

南京大學



Superconducting nanowire single-photon detectors and imagers

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ISS 2024, Kanazawa





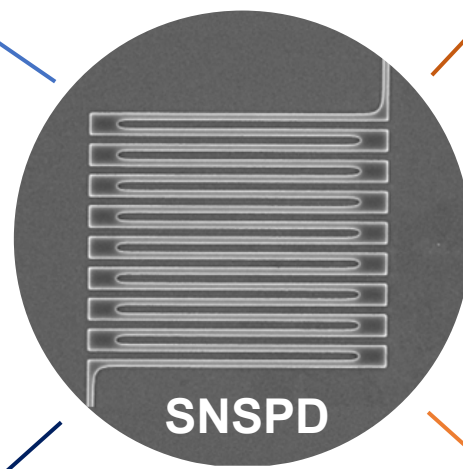
Superconducting Nanowire Single Photon Detector (SNSPD)

Popular detector for
Quantum information science

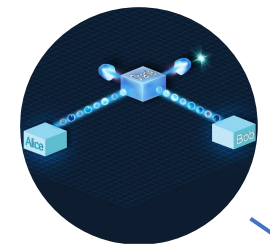
Exremely sensitive for
Exremely challenging missions

**Nanoscale
Detector**

**Massive
Power**



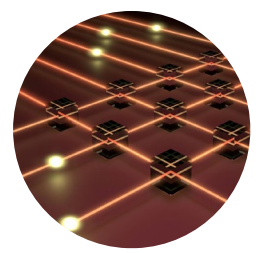
Quantum key
distribution



Deep Space
Communication



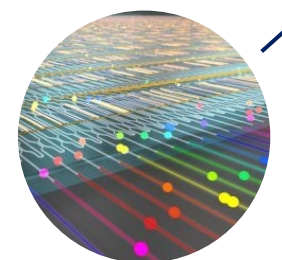
Quantum
Simulation



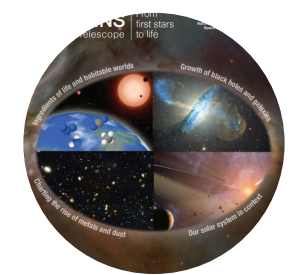
Small Debris
Detection



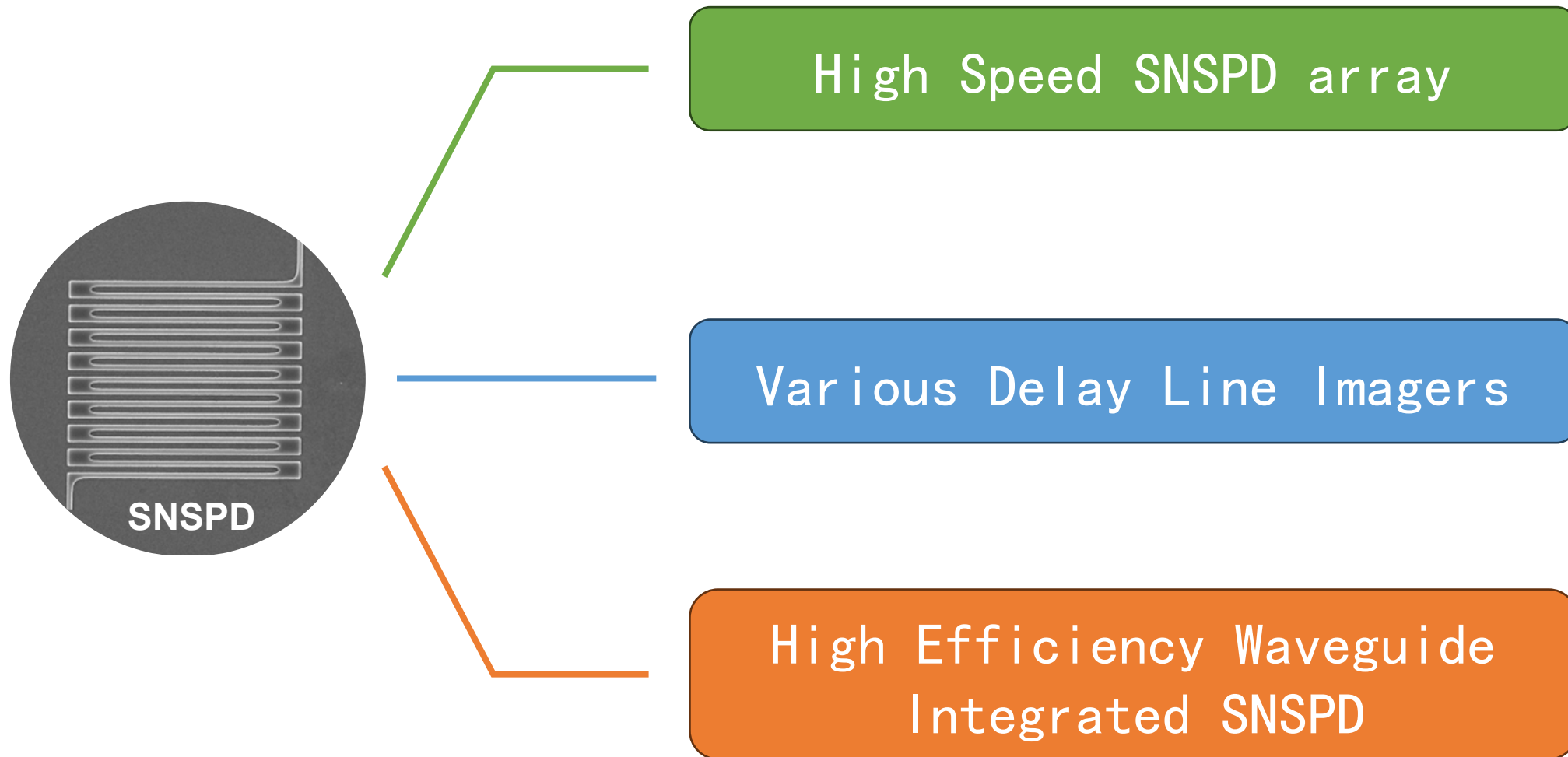
Quantum
Computation



Space
Telescope

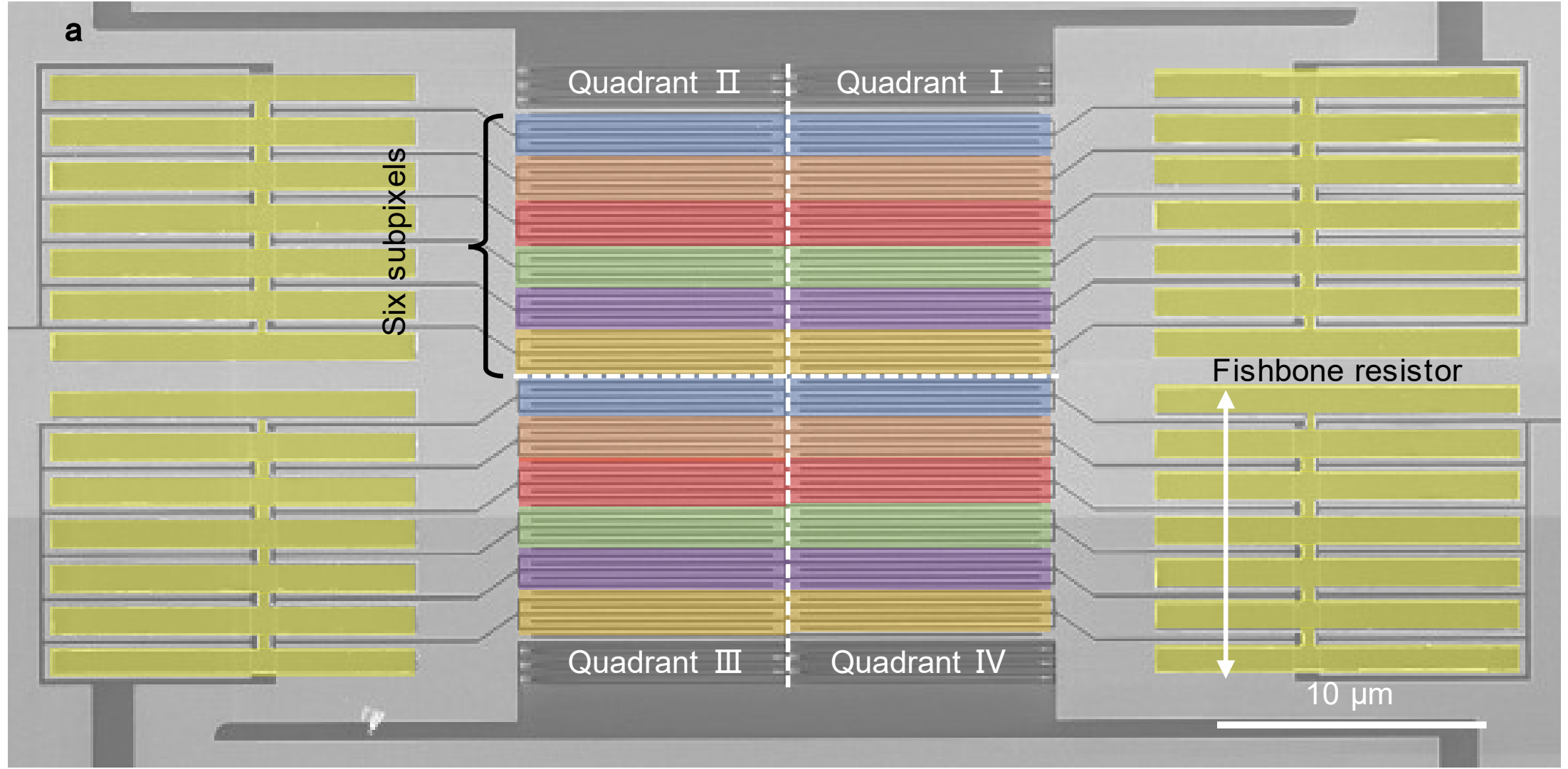


Outline





Four Quadrant Serial Nanowire Array

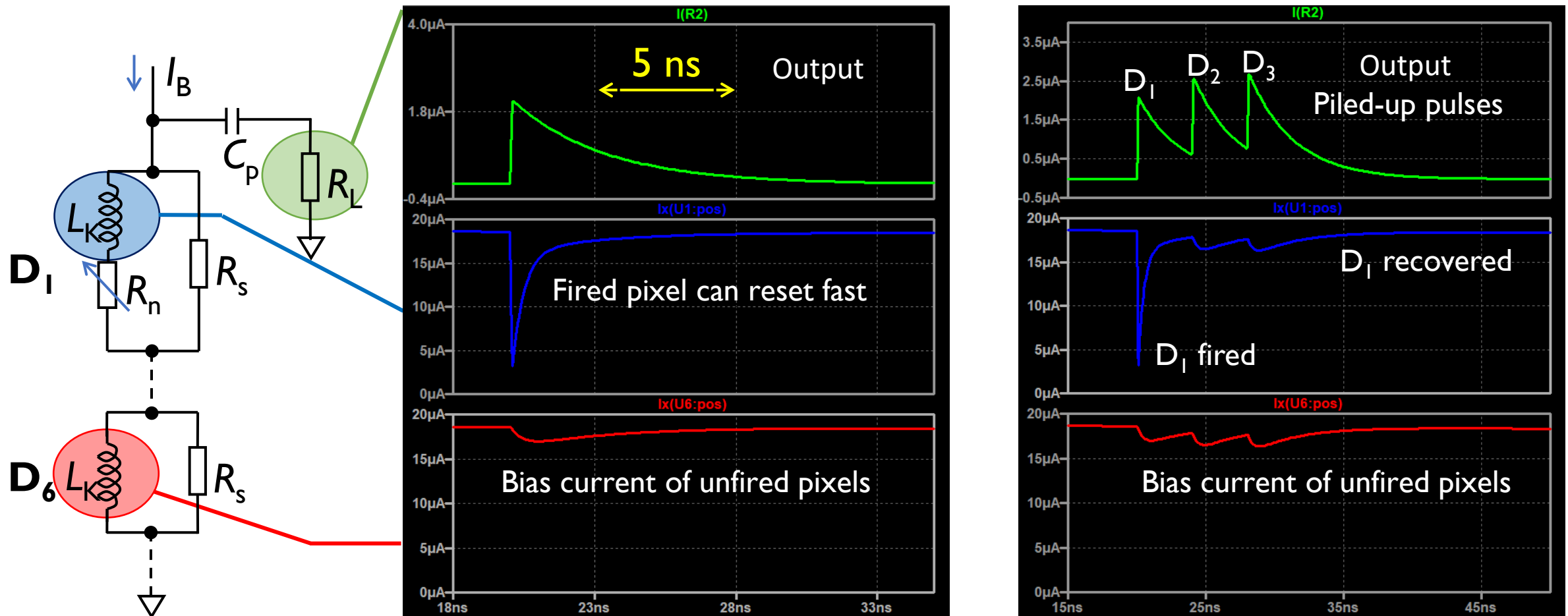


Light Sci. Appl. 13(1), 25 (2024).



Quasi-parallel counting in a serial nanowire architecture

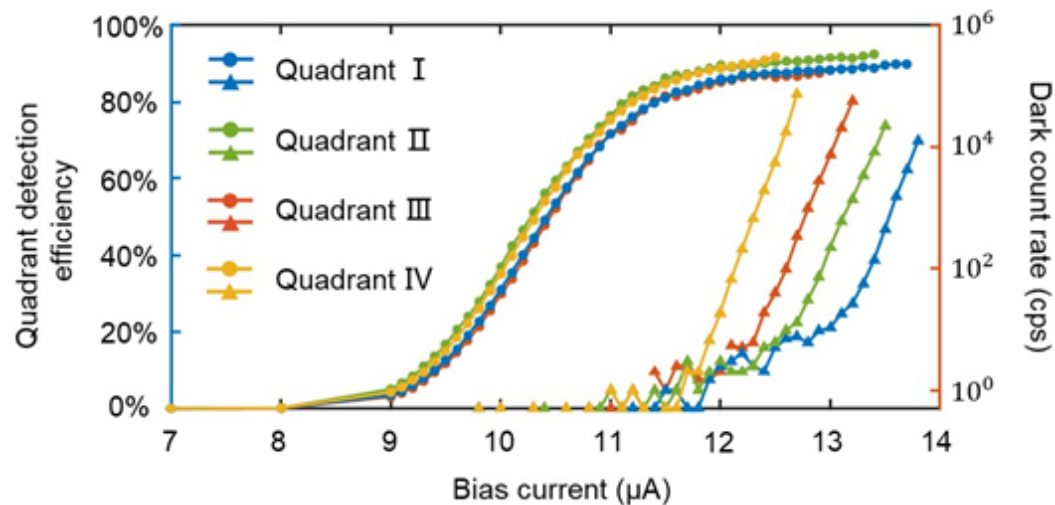
Single photon firing events will **NOT** affect the bias current of the unfired pixels.



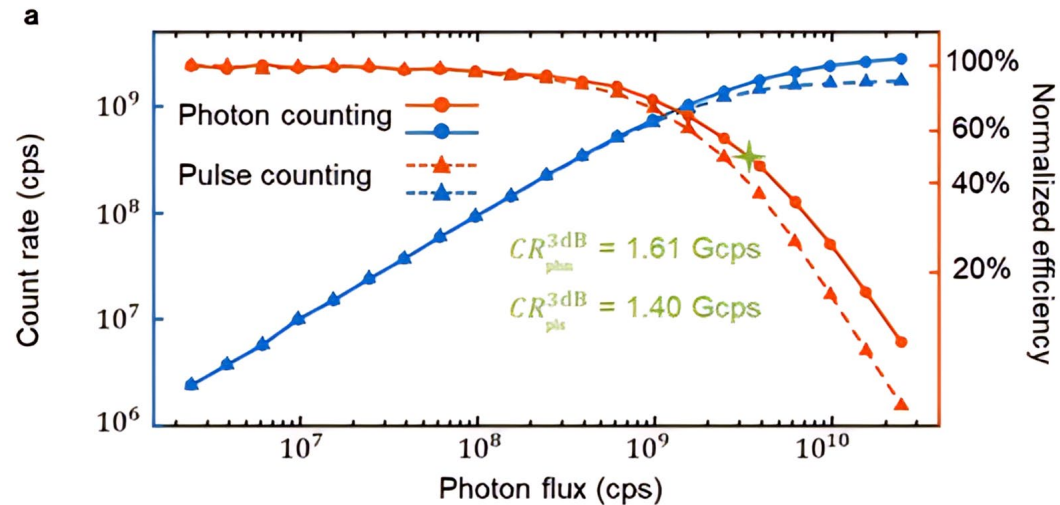


High-efficiency and high counting rate

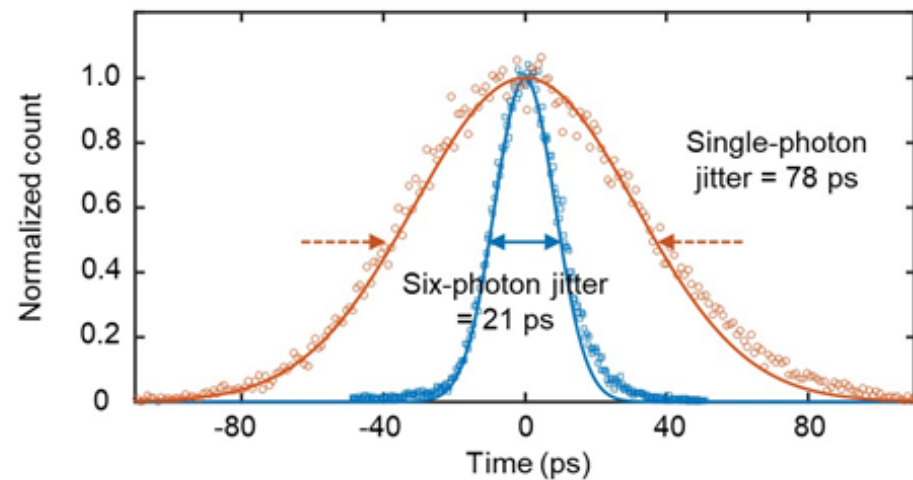
DE: >90%



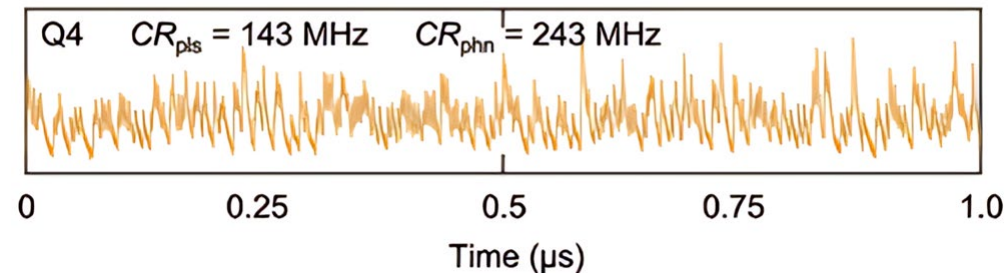
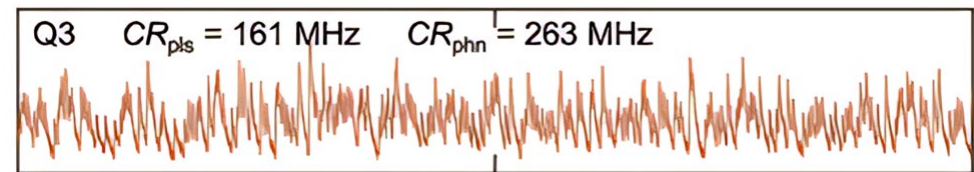
Counting rate: 1.6 G ph./sec @ 45% DE



Jitter: 21ps~78ps



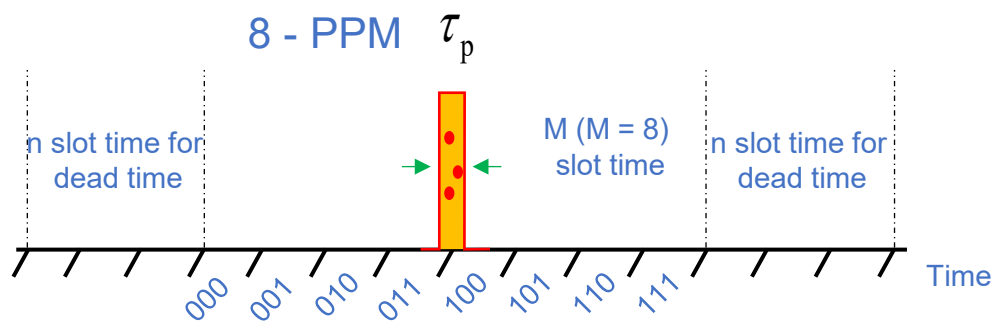
Examples of fast counting pulses





Single-photon optical communication characterizations

Pulse Position Modulation Format + 1/2 rate SCPPM FEC



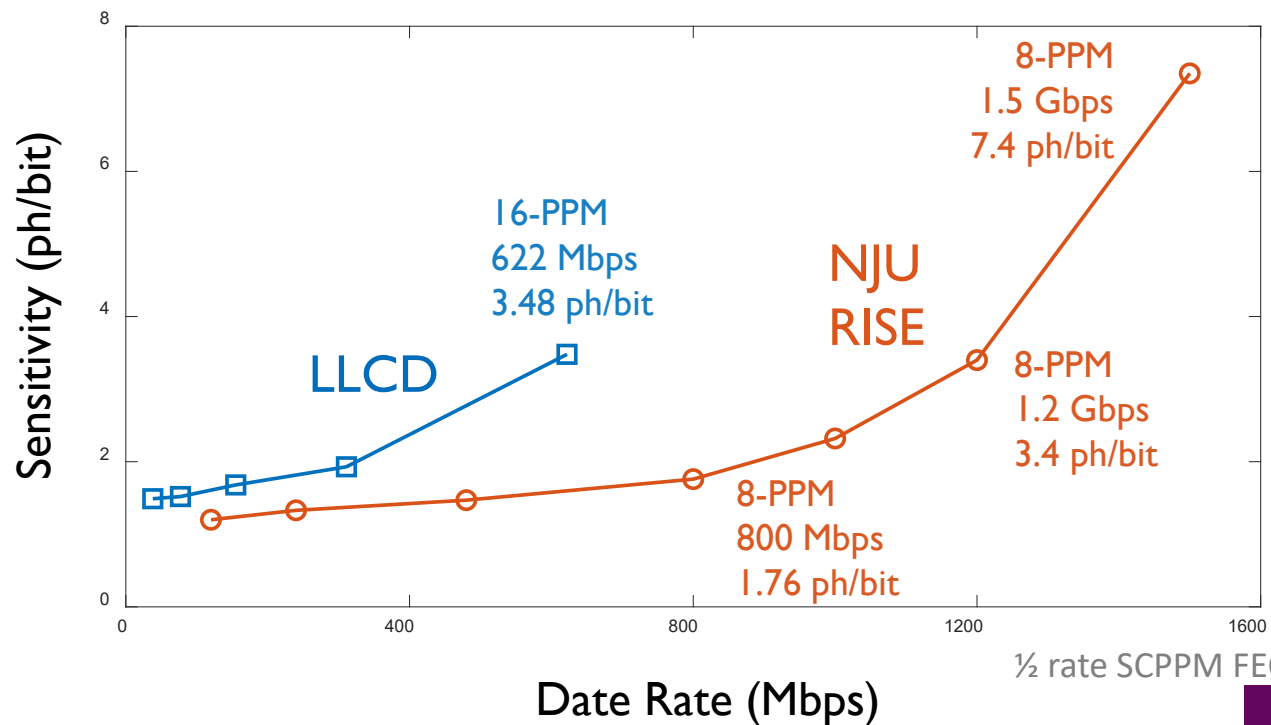
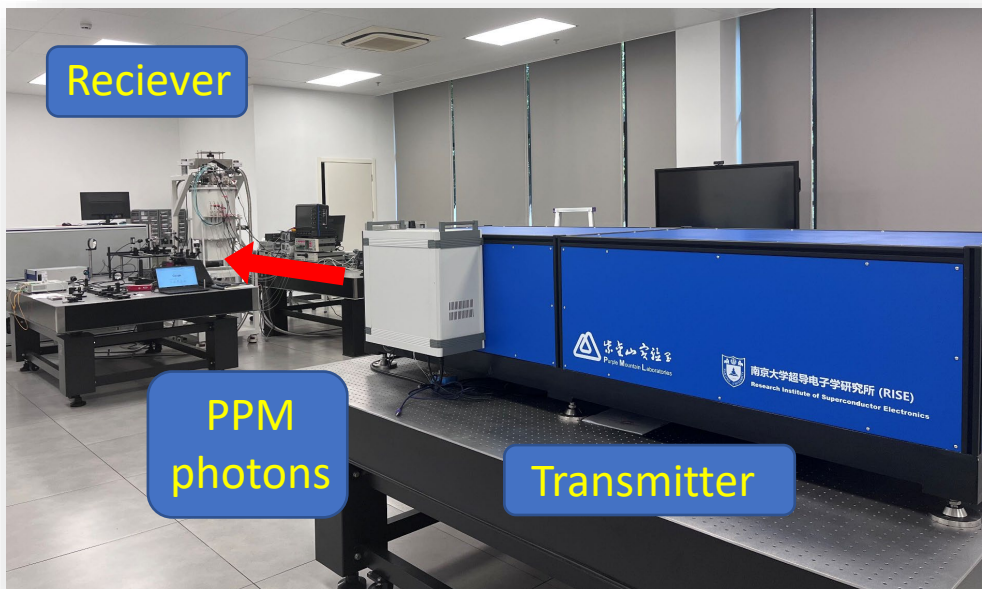
1.5 Gbps

3.4 ph./bit

Maximum Data Rate

sensitivity@1.2 Gbps

Free-space optical communication testbed

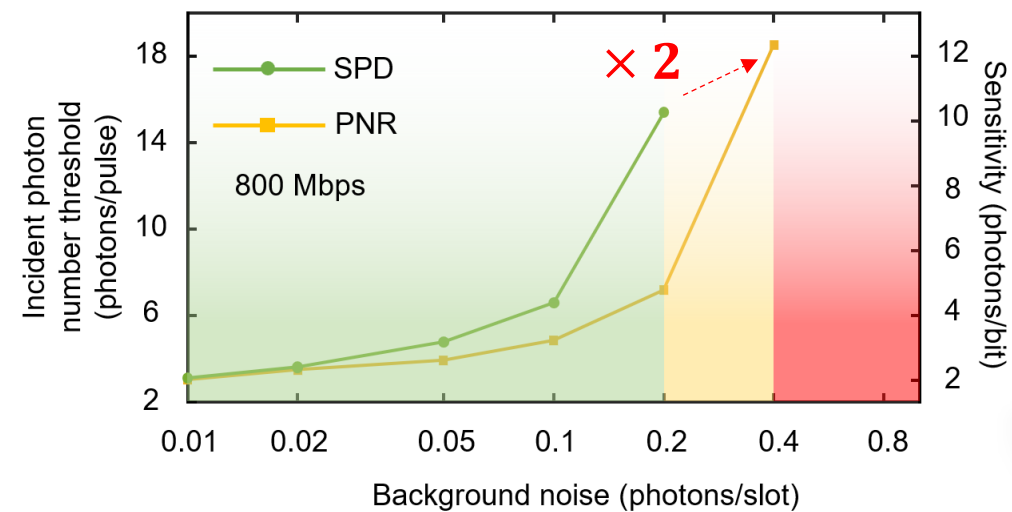
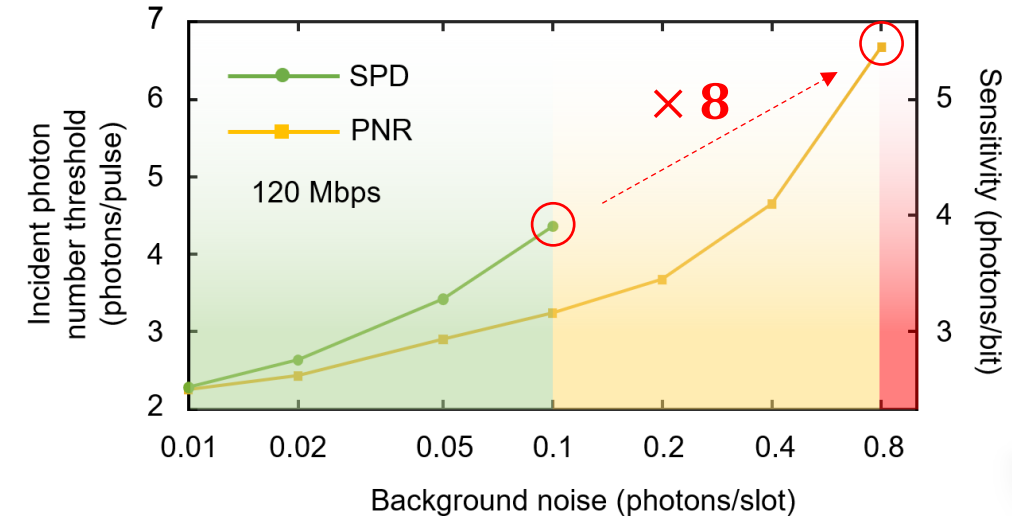
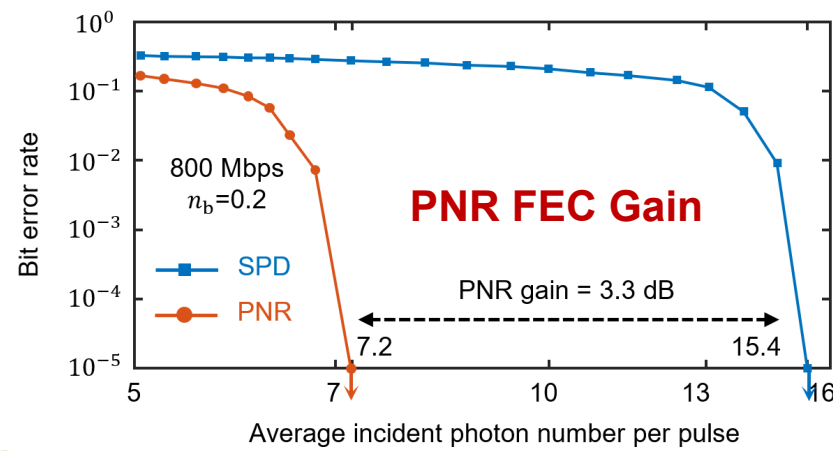
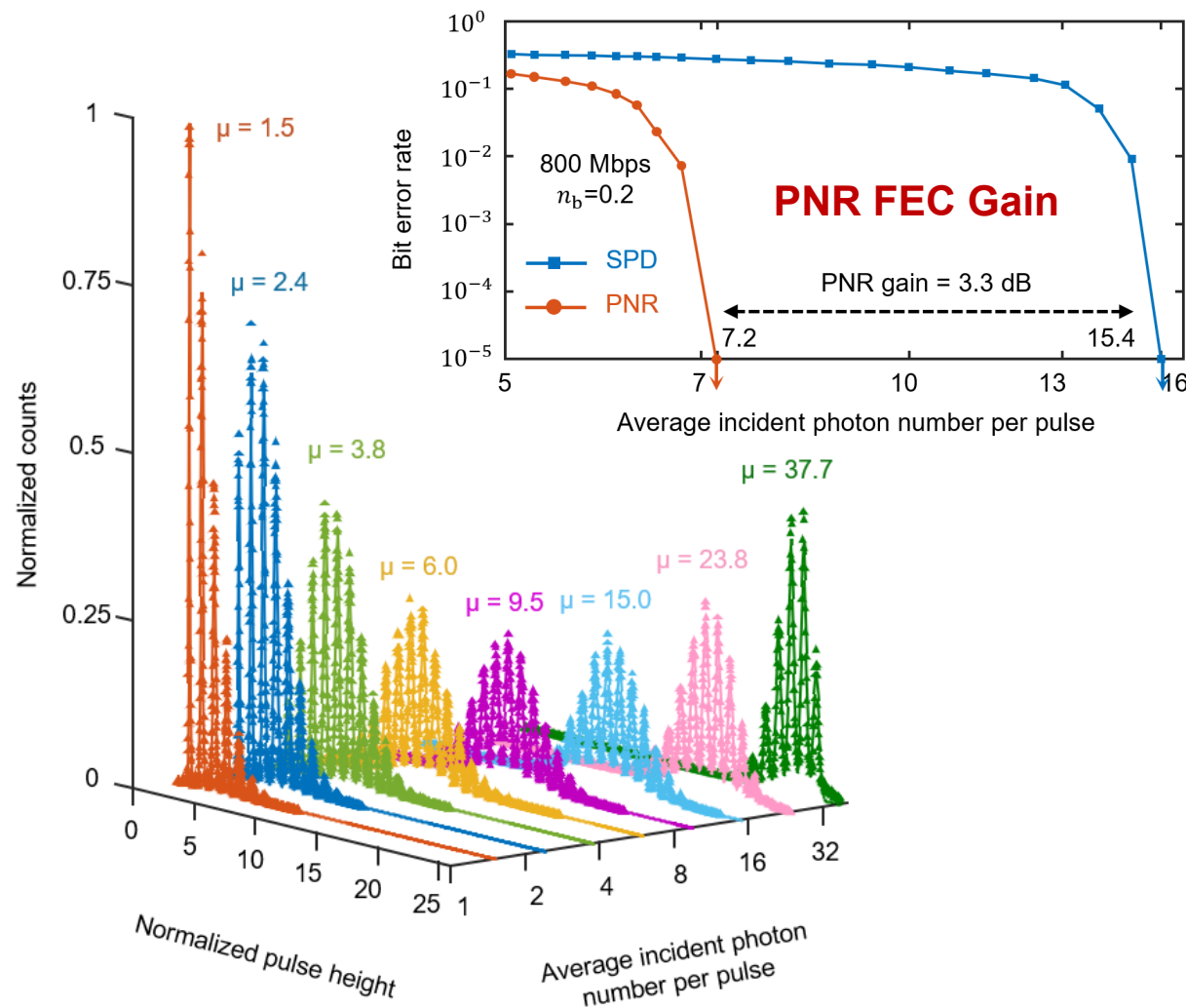




Tolerant to strong background noise for daytime communication

Maximum Photon Number Resolving Capability

$4 \times 6 = 24$ photons



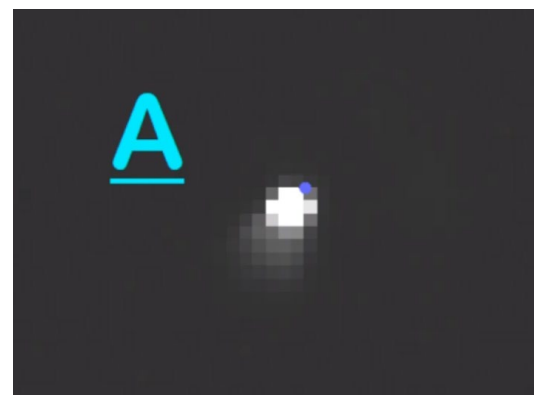
Beam spot tracking

Four-quadrant positioning under photon-counting mode

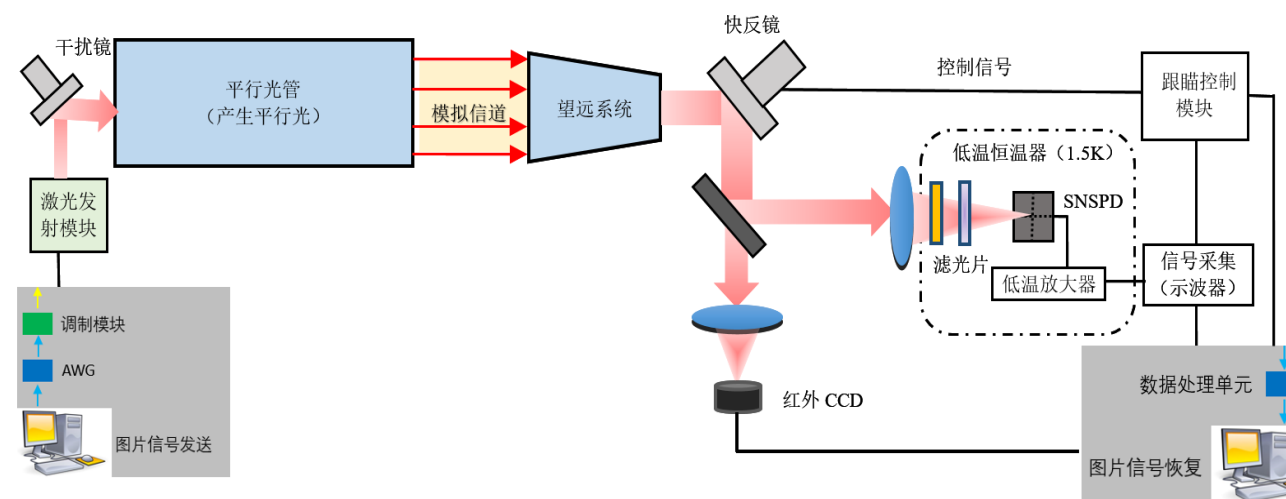
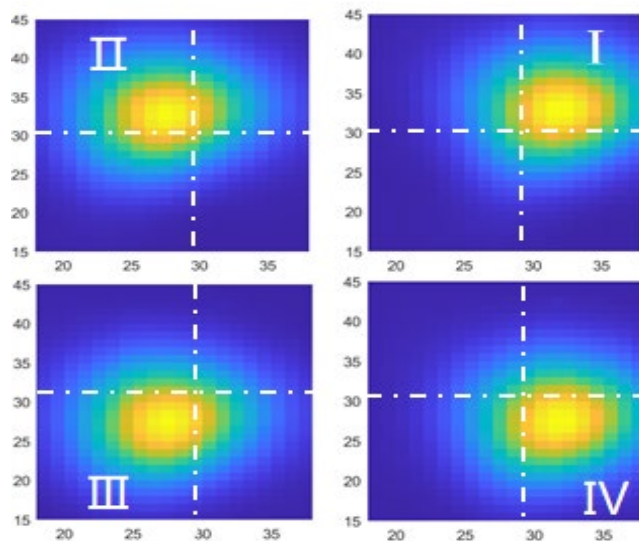
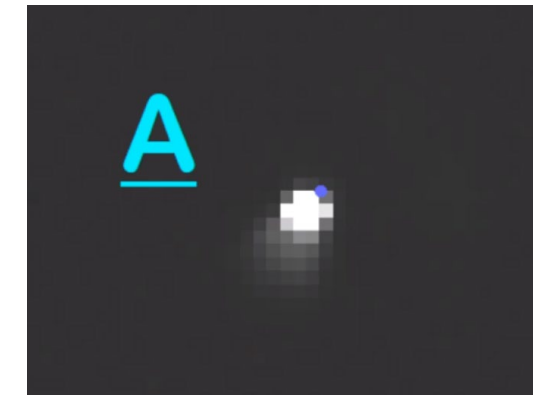
$$\Delta x = \frac{S_A + S_B - S_C - S_D}{S_A + S_B + S_C + S_D}$$

$$\Delta y = \frac{S_A + S_C - S_B - S_D}{S_A + S_B + S_C + S_D}$$

Tracking **OFF**



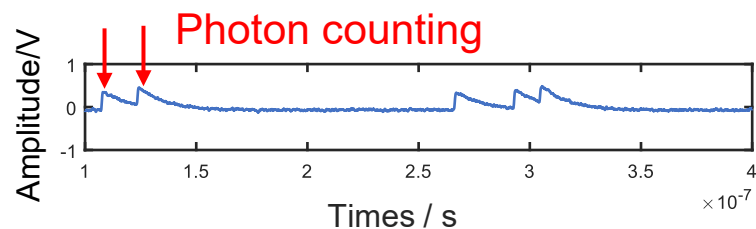
Tracking **ON**





High dynamic detection and imaging

Low Flux – Photon Counting

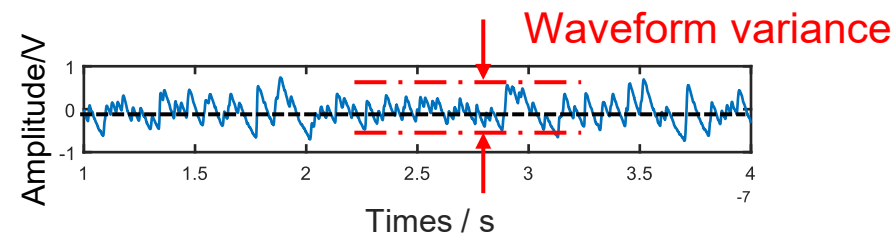


DE $\eta(t) = \frac{1}{1 + e^{-[I_b(1 - (e^{-t/\tau} - e^{-t/\tau_r})) - s]}}$

Reset time $\tau_\eta = -\tau \ln \left[1 - \frac{\ln 4 + s}{I_b} \right]$

PCFE: $\hat{\Phi} = \frac{N}{Q_s(T - N\tau_\eta)}$

High flux – waveform variance



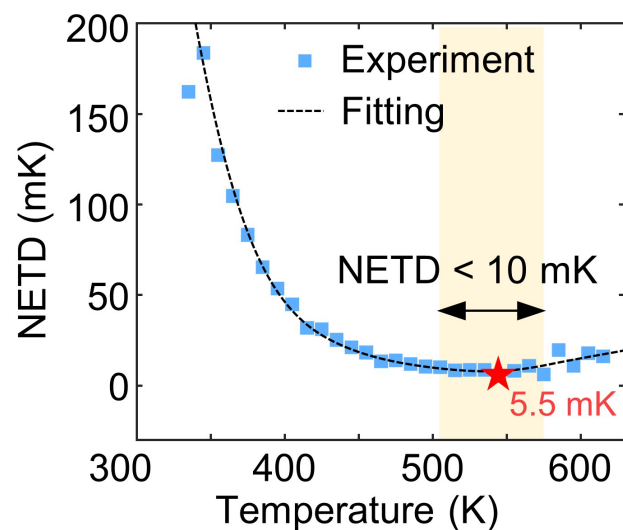
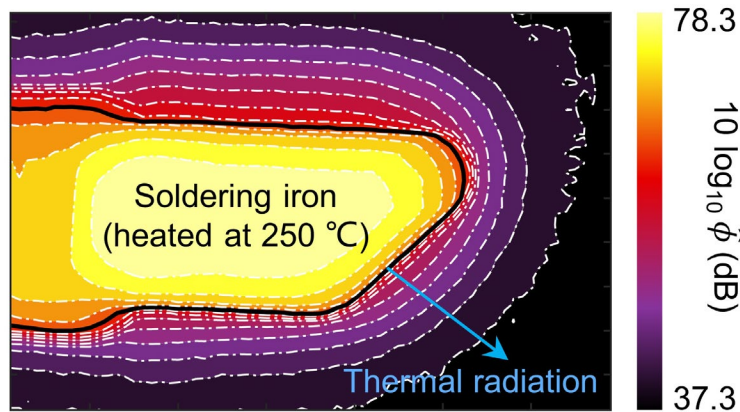
Waveform $V(t) = \sum_{i=1}^N A e^{(t-t_i(\phi))/\tau} + E \quad t_i \in [0, T]$

Variance $D = \frac{1}{B} \sum_{j=1}^B \left(\sum_{i=1}^N A e^{\frac{(t_j - t_i(\phi))}{\tau}} + E_j - \bar{V} \right)^2$

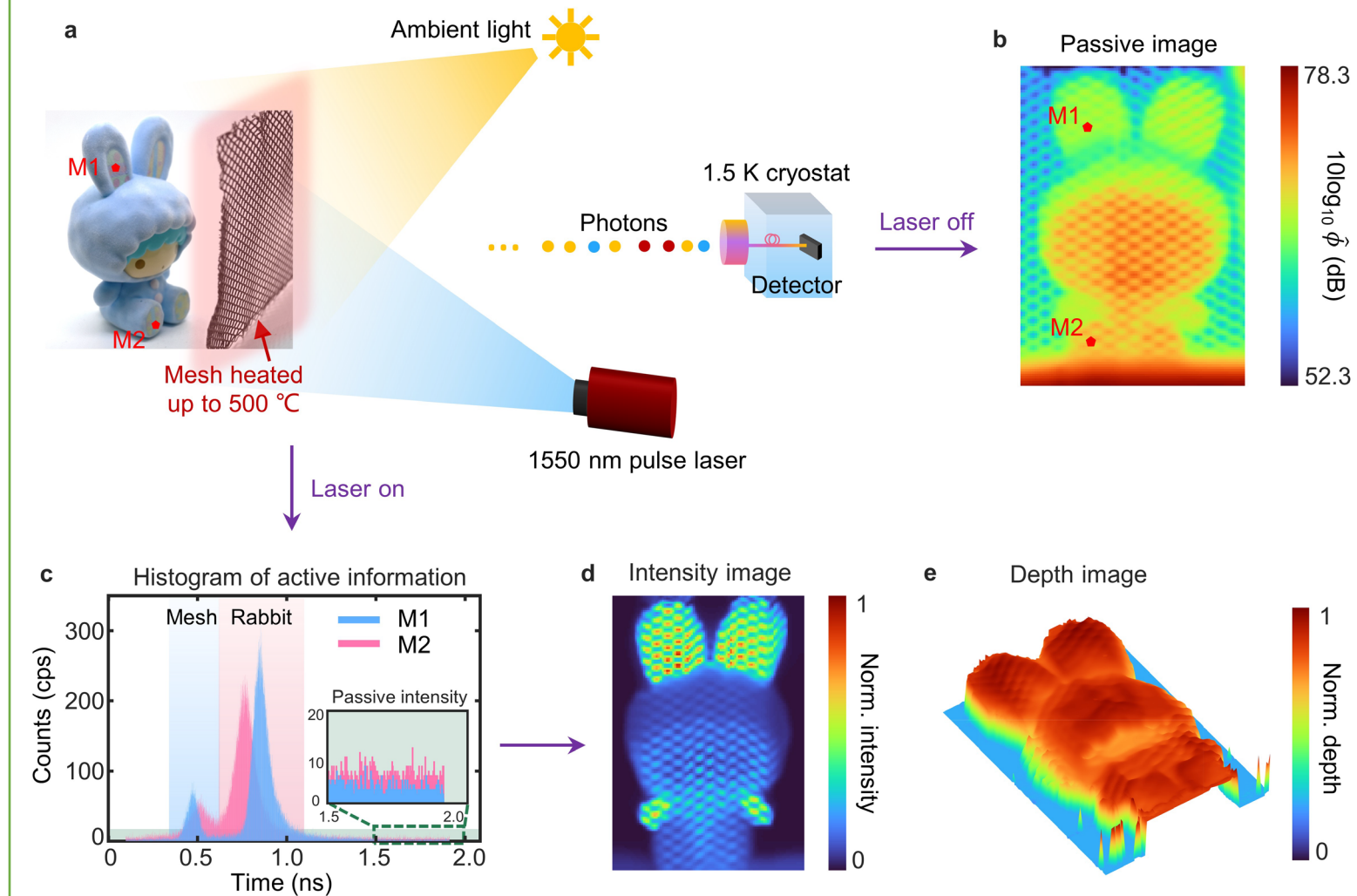
WVFE: $\hat{\Phi} = \frac{\sigma^2}{Q_s \left(\frac{\sigma^2}{f^{-1}(\sigma^2)} T - \sigma^2 \tau_\eta \right)}$

Demonstrations of high dynamic imaging

Passive Thermal Imaging

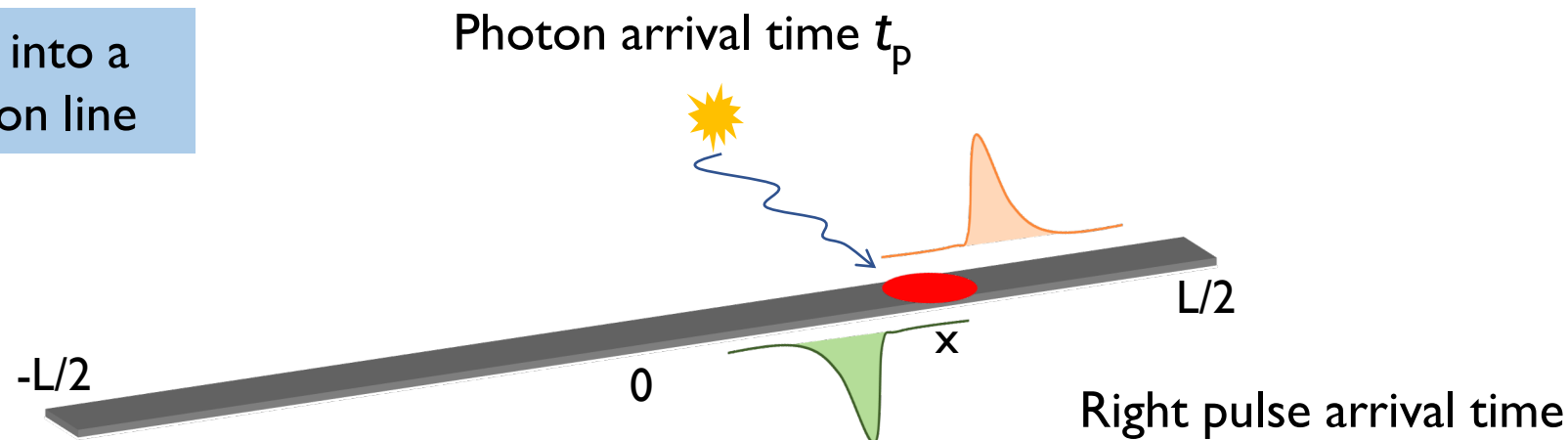


Passive and Active Imaging



Superconducting nanowire delay line imager

Design the nanowire into a slow-wave transmission line



Left pulse arrival time

$$t_L = t_p + (L/2+x)/v$$

$$t_R = t_p + (L/2-x)/v$$

Location: $x = (t_L - t_R)v/2$

differential time

time: $t_p = (t_L + t_R - L/v)/2$

sum time

A simultaneous readout for both photon location and time!

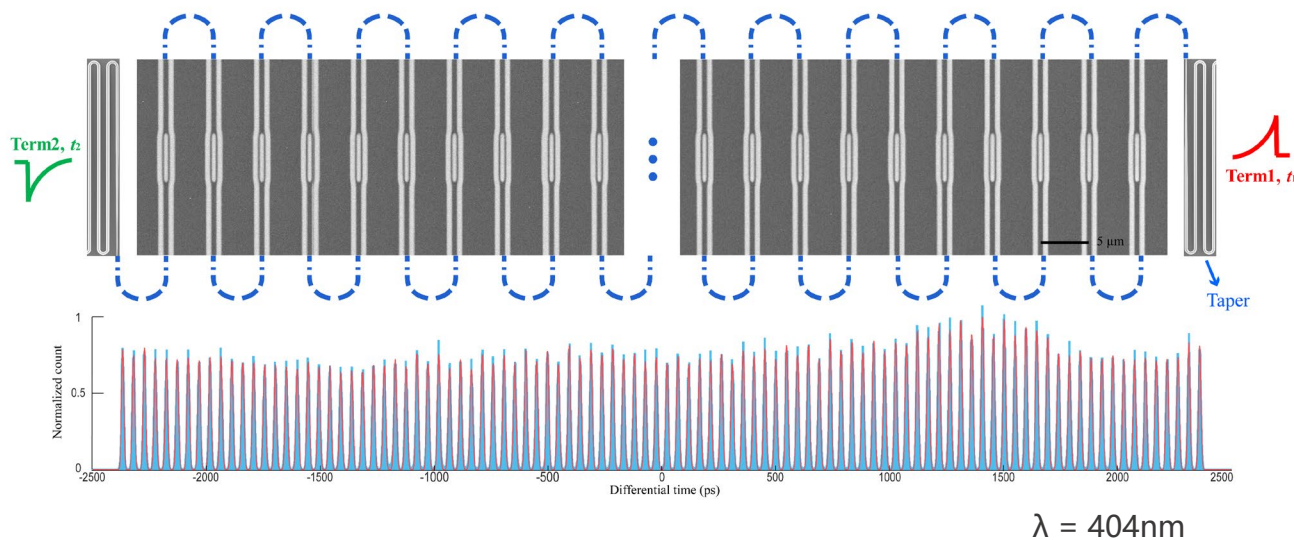
*Similar to MCP Delay line anode readout method.

Q.-Y. Zhao, ... K.K. Berggren et al.,
Nat. Photonics, 2017.



Scale up to various arrays

1D linear array 1×100

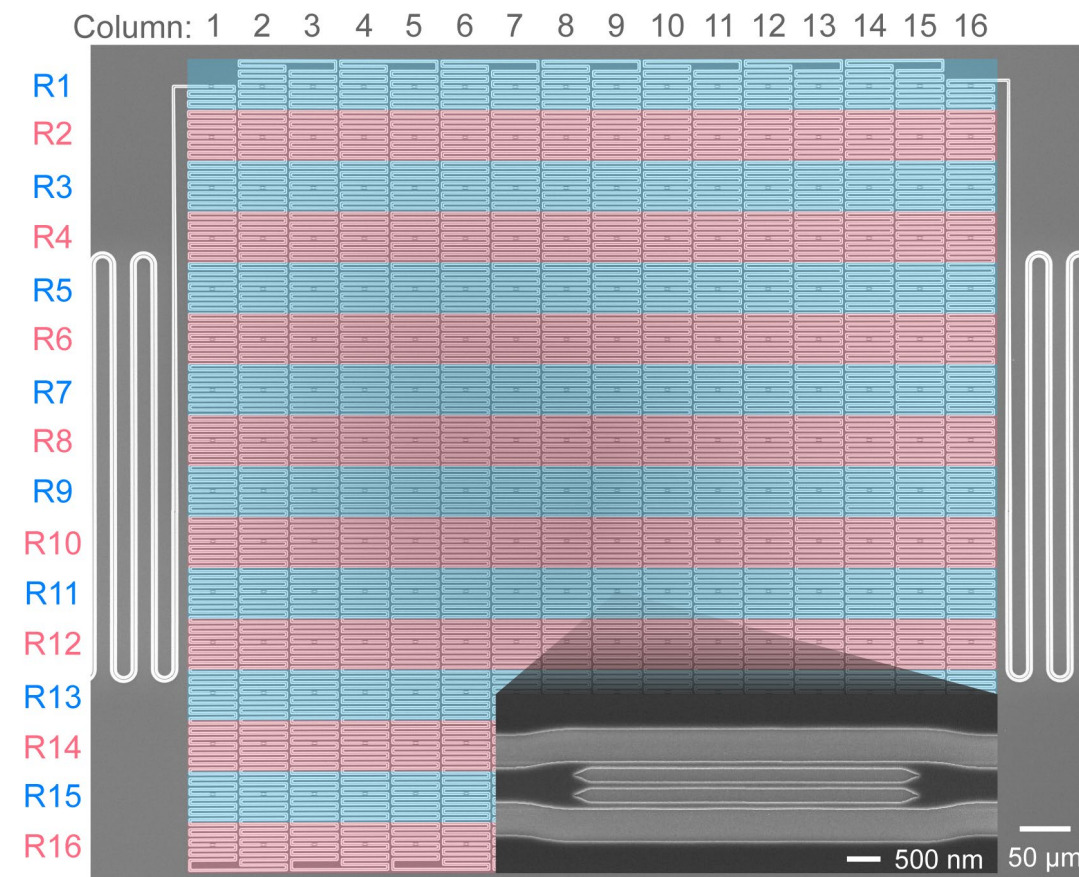


- Higher spatial resolution in 1D linear array
- Less crosstalk in 2D array

Limitation
in 2D array

1. Limited Spatial resolution
2. Low filling factor

2D array 16×16

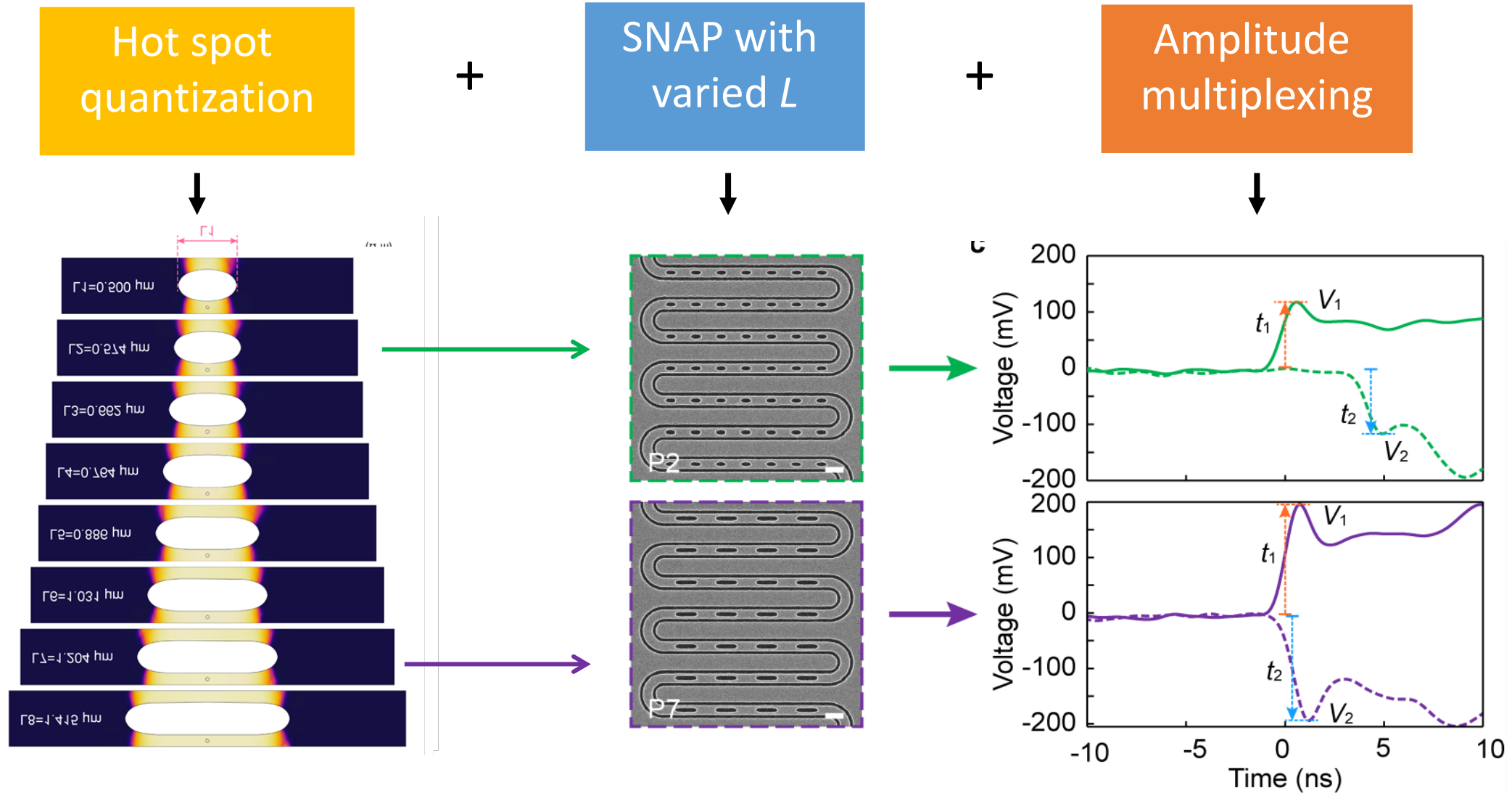


H. Wang, et. al., Opt. Lett. **47**(14), 3523 (2022).

L. Kong, et. al., Opt. Lett. **45**(24), 6732 (2020).



Orthogonal time–amplitude multiplexing array

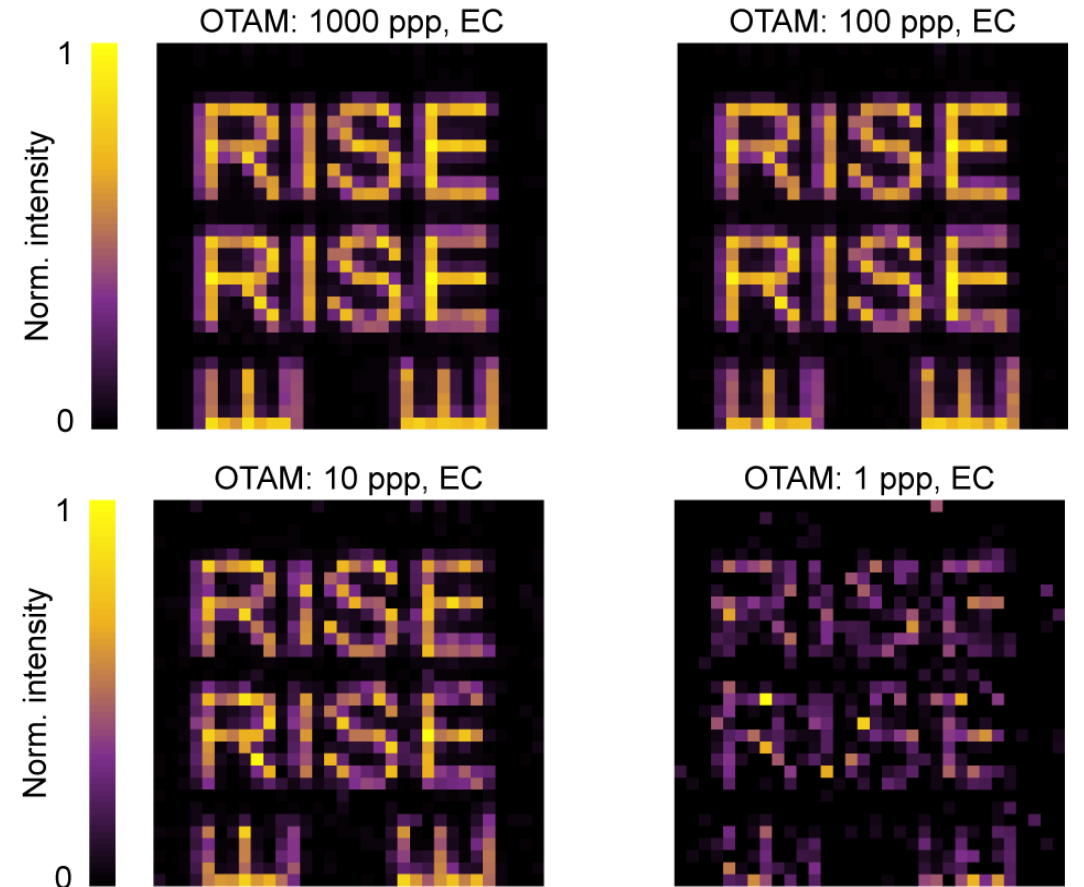
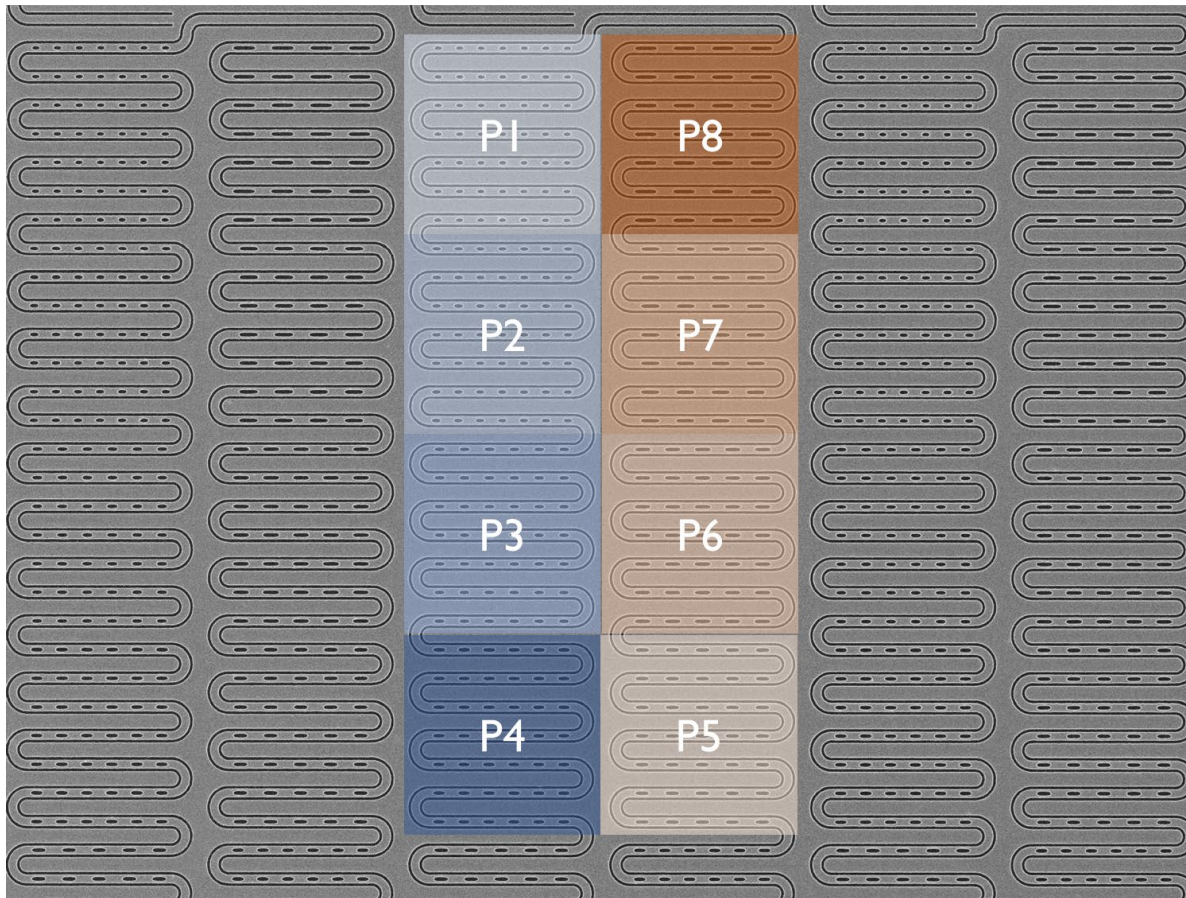


L. Kong, et.al., Nat. Photonics **17**(1), 65–72 (2023).

Orthogonal time–amplitude multiplexing array

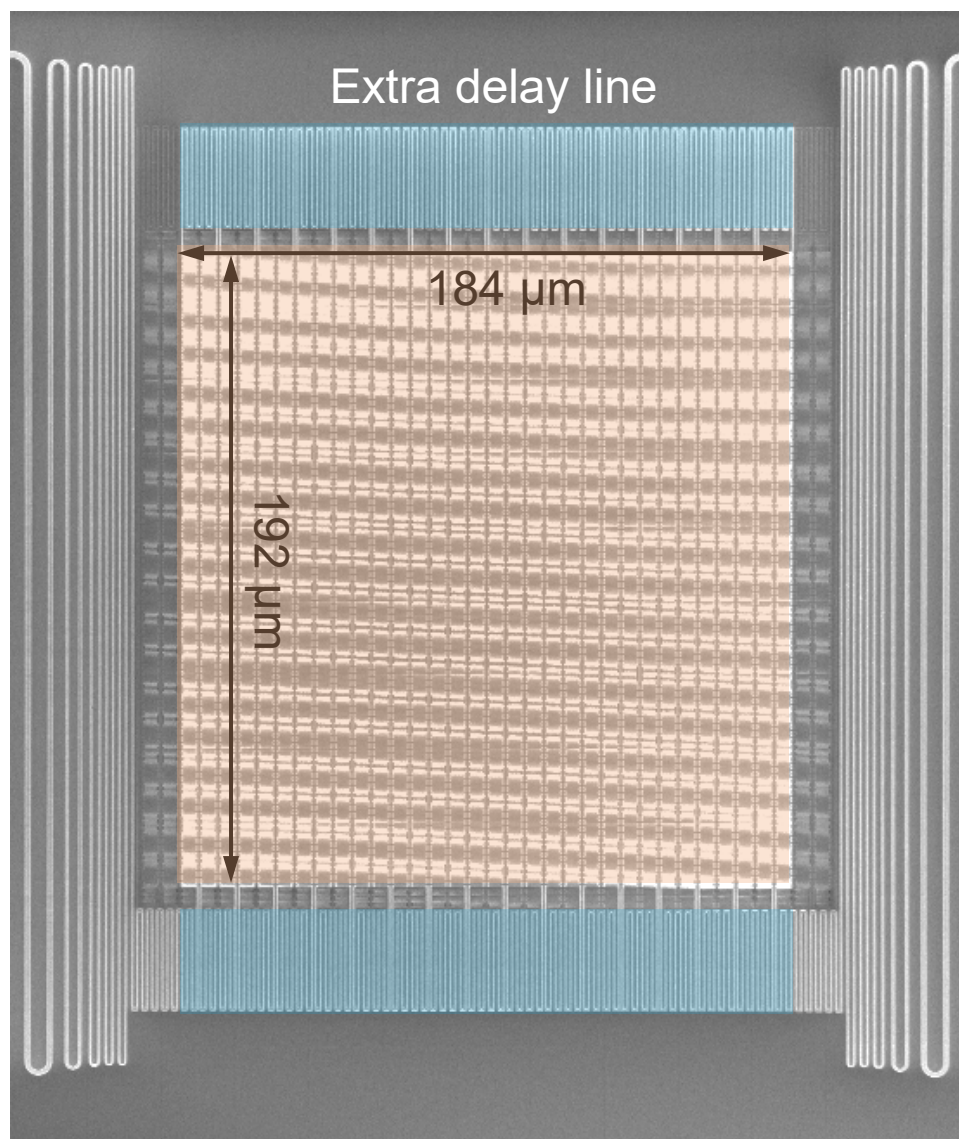
Nearby pixels: Amplitude multiplexing (Hotspot quantization)

Distant pixels: Time multiplexing (Delay line)

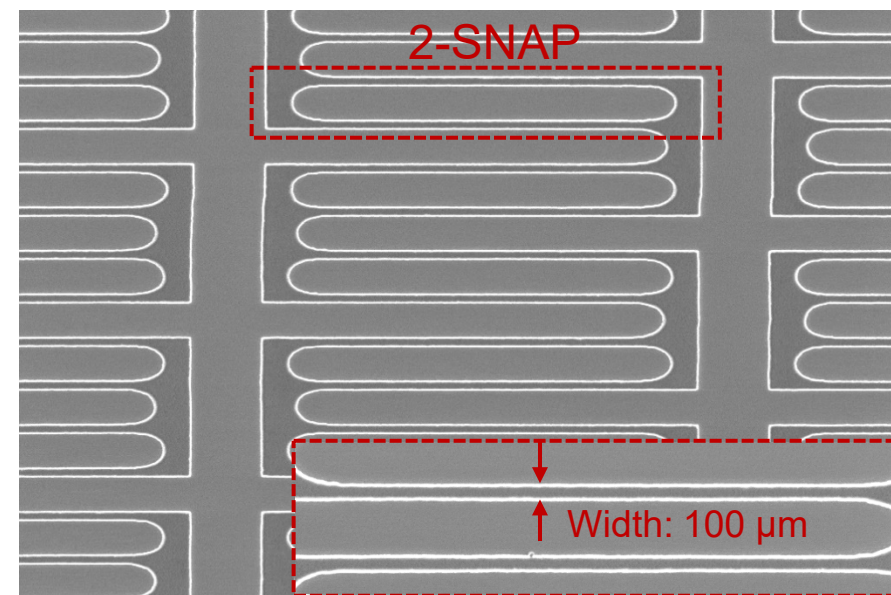


L. Kong, et.al., Nat. Photonics **17**(1), 65–72 (2023).

High-Efficiency Kilopixel Imager at 1550 nm



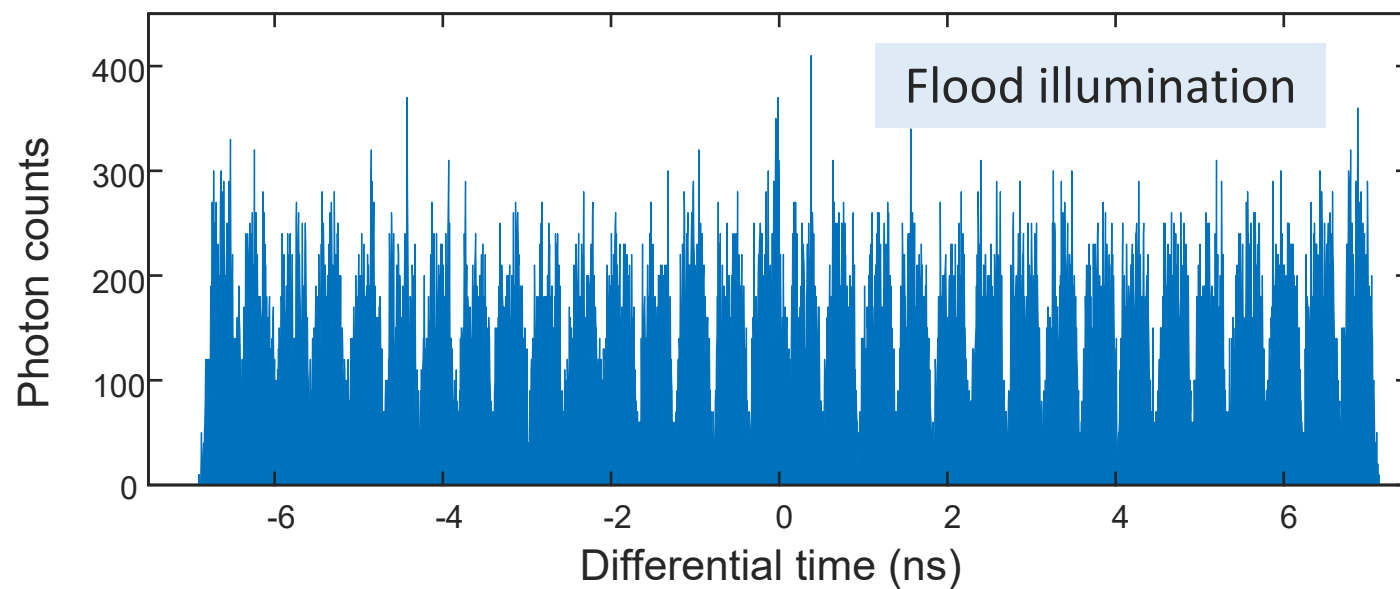
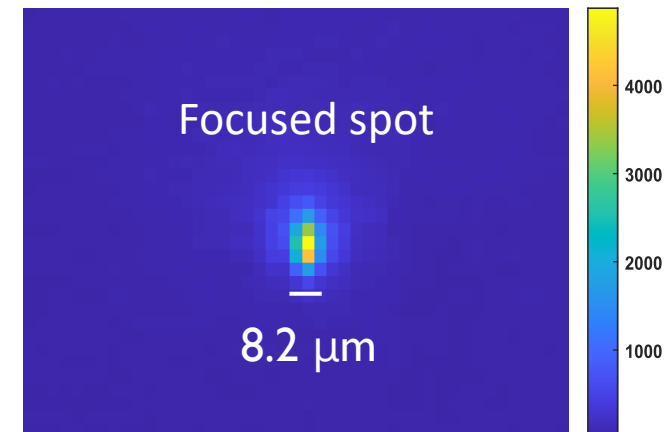
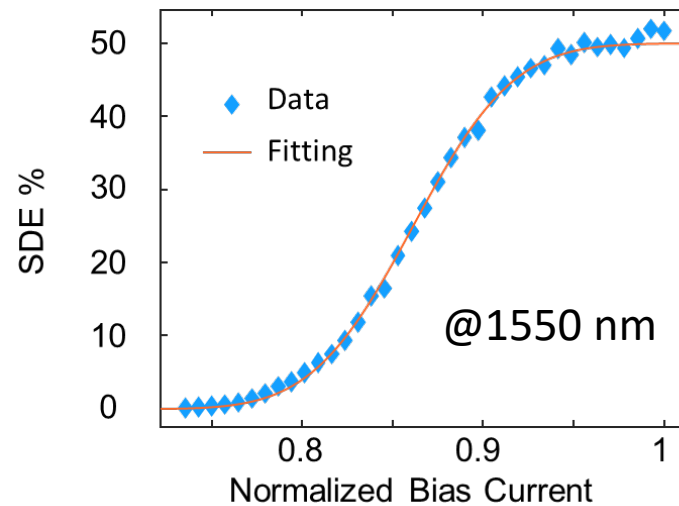
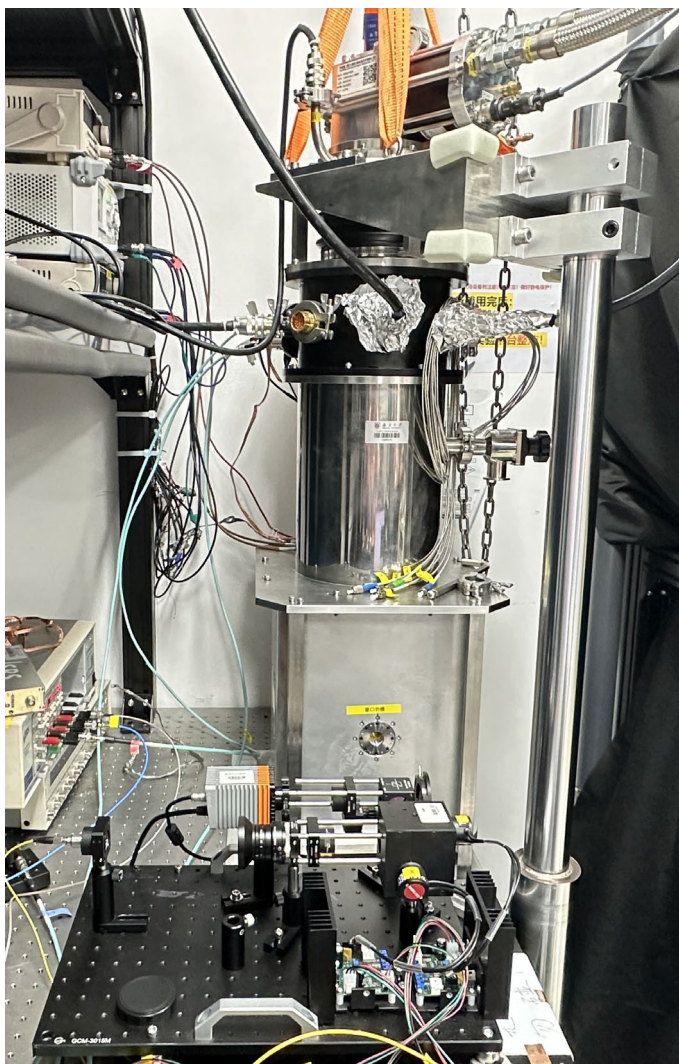
- Low Tc material: WSi6 for enhanced QE
- Microstrip transmission line + Optical Cavity
- Operate at 1 K



- Effective Area: 184 μm \times 192 μm
- Vertical Resolution: 4.8 μm (~40 pixels)
- Horizontal Resolution: 5.8 μm (~32 pixels)

High-Efficiency Kilopixel Imager at 1550 nm

Free space imaging 1K system





Single-photon event camera

CMOS

Conventional integral sampling

Frame determined by row-column sequence

Pixel 1 Pixel 2 Pixel 3 Pixel 4 Pixel 5 Pixel 6 Pixel 7 Pixel 8 Pixel 9

Voltage

Time

White noise

Spot moves at 500 Hz

Short-wave infrared camera

SNSPI

Photon event counting

No fixed frame, random pulse train

Pixel 4 Pixel 7 Pixel 2 Pixel 9 Pixel 1 Pixel 8 Pixel 3 Pixel 5 Pixel 6

(x, y, t)

Background

Dark Count

Background

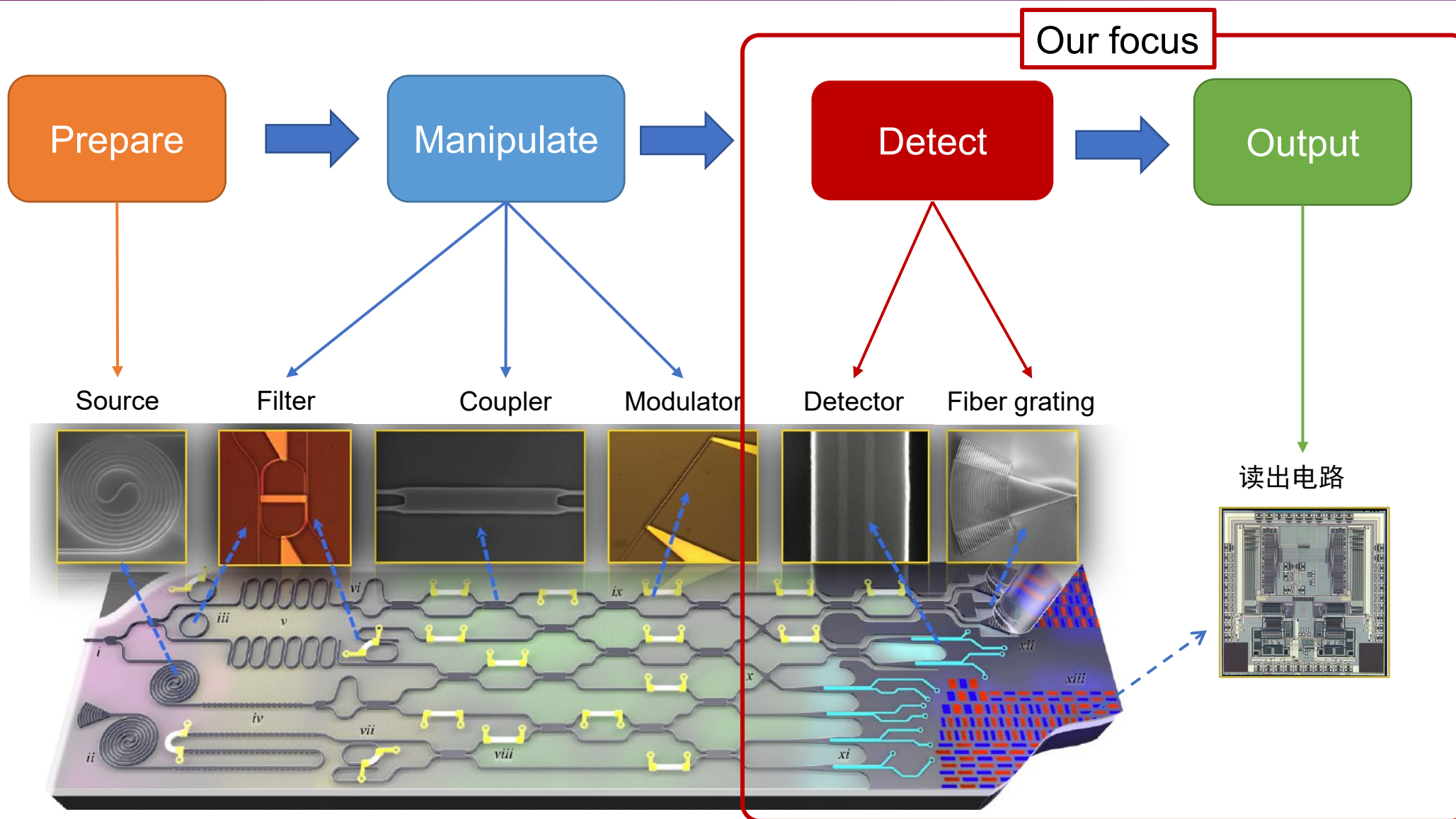
Dark count

Photon event synchronized, fast and low latency!

SNSPI event camera

Every frame = 200 photons

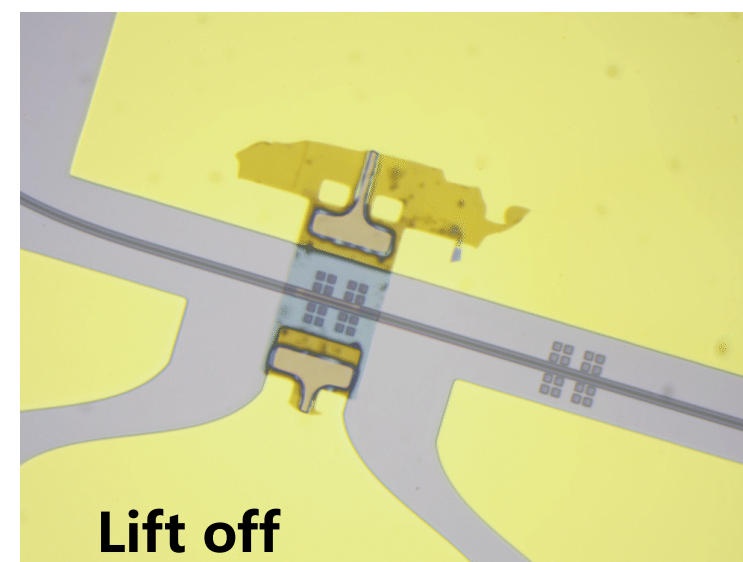
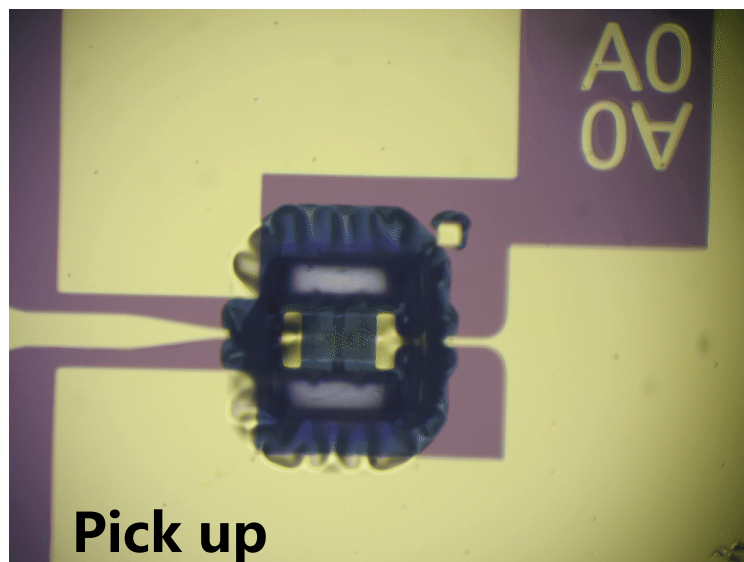
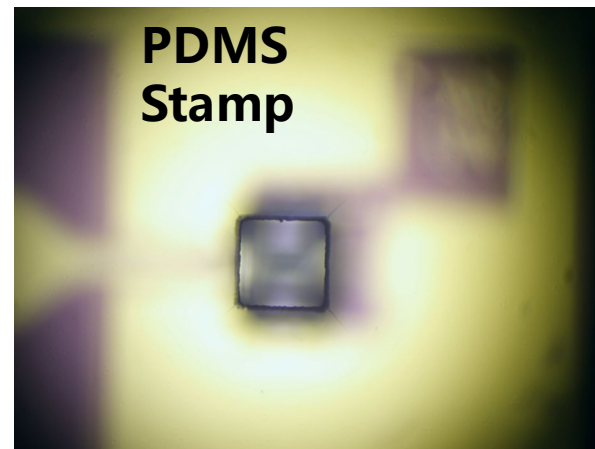
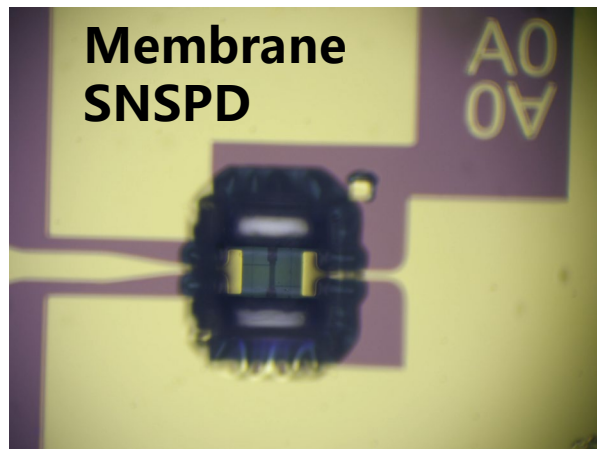
Hybrid integration quantum photonic circuits



J.W. Silverstone, et. al., IEEE J. Sel. Top. Quantum Electron. **22**, 390 (2016).

A. W. Elshaari, et. al., Nat. Photonics **14**(5), 285–298 (2020).

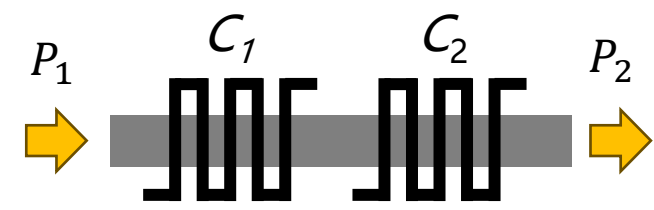
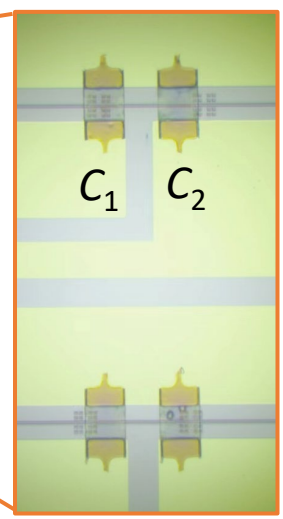
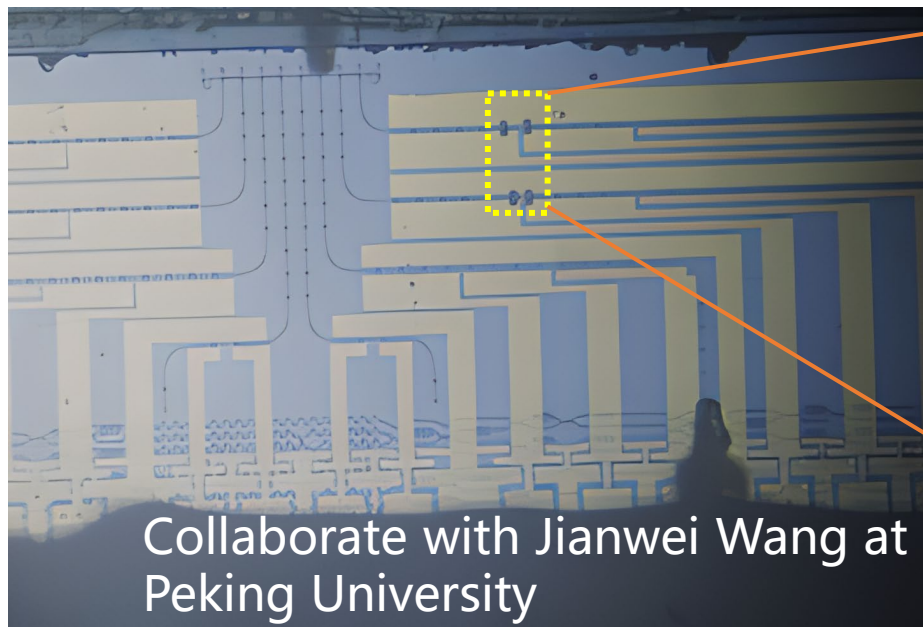
Hybrid integrated SNSPD on waveguides



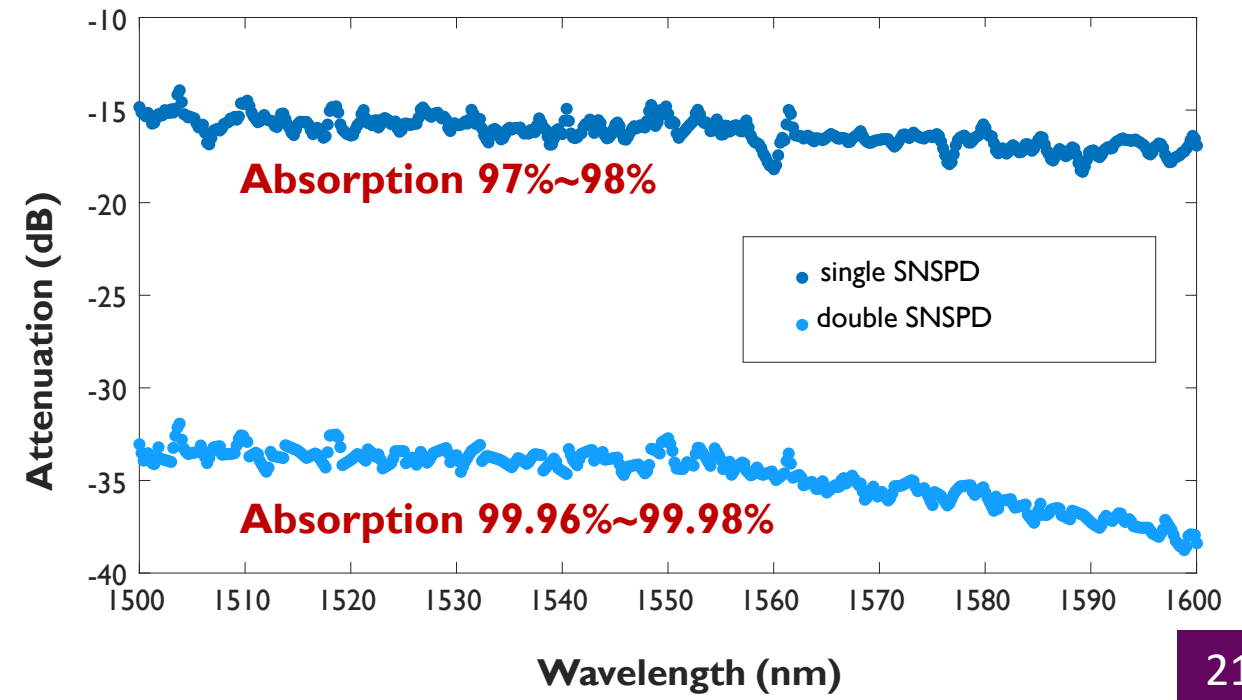
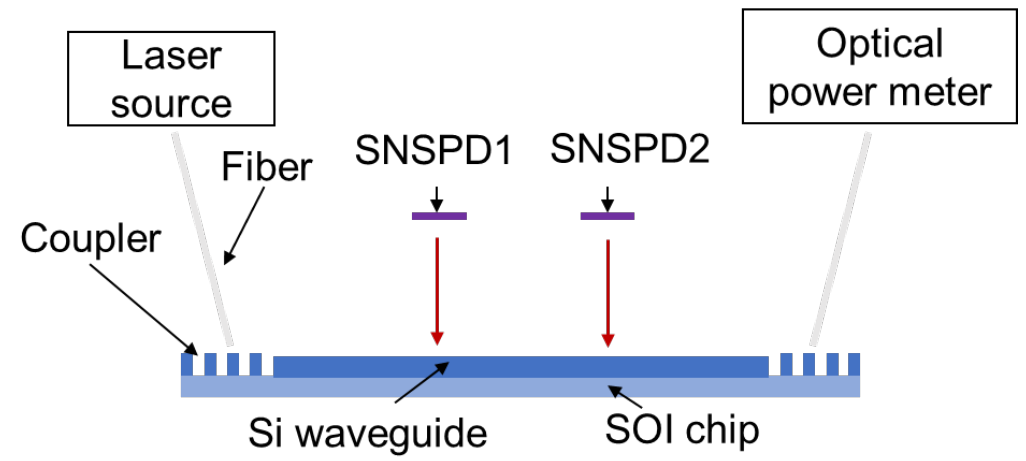
*Hybrid integration was first demonstrated by F. Najafi, et.al., Nat. Commun. 6, (2015).



>99% on Si waveguide detection efficiency



Single ODE: 98%
 Double ODE: 99.96%



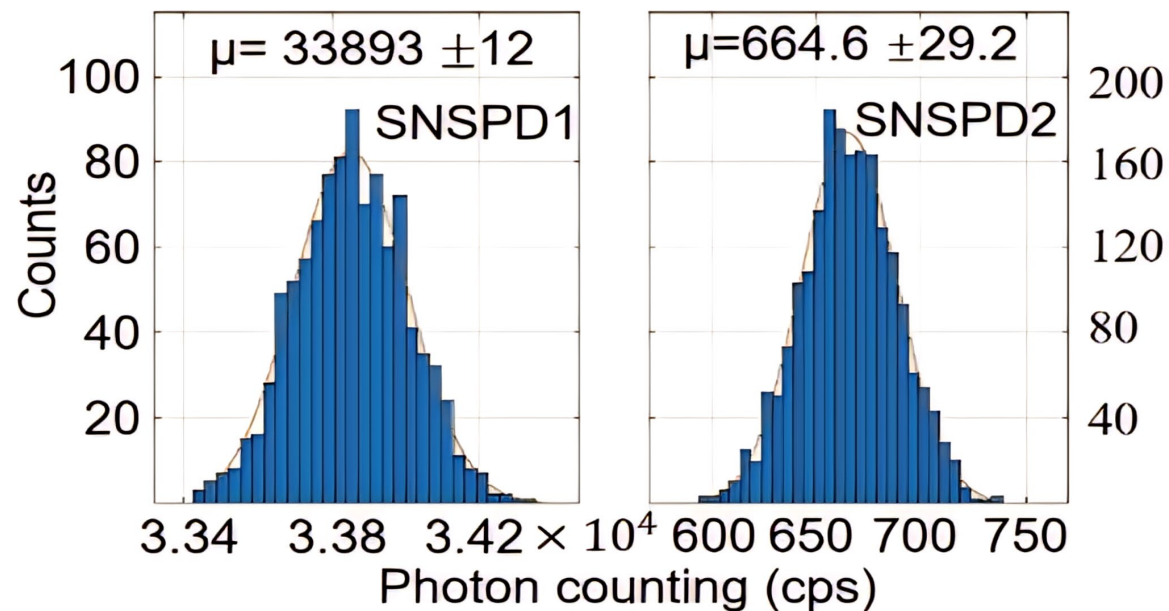
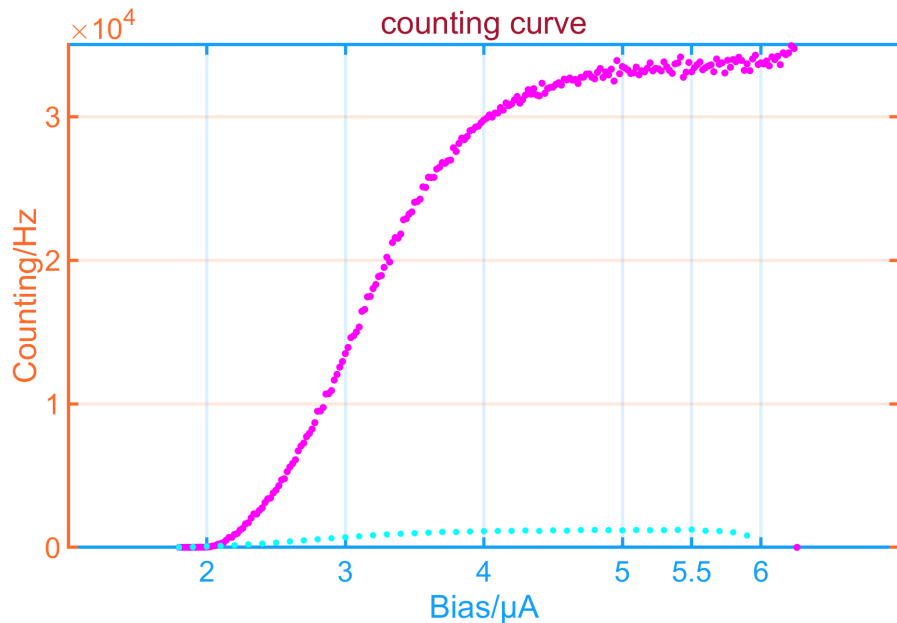


>99% on Si waveguide detection efficiency

$$ODE = \left(1 - \frac{C_2 \times QE_1}{C_1 \times QE_2}\right) \times QE_1$$

Other losses: Reflection $\approx 0.2\%$, and waveguide loss

$$DE = (1 - 0.2\%) \cdot 99.92\% = 99.72\%$$



Detection coincidence of
100 photons

$$98\%^{100} = 13.26\%$$

$$99.72\%^{100} = 75.54\%$$

Detection coincidence of
1000 photons

$$98\%^{1000} = 1.68e - 9$$

$$99.72\%^{1000} = 6\%$$

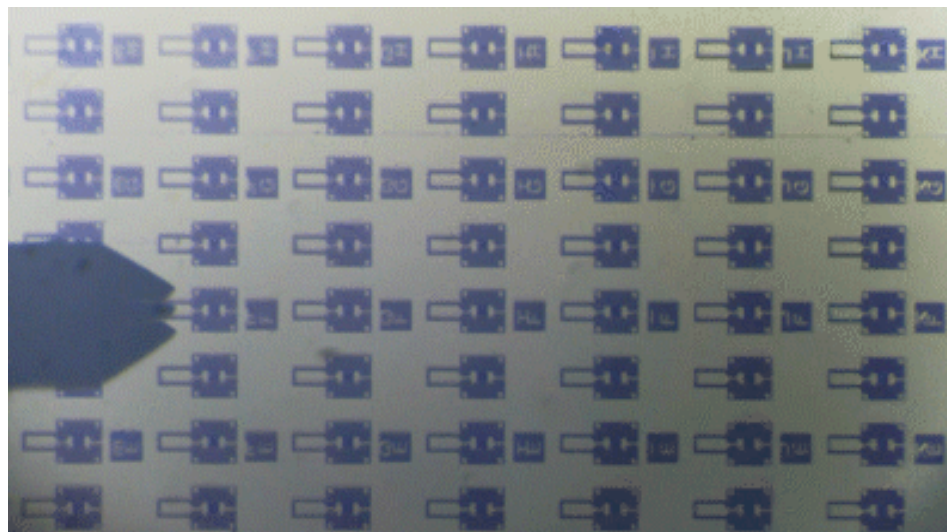


Large-scale chip production and automated testing



CPQ_Probe1K

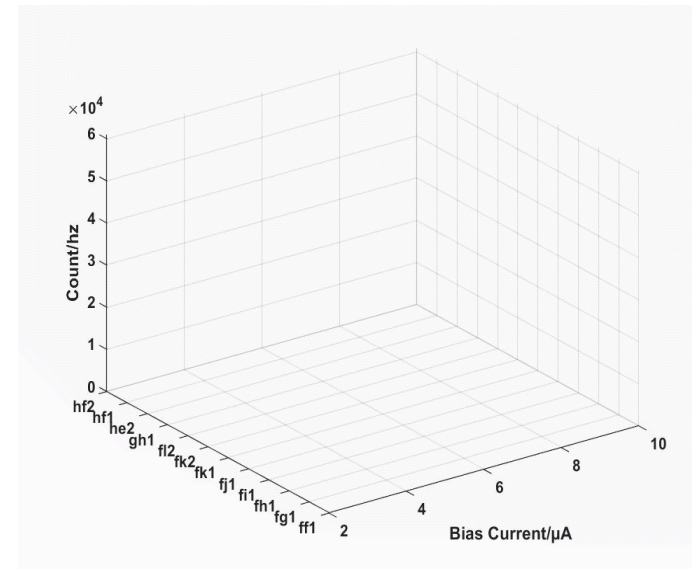
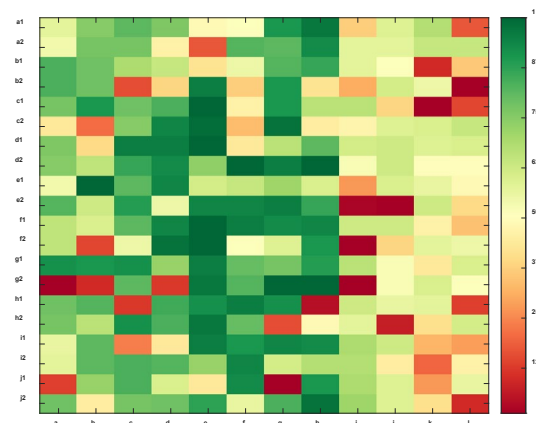
*与南京鹏力超低温联合研制



Probe Station

- Mininal temp.: **1.3 K**
- Vibration: **< 1 μm**
- Chip size: **20 mm \times 20 mm**
- Nanopositioner: **4 \times XYZ**

Switching current distribution



Total device	245
No response	26
Not saturated	37
Saturated	182
Yield	74.3%



More details are given in the posters...

2.4 Gbps laser communication based on a high-speed superconducting nanowire single photon detector array

Fan Yang¹, Hao Hao¹, Qing-Yuan Zhao^{1,2}, Jian Chen^{1,2}

Research Institute of Superconductor Electronics (RISE), School of Electronic Science and Engineering, Nanjing University, Nanjing, 210023, China

EDP1-11 I-S-S-2024

RISE Monolithic integrated superconducting nanowire digital encoder and its application in reading out a SNSPD array

Yanghui Huang^{1,2}, Qingyuan Zhao^{1,2*}

*Research Institute of Superconductor Electronics (RISE), School of Electronic Science and Engineering, Nanjing University, Nanjing, 210023, China

²Purple Mountain Laboratory, Nanjing 211111, China

DZ20230001@mail.nju.edu.cn

EDP1-5 I-S-S-2024

Locating Nanoscale Inhomogeneities in a Superconducting Nanowire by Probing and Mapping Self-Heating Hotspots

Zhen Liu^{1,2}, Qingyuan Zhao^{1,2}

¹Research Institute of Superconductor Electronics (RISE), School of Electronic Science and Engineering, Nanjing University, Nanjing, 210023, China

²Purple Mountain Laboratory, Nanjing 211111, China

EDP1-6 I-S-S-2024

A high efficiency superconducting nanowire single-photon detector at 10 μm wavelength integrated with a membrane optical cavity

Jie Deng^{1*}, Qing-Yuan Zhao^{1,2}

Research Institute of Superconductor Electronics (RISE), School of Electronic Science and Engineering, Nanjing University, Nanjing, Jiangsu, 210023, China*

Purple Mountain Laboratories, Nanjing, Jiangsu, 211111, China*

EPD1-4 RISE

Single photon event camera for fast target tracking

Sai-Ying Ru¹, Qing-Yuan Zhao^{1,2}

Research Institute of Superconductor Electronics (RISE), School of Electronic Science and Engineering, Nanjing University, Nanjing, Jiangsu, 210023, China*

Purple Mountain Laboratories, Nanjing, Jiangsu, 211111, China*

*65202230001@mail.nju.edu.cn

EDP1-1 I-S-S-2024

1. What is the single photon event camera?

Conventional frame camera

- Integral time imaging
- Output frame by frame

Conventional event camera

- Integrated light intensity
- Changes of the light intensity trigger events

Single photon event camera

- Photons detection trigger events
- Sensitive and fast

2. Build a single photon event camera

The principle of the single photon event camera

Superconducting nanowire delay lines

Event detection

Event readout

Equipped with 32 pixels

3. Results

(a) Imaging system at room temperature

(b) Differential response distribution

(c) Spot trajectory imaging at speed of 2 kHz

(d) Extraction of target vibration frequency

(e) Image of the spot at different locations

(f) Position accuracy vs. photon count curve

(g) SNR (frequency domain) vs. photons curve

4. Methods

(a) The shape of the output pulses

(b) SEW and OCR

(c) Time jitter

(d) Pixel uniformity characterization under flood illumination

5. Conclusion

- A kilohertz single-photon delay-line imager is demonstrated, which naturally operates in event-triggered mode.
- A single-photon imaging and tracking system is established, which has the max SDE of 56.2% and enables high-speed target imaging at a speed of 2 kHz.
- Based on high speed event-triggered of single-photon, multi-dimensional target information such as position, velocity and frequency can be extracted.

6. References

[1] Zhao, QY, et al. Single-photon imager based on a superconducting nanowire delay line. Nature Photon 11, 247-251 (2017).

[2] Varun Sundar, et al. Generalized Event Cameras, arXiv: 2407.02683.

