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20 YEARS QUANTUM INNOVATION

Ultra-fast multipixel SNSPD arrays with photon-number capabilities for quantum applications

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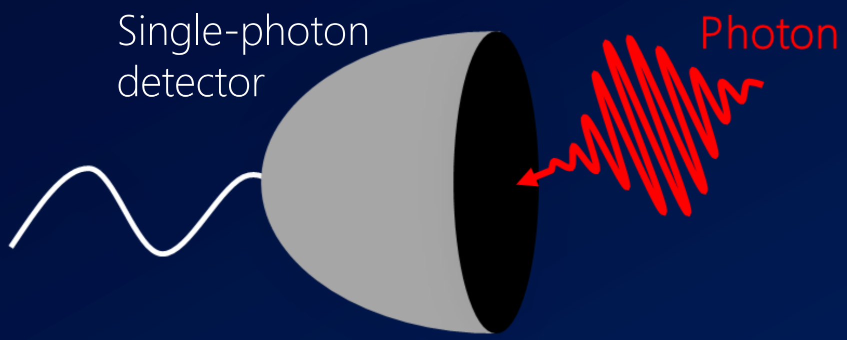
Qcrypt, University of Maryland – 18/08/2023

QKD

Demanding constraint on the single photon detectors



High efficiency	→	Reduce losses
Low recovery time	→	Fast QKD
Low dark counts	→	Long distance QKD
Low jitter	→	Reduce errors

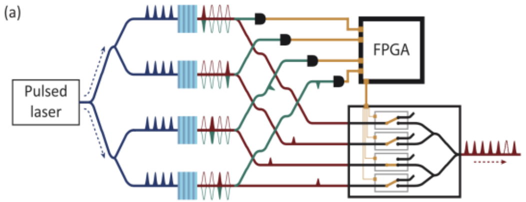
Applications requiring photon number resolution (PNR)

Far from an exhaustive list…

Stream of true single photons

Photonic quantum information processing: A concise review

Cite as: Appl. Phys. Rev. 6, 041303 (2019); https://doi.org/10.1063/1.5115814
Submitted: 20 June 2019 . Accepted: 16 September 2019 . Published Online: 14 October 2019

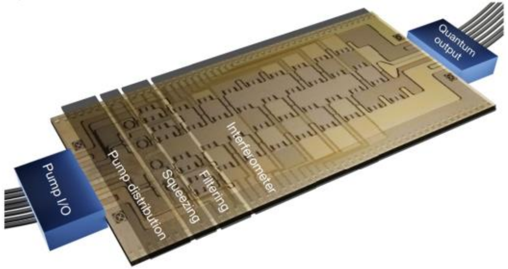


Optical quantum computing

Quantum circuits with many photons on a programmable nanophotonic chip

J. M. Arrazola, V. Bergholm, [...] Y. Zhang

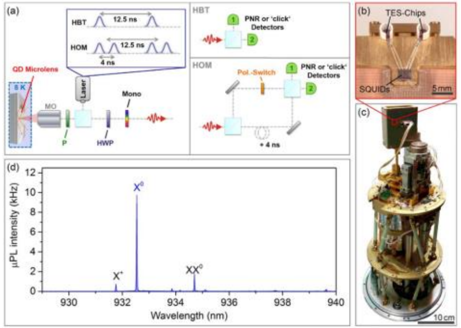
Nature **591**, 54–60 (2021)



Quantum metrology

Quantum metrology of solid-state single-photon sources using photon-number-resolving detectors

To cite this article: Martin von Helversen *et al* 2019 *New J. Phys.* **21** 035007



Lita, A. E., et al. "Development of superconducting single-photon and photon-number resolving detectors for quantum applications." Journal of Lightwave Technology (2022)

Superconducting Nanowire Single-Photon Detectors

A tool to enable new technologies

Quantum Optics

Life Science

QKD

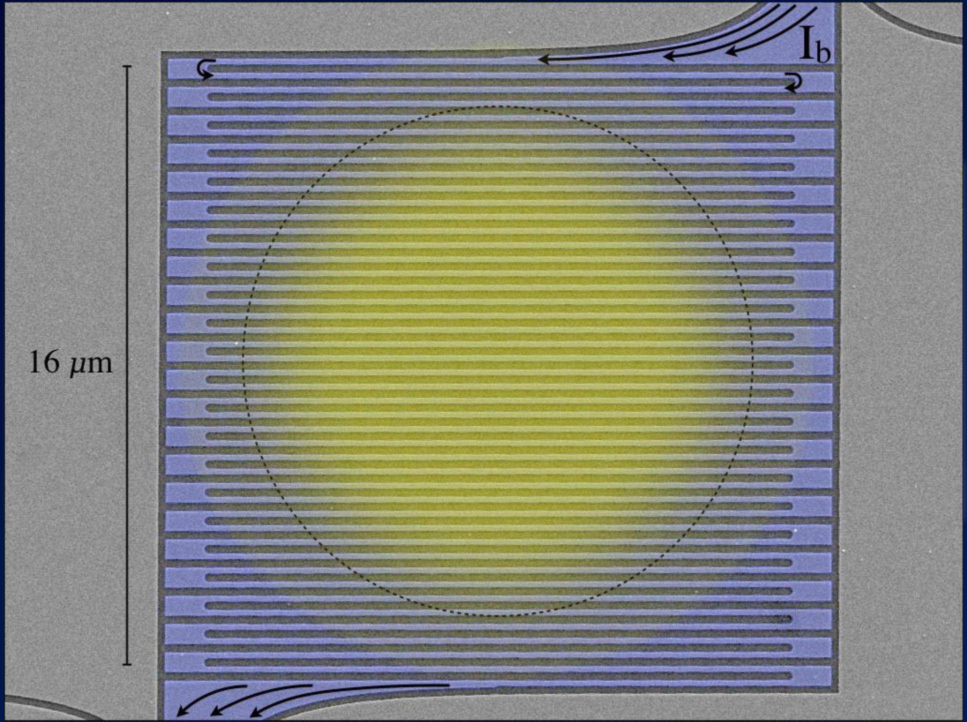
OTDR & LIDAR

Optical quantum computing

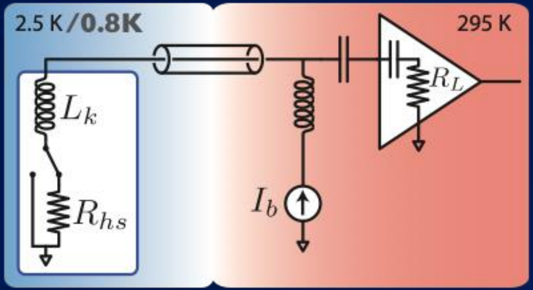
SNSPD operation principle

Single-pixel design

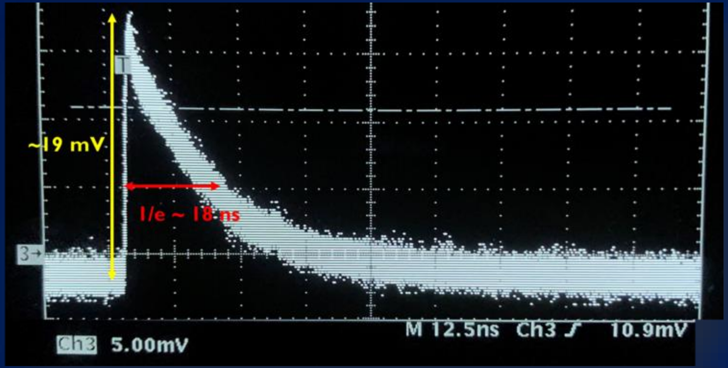
SEM of device



Biasing circuit

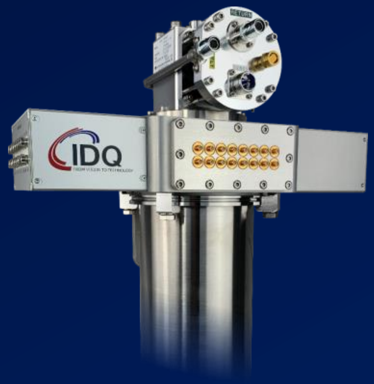


Output pulse

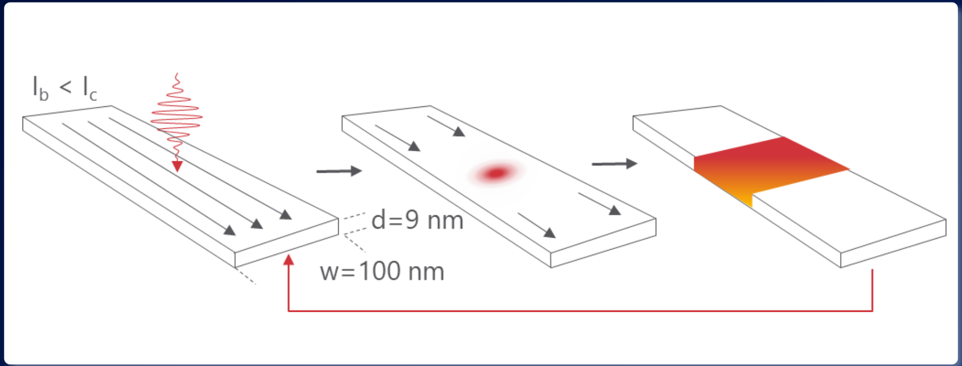


SNSPD operation principle

Single-pixel design



Operation principle



System Detection Efficiency (SDE): > 95%

Dark counts: < 1 to < 100 cps (at 1550nm)

Jitter: < 25 ps

Recovery time: ~ 30 ns

Limited maximum detection rate

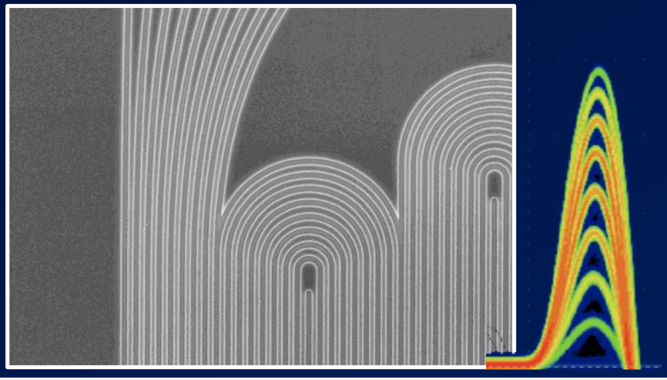
Limited photon-number resolving capability

Photon-number resolution with SNSPDs

Divide detection area in multiple smaller SNSPDs (pixels)

Parallel SNSPD: P-SNSPD

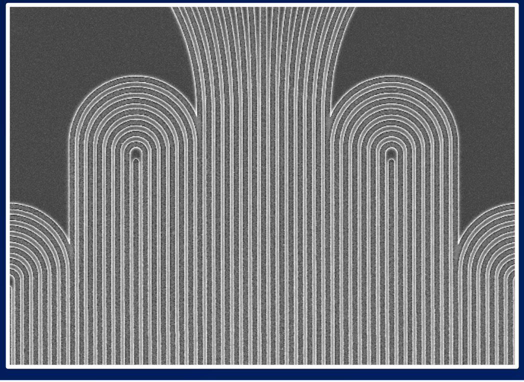
- 4 to 8 pixels connected with 1 readout line (up to 16 devices in a 16-channel cryostat)
- Amplitude of output pulse encodes photon number info
- PNR + Fast detection (up to 100 Mcps)



Perrenoud, M. et al. *Superconductor Science and Technology*, *34*(2), p.024002 (2021)
Stasi, L. et al. *Physical Review Applied*, *19*(6), p.064041 (2023)
Stasi, L. et al. *Quantum Sci. Technol.* 8 045006 (2023)

Multi-pixel SNSPD: MP-SNSPD

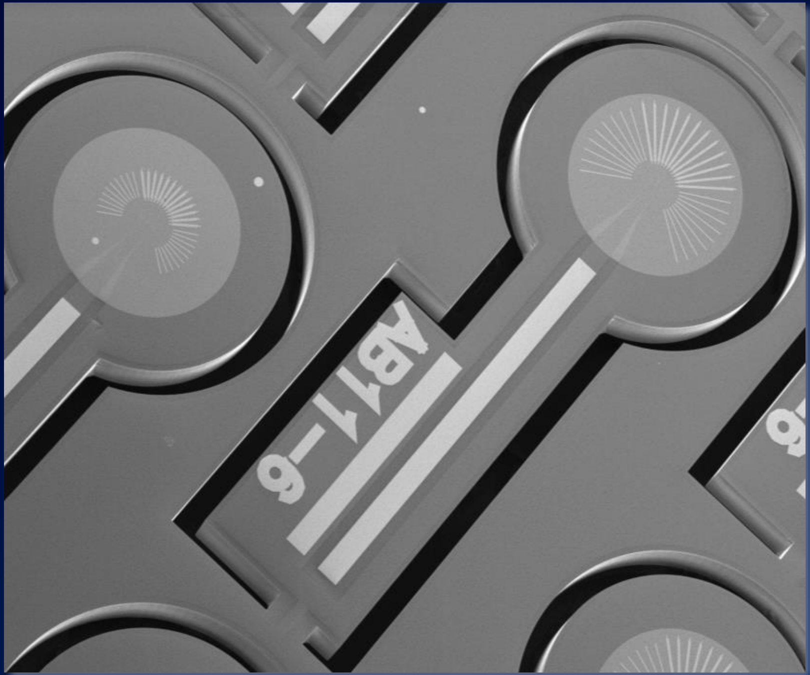
- 4 to 16 independent pixels with as many readout lines
- Number of pixels clicking encodes photon number info
- Dynamic PNR (no limitation on input light) + Ultrafast detection (up to > 1 Gcps)

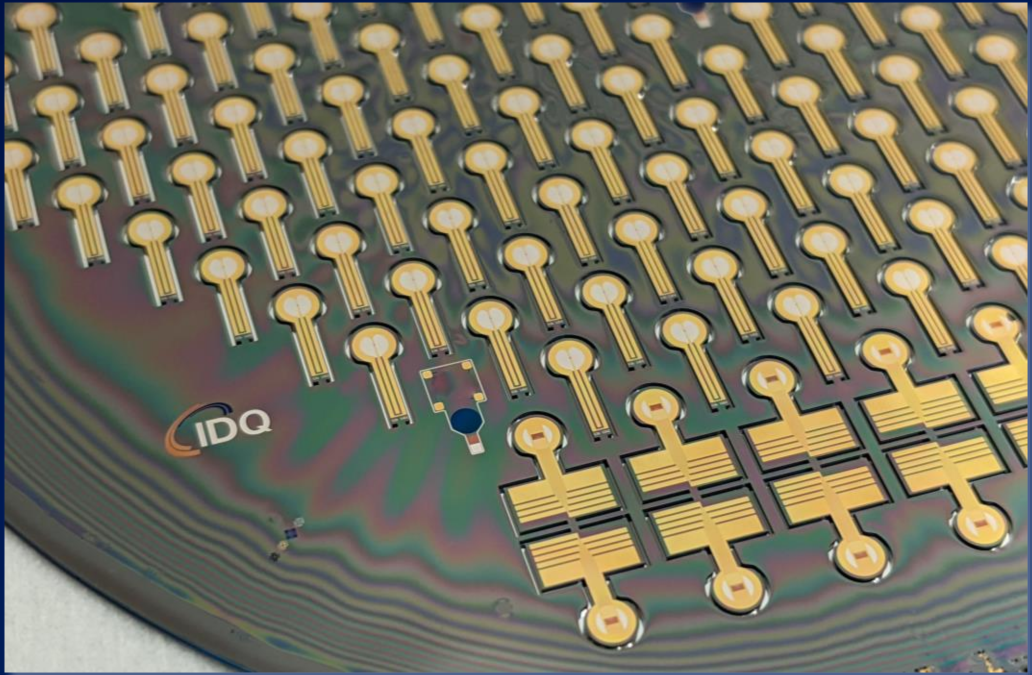


Grünenfelder, F. et al. *Nature Photonics*, *17*(5), pp.422-426 (2023).
Resta, G.V. et al *Nano Letters*, *23* (13), 6018-6026 (2023)

Fabrication details

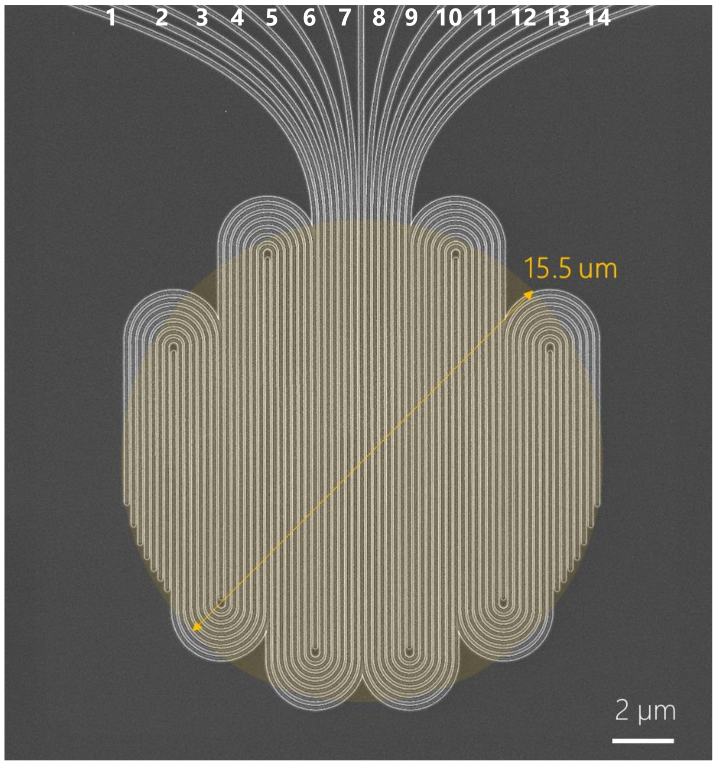
Final etched devices

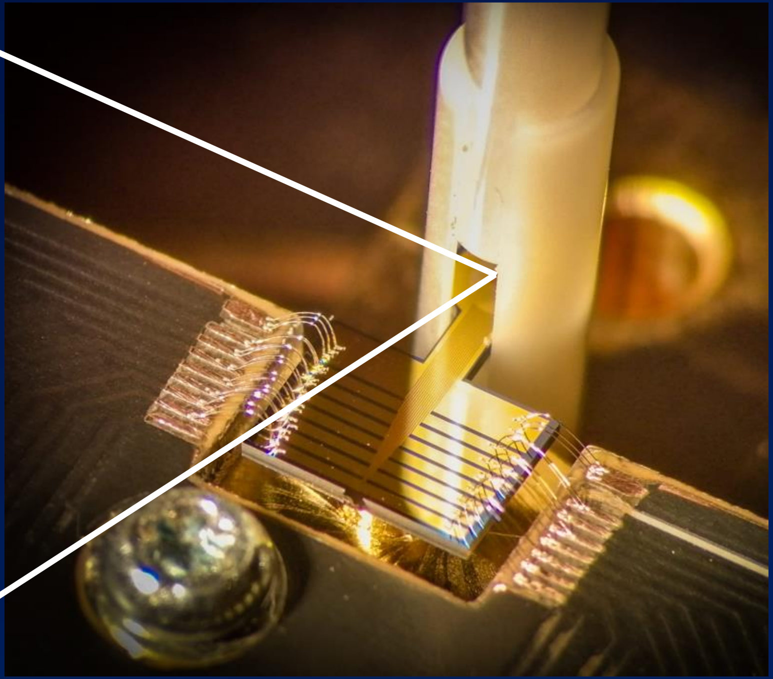




Multipixel (MP-) SNSPD

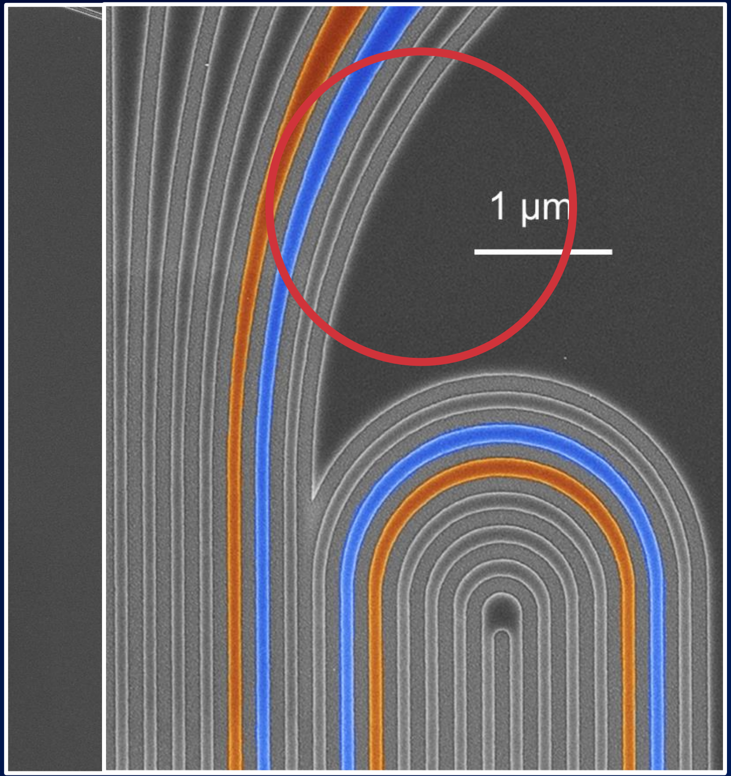
14 independent pixels





MP-SNSPD

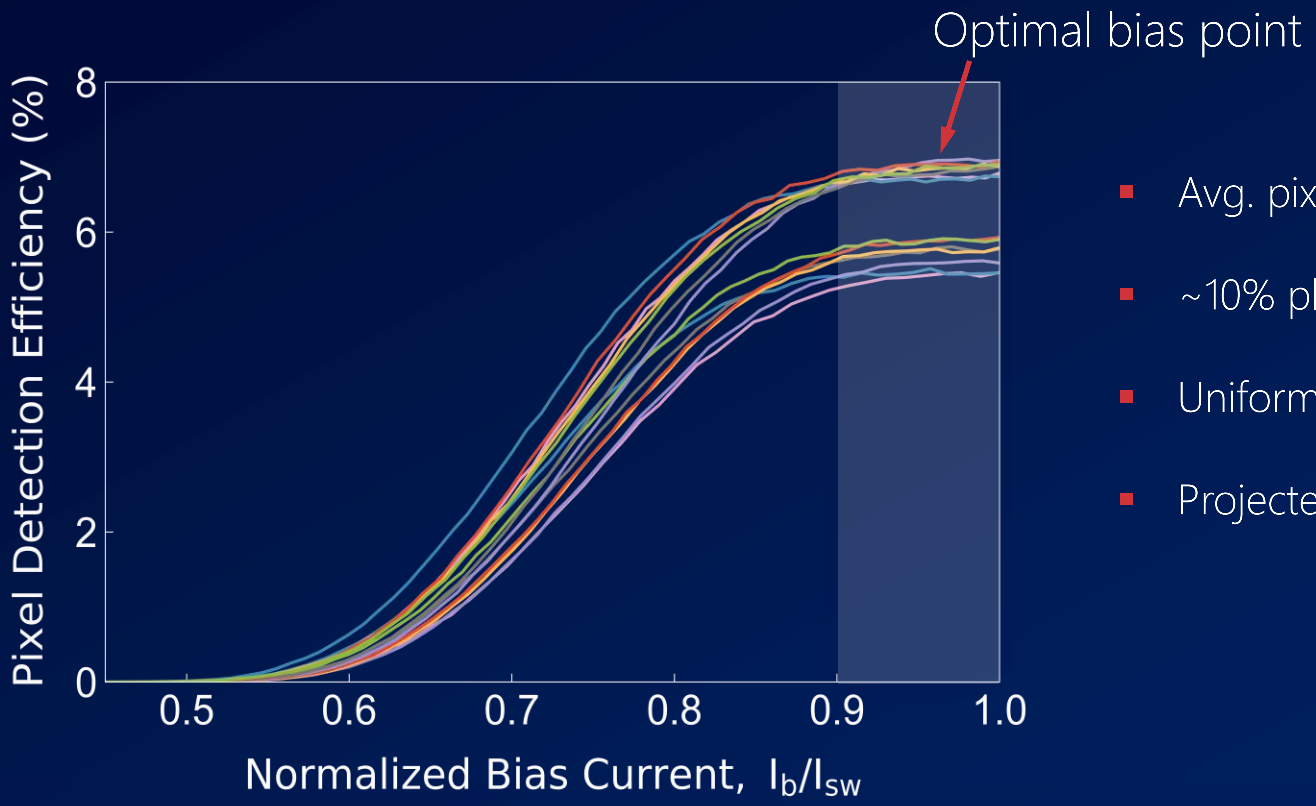
Architecture Overview



Interleaved pixels	→	Uniform light distribution
Short nanowires	→	Low recovery time
Individual bias and readout	→	Highest count rate and dynamic PNR
NbTiN Superconductor	→	Low jitter & low thermal crosstalk
1 single-mode fiber	→	Simple optical set-up

MP-SNSPD performances

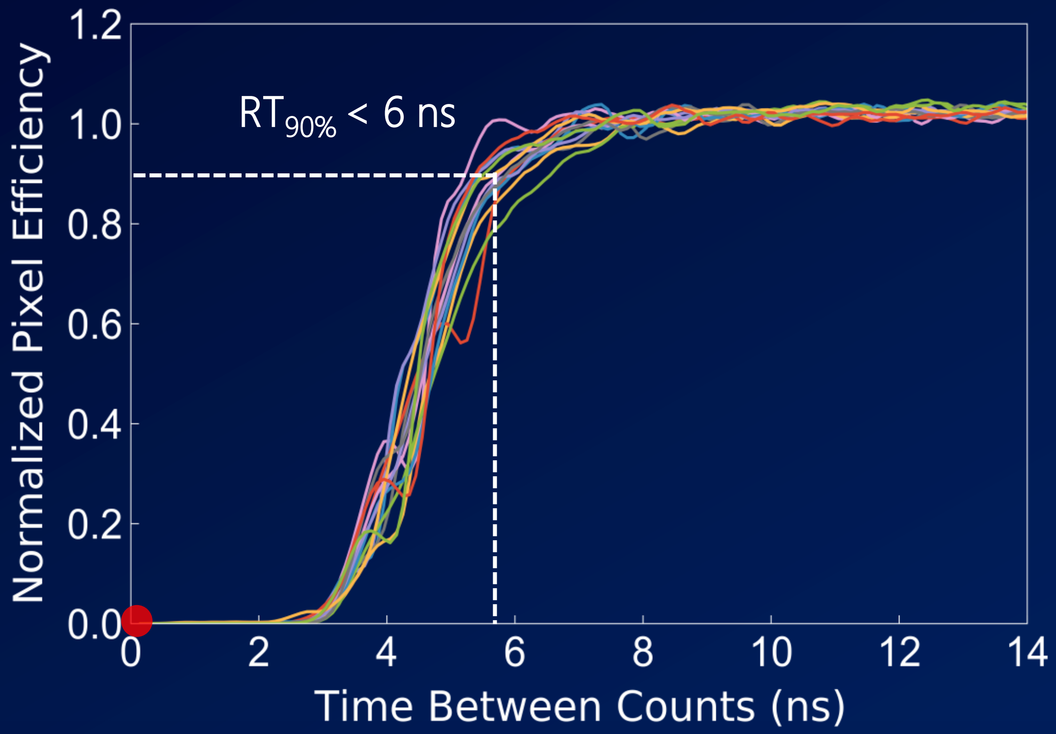
Pixel detection efficiencies at 1550nm



- Avg. pixel efficiency of 6.4%
- ~10% plateau width
- Uniform distribution
- Projected total SDE ~ 90%

MP-SNSPD performances

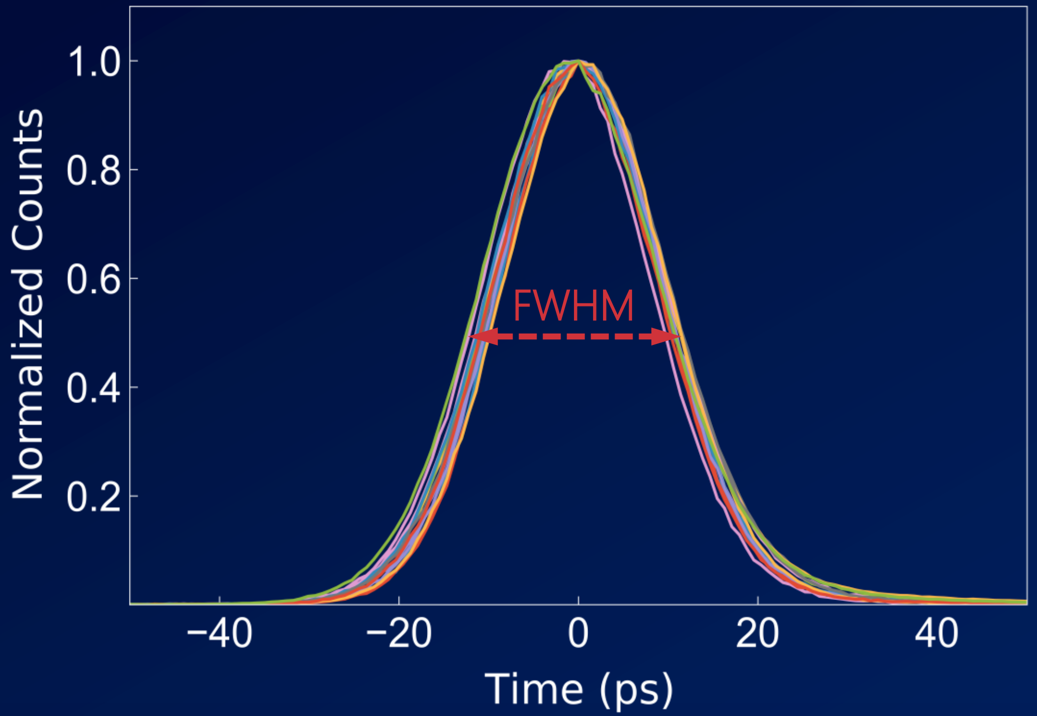
Pixel recovery times at 1550nm



- True measure of the recovery of the efficiency after a detection
- Pixels back at 90% of max SDE after ~ 6 ns
- While 1 pixel is recovering the other 13 pixels are still active
- Possibility to achieve ultra-high detection-rates

MP-SNSPD performances

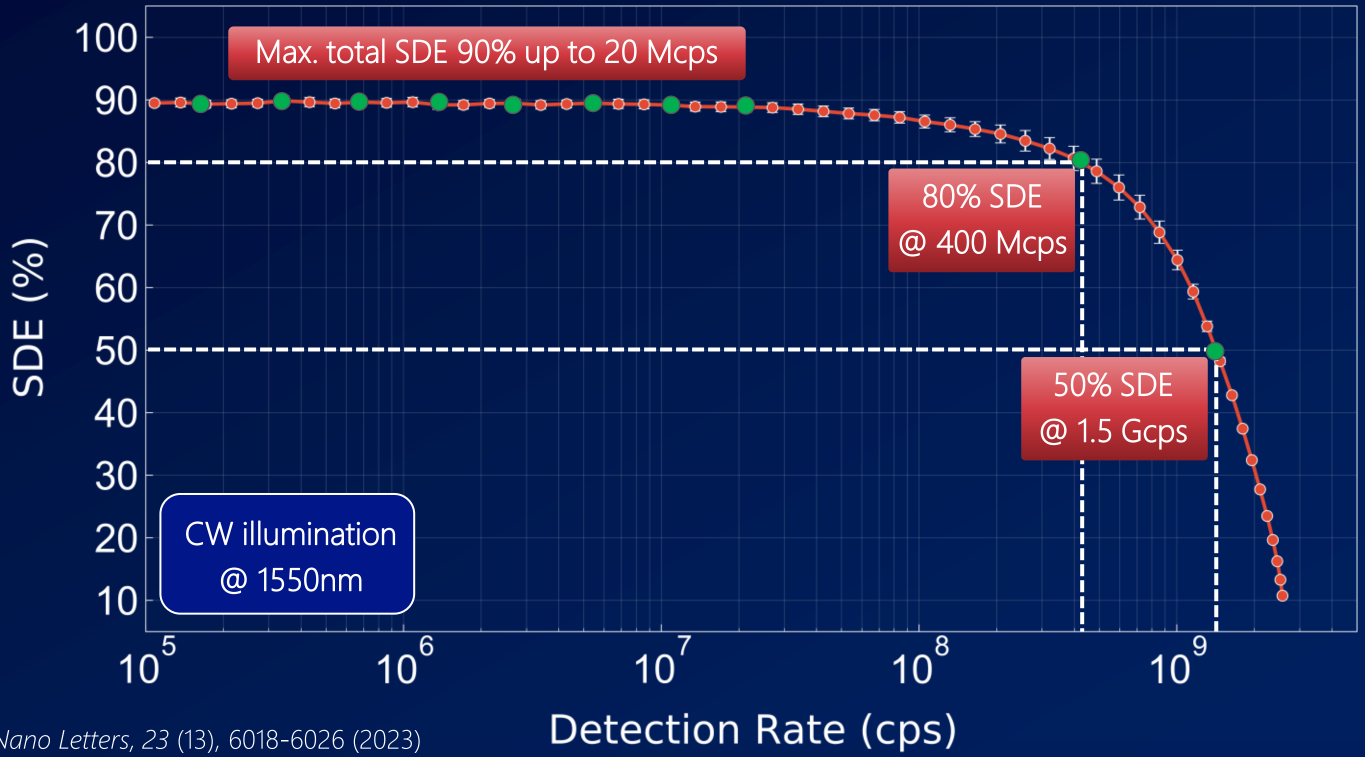
Pixel jitter at 1550 nm



- Avg. jitter of 21.5 ps @ 15 Mcps
- Avg. jitter of 46 ps @ 320 Mcps
- Pixel uniformity

MP-SNSPD performances

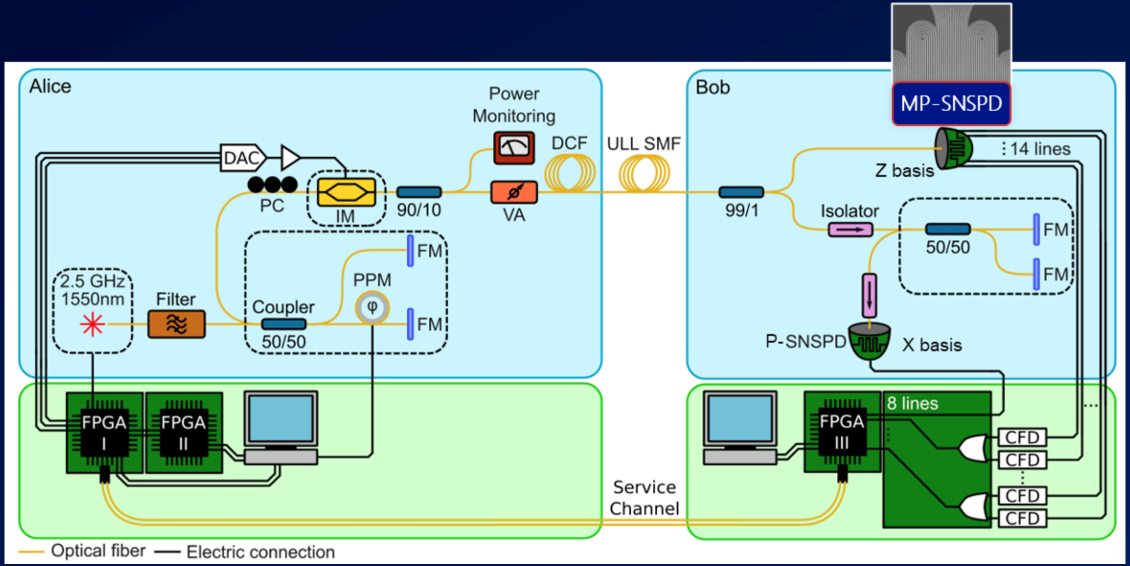
Efficiency vs. detection rate with 1550 nm CW light



Resta, G.V. et al *Nano Letters*, *23* (13), 6018-6026 (2023)

Enabling high secret key rates

Simplified BB84 protocol



fiber length (km)	att. (dB)	SKR (Mbps)
10.0	1.58	64
102.4	16.34	3.0

Improved resilience against blinding attacks, by monitoring coincidences between the pixels.

Grünenfelder, F. et al. *Nature Photonics*, *17*(5), pp.422-426 (2023).

Gras, G. *et al.* Physical Review Applied, 15(3), p.034052 (2021).

Photon number resolution (PNR)

State reconstruction and single-shot fidelities

The problem to solve

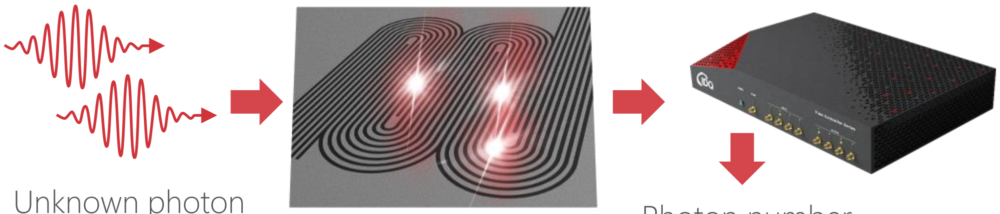
$$Q(n) = \sum_{m=0}^{\infty} P_{nm} \cdot S(m)$$

n-click event

m input photons

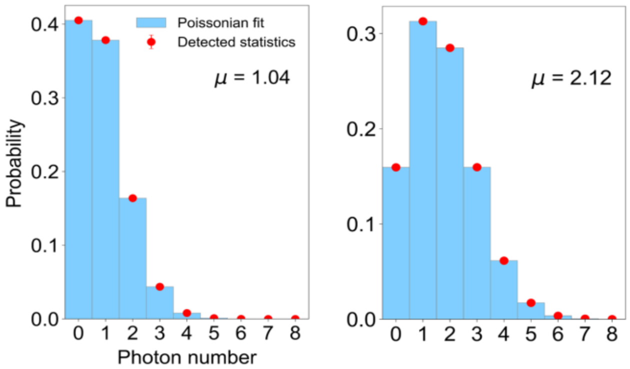
Problem : finding the matrix elements P_{nm}

Once the P_{nm} of the MP-SNSPD are known



Unknown photon number distribution

Photon number distribution characterized



Single-shot fidelities (14-pixel MP-SNSPD)

P_{11} = 90% P_{22} = 74%

P_{33} = 57% P_{44} = 40%

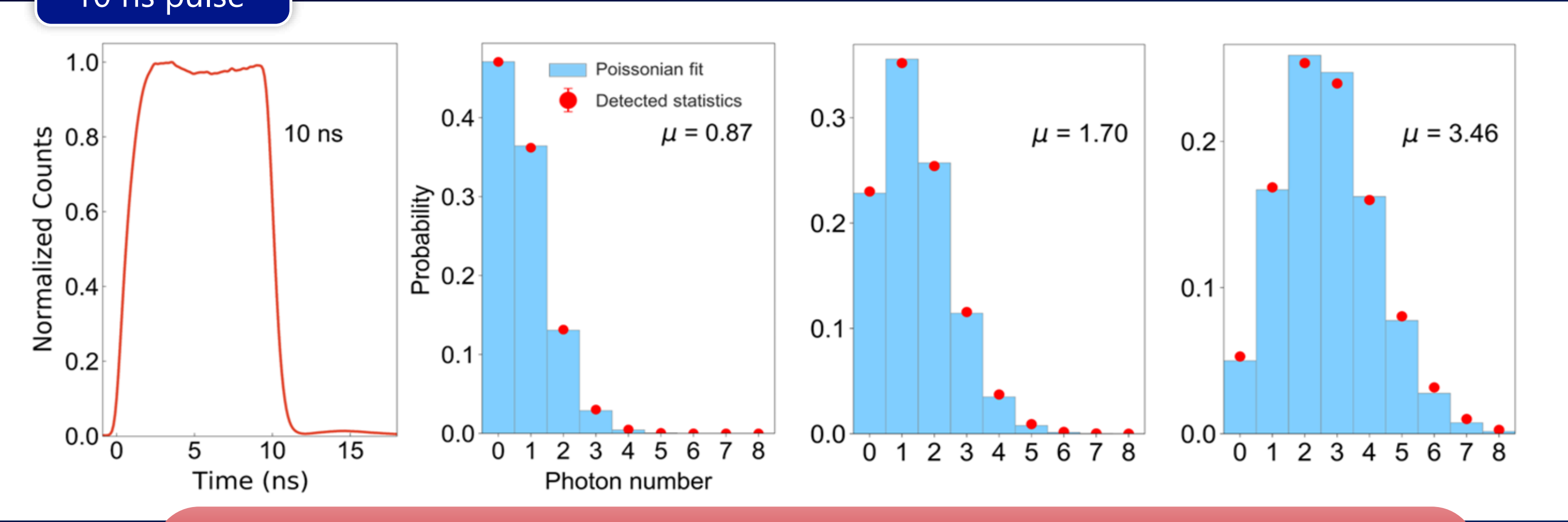
Gaussian Boson Sampling

Optical Quantum Computing

MP-SNSPDs : “dynamic” PNR detection

Photons with long coherence time

10 ns pulse

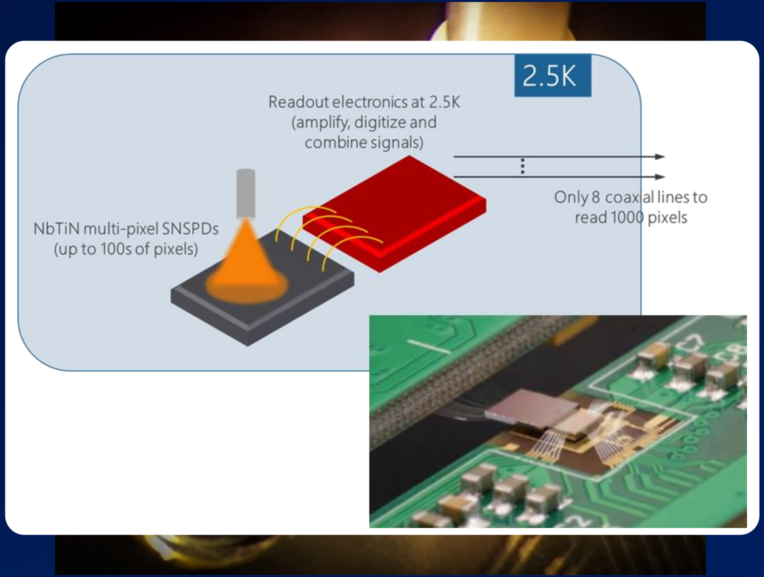


Works with long light pulses
(e.g. cavity SPDC, SFWM, squeezed light, quantum dots)

Resta, G.V. et al *Nano Letters*, *23* (13), 6018-6026 (2023)

Conclusion and Outlook

- Ultra-fast multipixel SNSPD:
  - 14 independent pixels with total SDE of 90%
  - Pixel jitter of ~ 21 ps
  - Pixel recovery time (90% SDE) of ~ 6 ns
  - 1.5 GHz detection rate at 50% abs. SDE with CW light
  - Record-breaking secret key rates in QKD experiment (63 Mbit/s over 10 Km of fiber)
  - PNR capability with photons with long coherence time
  - 2-photon fidelity of 74%
- Future directions:
  - Increase number of pixels (increase speed and fidelities)
  - Integrate amplification and digitization electronics at 2.3 K



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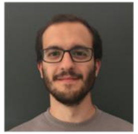

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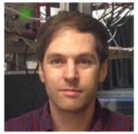

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Thank you for your attention !

Questions ?