Direct Time-of-Flight (dTOF) imaging for depth sensing applications

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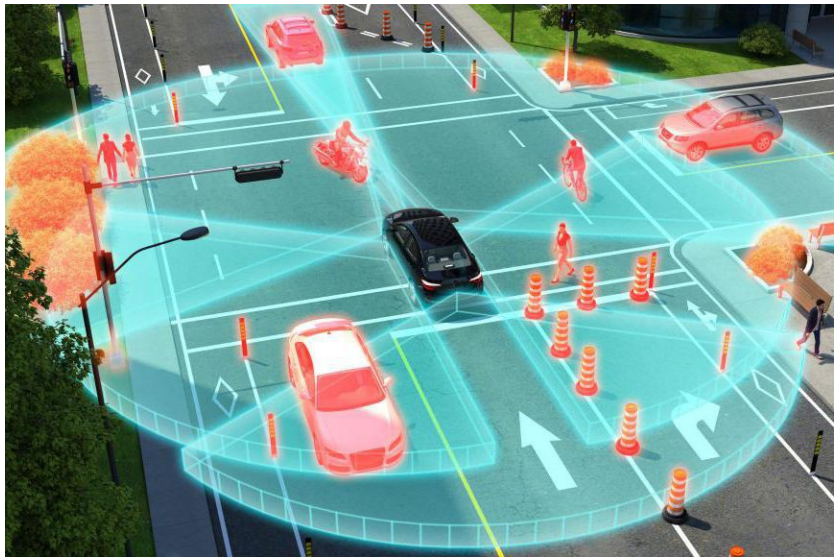
Agenda

- Applications
- Direct Time-of-Flight (dTOF) operation
- Challenges
- Our approach
- Conclusion

Applications

Advanced driver-assistance systems (ADAS) and autonomous vehicles

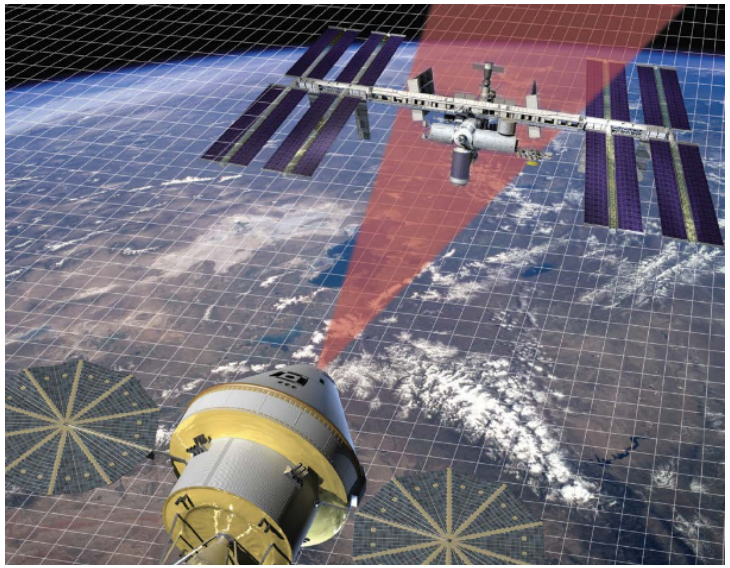


LeddarTech

Face recognition and human-machine interface

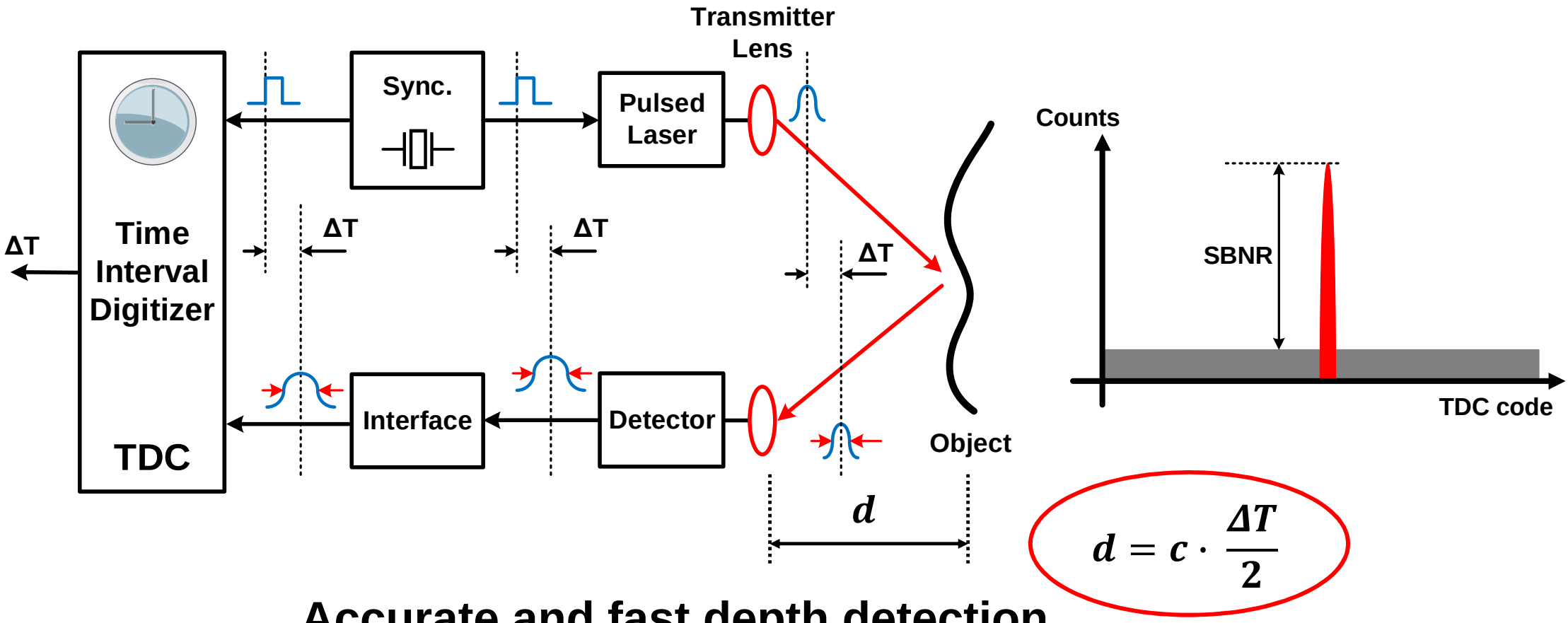
Apple

Spacecraft navigation systems



NASA

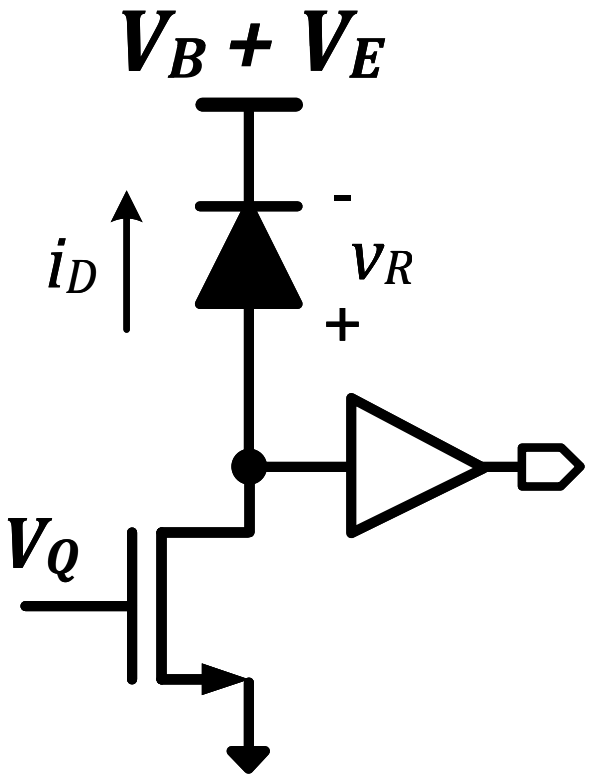
Direct Time-of-Flight (TCSPC)

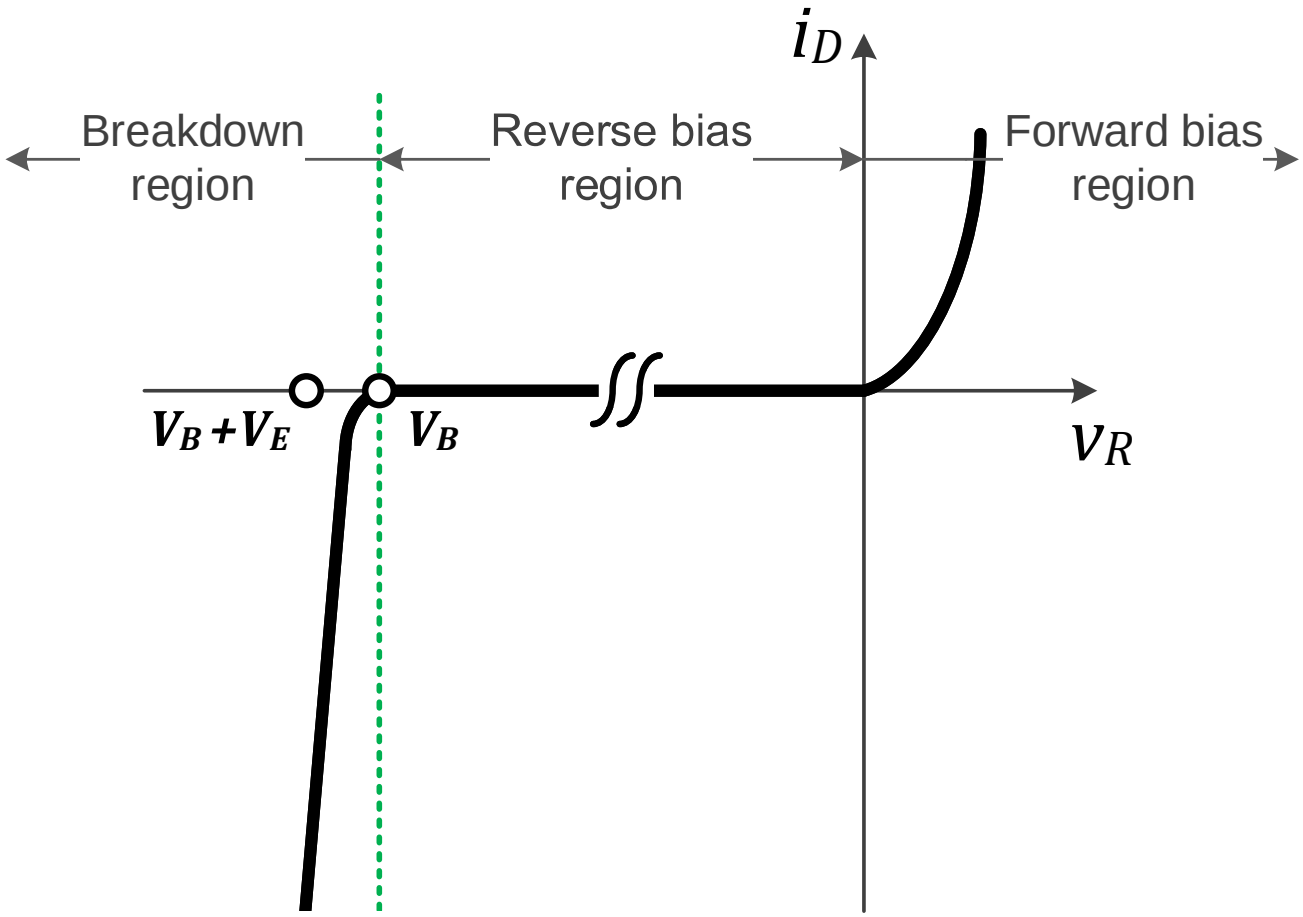


$$d = c \cdot \frac{\Delta T}{2}$$

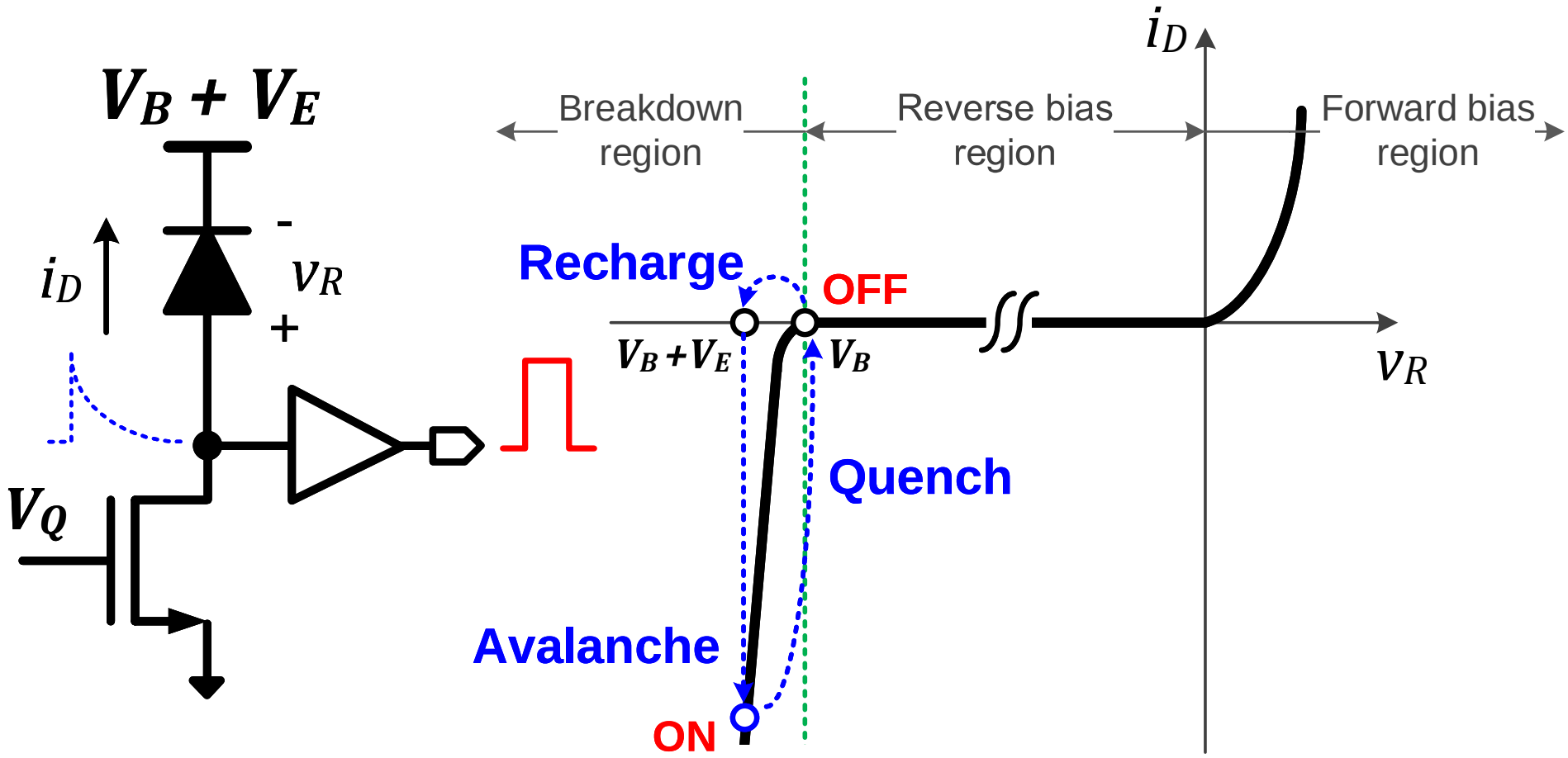
Accurate and fast depth detection

Single-Photon Avalanche Diode Technology



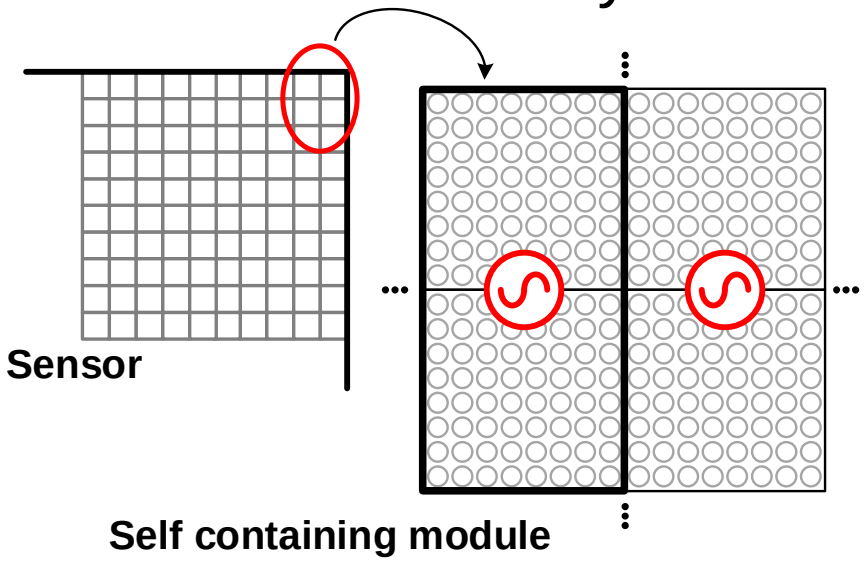


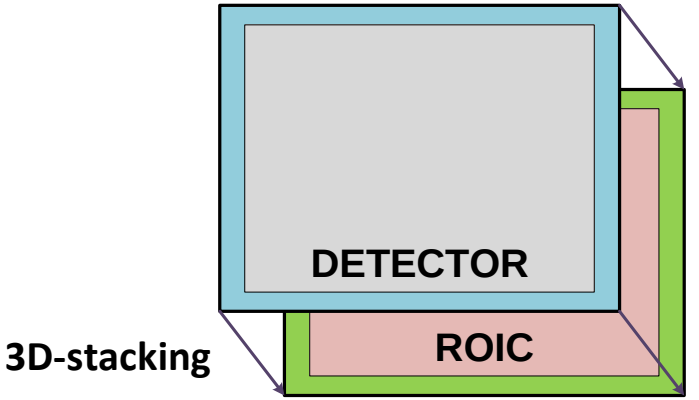
Single-Photon Avalanche Diode Technology

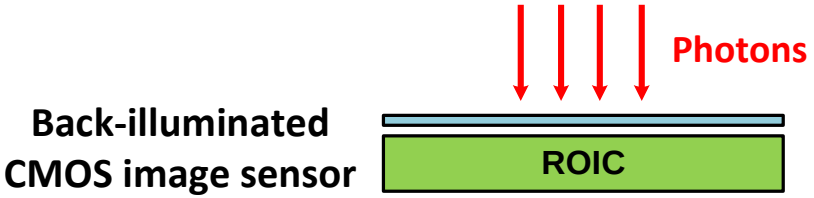


Challenges

- Increase functionality at lower power consumption
- Increase sensitive area
- Precise timing in megapixel arrays
- Robust to wide variety of conditions





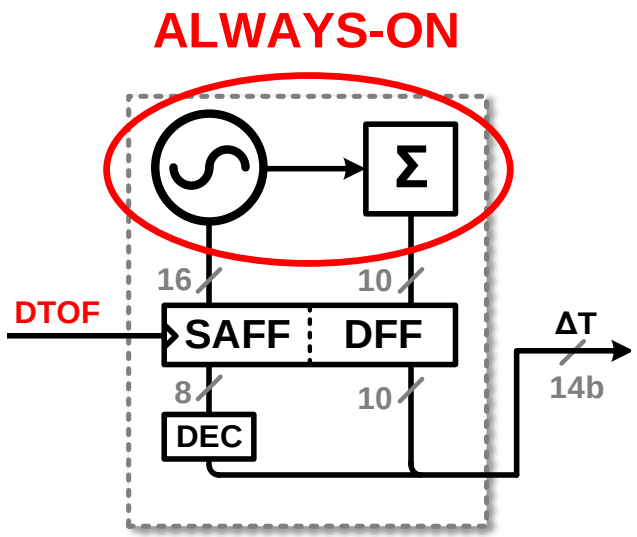


Sensor architecture

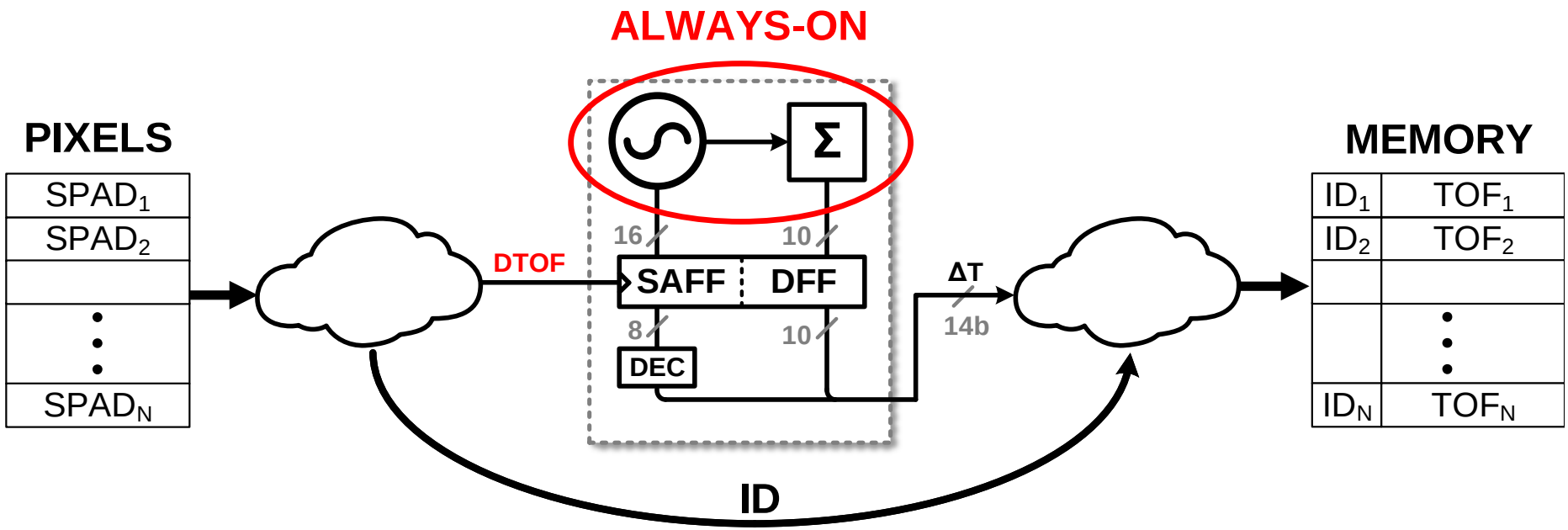
ISSCC 2018: *A 256x256 45/65nm 3D-Stacked SPAD-Based Direct TOF Image Sensor for LiDAR Applications with Optical Polar Modulation for up to 18.6dB Interference Suppression*

A. R. Ximenes[1], P. Padmanabhan[2], M.-J. Lee[2], Y. Yamashita[3], D. N. Yaung[3], E. Charbon[1,2]

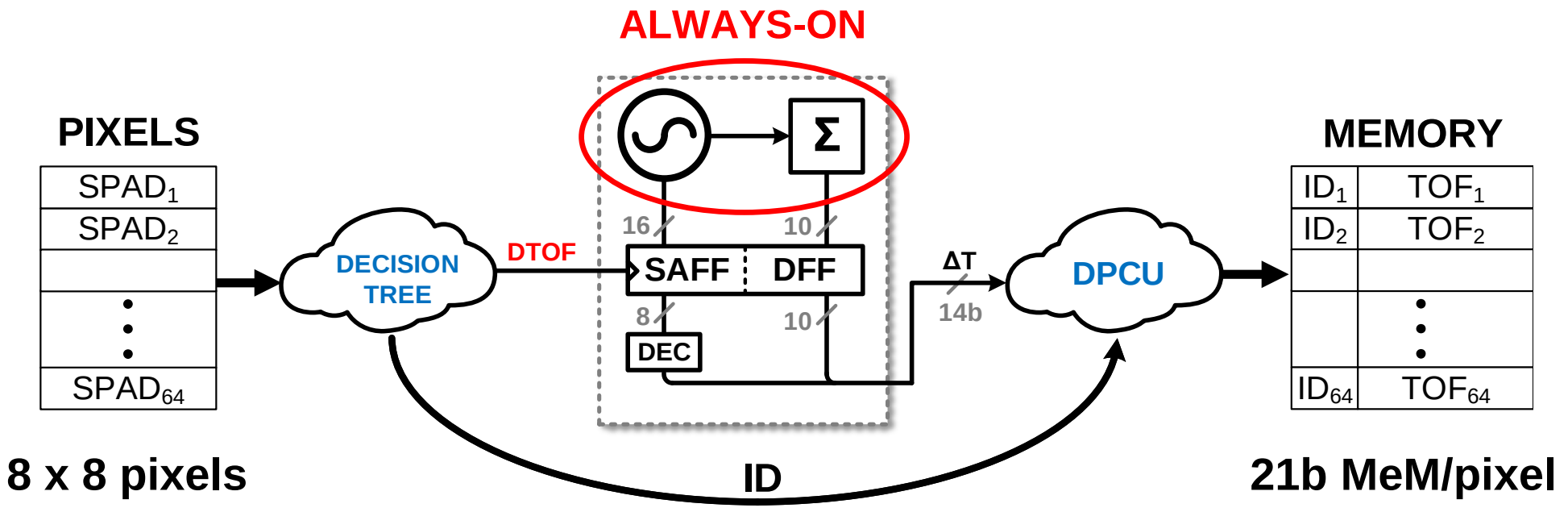
Time-to-Digital Converter (TDC) operation



TDC sharing

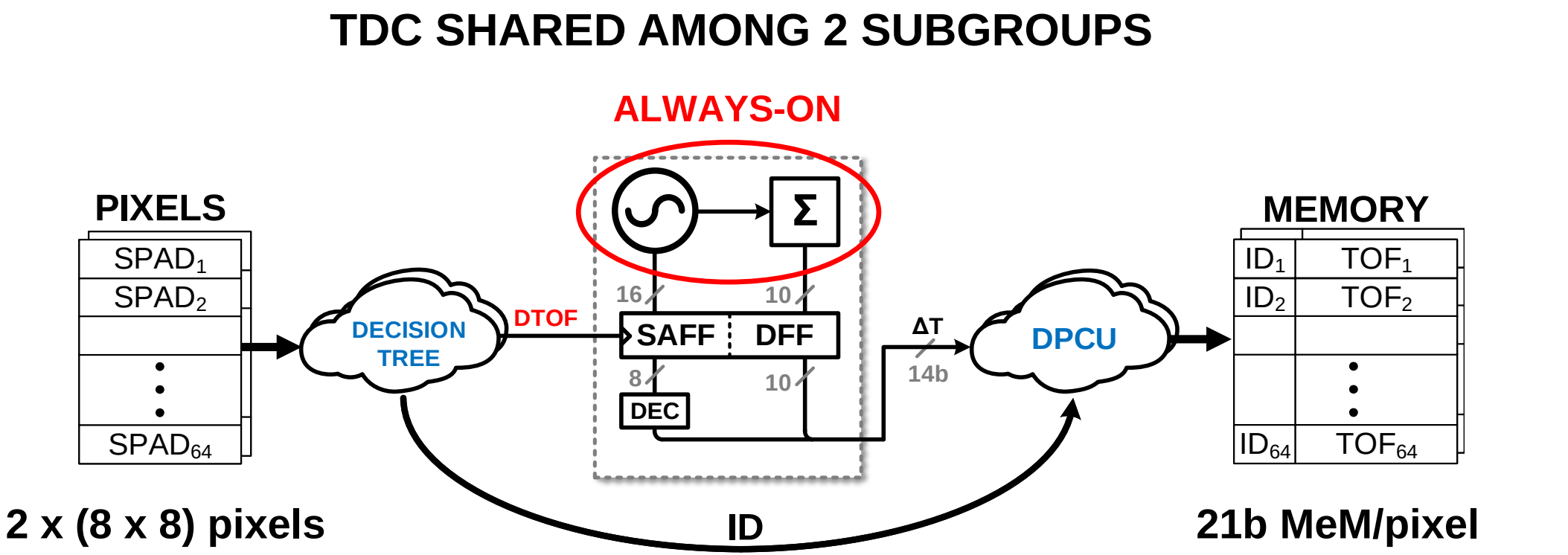

ALWAYS-ON
PIXELS
SPAD1
SPAD2
SPADN
DTOF
16
10
SAFF
DFF
8
10
DEC
Σ
ΔT
14b
ID
MEMORY
ID1
TOF1
ID2
TOF2
IDN
TOFN

Complete subgroup



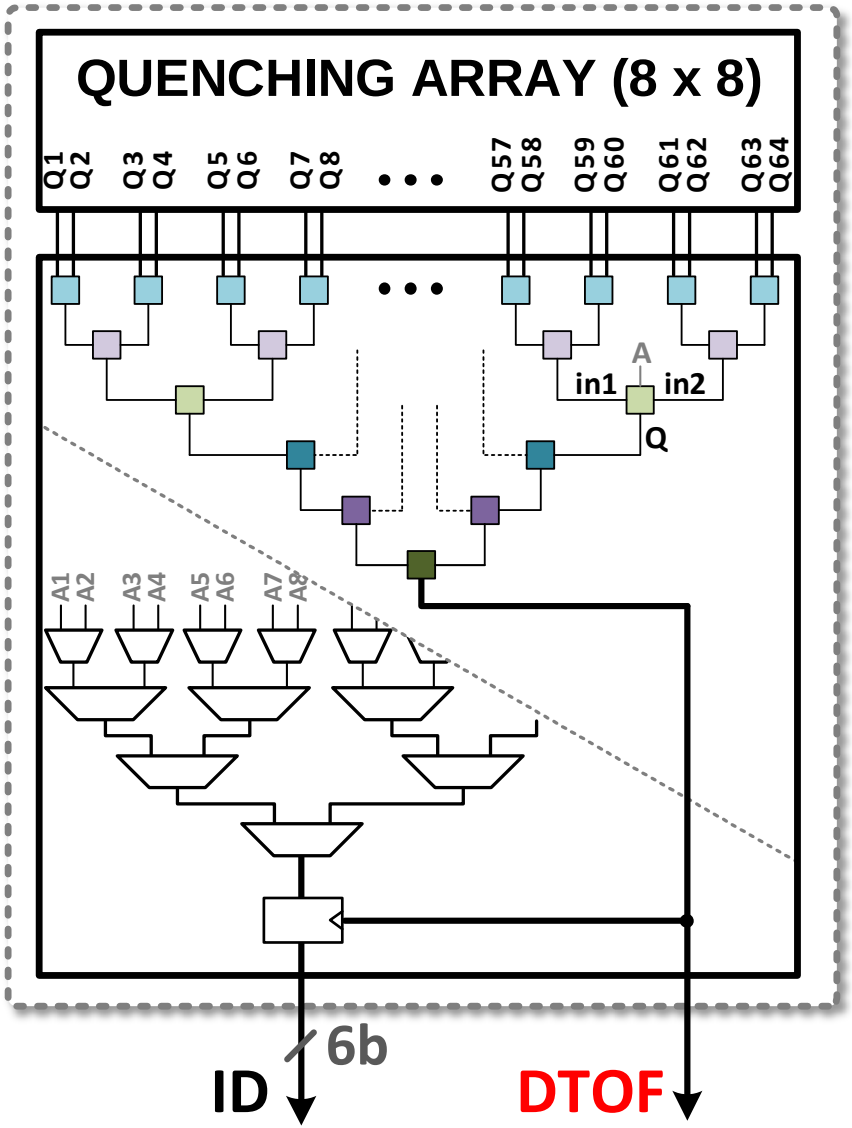
*DPCU: Digital Processing and Communication Unit

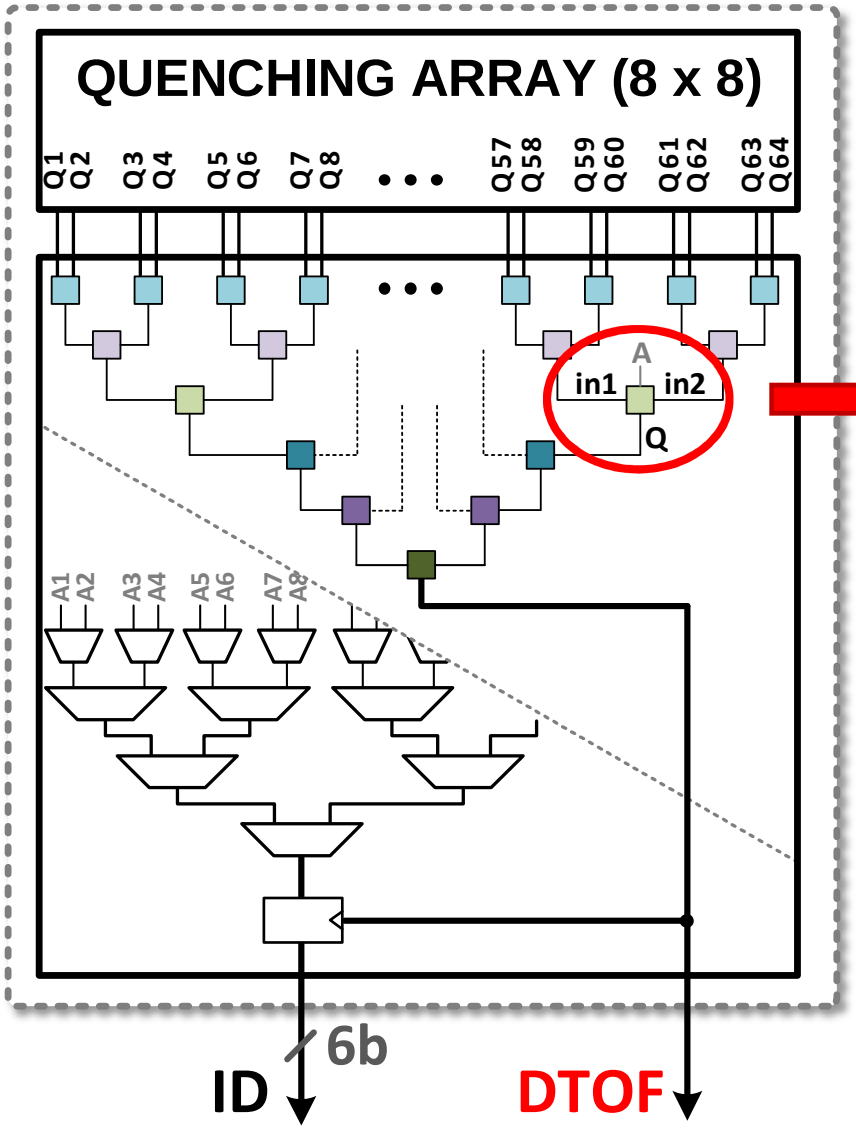
Self-contained module



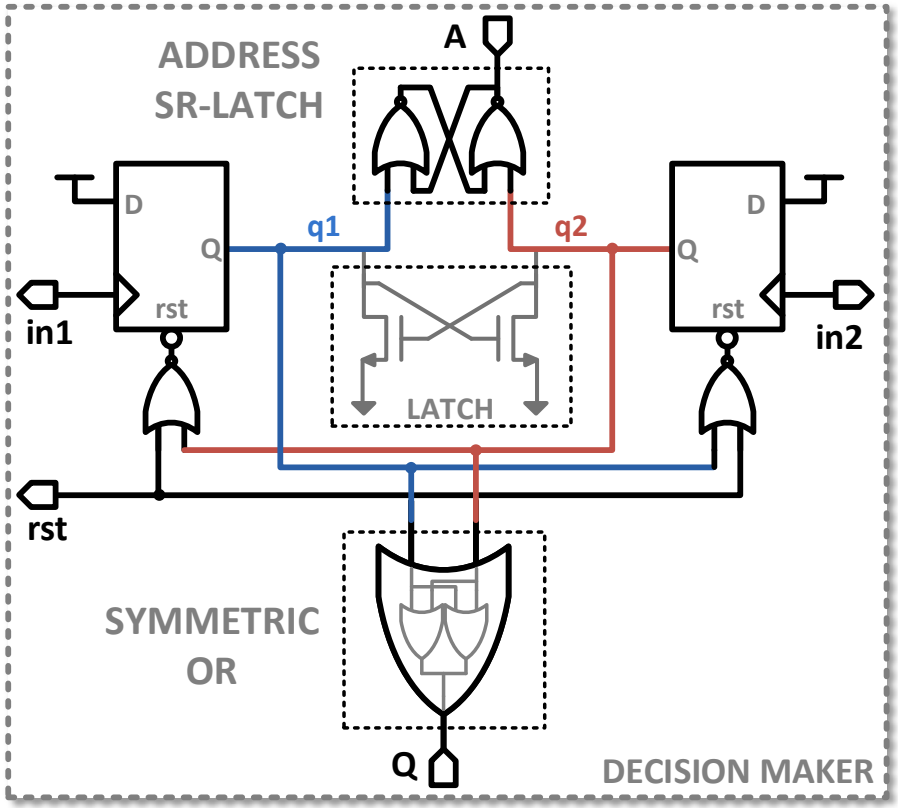
*DPCU: Digital Processing and Communication Unit

Decision Tree





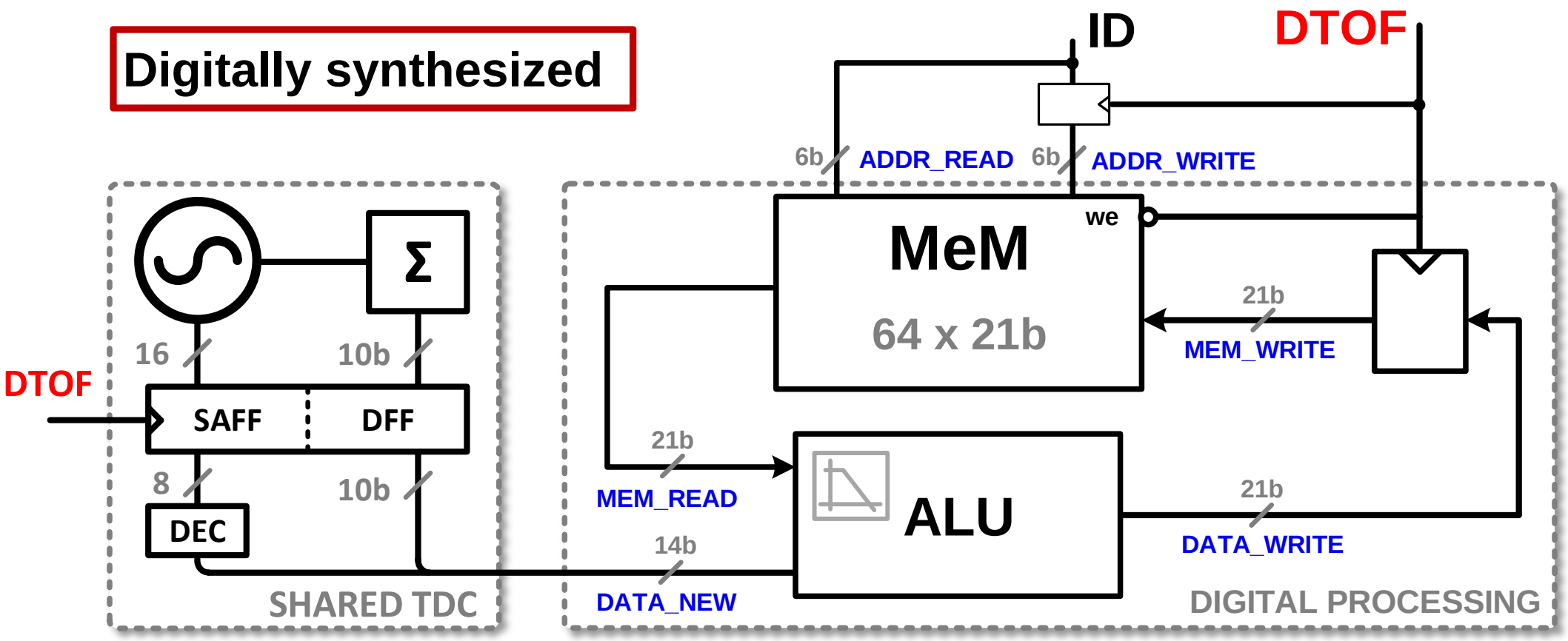
Decision Tree



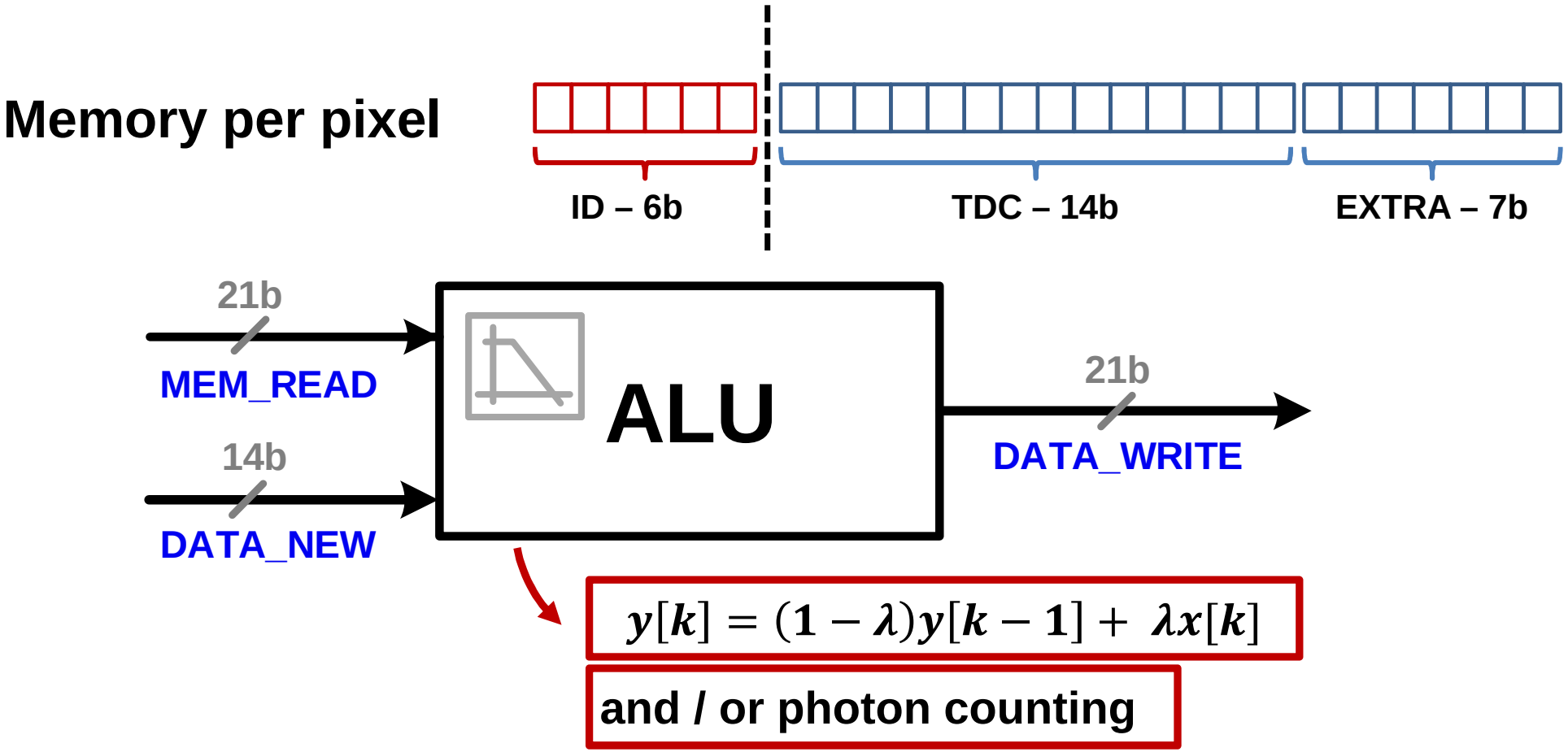
Metastability < 10 ps

Overall tree skew < 14 ps

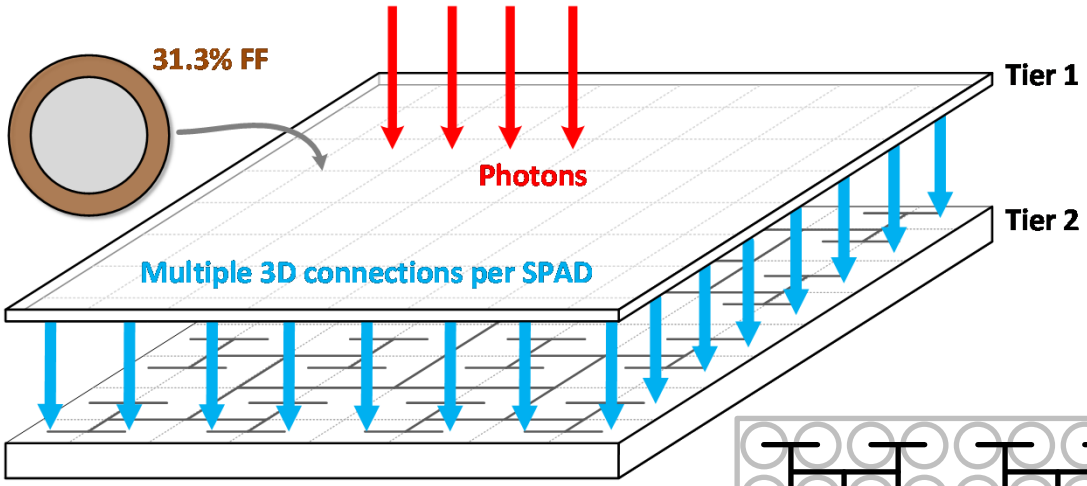
Digital Processing and Communication Unit

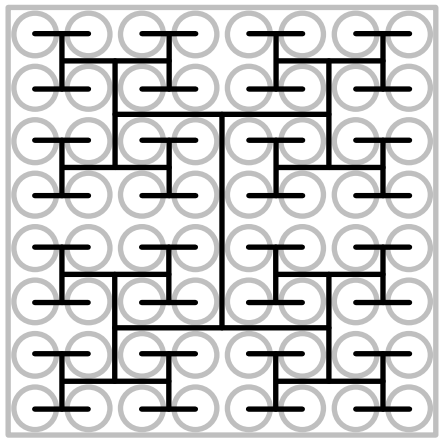


Digital Processing and Communication Unit

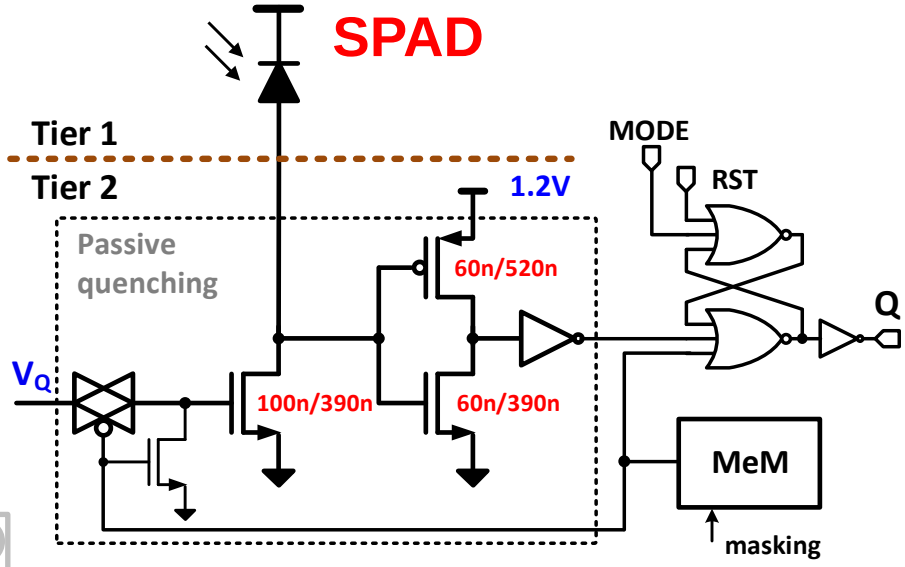


3D stacking and modularity





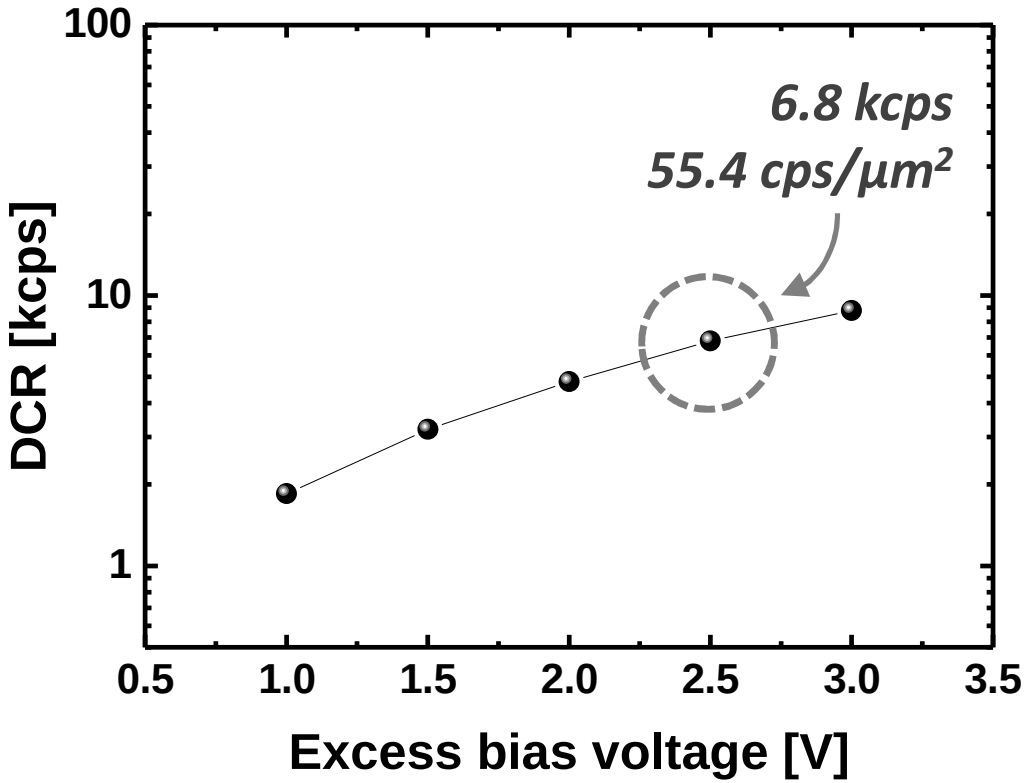
SUBGROUP
8 x 8 SPADs



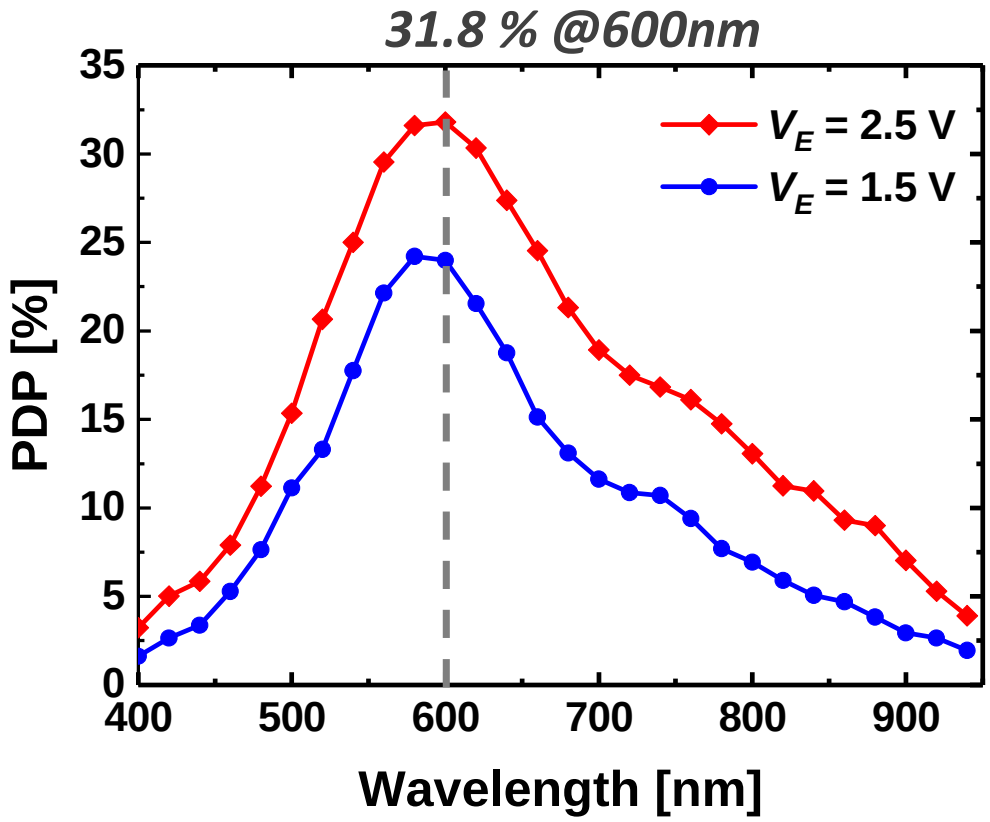
- Passive quenching
- Electrical & optical mask
- Pulse/State output modes
- External Reset

Results

BSI SPAD performance

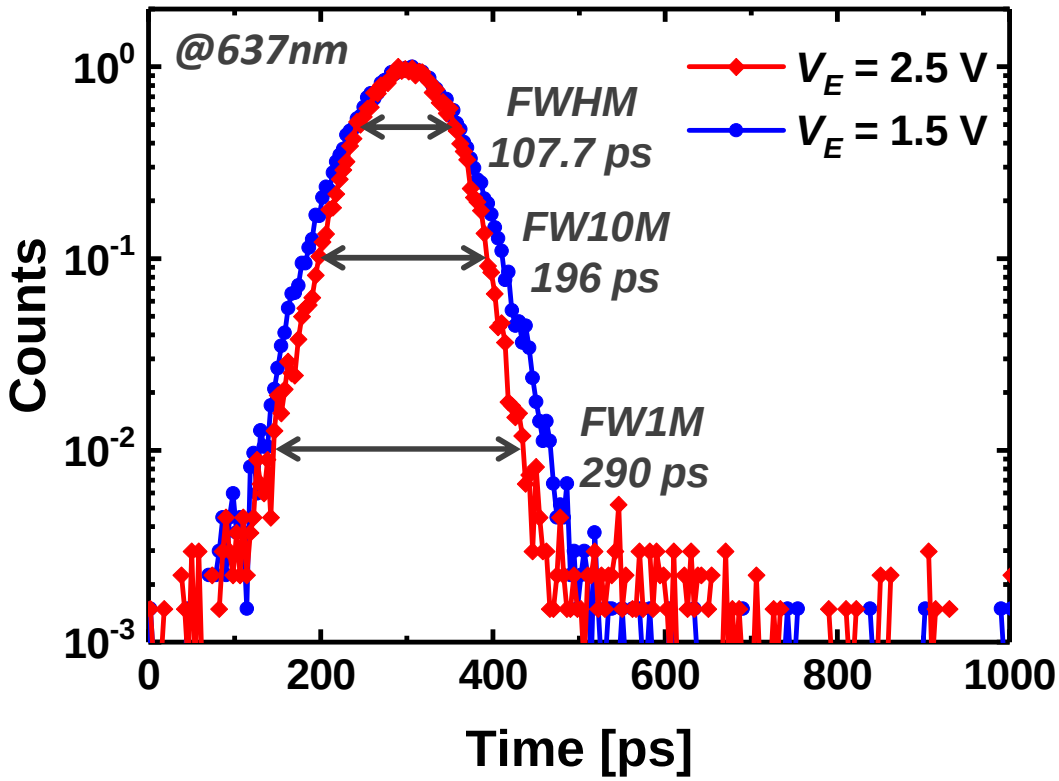


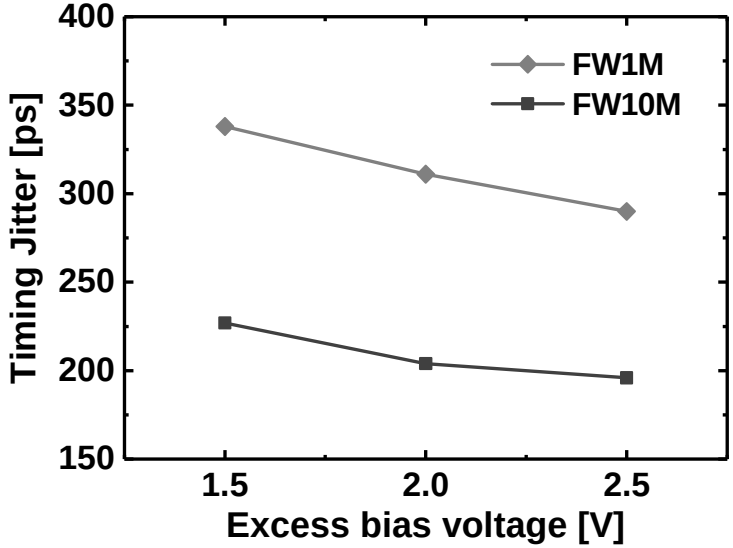
Triggered by any generation of free carriers instead of incident photons

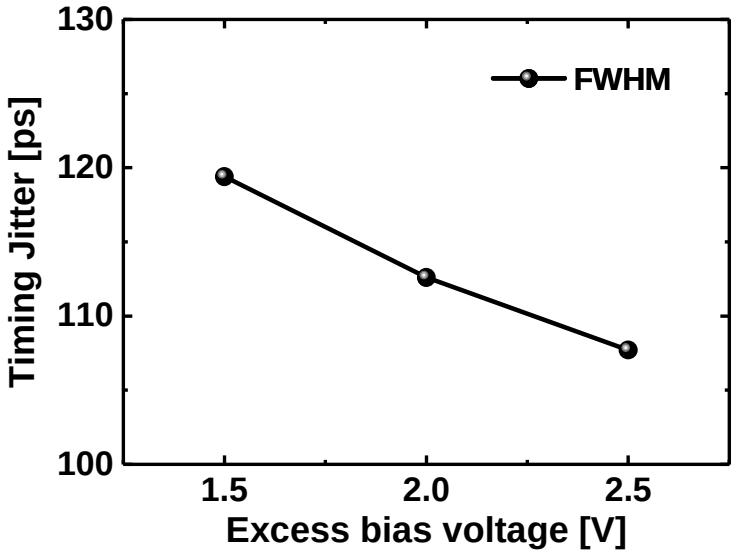


Probability of detection when a photon hits the SPAD's active area

BSI SPAD performance

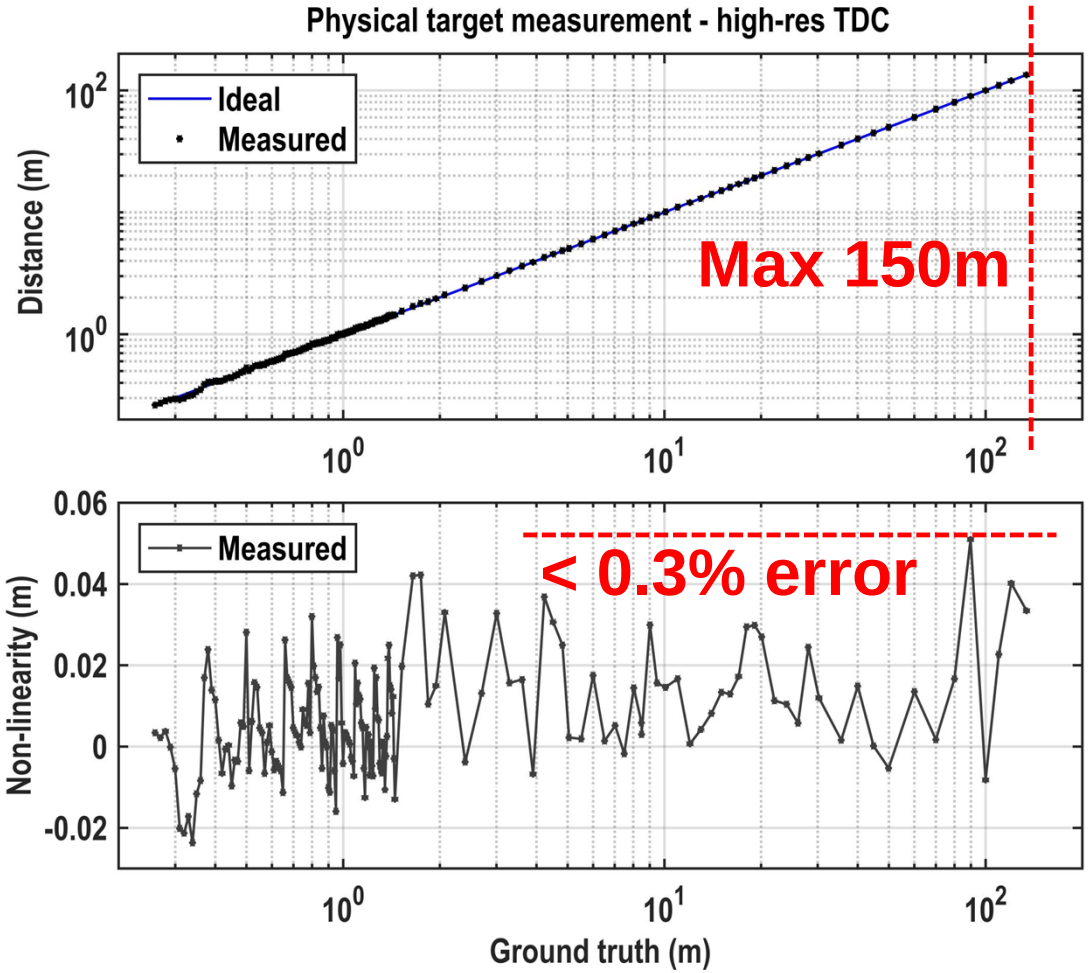


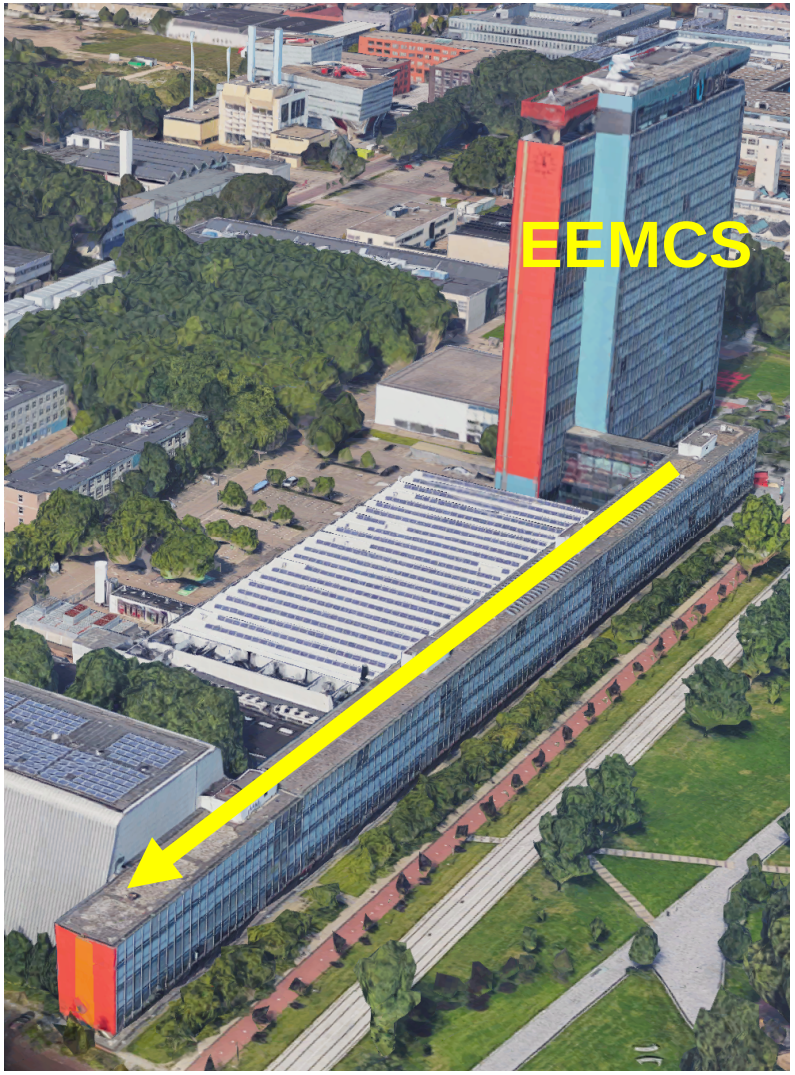




***IEDM 2017:** *A Back-Illuminated 3D-Stacked Single-Photon Avalanche Diode in 45nm CMOS Technology, MJ Lee, at. al., TUDELFT, EPFL, TSMC.*

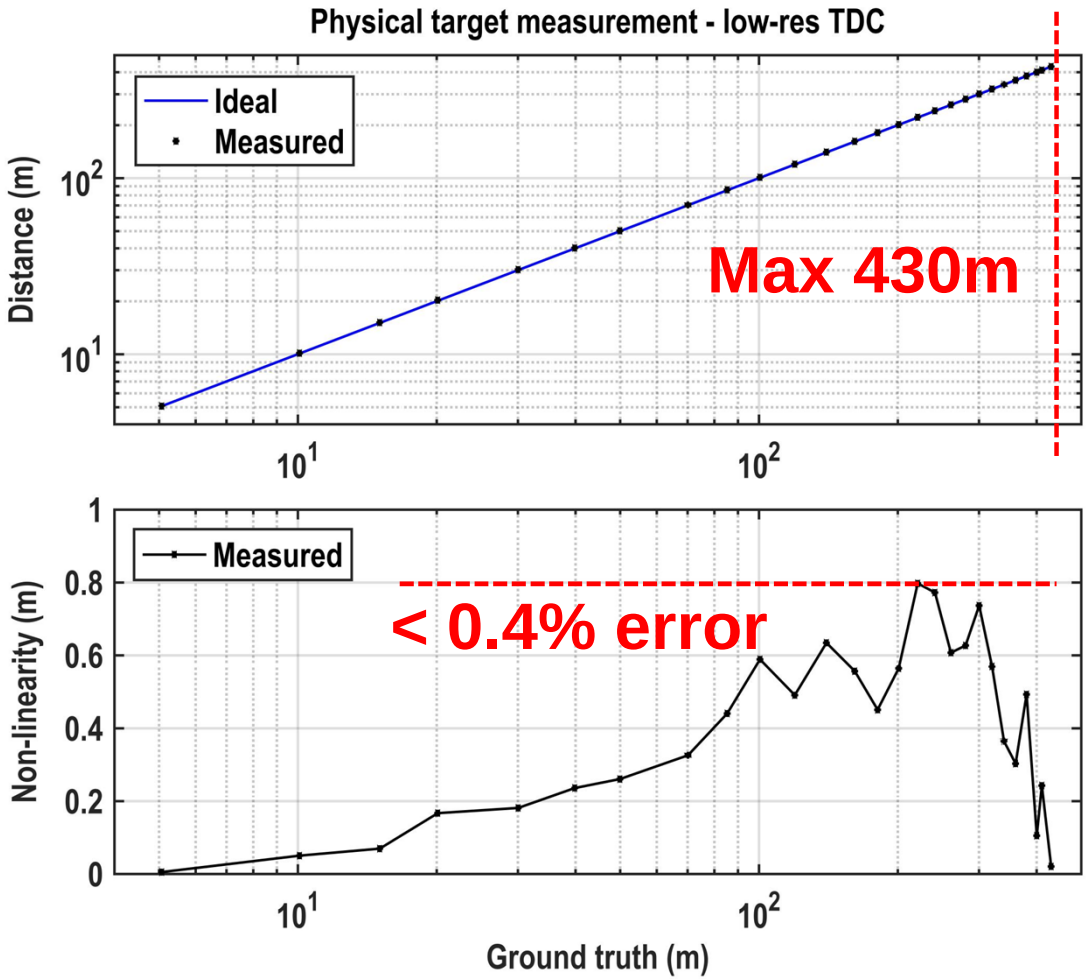
High res TDC

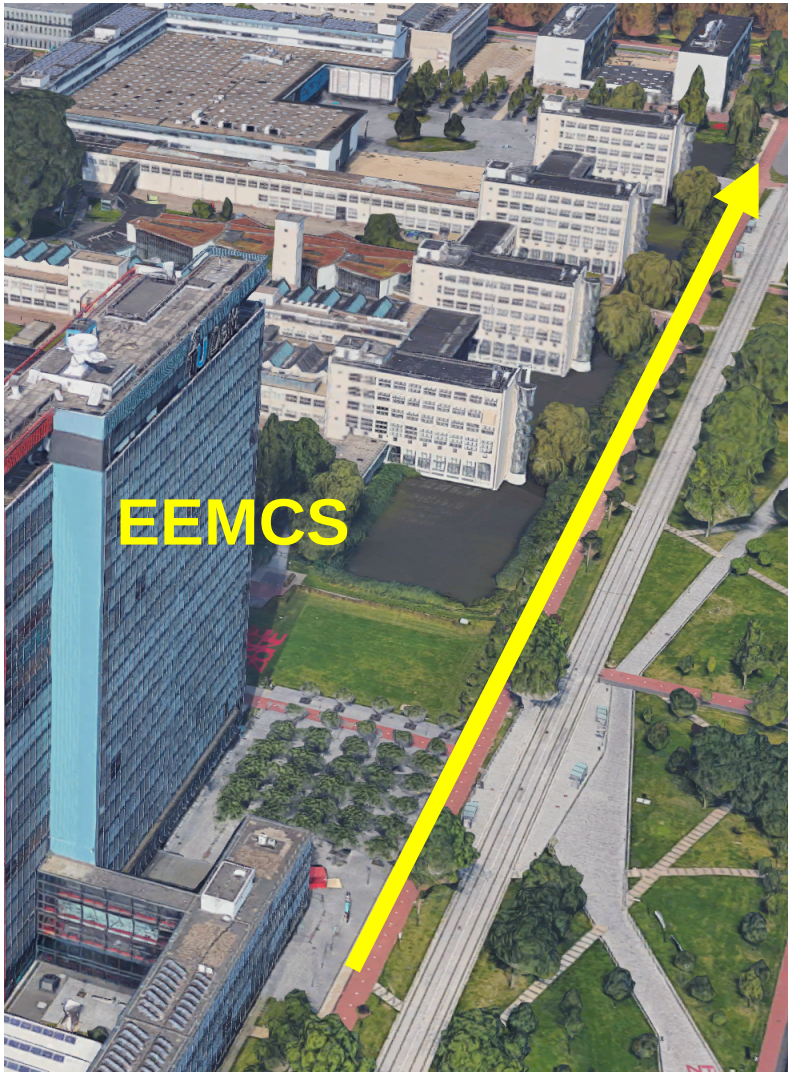




TU Delft campus @ googlemaps

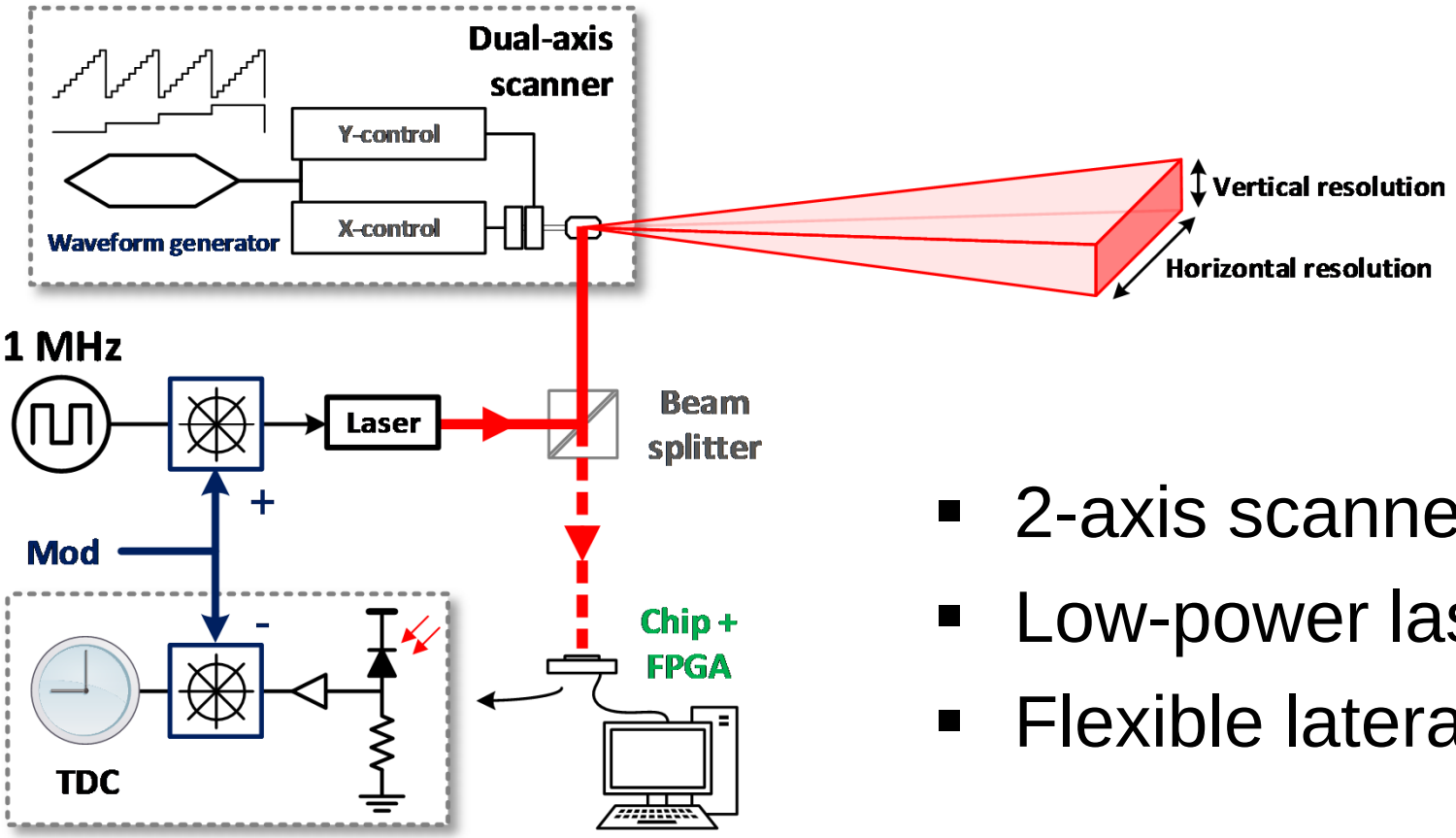
Low res TDC





TU Delft campus @ googlemaps

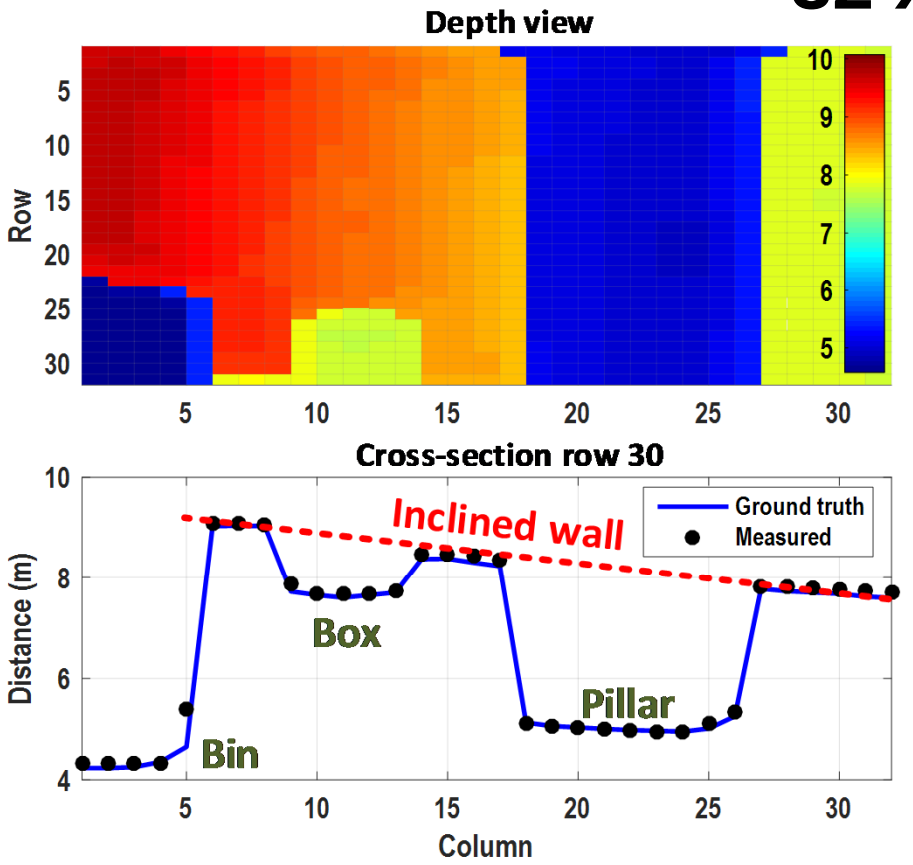
Scanner system

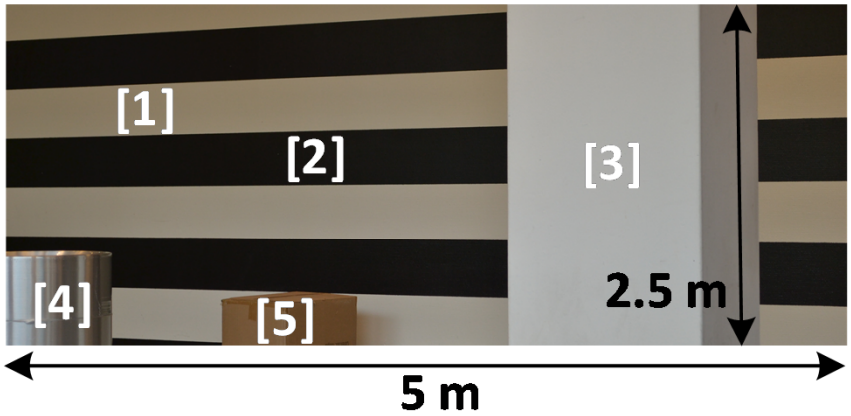


- 2-axis scanner
- Low-power laser
- Flexible lateral resolution

Scanner system

32 x 32



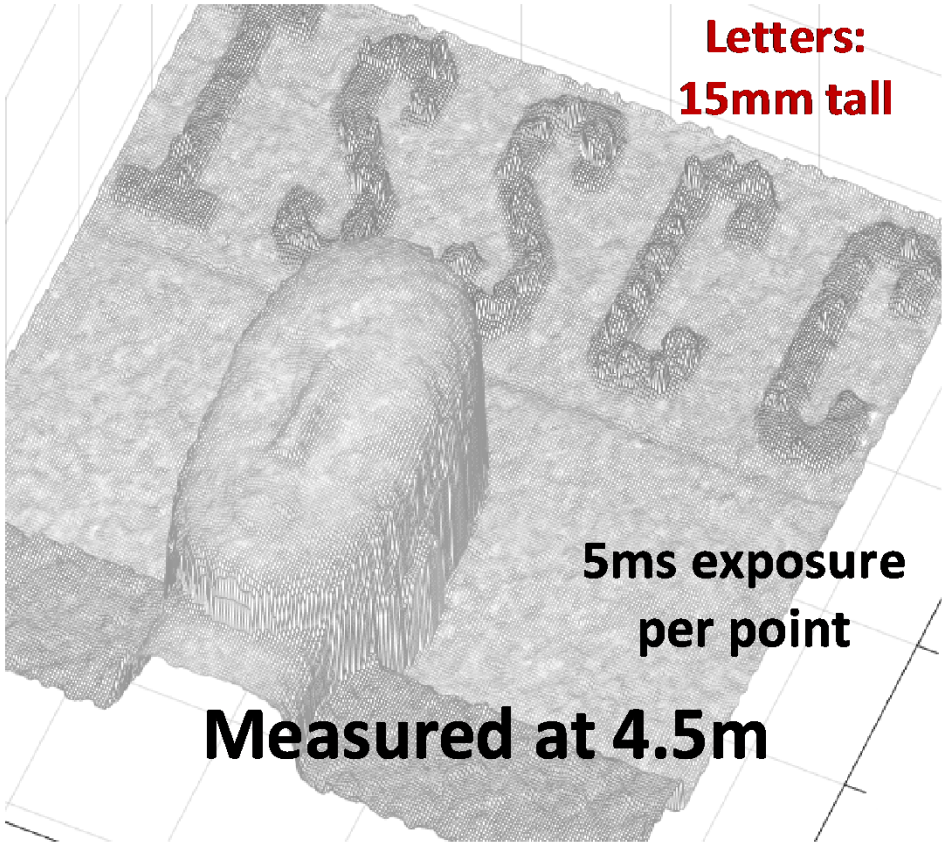


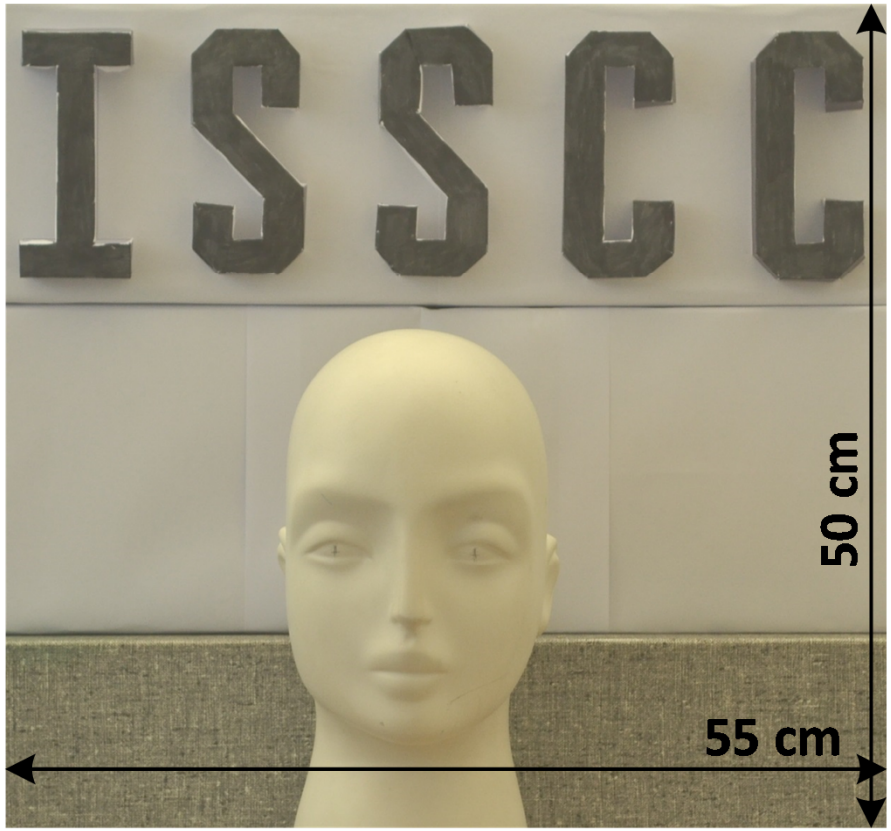
Different target reflectivities

[1] – White wall – 50%
[2] – Black wall – 8%
[3] – White pillar – 60%
[4] – Aluminum bin – 54%
[5] – Cardboard box – 21%

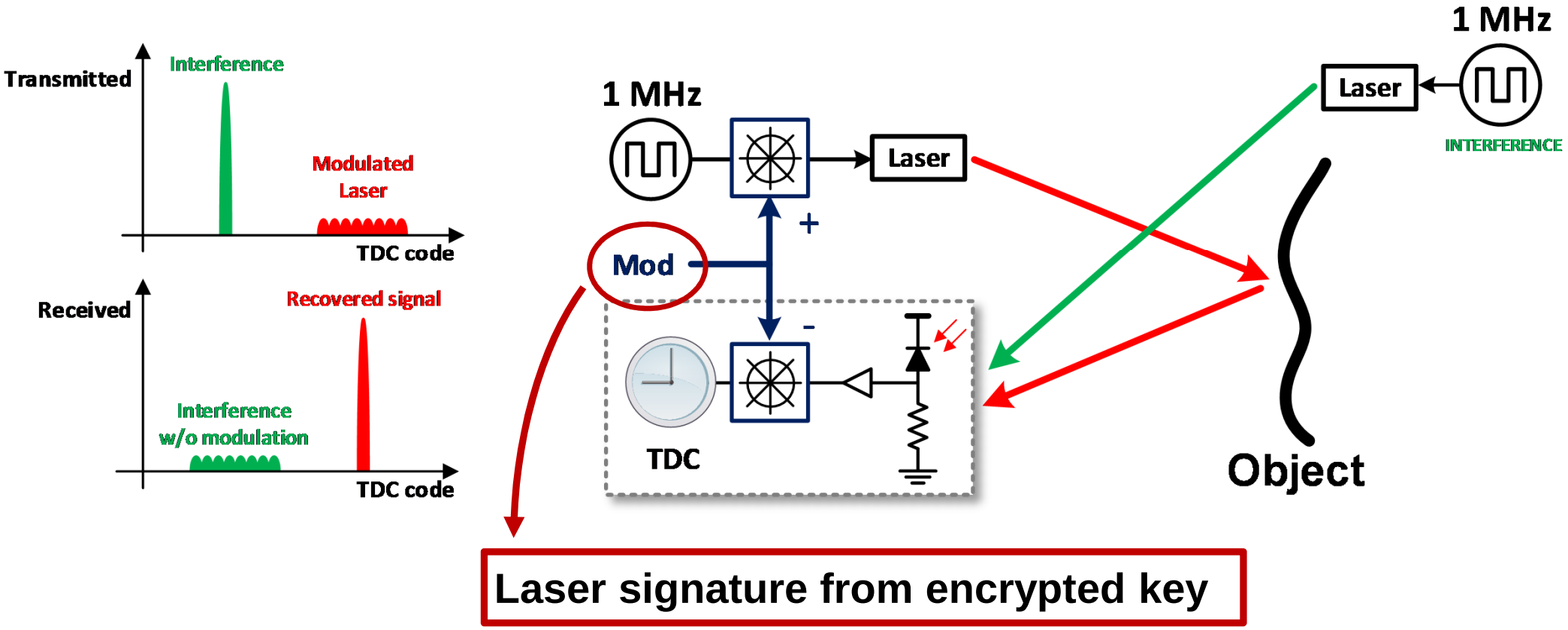
Scanner system

256 x 256

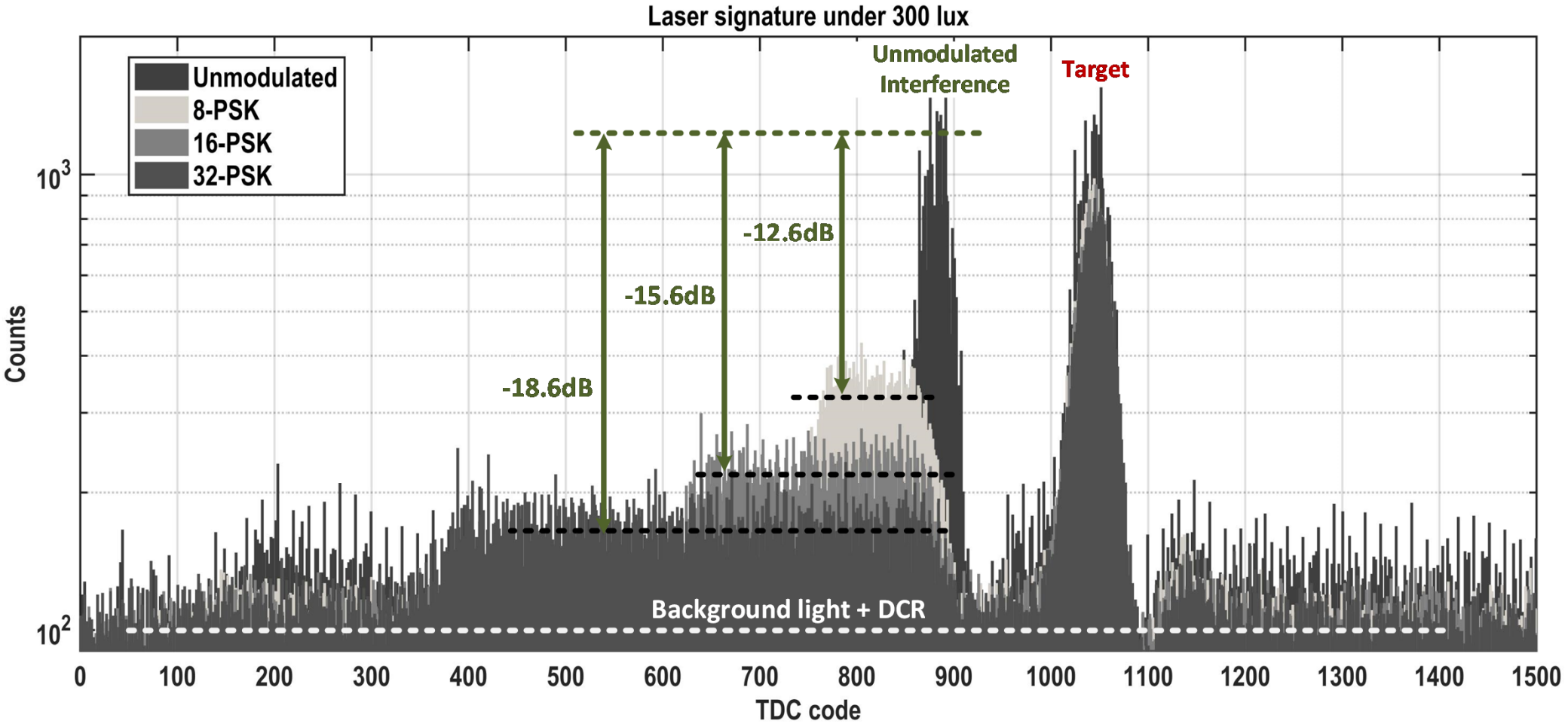




Interference suppression – Laser signature

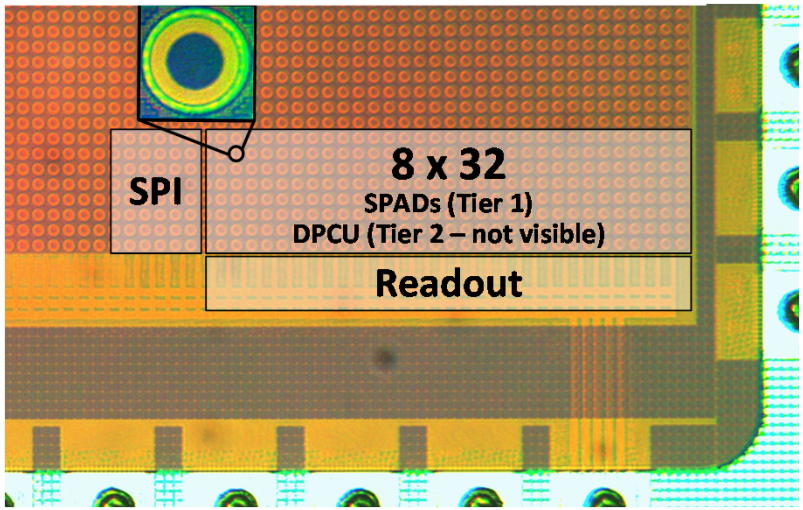


Interference suppression



Summary

- First 3D-stacked **dTOF** sensor
- **ROIC** digitally synthesized
- Longest single-point measurement in CMOS
- Proposed laser signature

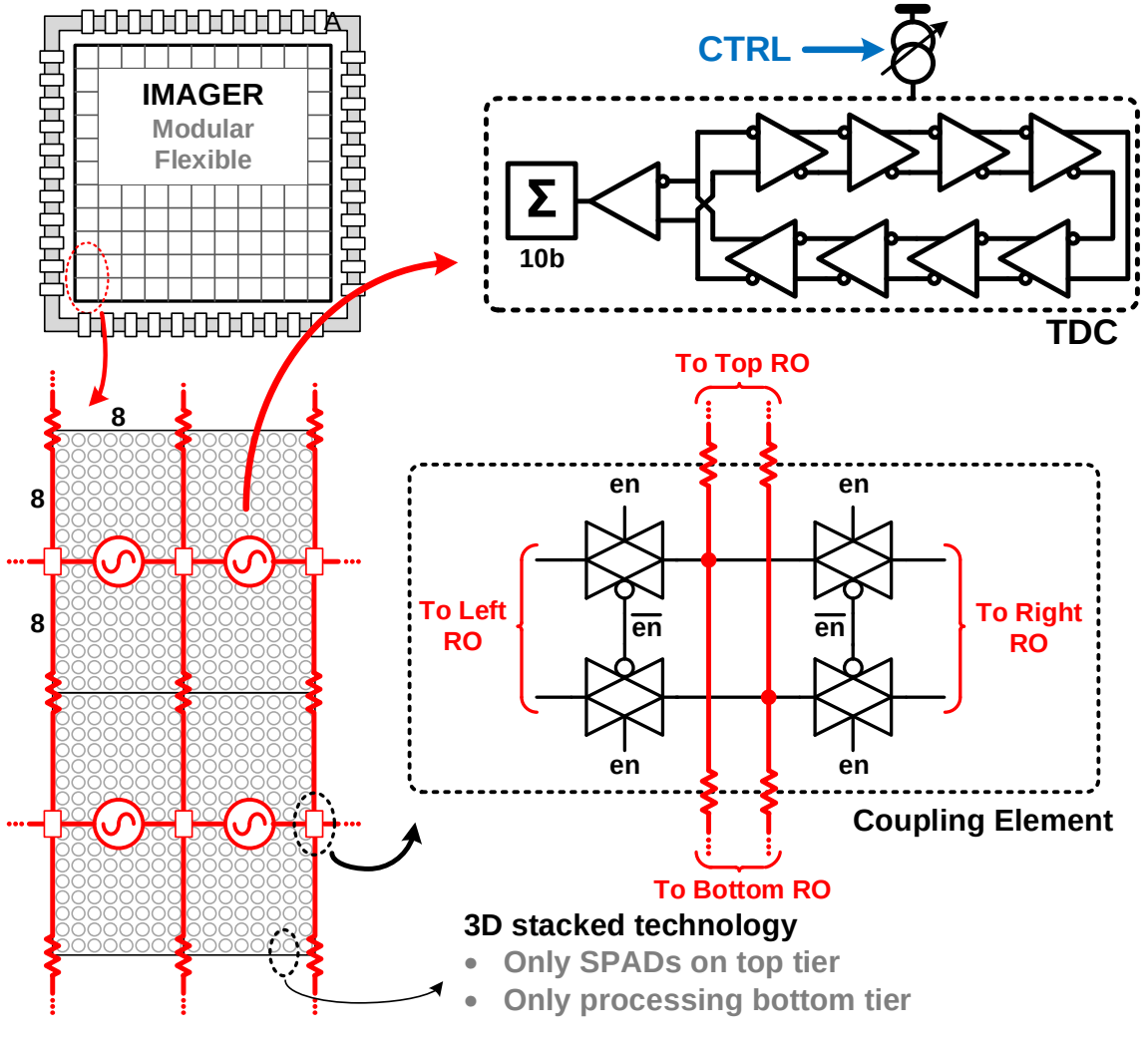


Parameter	Performance
Technology	45/65nm CMOS
Pixel pitch	19.8µm
Pixel fill factor	31.3/50.6%
SPAD median DCR	55.4 cps/µm^2 @ 2.5V
TDC resolution	60 – 320ps
TDC power	0.5 – 0.1mW
TDC area	**550µm^2**
Distance range	**150 – 430m**
Precision (σ) (Repeatability)	0.15 – 0.47m
	0.1 – 0.11%
Accuracy (Non-linearity)	0.07 – 0.8m
	0.3 – 0.4%

Timing

Timing reference

- Precise timing is essential
- Stable and well-known resolution
- Robust to PVT variations
- Low power and area



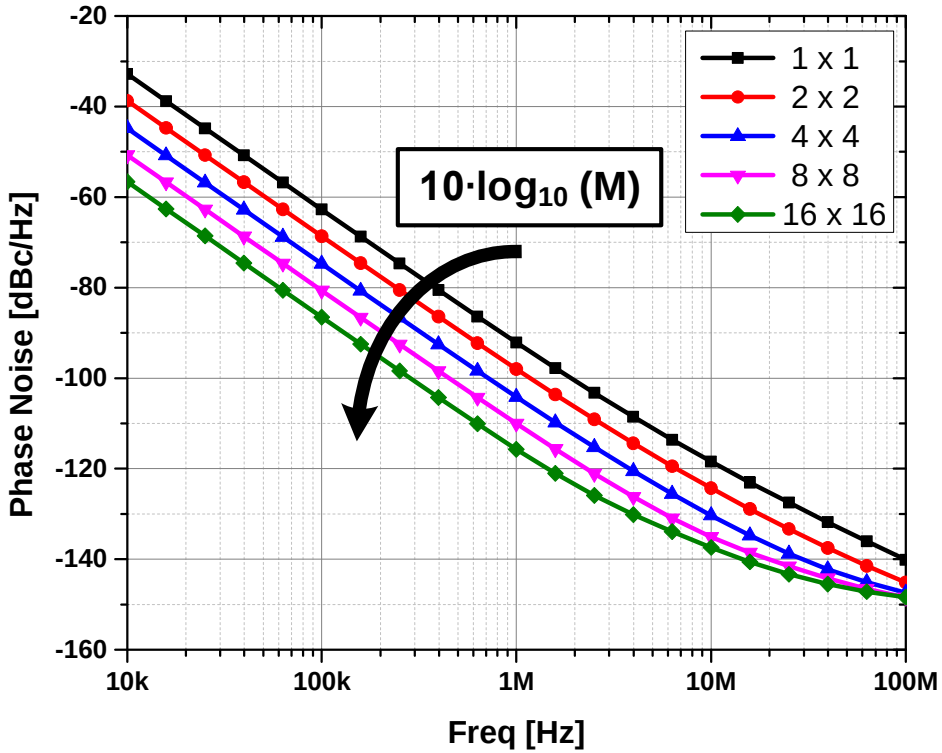
Timing in large sensors

IISW 2017: *Mutually Coupled Ring Oscillators for Large Array Time-of-Flight Imagers*

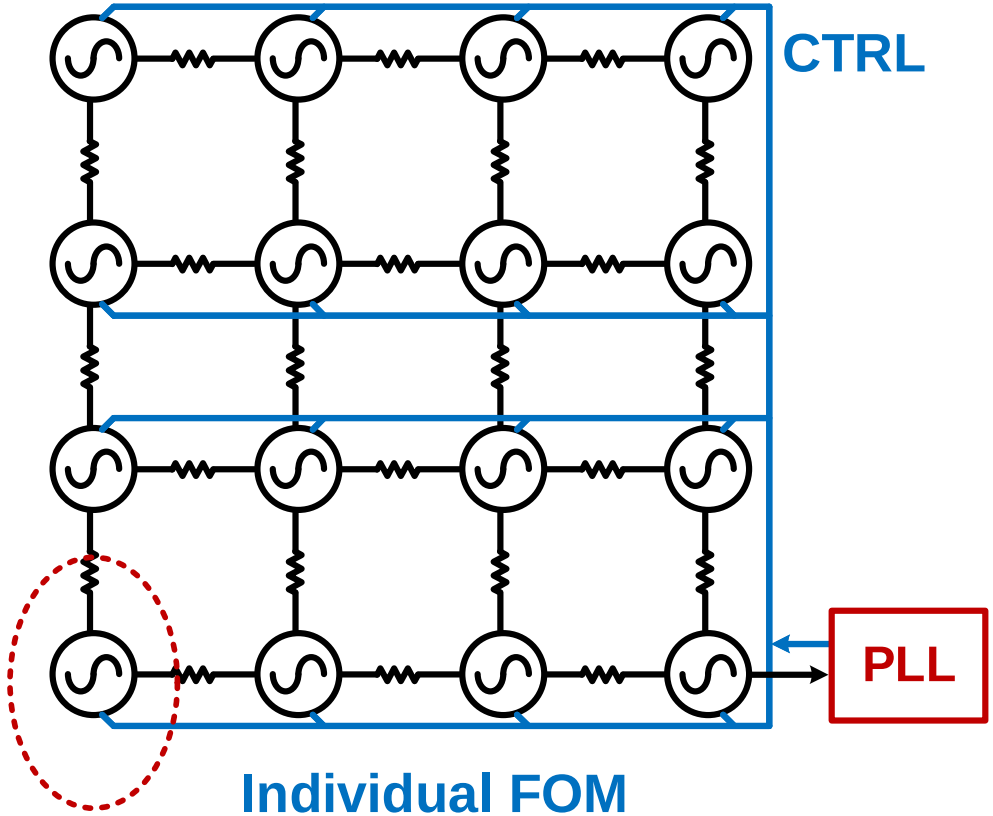
A. R. Ximenes[1], P. Padmanabhan[2], E. Charbon[1,2]

High-quality timing

Phase noise simulation
FOM ~ 150 dB @ 500 MHz

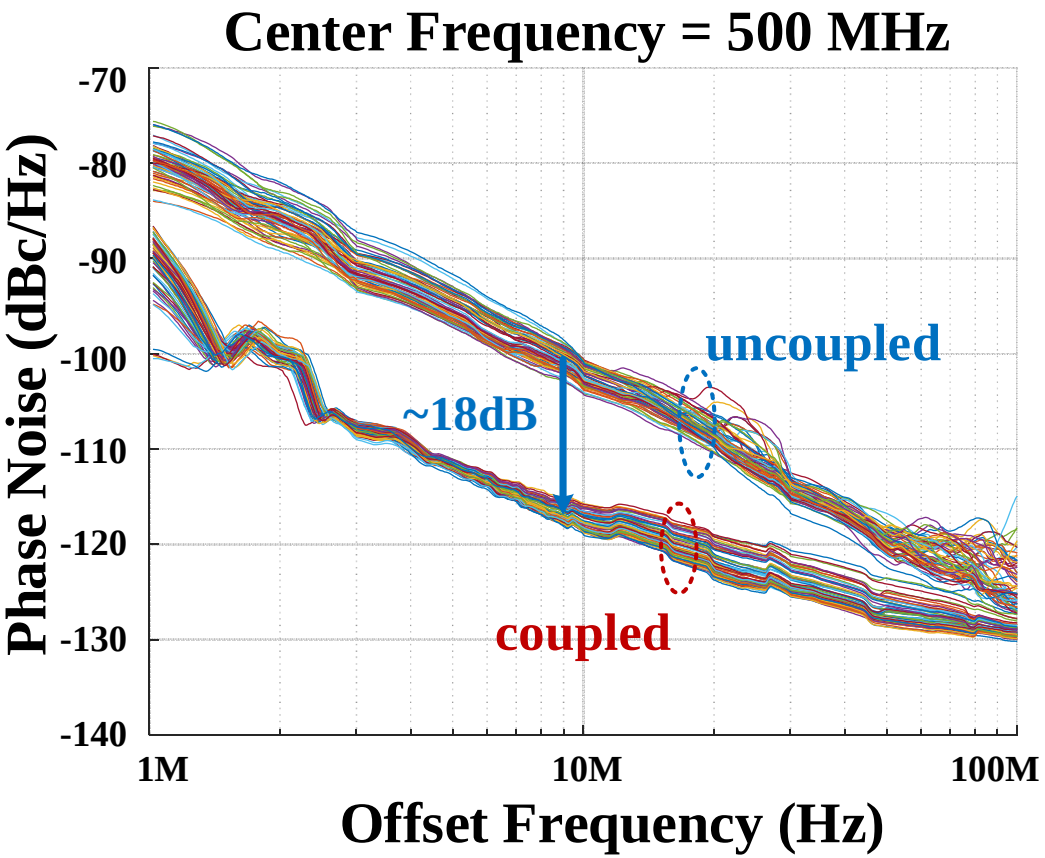


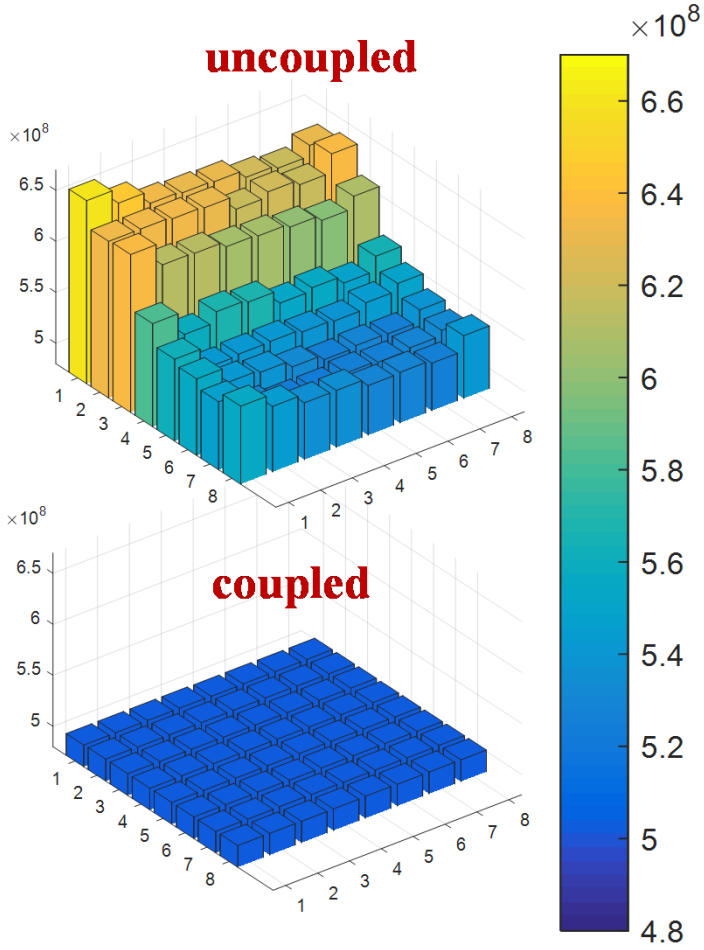
Overall constant FOM



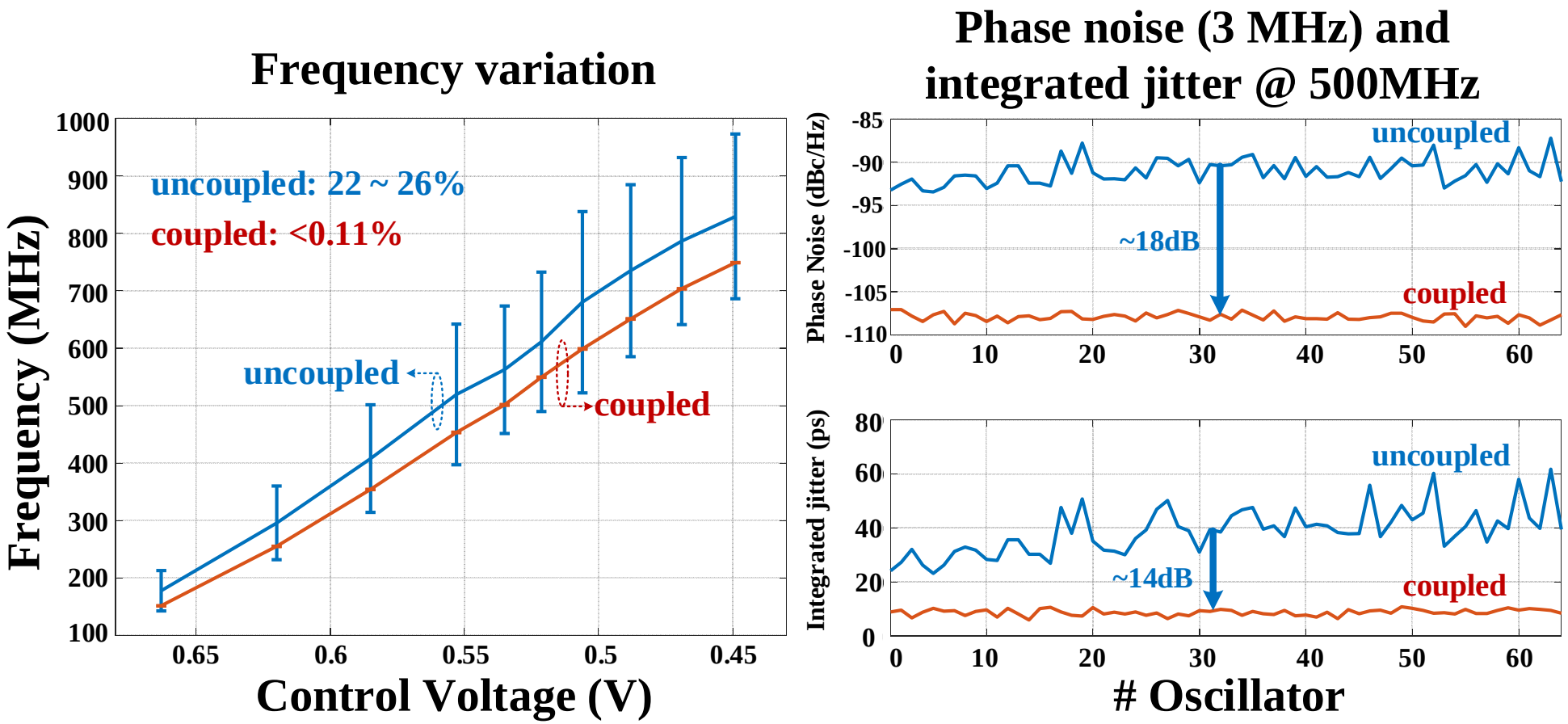
Individual FOM
improved by $10 \cdot \log_{10}(M)$

High-quality timing





High-quality timing



Conclusion

- Reducing power consumption and data is essential
- Precise timing in large arrays challenging
- Future work
  - Implement both solutions in a large array

Thank you!

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