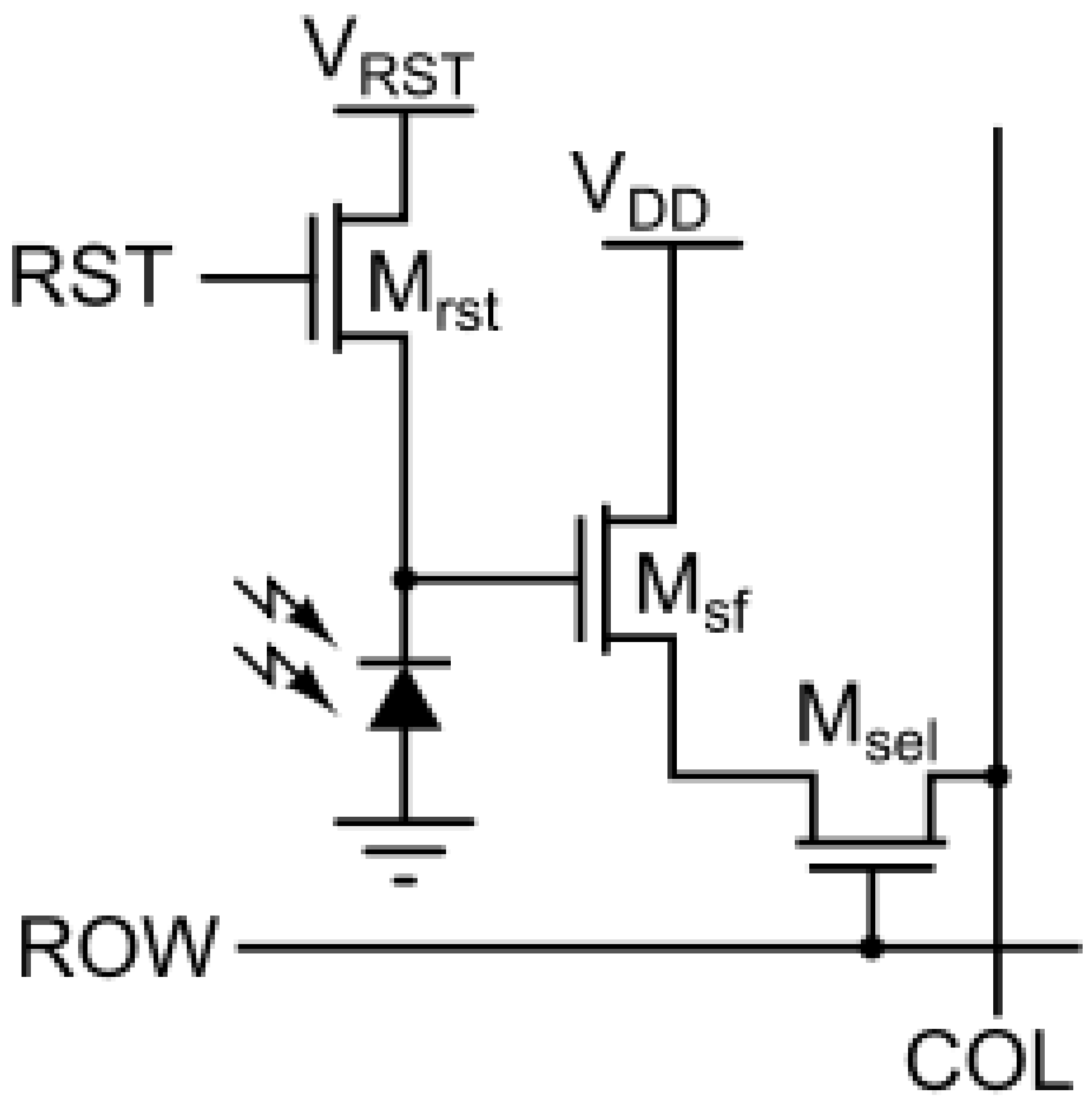
But what is different about computational sensors vs. regular sensors?

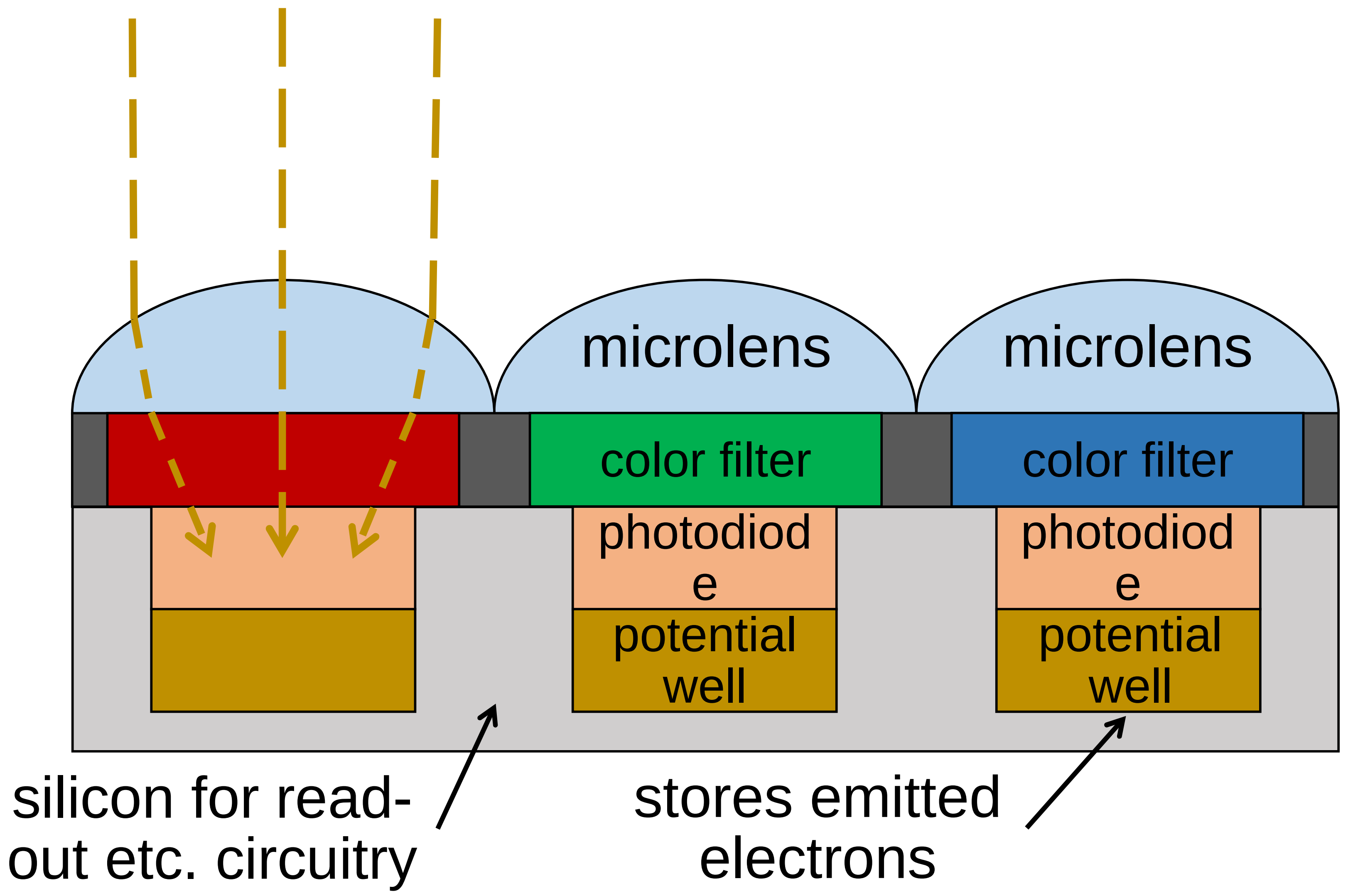
Some options:

(1) Change the readout/timing

(2) Change the pixel design itself

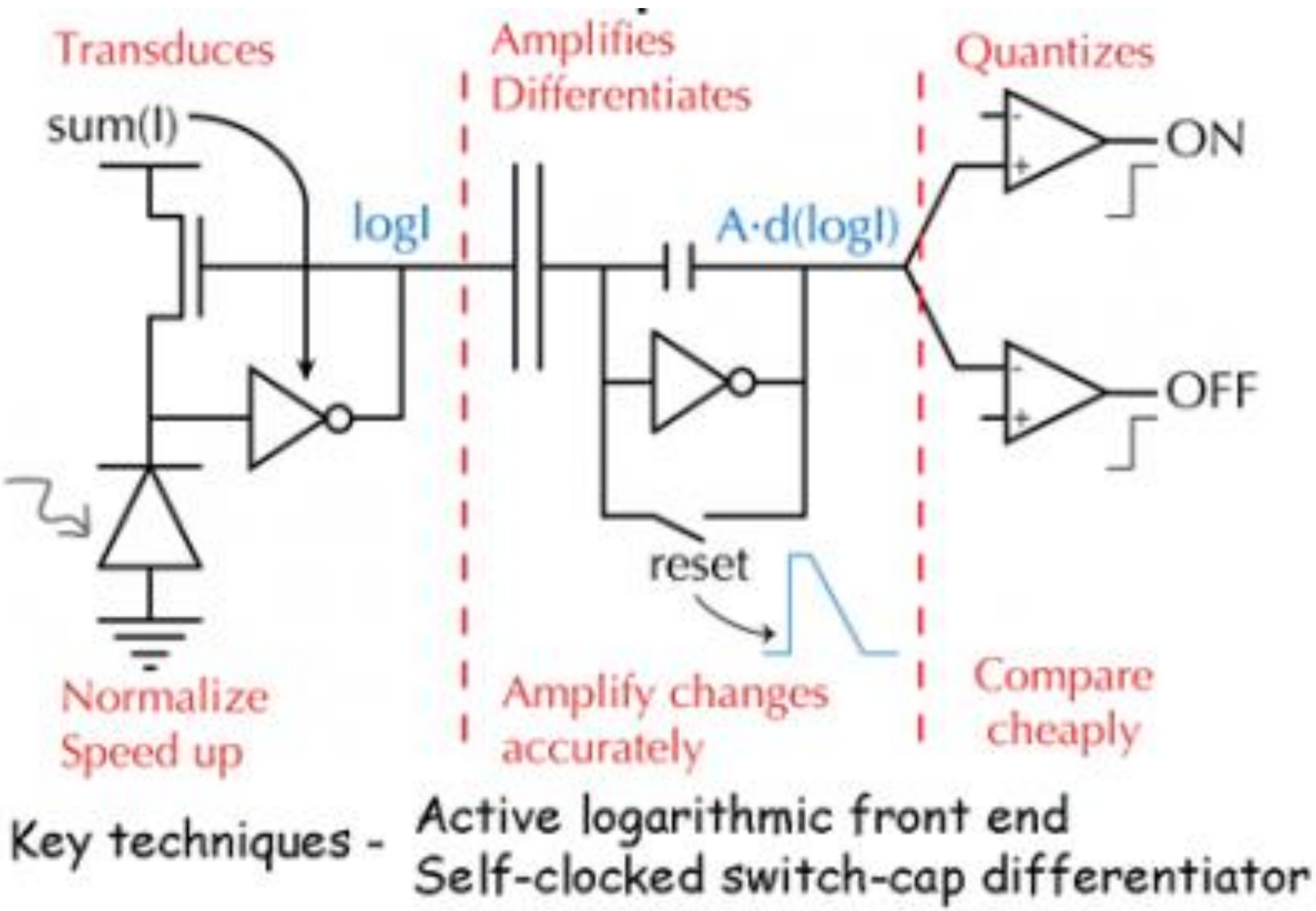
(3) Change the on-chip processing





Event-Based Cameras (also called Dynamic Vision Sensors)

Dynamic Vision Sensor



Event-Based Cameras (also called Dynamic Vision Sensors)

Dynamic Vision Sensor

Concept Figure for Event Based Camera

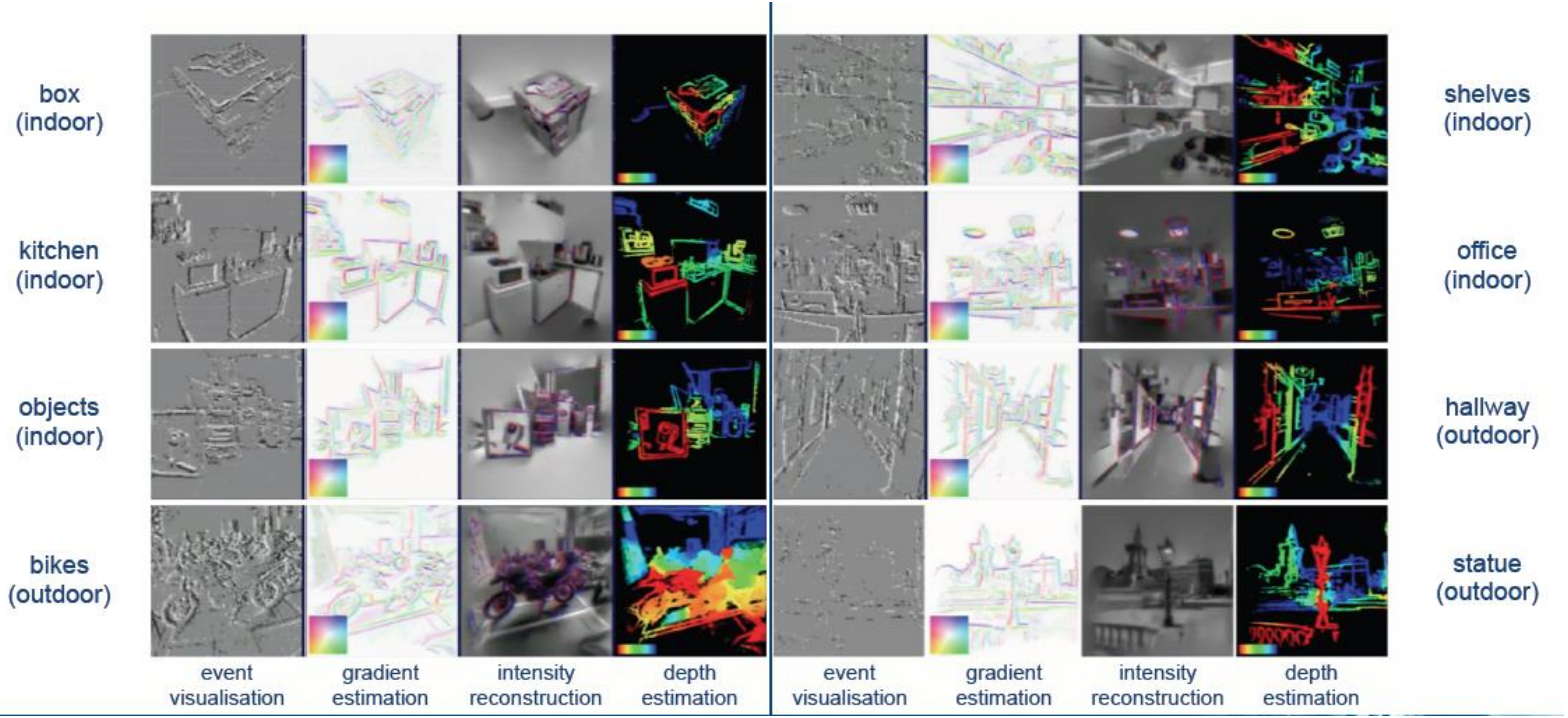
https://www.youtube.com/watch?v=kPCZESVfHoQ

High Speed Output on a Quadcopter

https://www.youtube.com/watch?v=LauQ6LWTkxM

	CMOS (Grasshopper3)	DVS (DVS128)
Resolution	2048 x 2048	128 x 128
Power	4.5 W	23 mW
Frame Rate	90 Hz	3-10 kHz
Dynamic Range	52.87 dB	120 dB
Data Rate	Very High	Very Low

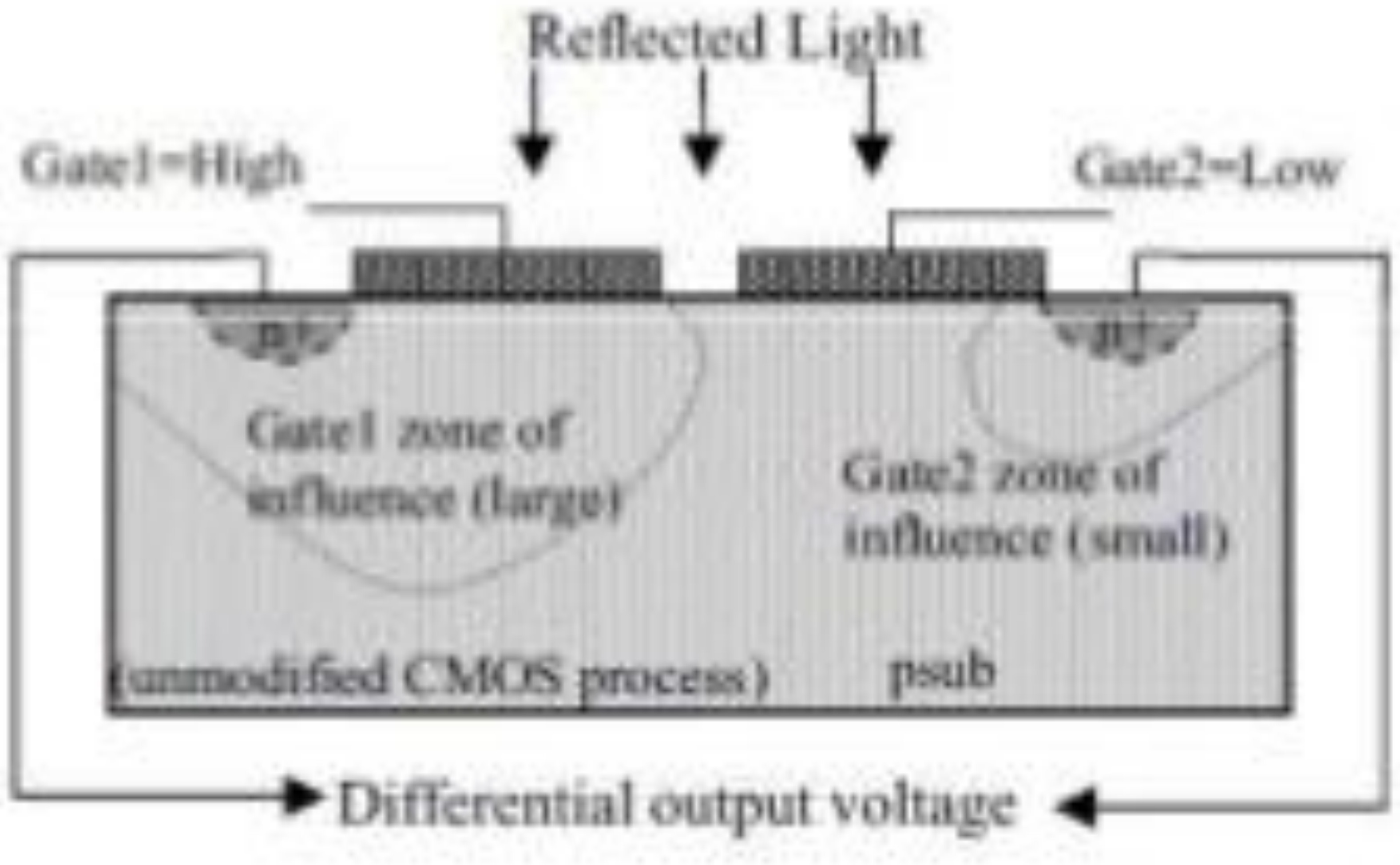
Applications of Event Based Cameras



Kim et al, “Real-Time 3D Reconstruction and 6-DoF Tracking with an Event Camera” ECCV 2016 (Best Paper Award!)

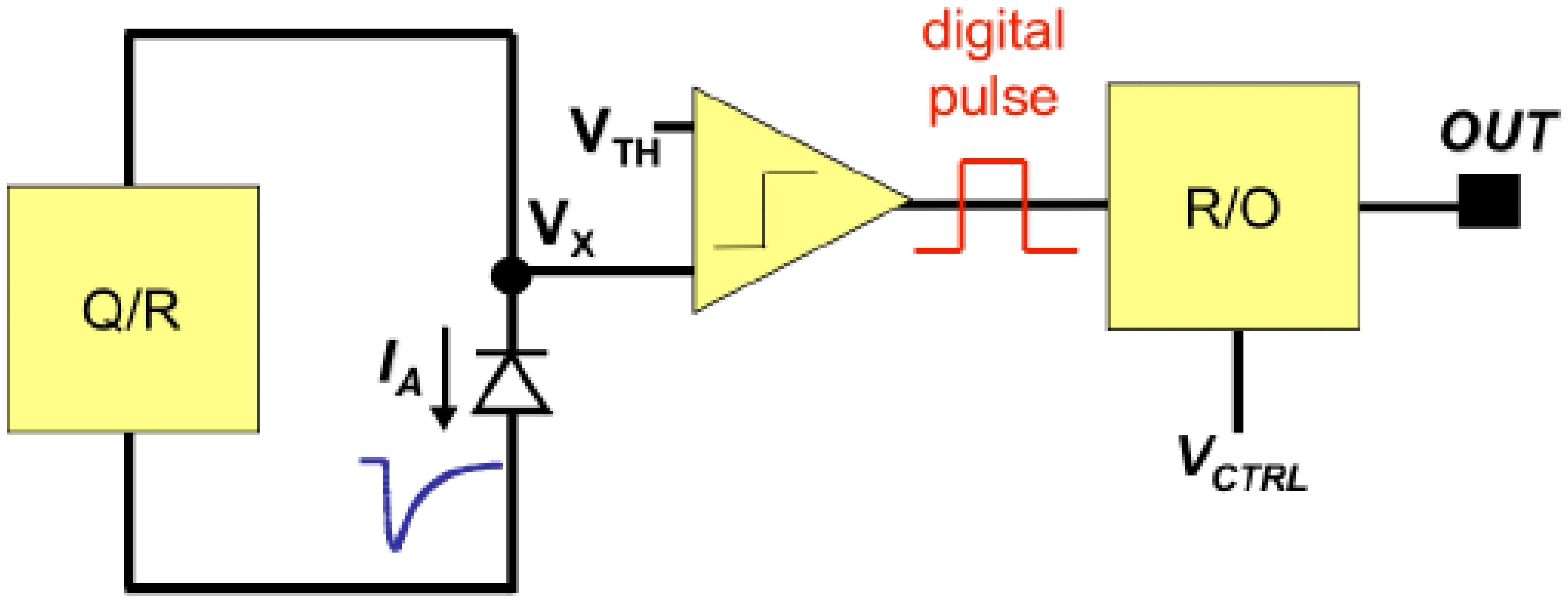
Time-of-Flight (TOF) Imaging and Transient Imaging

Demodulating Pixel

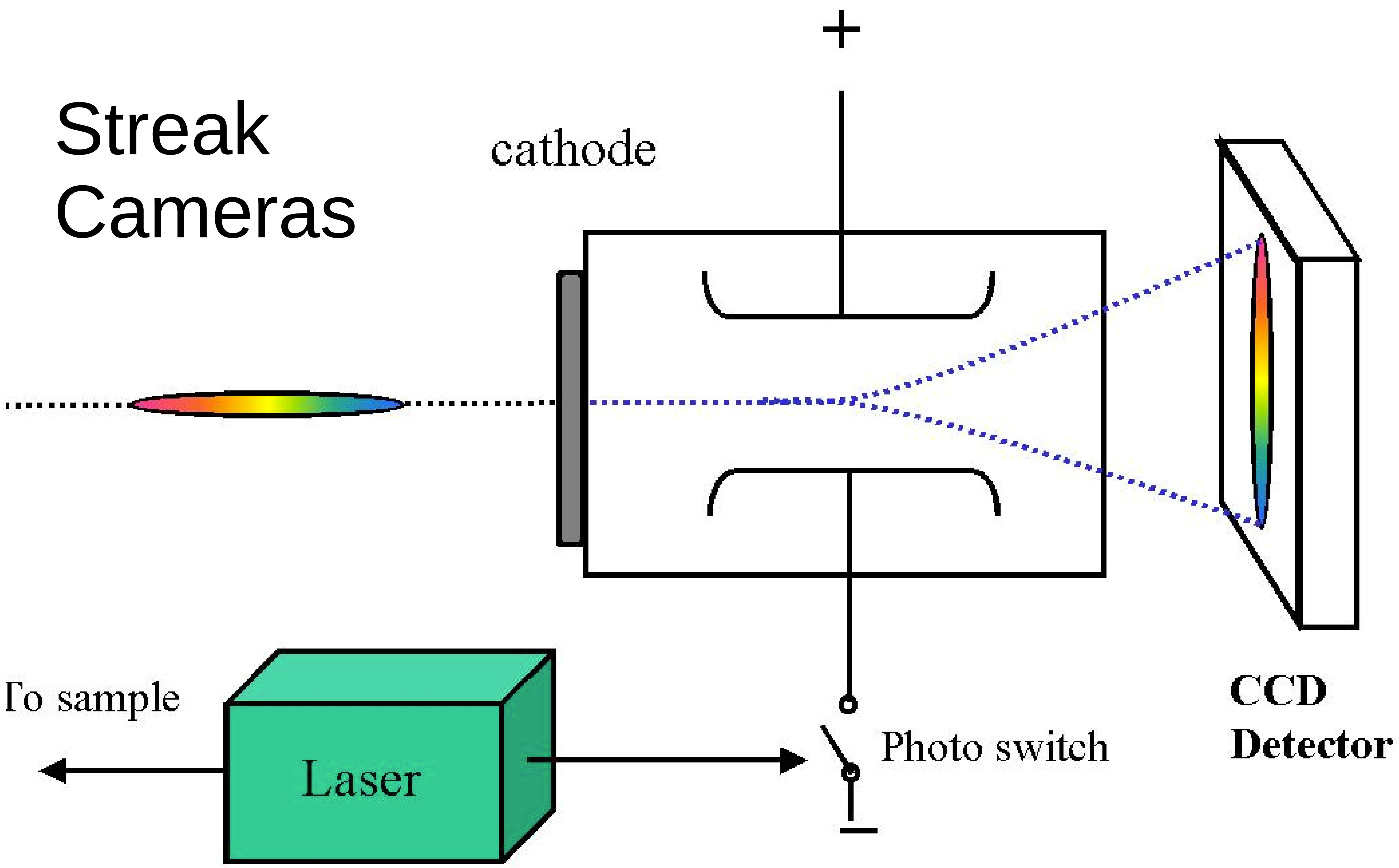


Microsoft Kinect V2

Single Photon Avalanche Diodes (SPAD)



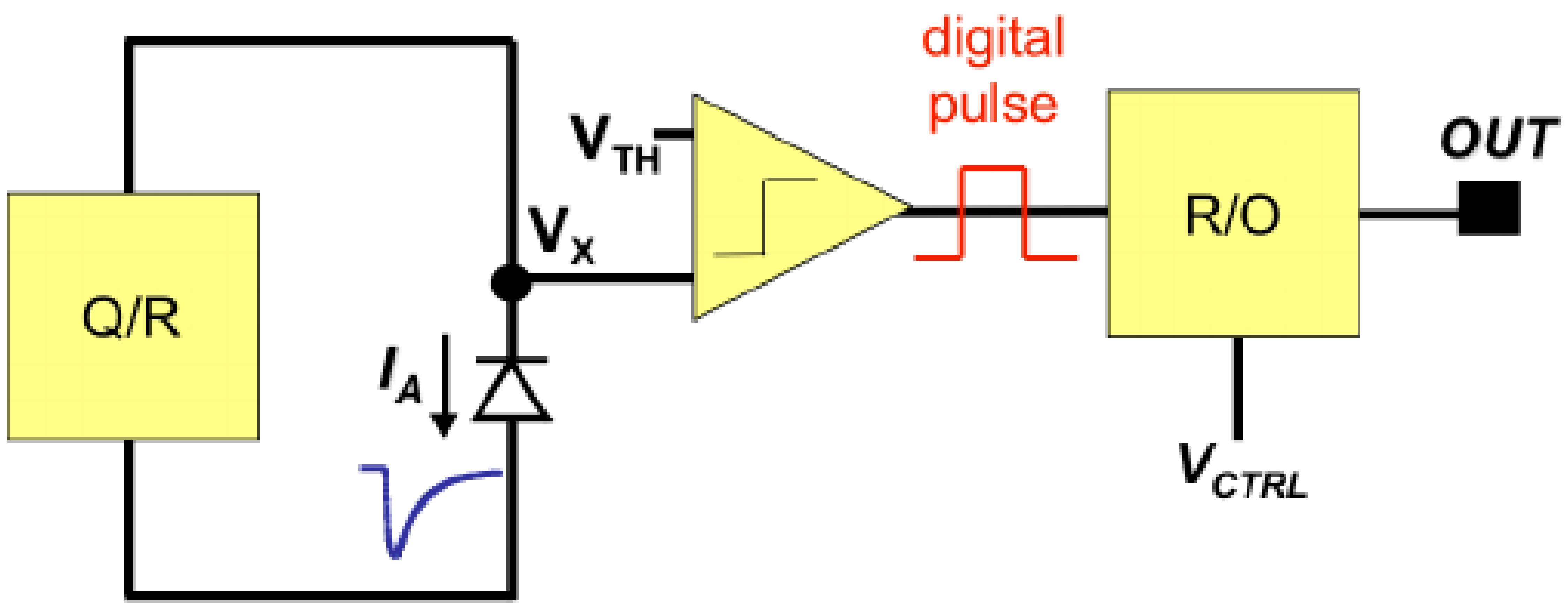
Streak Cameras



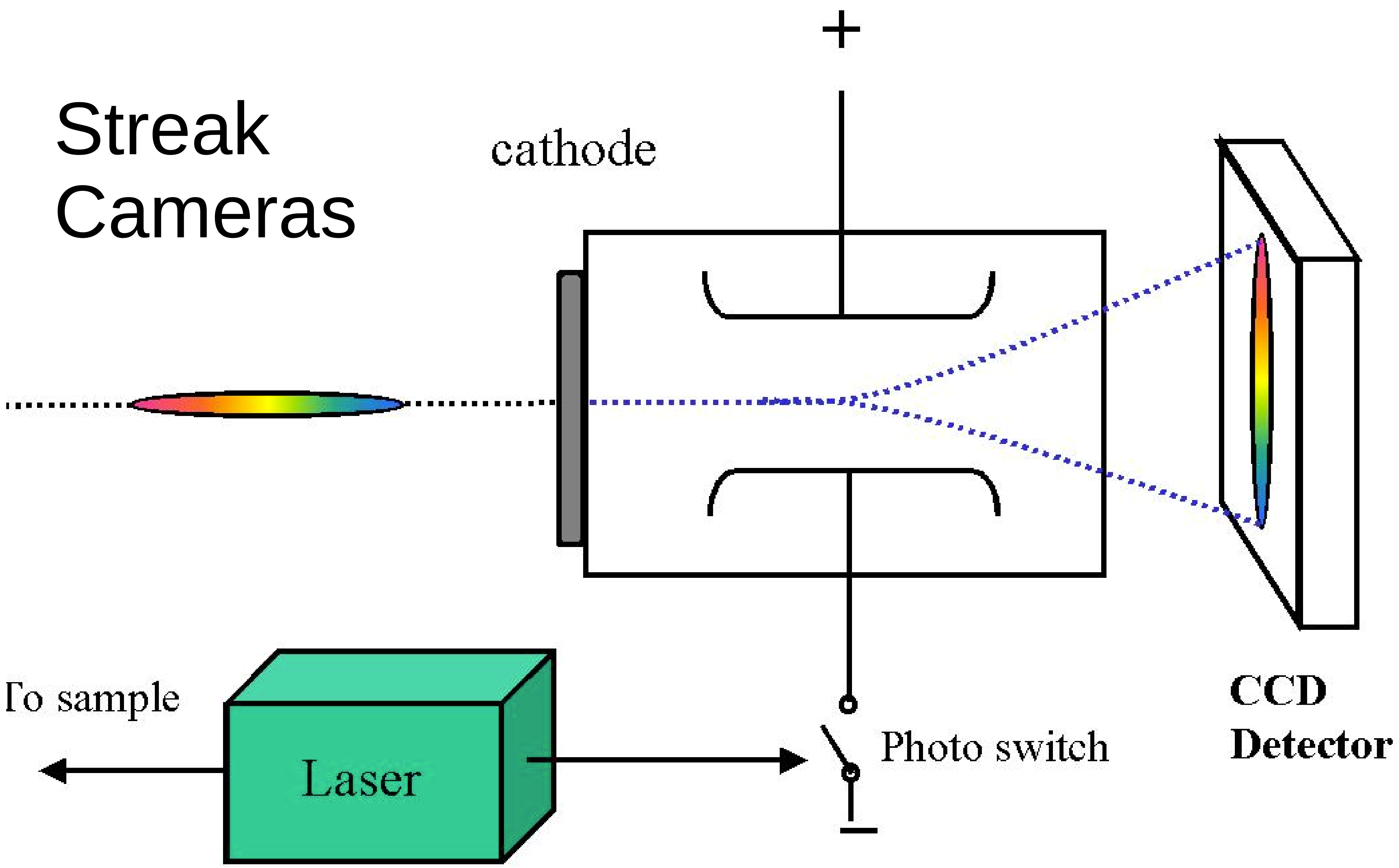
Time-of-Flight (TOF) Imaging and Transient Imaging

More on TOF and transient imaging in future lectures

Single Photon Avalanche Diodes (SPAD)



Streak Cameras



Computational Sensors

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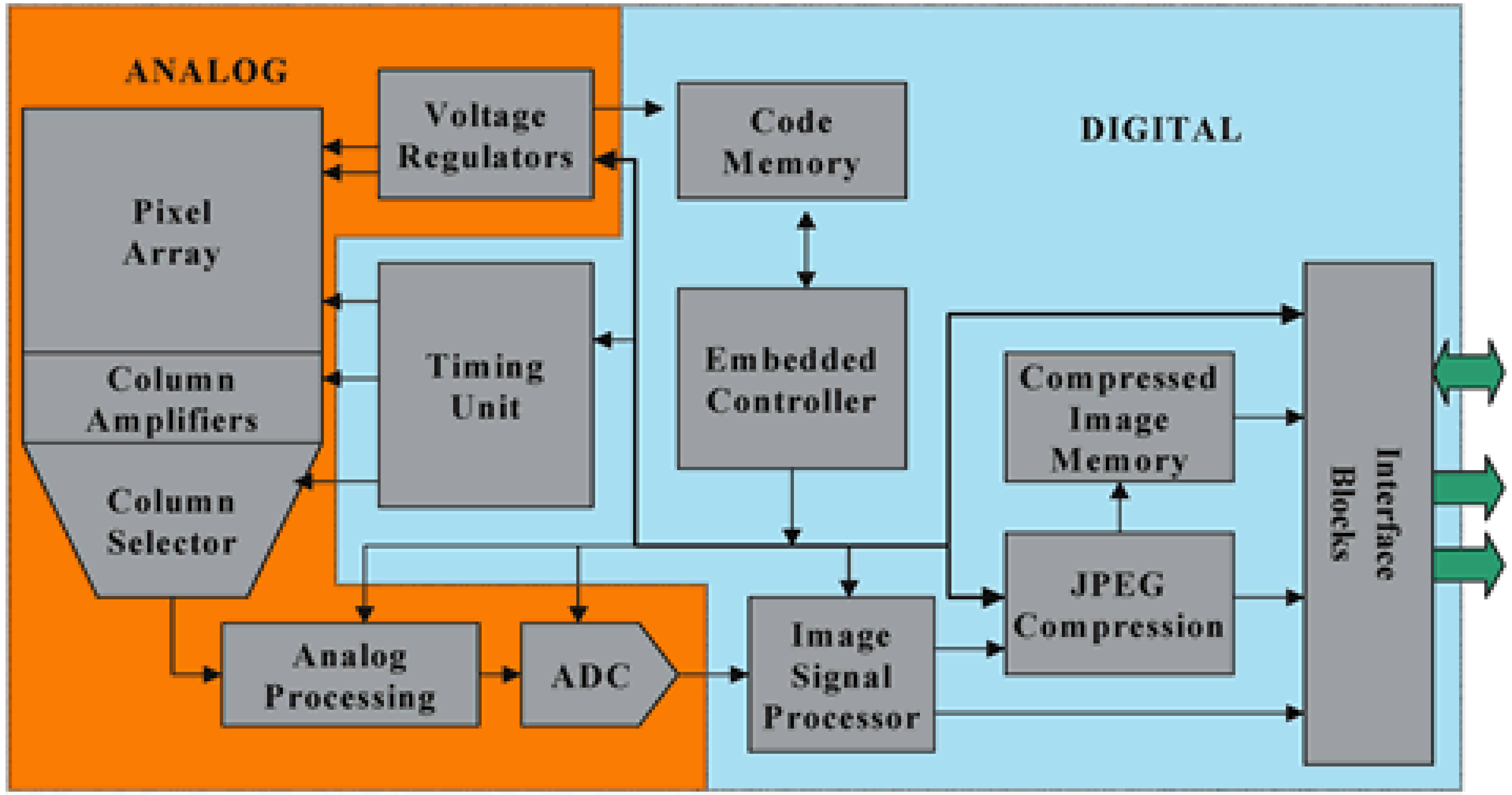


On-Chip Image Compression

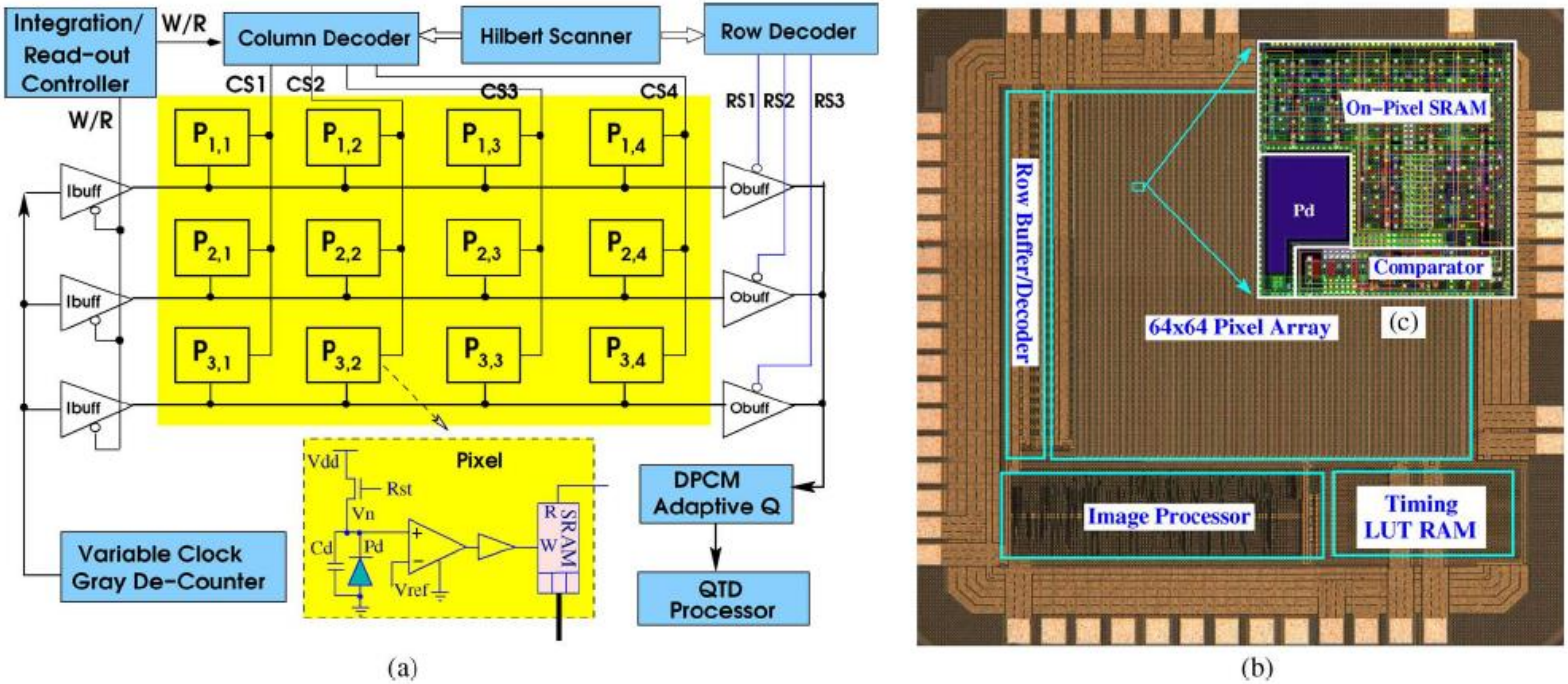


Fig. 5. (a) Architecture of the overall imager including the sensor and the processor. (b) Corresponding microphotograph of the chip implemented in Alcatel 0.35-μm CMOS technology with the main building blocks highlighted. (c) Layout of the pixel.

Chen et al, A CMOS Image Sensor with On-Chip Image Compression Based on Predictive Boundary Adaptation and Memoryless QTD Algorithm, VLSI 2011

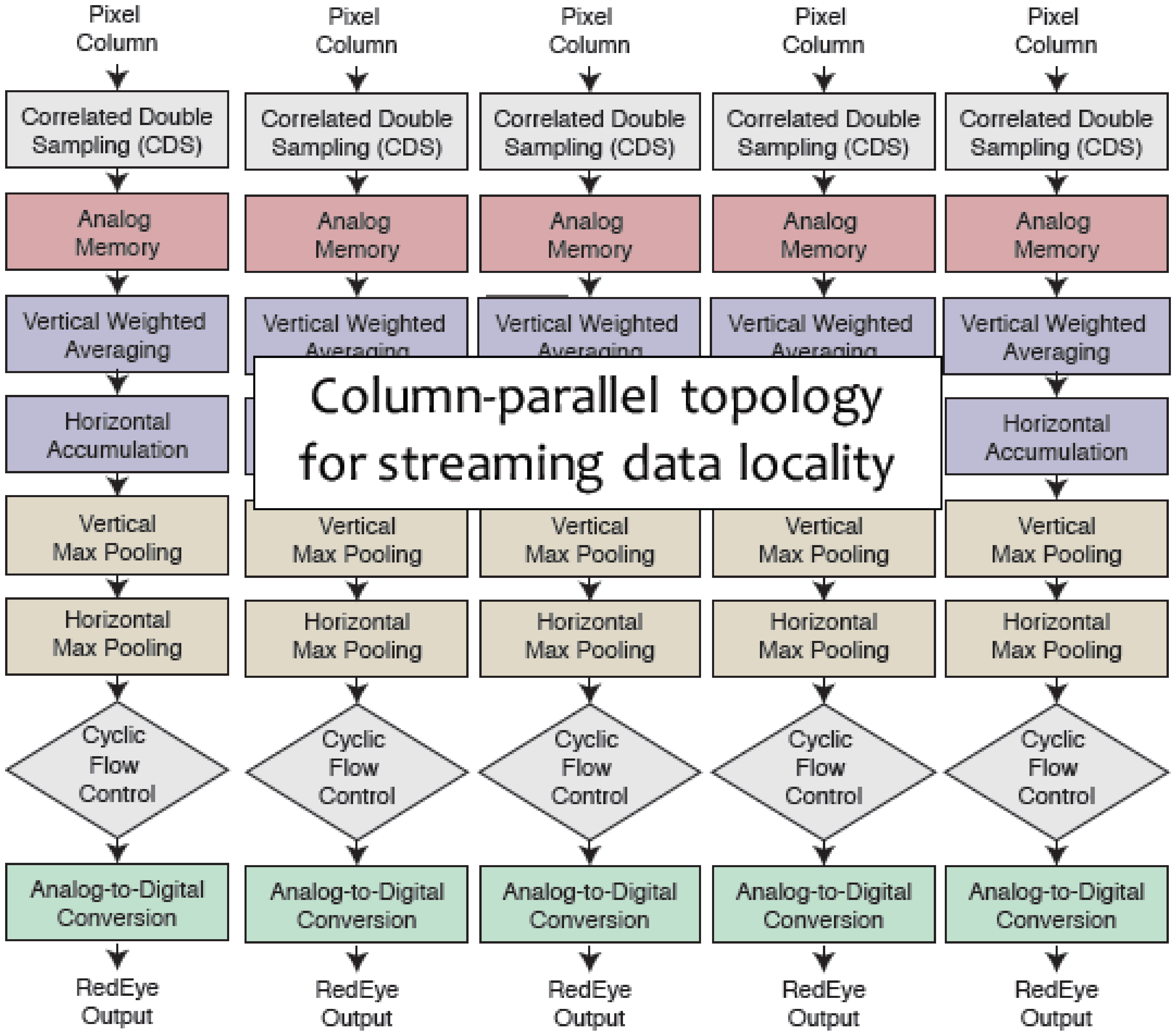
On-chip CNNs

Design of on-chip mixed-signal ADC for implementing a CNN on chip

Goal: Energy-efficient computer vision

Reusable Modules
- Programmable kernel
- Cyclic flow for reuse

Data locality for patches
- Streaming processing
- Column topology



LiKamWa et al, RedEye ISCA 2016

Future of Computational Image Sensors

- Tighter integration of hardware and software, spanning programming languages to computer architecture to circuits to optics
- Image sensors custom for specific applications (machine vision, scientific imaging, etc)
- New pixel/sensing technologies: MEMS, Photonics, 3D stacking, etc.
- What do you predict?

References

Basic Reading:

A El Gamal, H Eltoukhy, “CMOS Image Sensors” IEEE Circuits and Devices Magazine, 2005

Additional Readings:

- J. Gu et al, “Coded Rolling Shutter Photography: Flexible Space-Time Sampling”, ICCP 2010
- M. Hirsch et al, “A Switchable Light Field Camera Architecture using Angle Sensitive Pixels and Dictionary-based Sparse Coding”, ICCP 2014
- H. Kim et al, “Real-Time 3D Reconstruction and 6-DoF Tracking with an Event Camera” ECCV 2016
- R. LiKamWa et al., “RedEye: Analog ConvNet Image Sensor for Continuous Mobile Vision”, ISCA 2016