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INFORMAZIONE E BIOINGEGNERIA

Fast-gated 16×16 SPAD array with on-chip 6 ps TDCs for non-line-of-sight imaging

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Outline

Non-line-of-sight (NLOS) imaging

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2. System requirements
3. State-of-the-art

16 × 16 SPAD array architecture

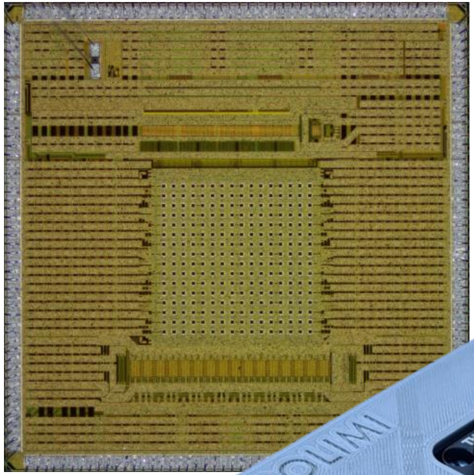
1. SPAD performance
2. Time-gated frontend
3. Resource sharing
4. Time-to-digital converters (TDCs)

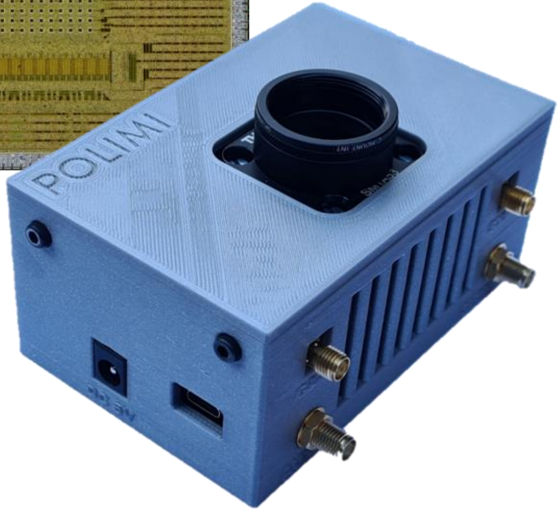
Camera overview

Characterization results

1. IRF
2. Time-gating
3. Conversion linearity

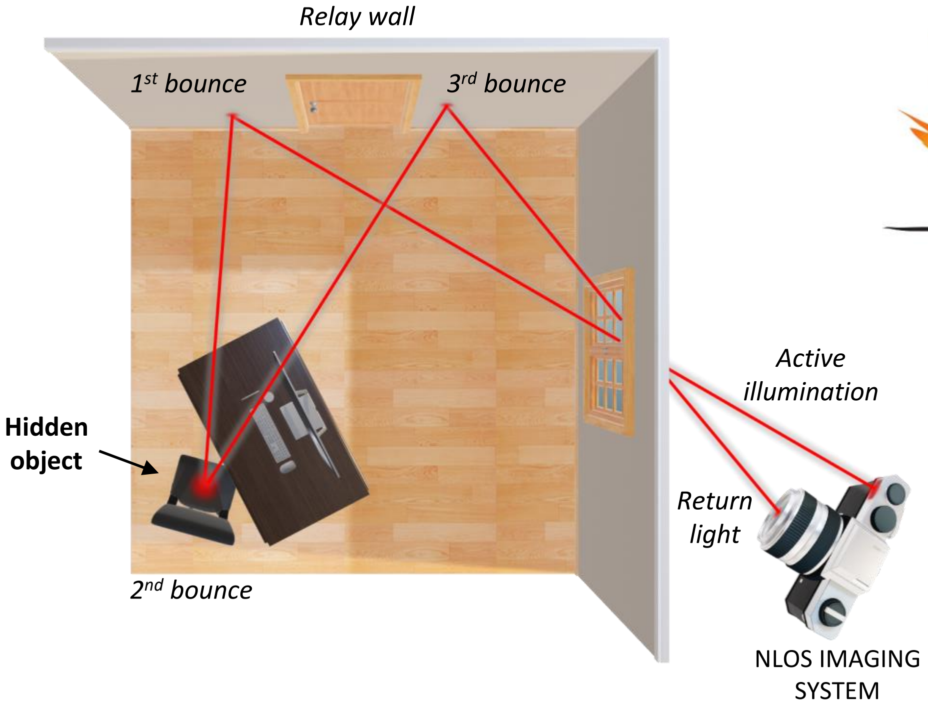
Conclusions

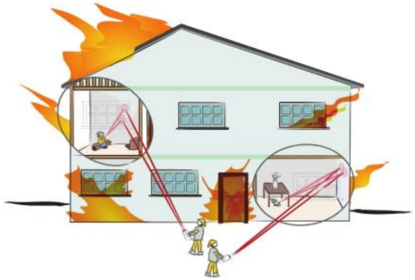


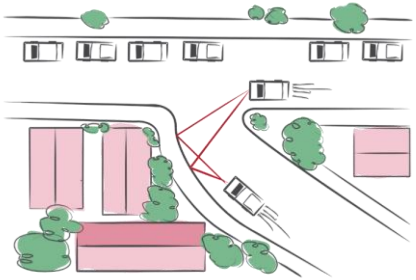


Non-line-of-sight imaging

Reconstruction of hidden objects by collecting light that diffuses multiple times



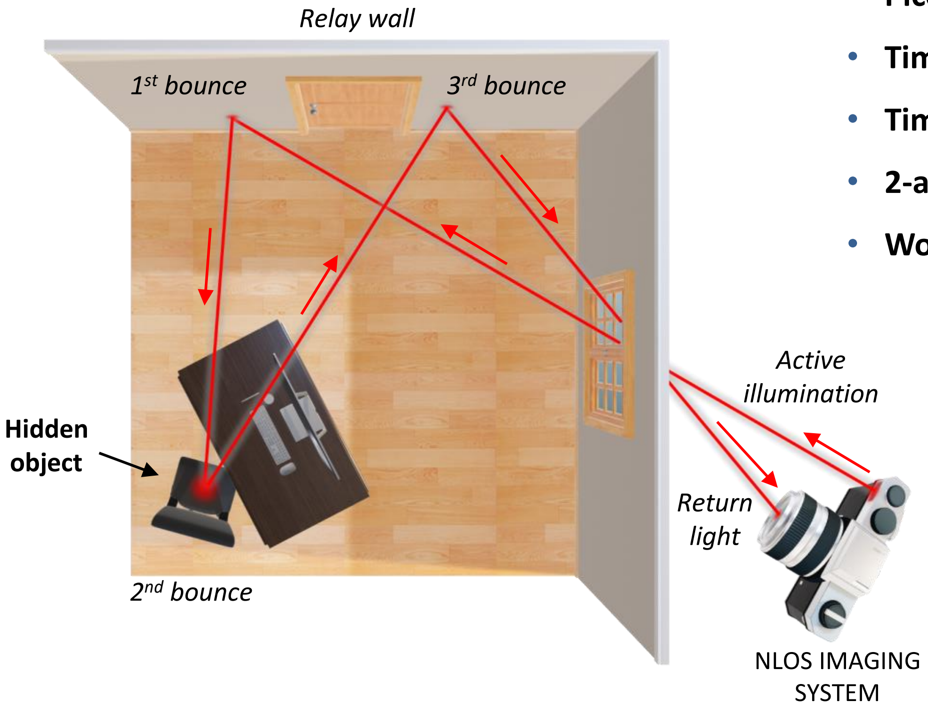




Examples of applications:

- Security and defense
- Search and rescue
- Monitoring hazardous environments
- Autonomous vehicles and ADAS
- Remote sensing

Time-of-flight NLOS imaging system

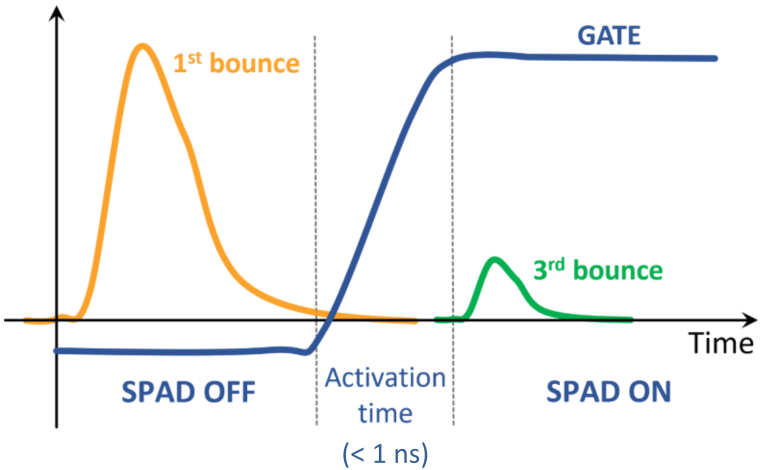


- **Picosecond pulsed laser** → illuminates a relay wall
- **Time-resolved detector** → acquires return light
- **Time-of-flight processing unit** → time stamps single-photons
- **2-axis scanning system** → increases image resolution
- **Workstation** → runs the reconstruction algorithms

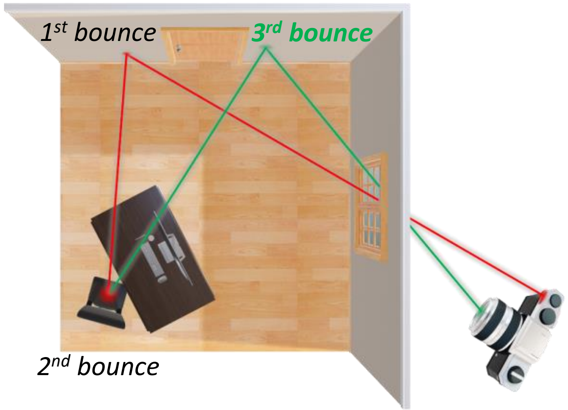
Detector requirements

- Multiple scattering events → faint **3rd bounce** signal → **single-photon sensitivity**
- Undesired **1st bounce** reflections → time-domain filtering → **time-gated detector**

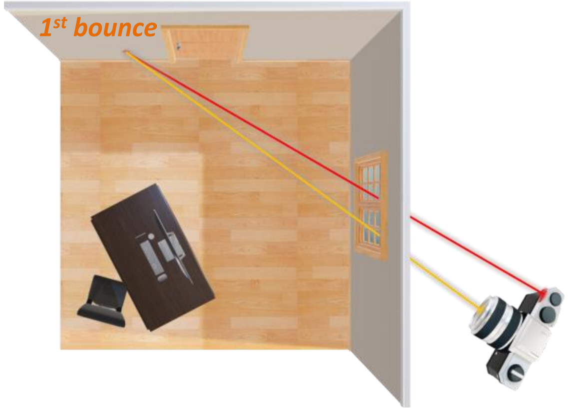
NLOS imaging requires **SPAD**-based sensors



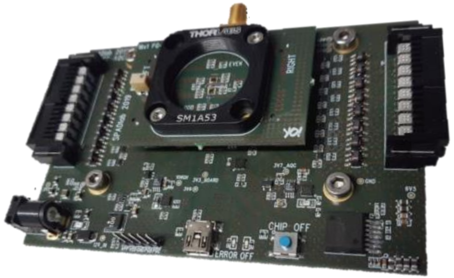
INDIRECT LIGHT PATH



DIRECT LIGHT PATH



State-of-the-art



Fast-gated 16 × 1 SPAD array

External TCSPC unit (PicoQuant HydraHarp 400)

→ Reaches up to **5 fps**, **0.5 MP resolution**

→ Hardware limited to **few pixels**, **8 TCSPC channels**

J. H. Nam, E. Brandt, S. Bauer, X. Liu, M. Renna, A. Tosi, E. Sifakis, and A. Velten, "Low-latency time-of-flight non-line-of-sight imaging at 5 frames per Second," *Nature Communications*, vol. 12, no. 1, 2021.

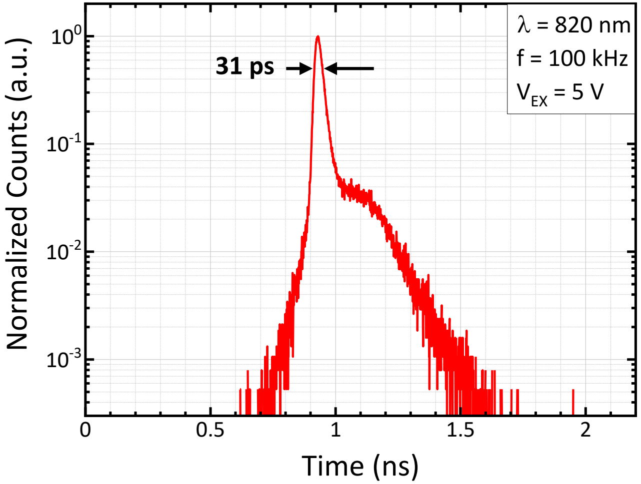
NLOS at **video rates** → **Design of a new fully-integrated 16 × 16 SPAD array:**

- Parallel acquisition: **multi-pixel sensor**
- Narrow IRF: **few tens of ps (FWHM)**
- Fast-gating: **< 1 ns gate-ON transition**
- SWaP-C optimized: **integrated TCSPC processing**

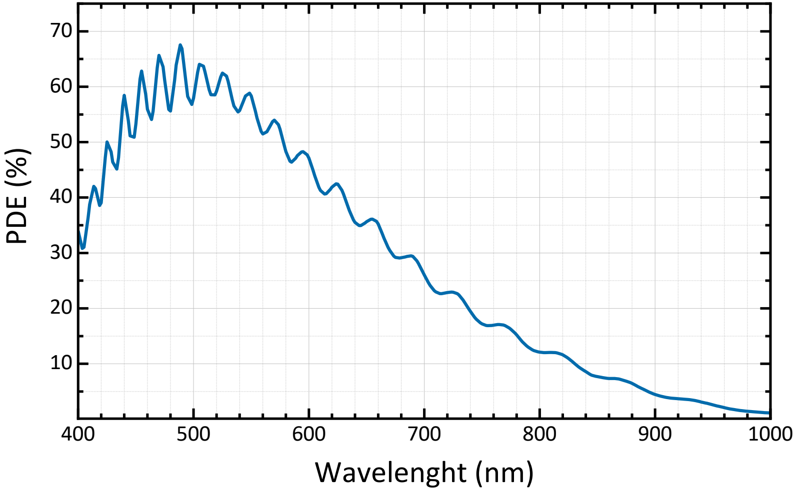
16 × 16 SPAD array: fabrication technology

Narrow IRF + High PDE → 160 nm BCD technology by STMicroelectronics

30 ps SPAD timing jitter FWHM

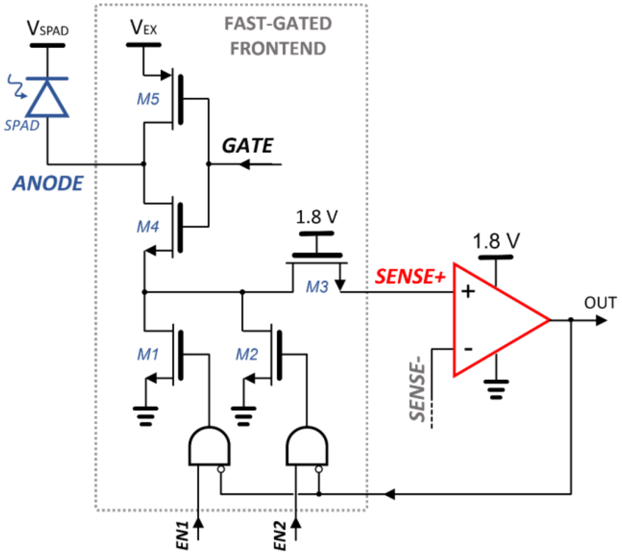


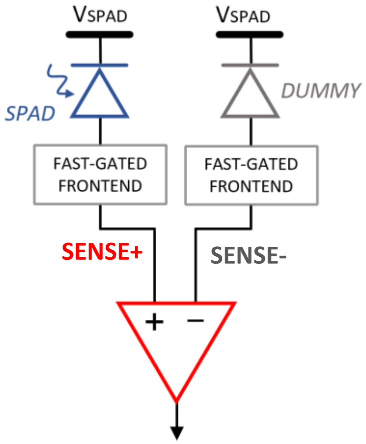
60% PDE @ 500 nm, V_{EX} = 5 V

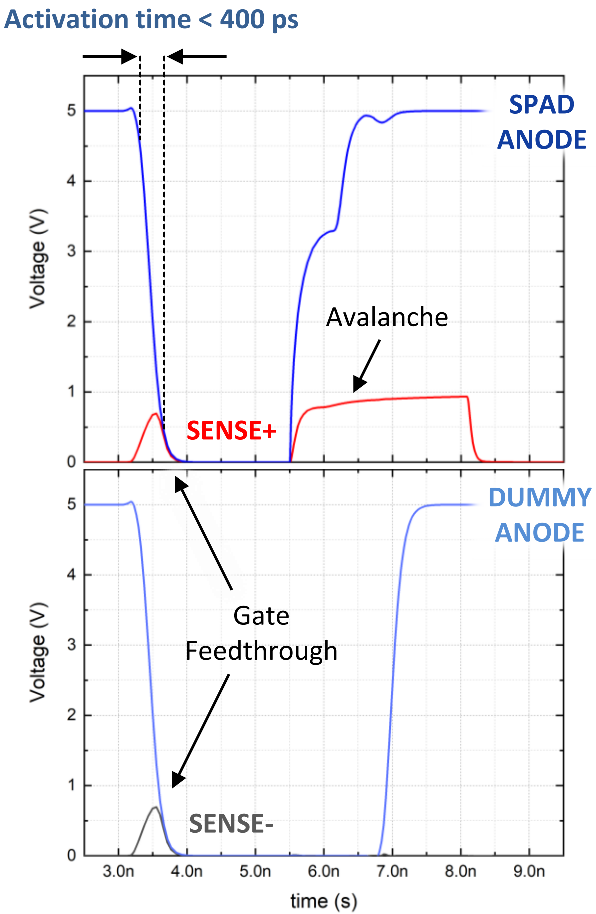


M. Sanzaro, P. Gattari, F. Villa, A. Tosi, G. Croce, and F. Zappa, "Single-photon avalanche diodes in a 0.16 µm BCD technology with sharp timing response and red-enhanced sensitivity," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 24, no. 2, pp. 1–9, 2018.

16 × 16 SPAD array: fast-gated frontend







- → M1 and M2 programmable to sense avalanches and tune the **activation time**
- → M3 for level translation from 5 V (GATE) to 1.8 V (fast comparator)

- → **Differential sensing** to reject feedthrough pulses
- → **Low threshold** for low timing jitter

16 × 16 SPAD array: differential sensing approaches

Area (2x)
Power (2x)
No collisions

Area
Power
2-photon collisions

Area
Power
4-photon collisions
Fixed priority list

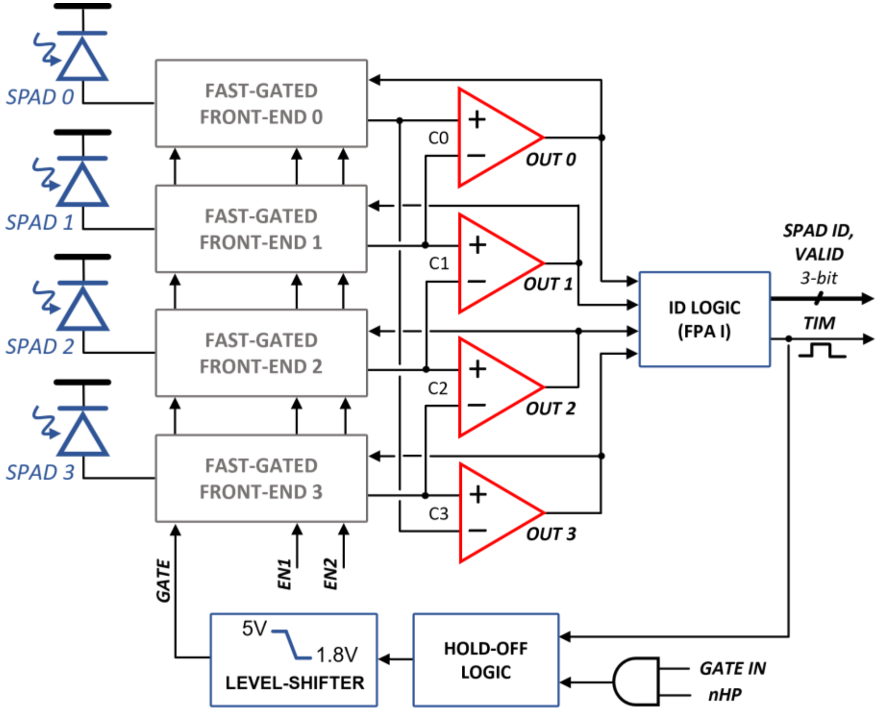
16 × 16 SPAD array: microcell circuitry

→ **4 SPADs + low-threshold comparators**
Low-jitter avalanche sensing
Optimizes area and power + fast quenching

→ **Identification logic**
Encodes the firing SPAD address (SPAD ID)

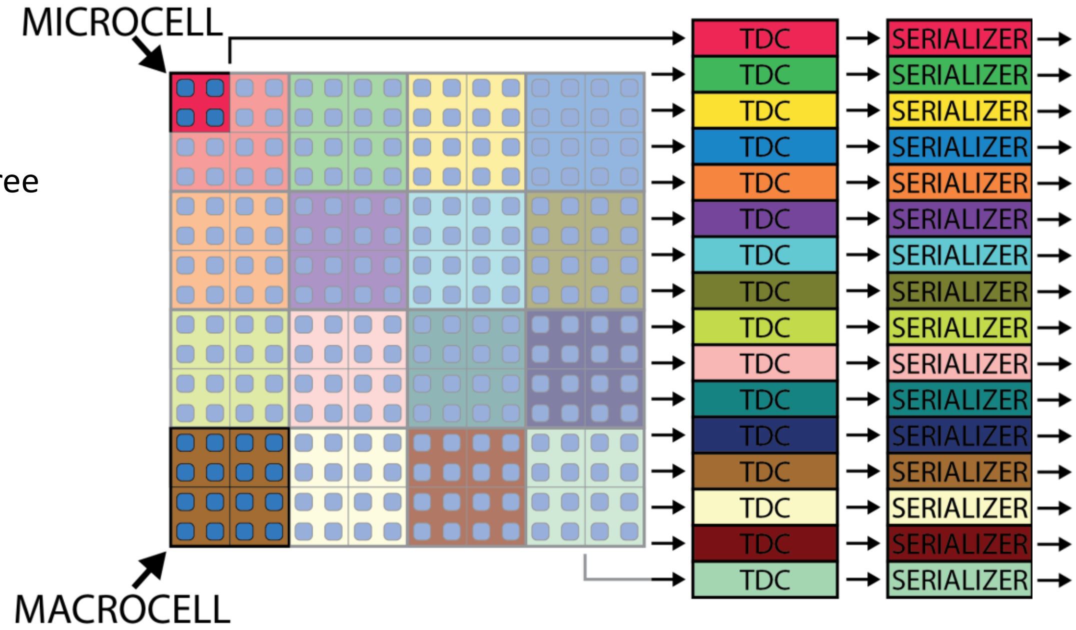
→ **Hold-off logic**
Forces 30 ns dead-time to reduce afterpulsing

→ **1.8 V to 5 V level shifter**
Maximizes V_{EX}, hence PDE



16 × 16 SPAD array: resource sharing

- **Sharing logic:** 2-level fixed priority arbiter tree
  → Microcells: 2 × 2 SPADs
  → Macrocells: 2 × 2 microcells
- **16 Time-to-Digital Converters (TDCs)**
- **16 event-driven output serializers**



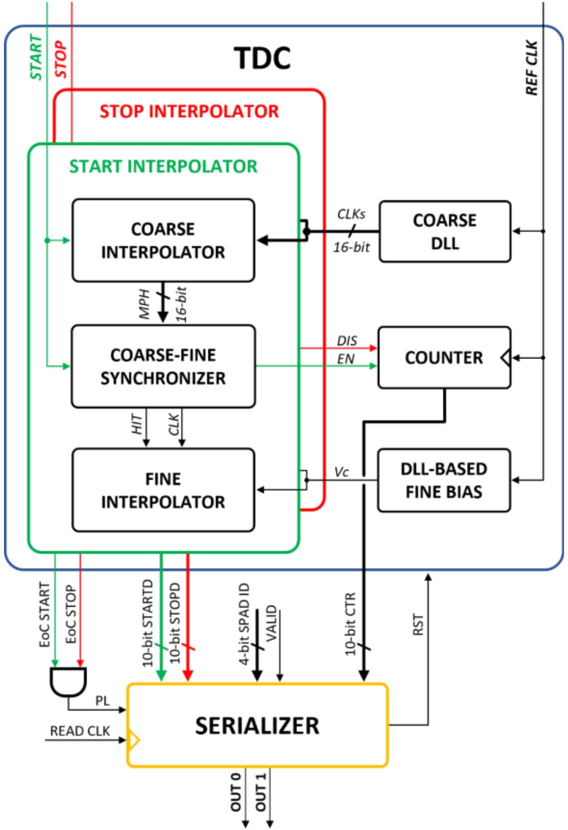
16 × 16 SPAD array: TDCs and output serializers

16 TDCs:

- START and STOP interpolators → sliding scale → **improved linearity**
- 10-bit counter @ 420 MHz → **FSR = 2.45 µs**
- Coarse multiphase interpolator → **conversion time < 50 ns**
- Single-stage Vernier fine interpolator → **LSB = 6 ps**

16 Serializers:

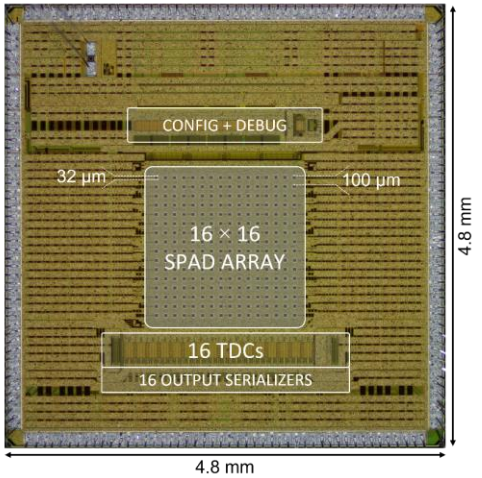
- 18-bit dual-channel @ 200 MHz → up to **10 Mevents/s** per TDC
- **Event-driven readout** → Time-Tagged Time-Resolved (TTTR) operation
- **Pipelined architecture** → conversion during data-transfers



Camera overview

IC:

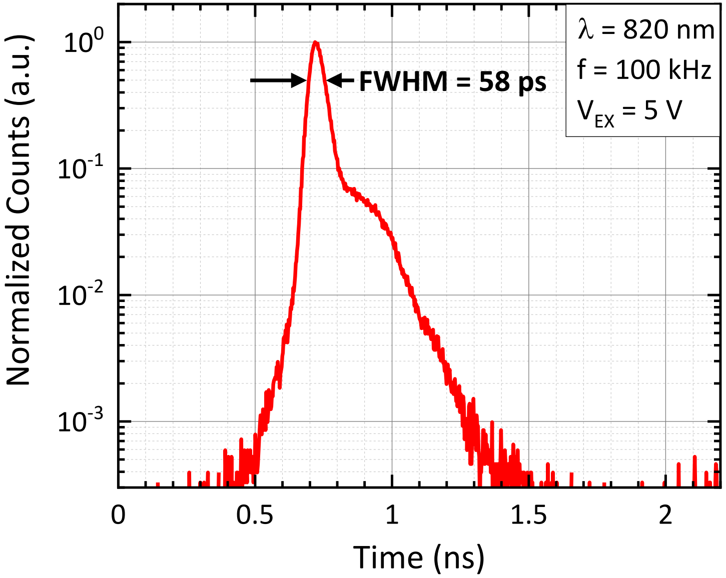
- 4.8 mm x 4.8 mm, PAD-limited
- In-pixel decoupling capacitors + deep trench isolation
- 32 µm squared SPADs @ 100 µm pitch → **Fill-factor = 9.6%**



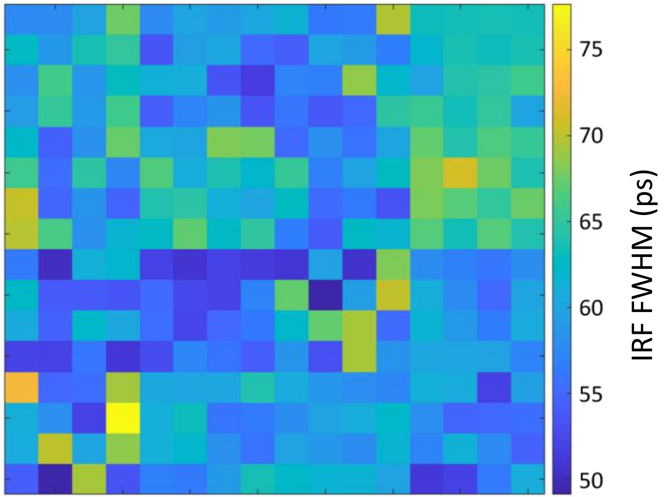
Camera:

- **Chip-carrier board** → hosts the wire-bonded IC
- **Power board** → power management + signal conditioning
- **FPGA board** → TCSPC processing + USB 3.0 interface

Characterization results: instrument response function



IRF of a representative pixel



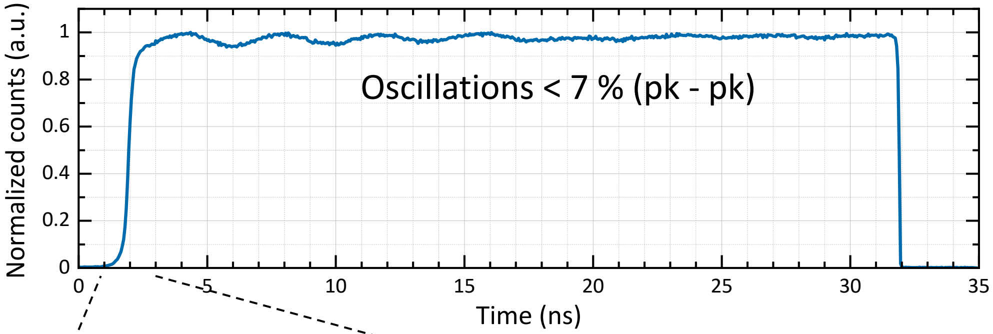
Map of the IRF (FWHM) of the array

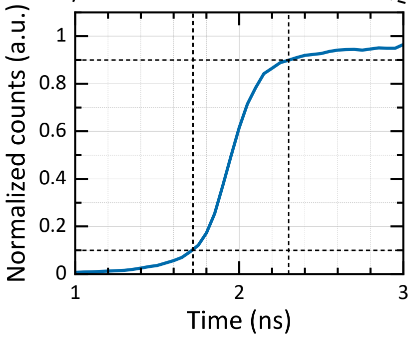
Average = 62 ps

Max = 77 ps

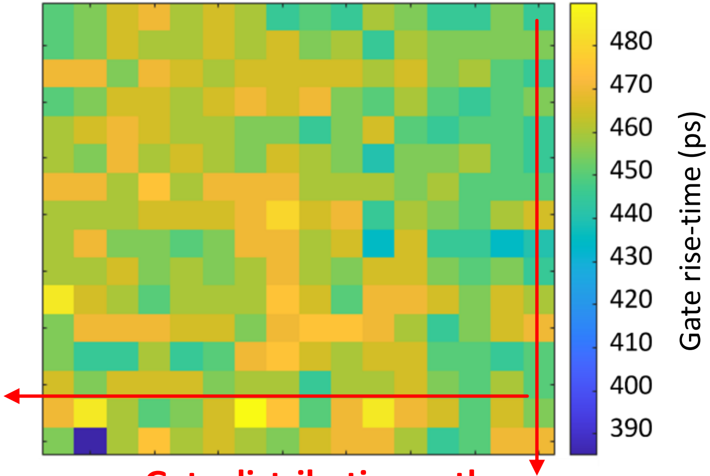
→ *Values obtained by illuminating the array with a 10 ps 820 nm pulsed laser running at 100 kHz*

Characterization results: gating performance



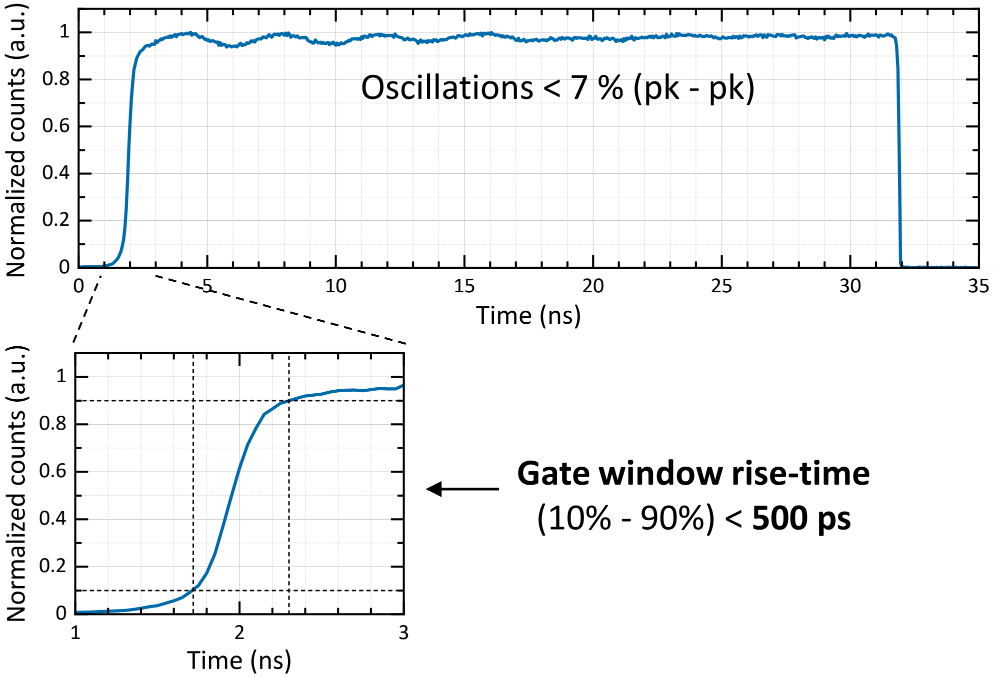


Gate window rise-time
(10% - 90%) < **500 ps**



→ *Values obtained scanning a 52 ps (FWHM) 850 nm pulsed laser at* ***50 ps steps*** *across a 30 ns gate window at 1 MHz repetition rate*

Characterization results: gating performance



← **Gate window rise-time**
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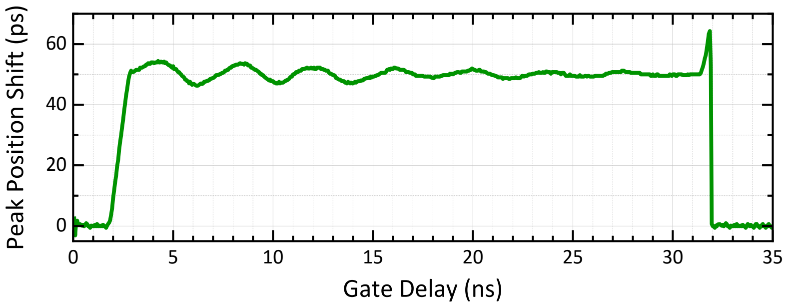
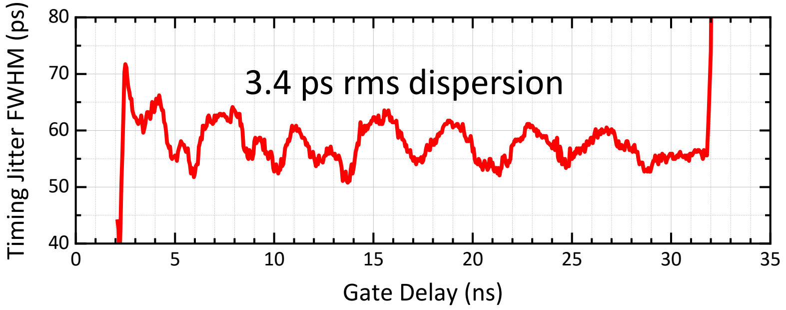
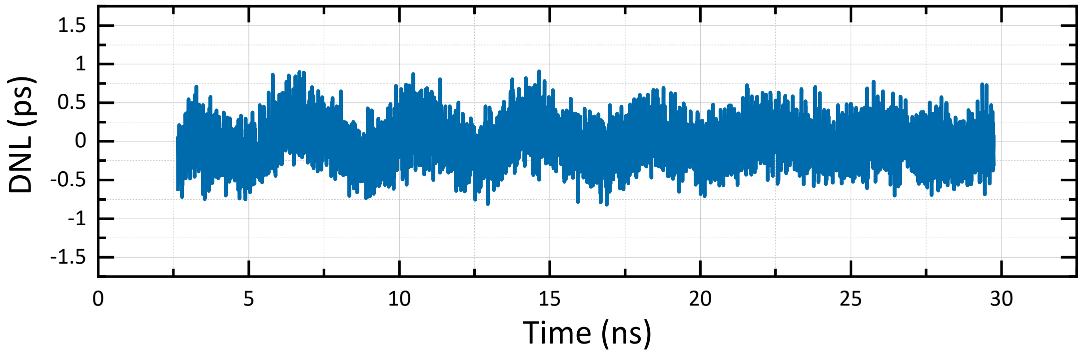


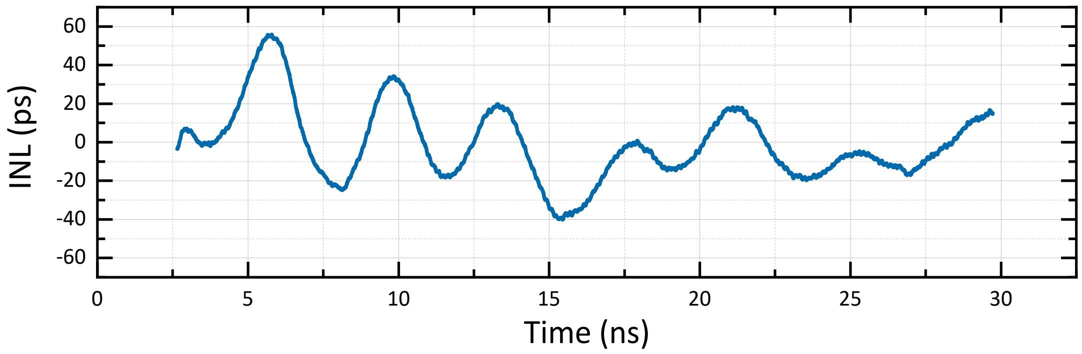


→ *Values obtained scanning a 52 ps (FWHM) 850 nm pulsed laser at* ***50 ps steps*** *across a 30 ns gate window at 1 MHz repetition rate*

Characterization results: conversion linearity

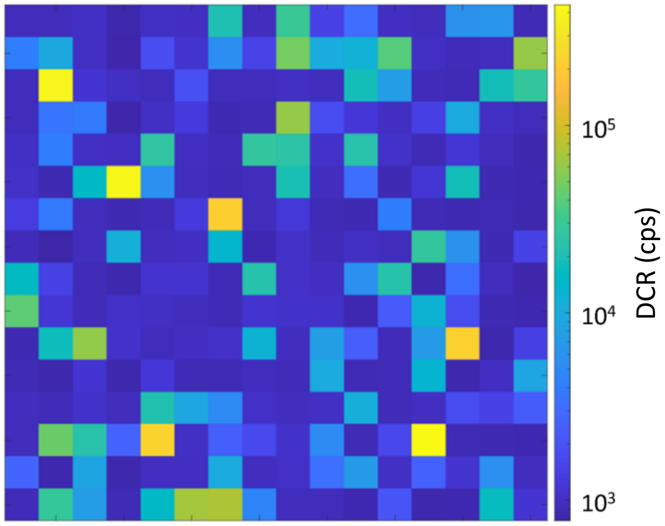


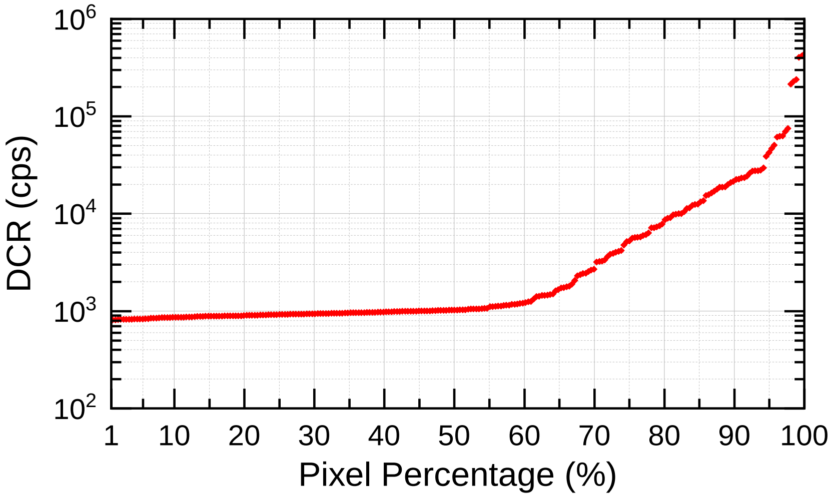
→ **DNL = 250 fs rms** (0.04 LSB)



→ **INL = 22 ps rms** (3.6 LSB)

Characterization results: dark count rate





Median DCR = 1 kcps @ operating temperature (~ 45° C)

→ Temperature increase due to **500 mW power consumption**

Conclusions

High-performance NLOS SPAD array:

- 16 × 16 pixels
- **Sub-ns gating**
- State-of-the-art IRF:
  FWHM < 75 ps, 62 ps on average
- 16 integrated high-resolution TDCs

Integrated in a portable camera:

- 10 × 7 × 5 cm^3
- **USB 3.0 connection** + single 5 V power supply
- **Up to 160 Mevents/s sustained throughput**
- SM1 or C-mount thread for filters and lenses

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→ NLOS measurements ongoing at the University of Wisconsin-Madison

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