IEEE CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 58, Feb. 2025.
Presentation given at ISS 2024, Kanazawa, Japan, Dec. 3-5, 2024.

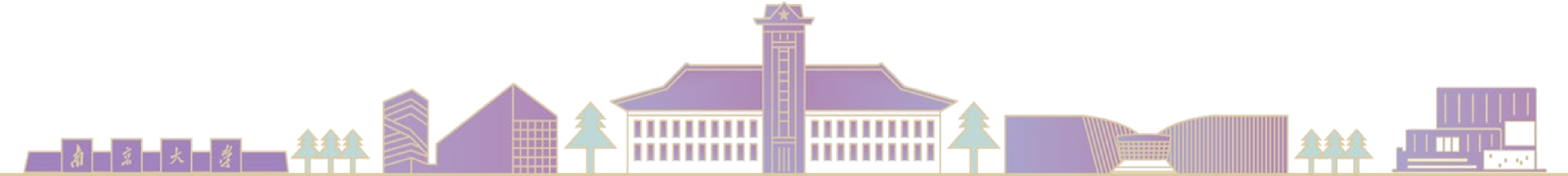
南京大學

Superconducting nanowire single-photon detectors and imagers

Qingyuan Zhao

Nanjing University

ISS 2024, Kanazawa



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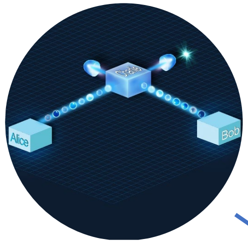
Superconducting Nanowire Single Photon Detector (SNSPD)

Popular detector for
Quantum information science

Extremely sensitive for
Extremely challenging missions

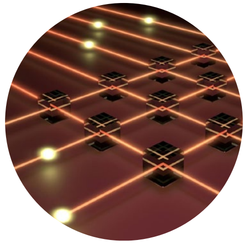
Quantum key distribution

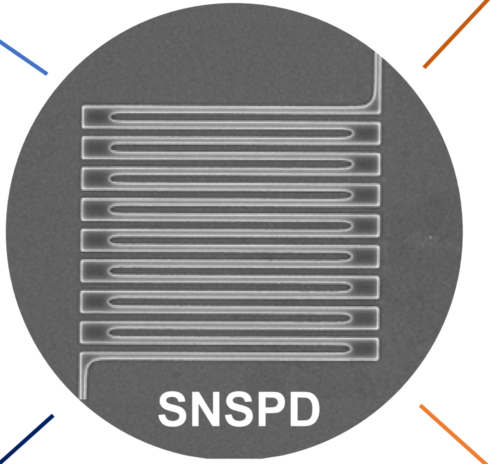


Nanoscale Detector

Deep Space Communication

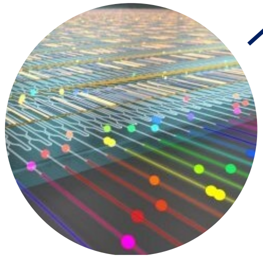
Quantum Simulation



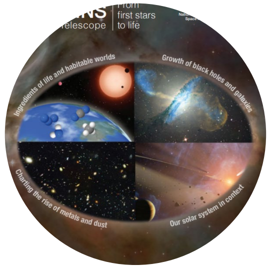


Small Debris Detection

Quantum Computation



Massive Power



Space Telescope

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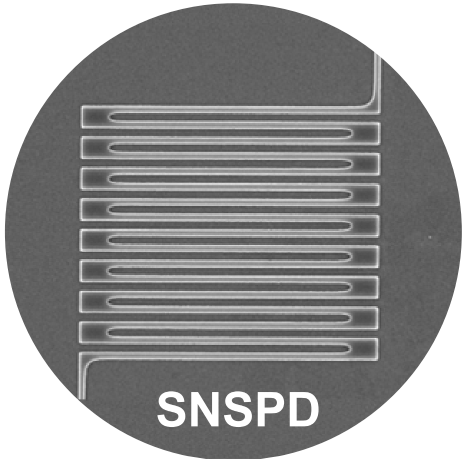
Outline



- High Speed SNSPD array
- Various Delay Line Imagers
- High Efficiency Waveguide Integrated SNSPD

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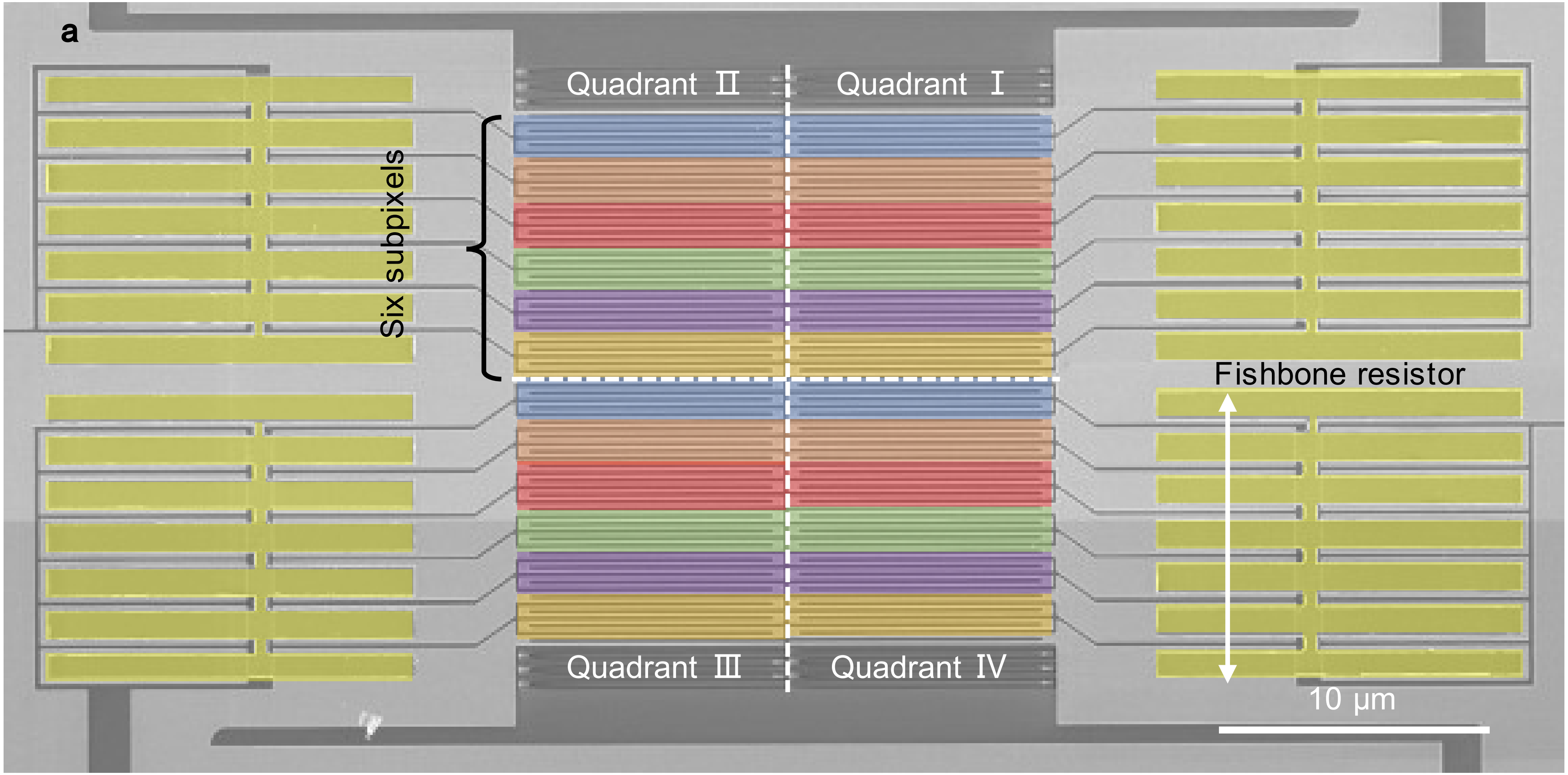
Four Quadrant Serial Nanowire Array

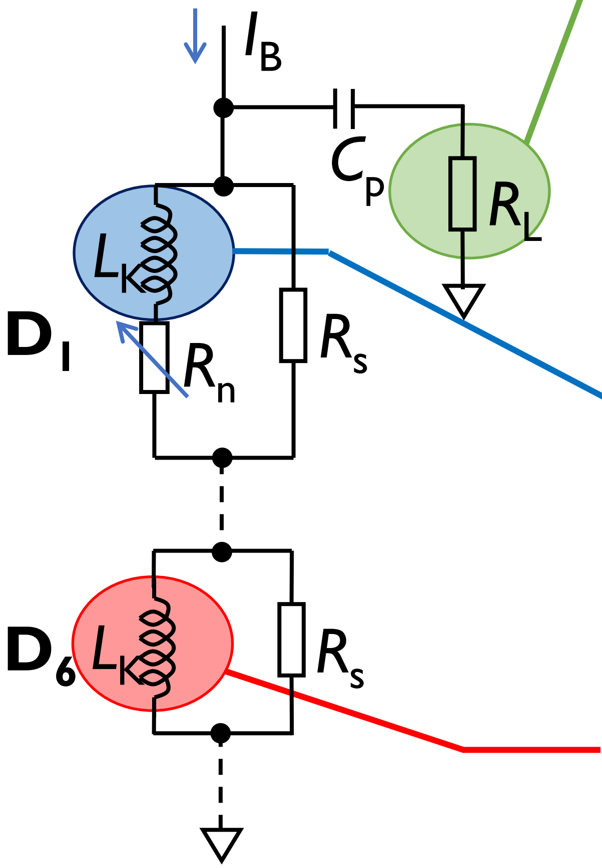


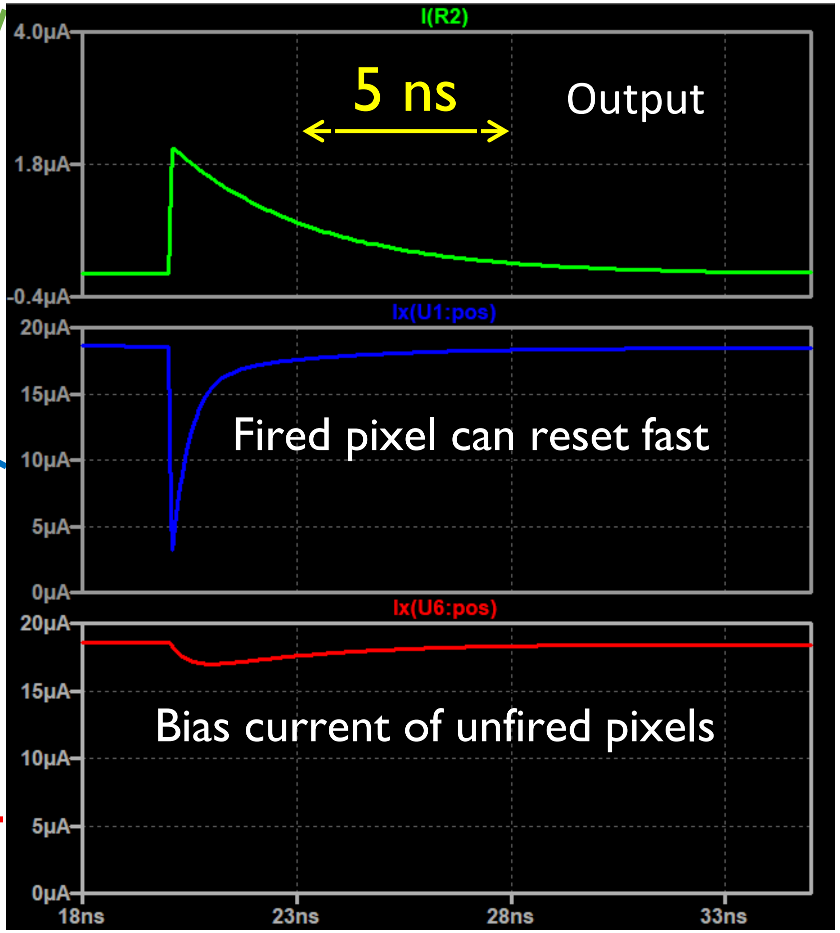
Light Sci. Appl. 13(1), 25 (2024).

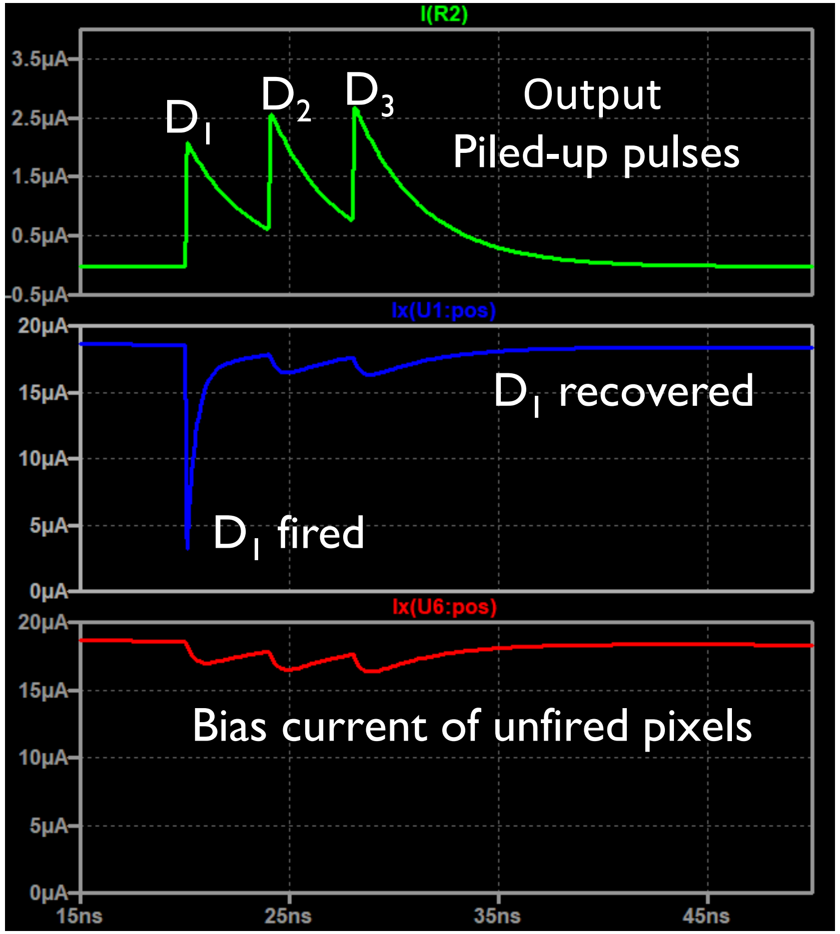
IEEE CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 58, Feb. 2025. Presentation given at ISS 2024, Kanazawa, Japan, Dec. 3-5, 2024.

Quasi-parallel counting in a serial nanowire architecture

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



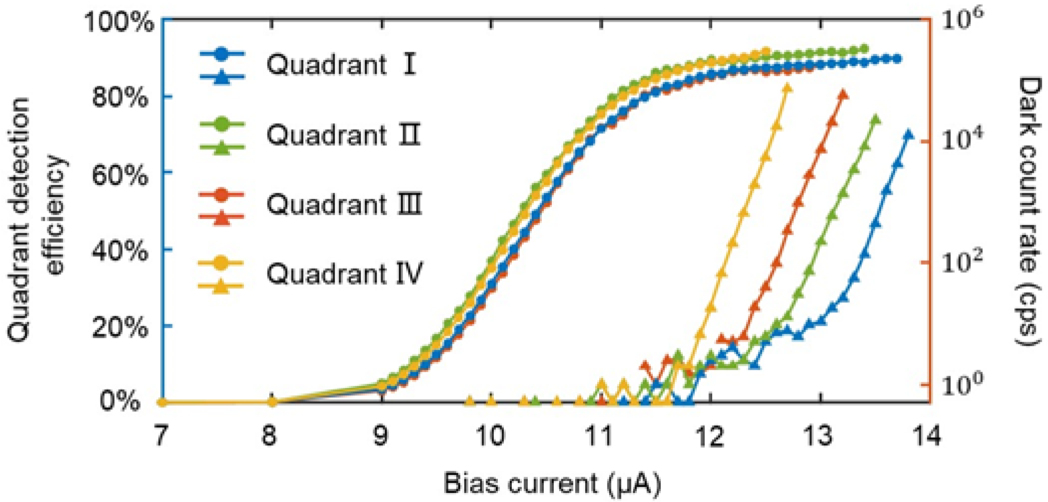




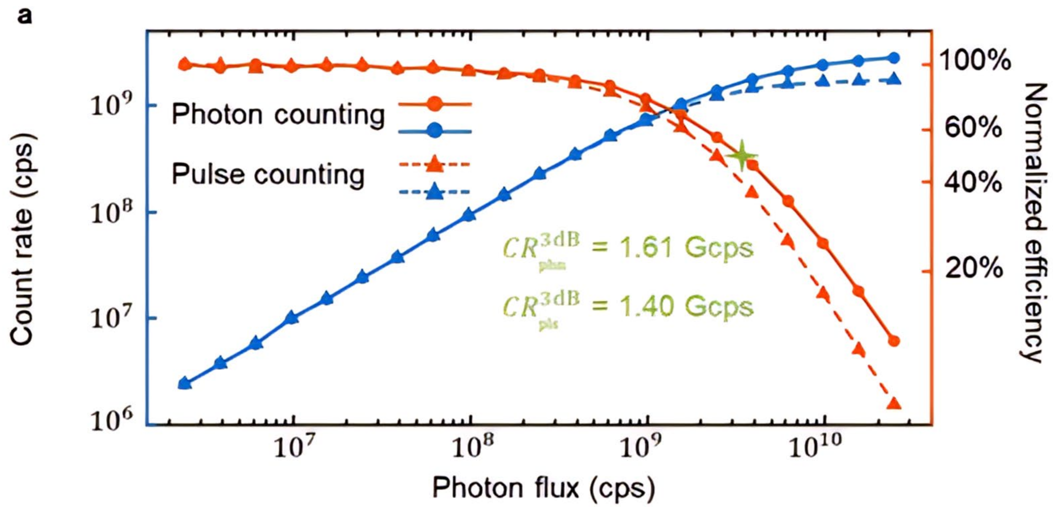
S. Jahanmirinejad, et. al., Appl. Phys. Lett. **101**(7), (2012). X. Tao, et.al IEEE Photonics J. **12**(4), (2020).

High-efficiency and high counting rate

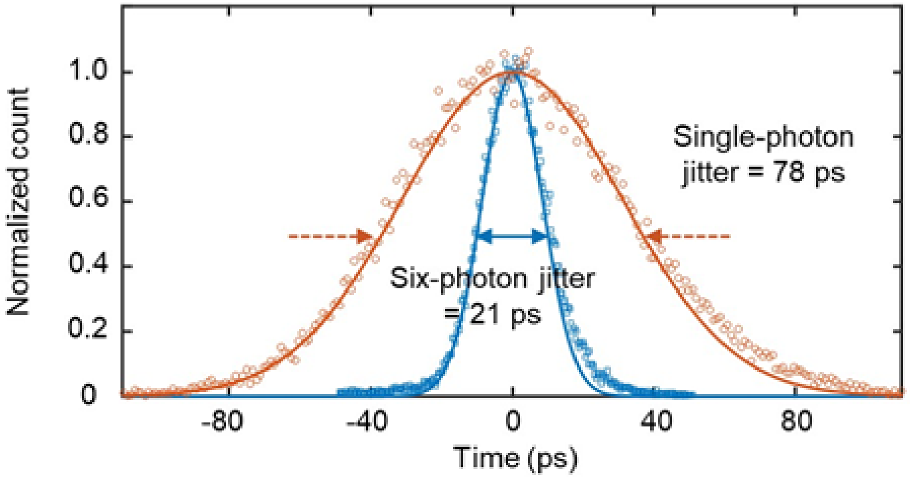
DE: >90%



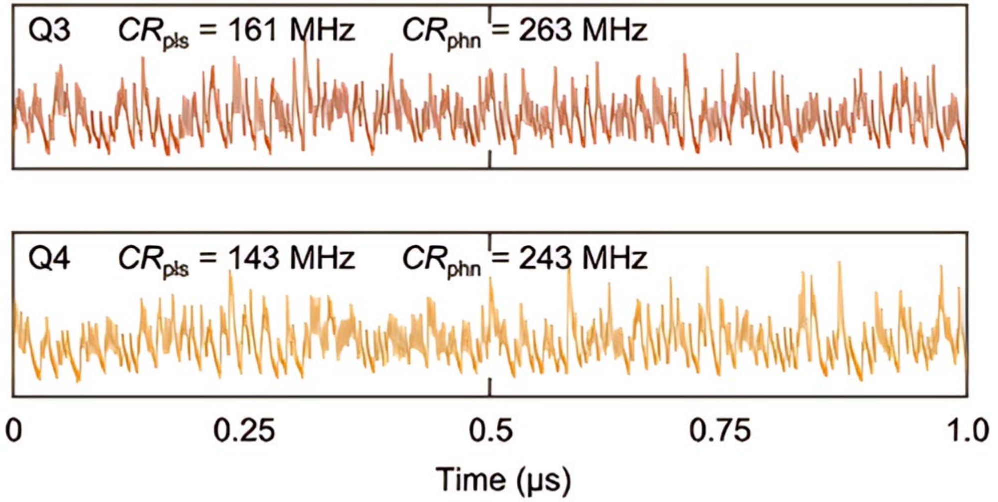
Counting rate: 1.6 G ph./sec @ 45% DE



Jitter: 21ps~78ps



Examples of fast counting pulses



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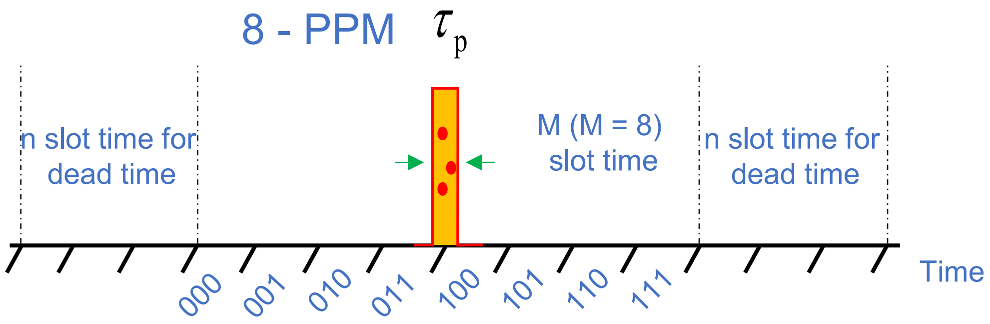
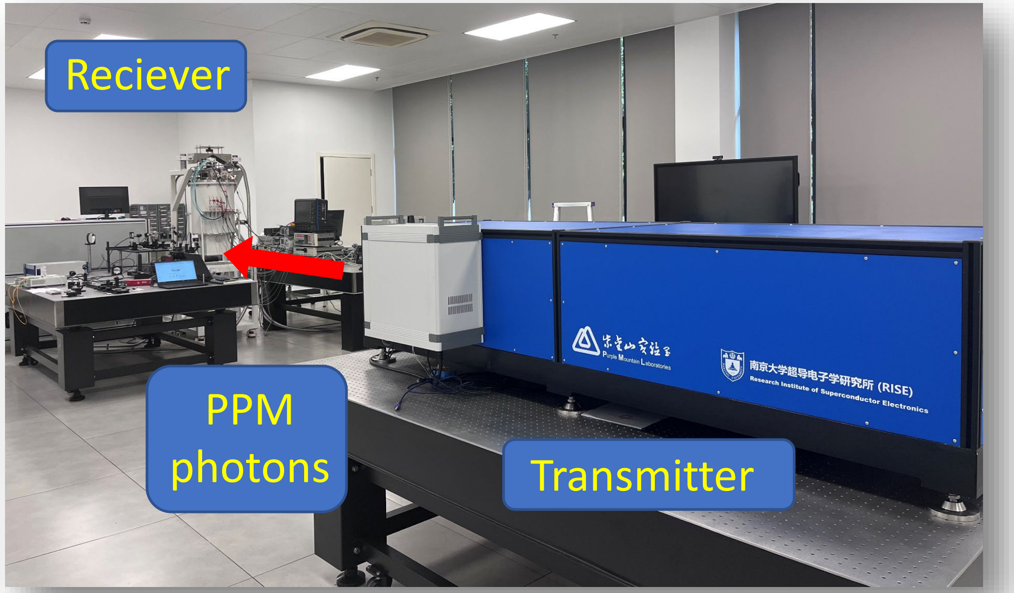
Single-photon optical communication characterizations

Pulse Position Modulation Format + ½ rate SCPPM FEC

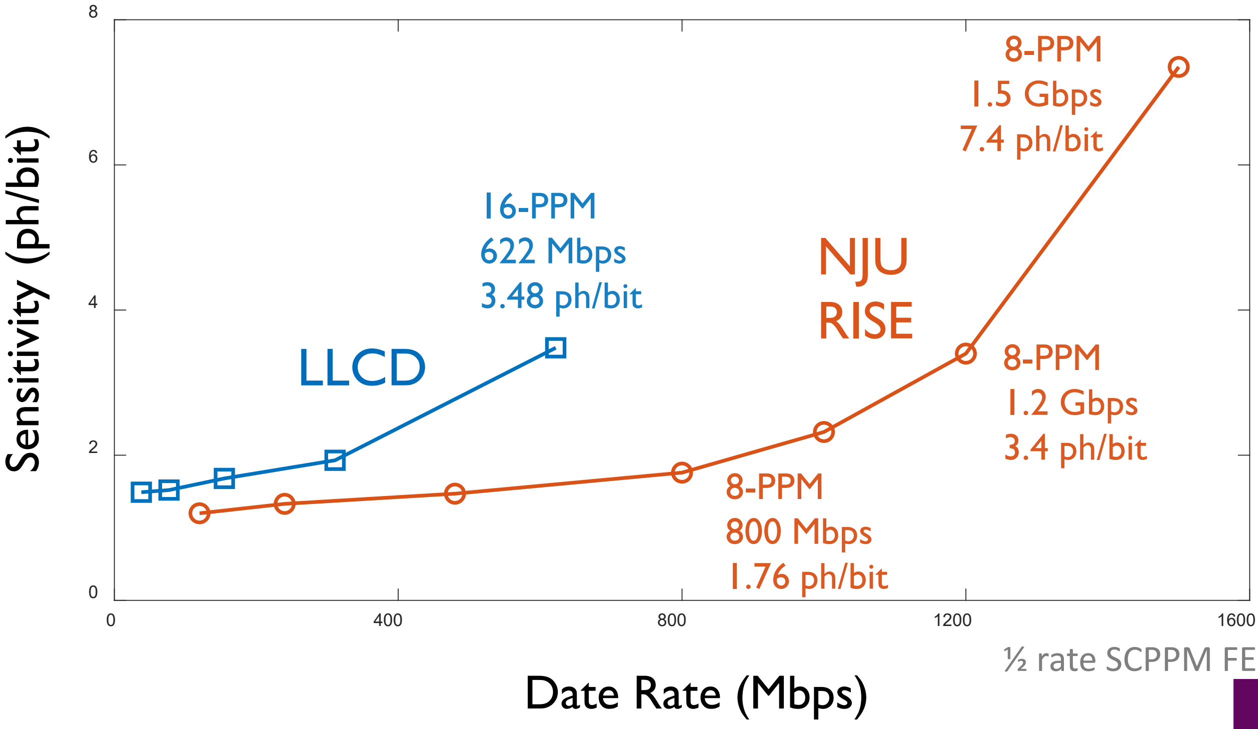


Free-space optical communication testbed



1.5 Gbps — Maximum Data Rate

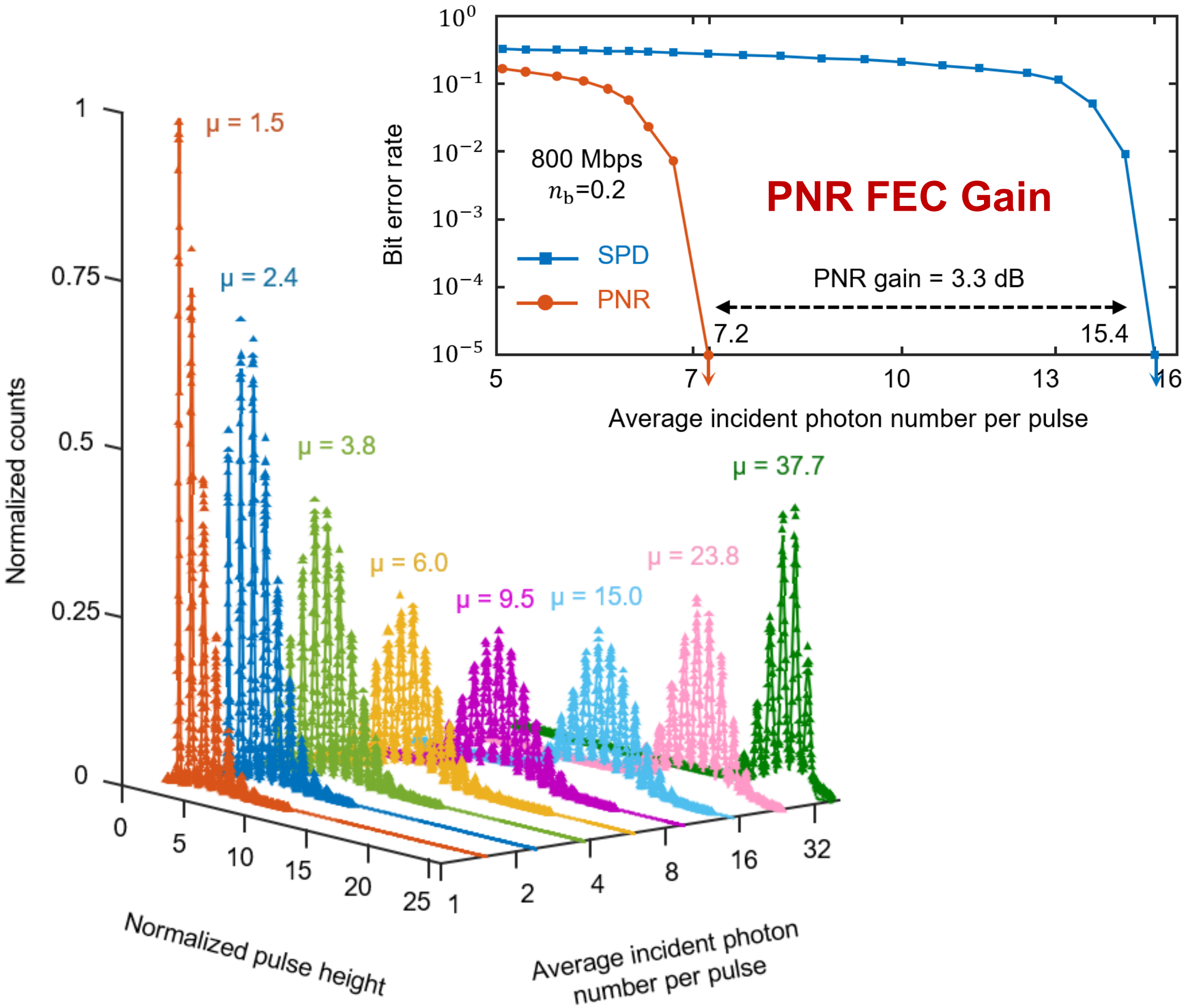
3.4 ph./bit — sensititivity@1.2 Gbps

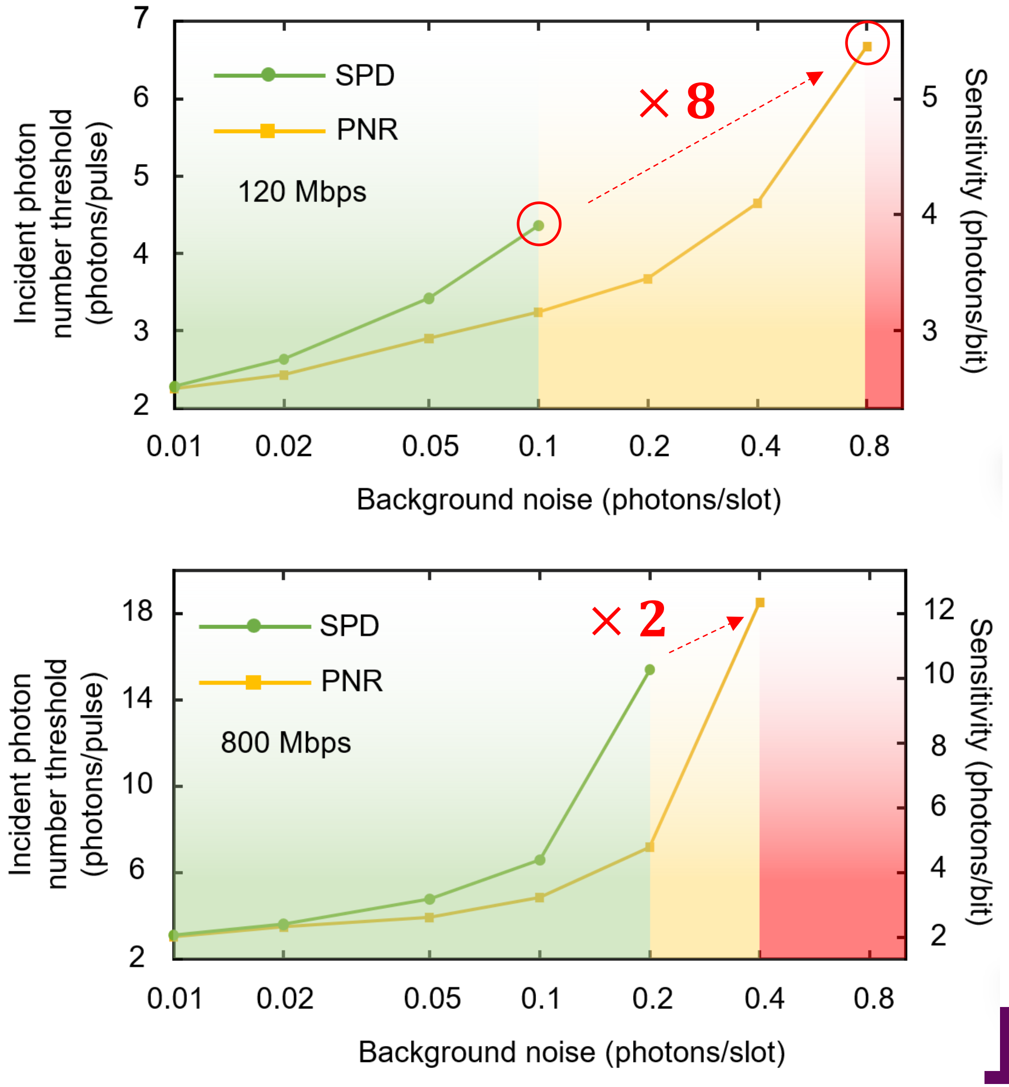


Tolerant to strong background noise for daytime communication

Maximum Photon Number Resolving Capability

$4 \times 6 =$ 24 photons





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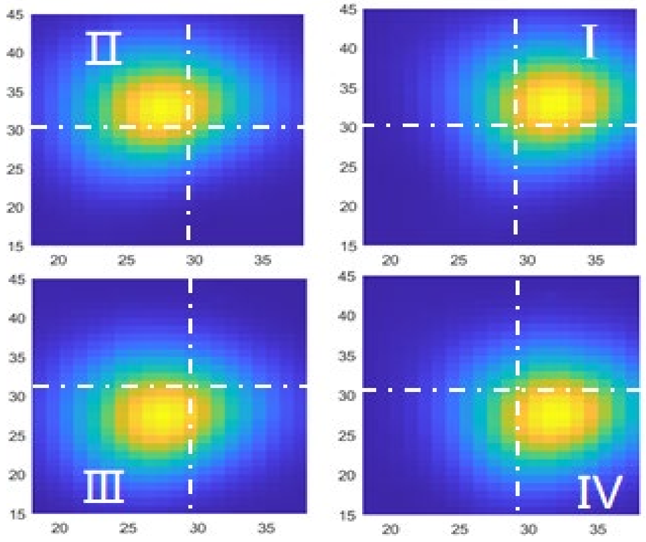
Beam spot tracking

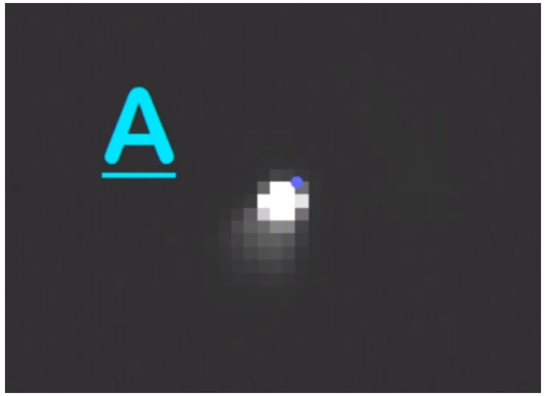
Four-quadrant positioning under photon-counting mode

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

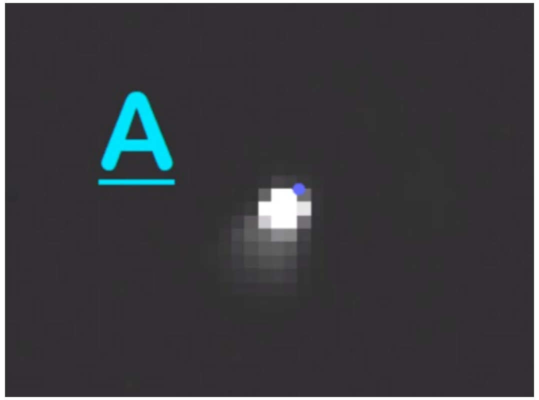
$$\Delta y = \frac{S_A + S_C - S_B - S_D}{S_A + S_B + S_C + S_D}$$

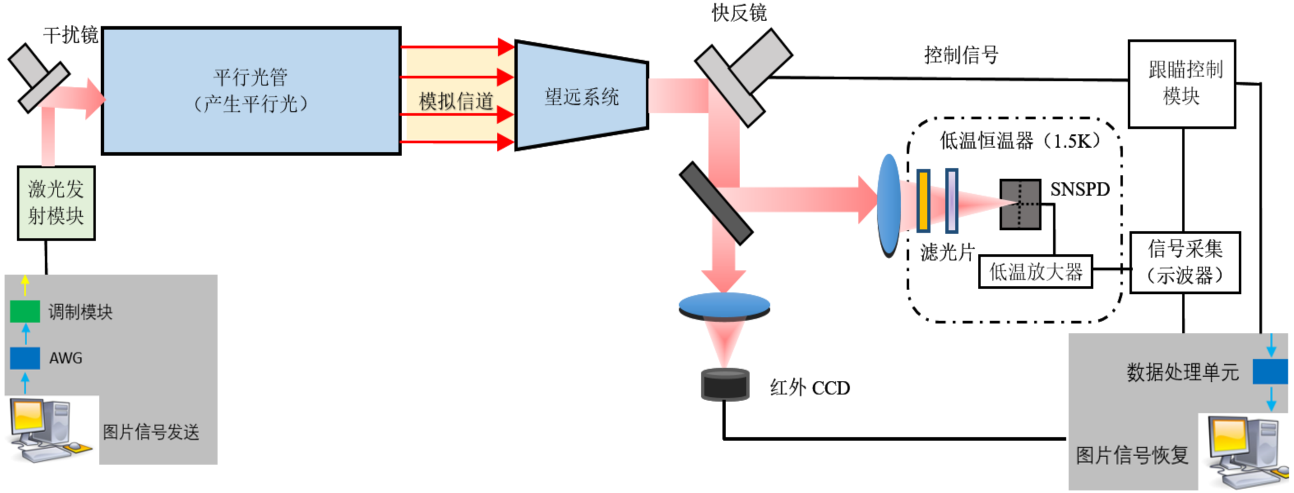


Tracking OFF



Tracking ON





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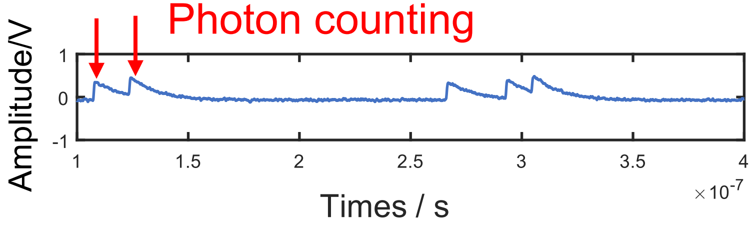
High dynamic detection and imaging

Low Flux – Photon Counting

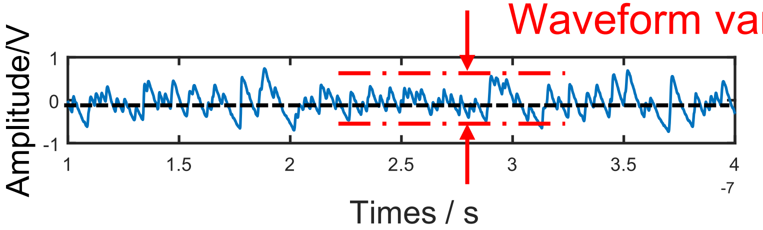


DE $\eta(t) = \dfrac{1}{1 + e^{-\left[I_b\left(1-\left(e^{-t/\tau}-e^{-t/\tau_r}\right)\right)-s\right]}}$

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

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

High flux – waveform variance



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

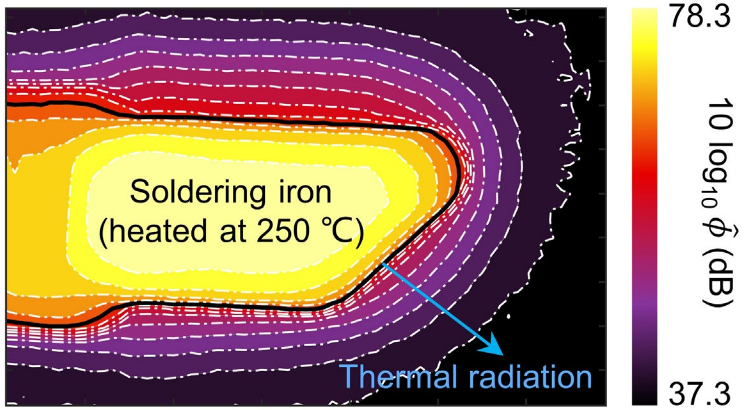
Variance $D = \dfrac{1}{B}\sum_{j=1}^{B}\left(\sum_{i=1}^{N} Ae^{\frac{(t_j - t_i(\phi))}{\tau}} + E_j - \bar{V}\right)^2$

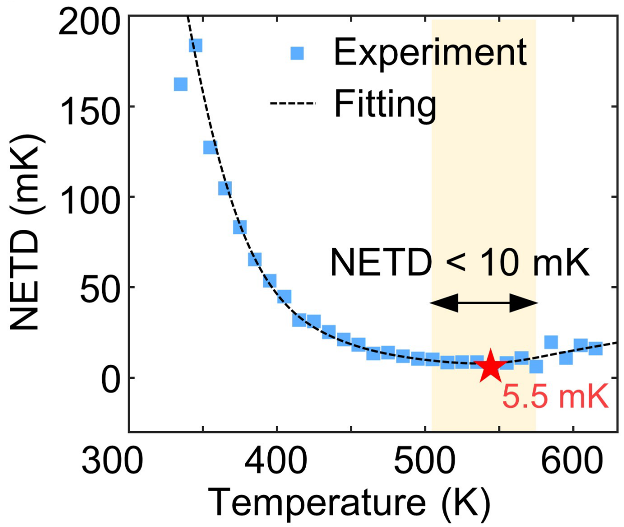
WVFE: $\hat{\Phi} = \dfrac{\sigma^2}{Q_s\left(\frac{\sigma^2}{f^{-1}(\sigma^2)}T - \sigma^2\tau_\eta\right)}$

Laser Photonics Rev. 2400483, 1–12 (2024).

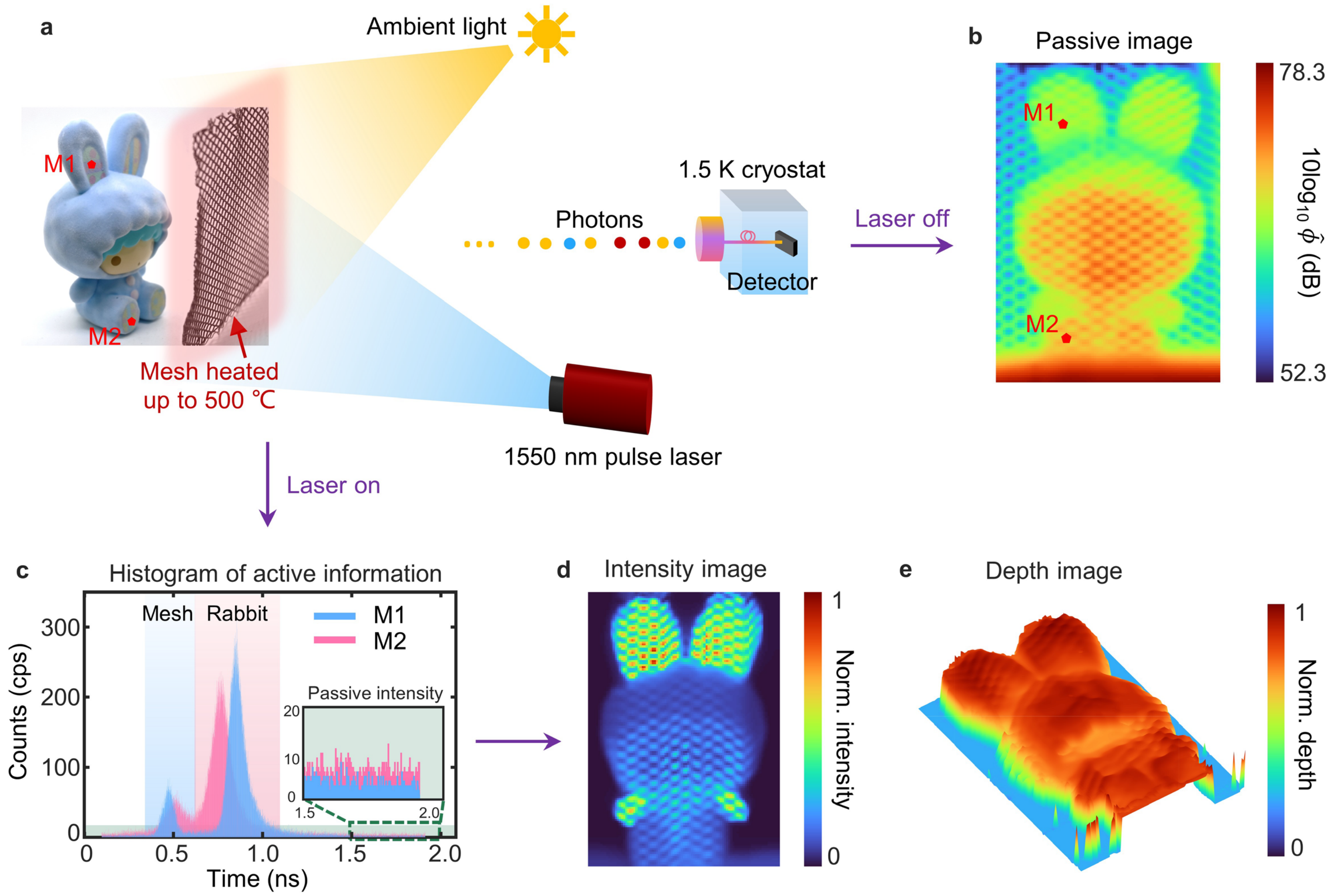
Demonstrations of high dynamic imaging

Passive Thermal Imaging





Passive and Active Imaging



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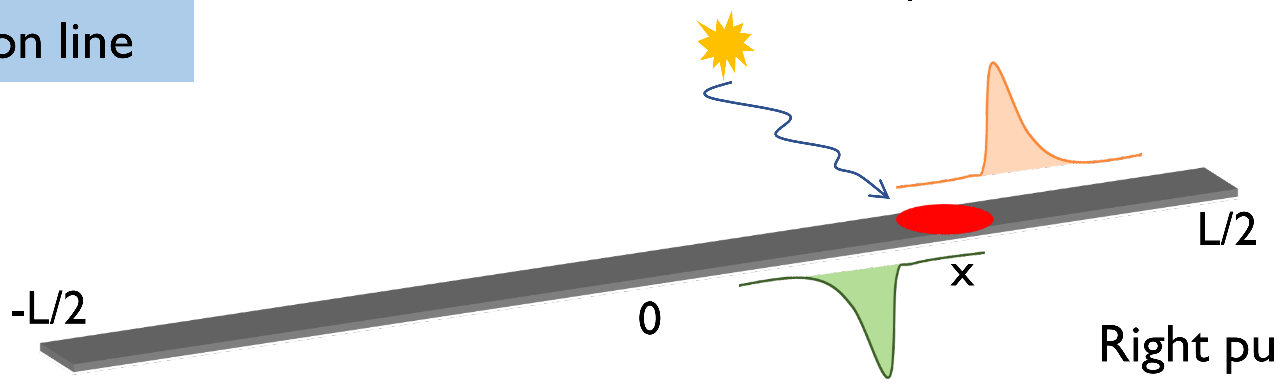
Superconducting nanowire delay line imager

Design the nanowire into a slow-wave transmission line

Photon arrival time t_p



Right pulse arrival time

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

Left pulse arrival time

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

Locaiton: $x = (t_L - t_R)v/2$ — differential time

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

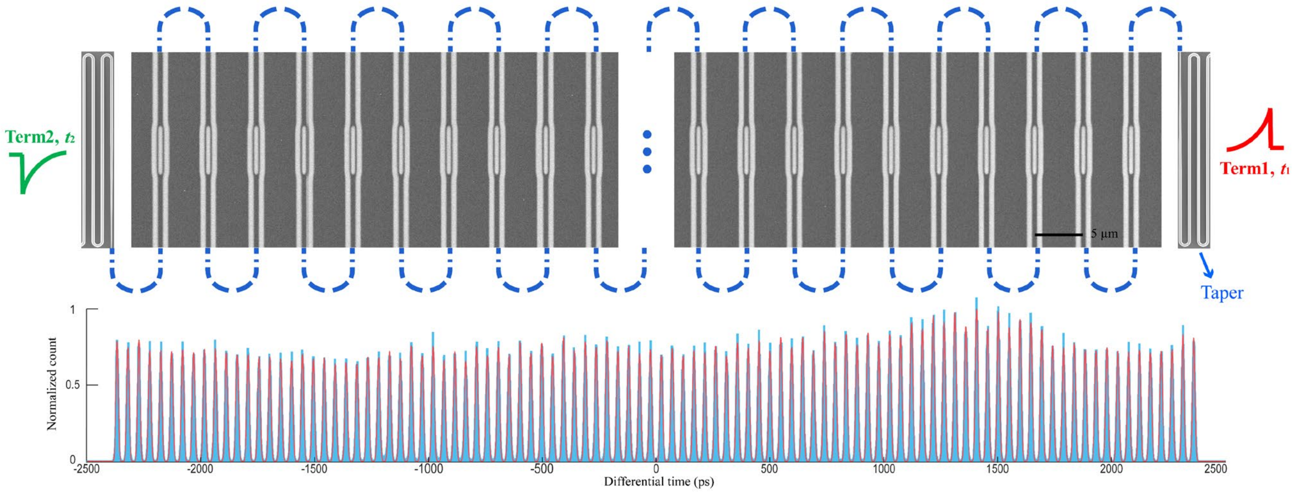
A simultaneous readout for both photon location and time!

*Similar to MCP Delay line anode readout method.

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

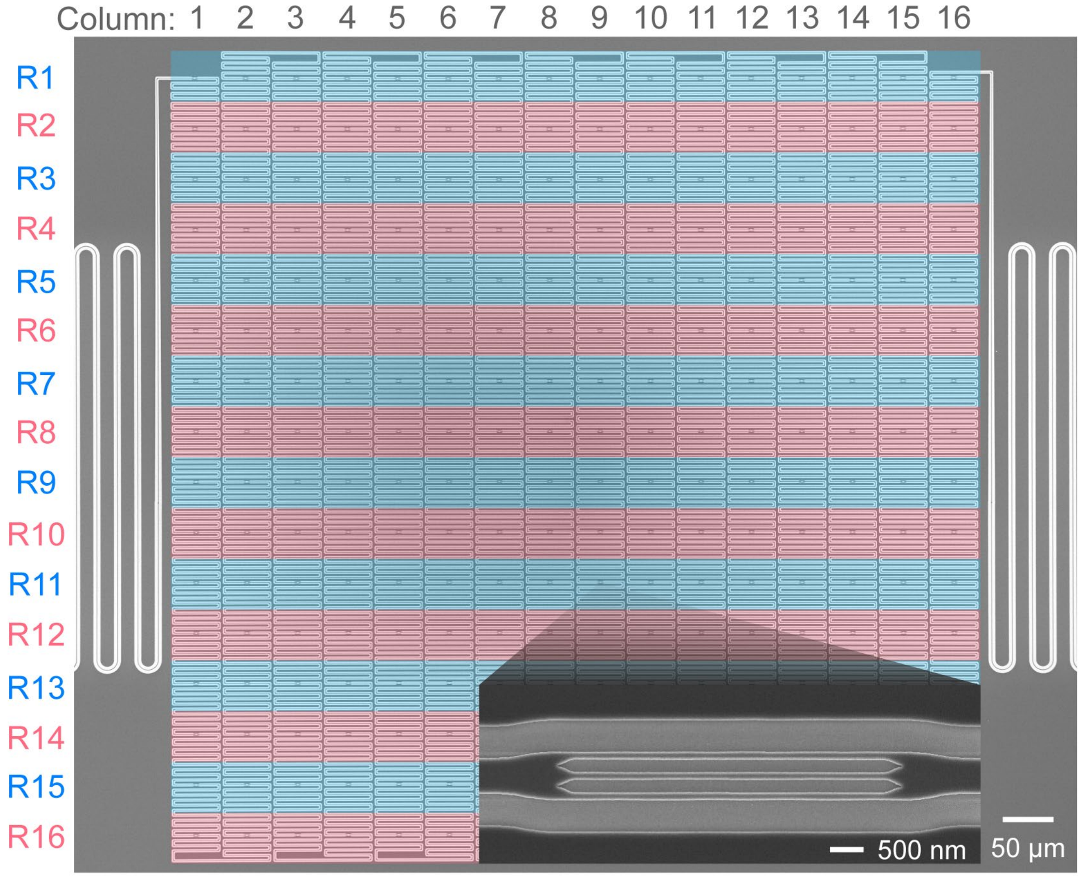
Scale up to various arrays

1D linear array 1×100



λ = 404nm

2D array 16×16



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

✕ Limitation in 2D array

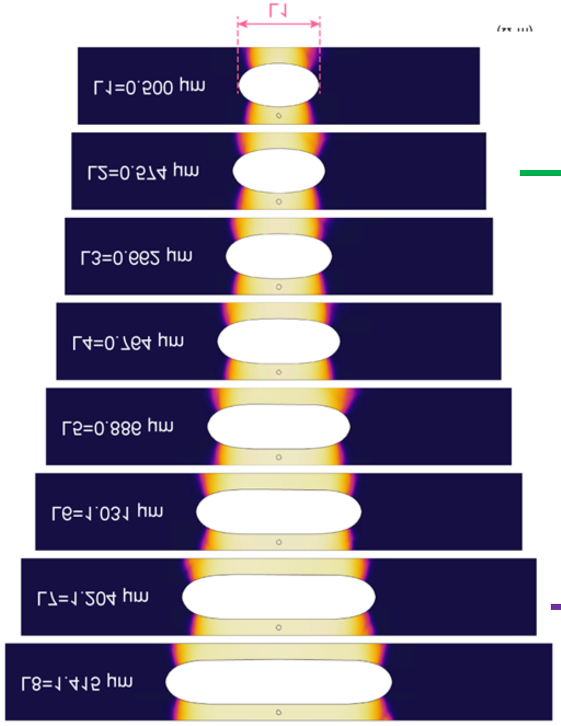
1. Limited Spatial resolution
2. Low filling factor

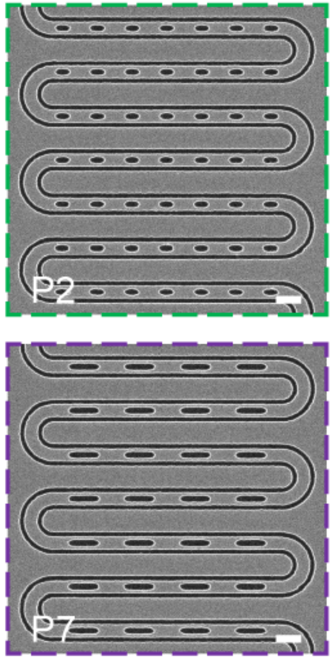
H. Wang, et. al., Opt. Lett. **47**(14), 3523 (2022).

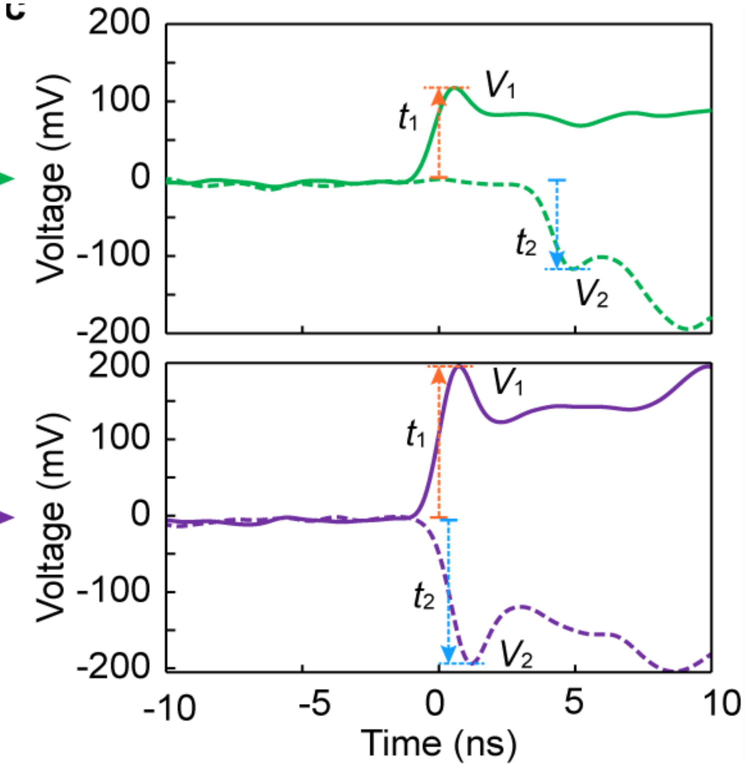
L. Kong, et. al., Opt. Lett. **45**(24), 6732 (2020).

Orthogonal time–amplitude multiplexing array

Hot spot quantization + SNAP with varied *L* + Amplitude multiplexing





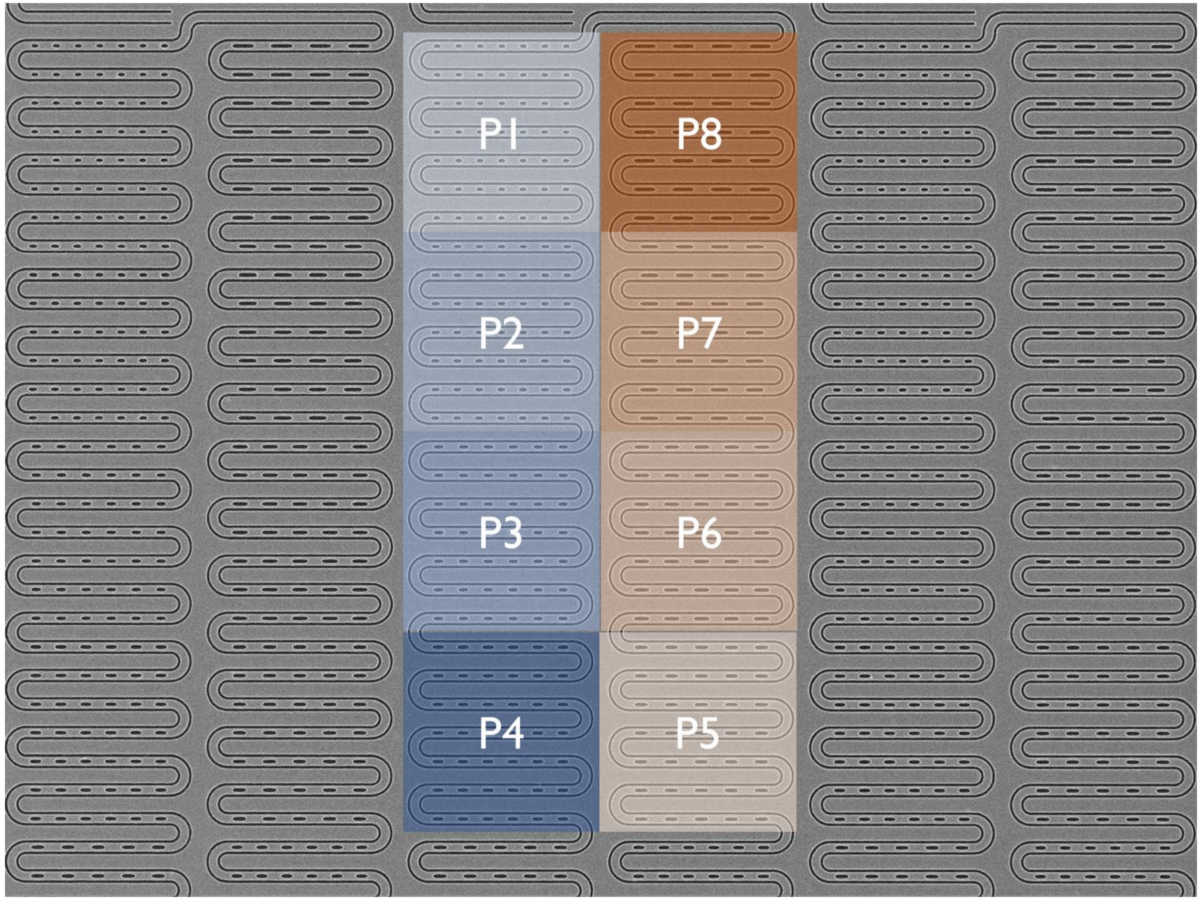


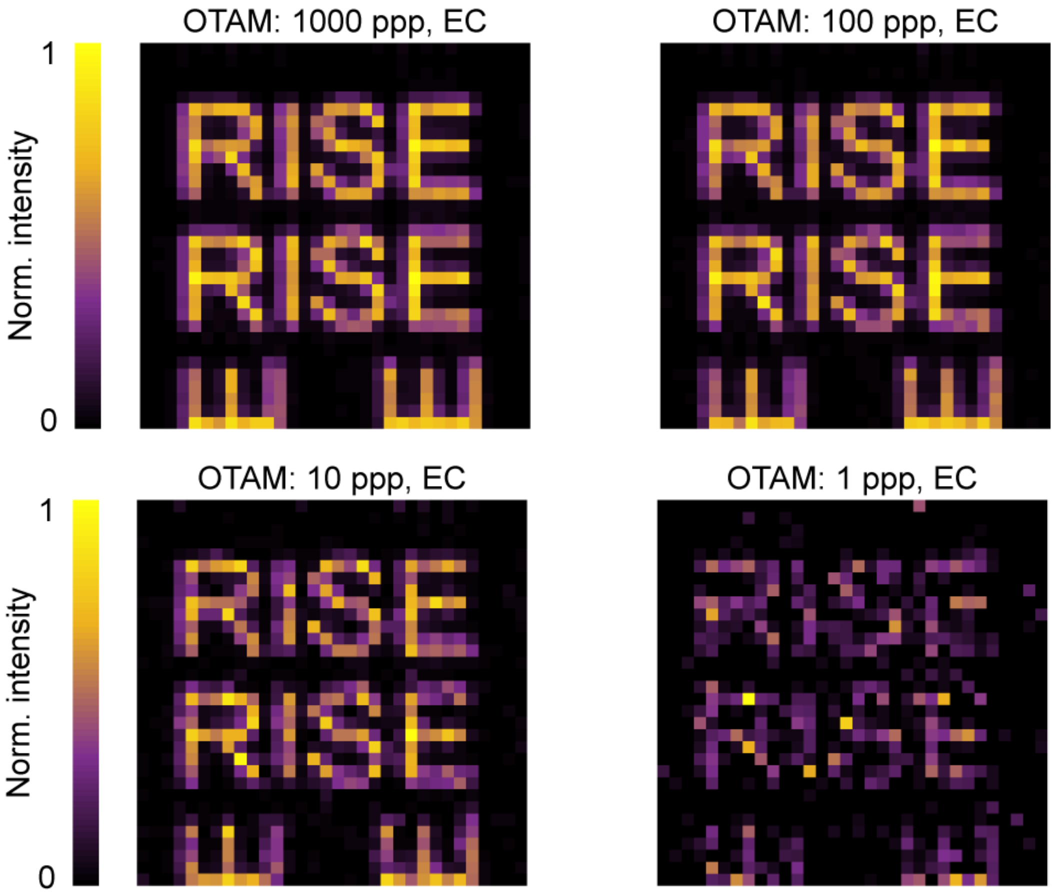
L. Kong, et.al., Nat. Photonics **17**(1), 65–72 (2023).

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).

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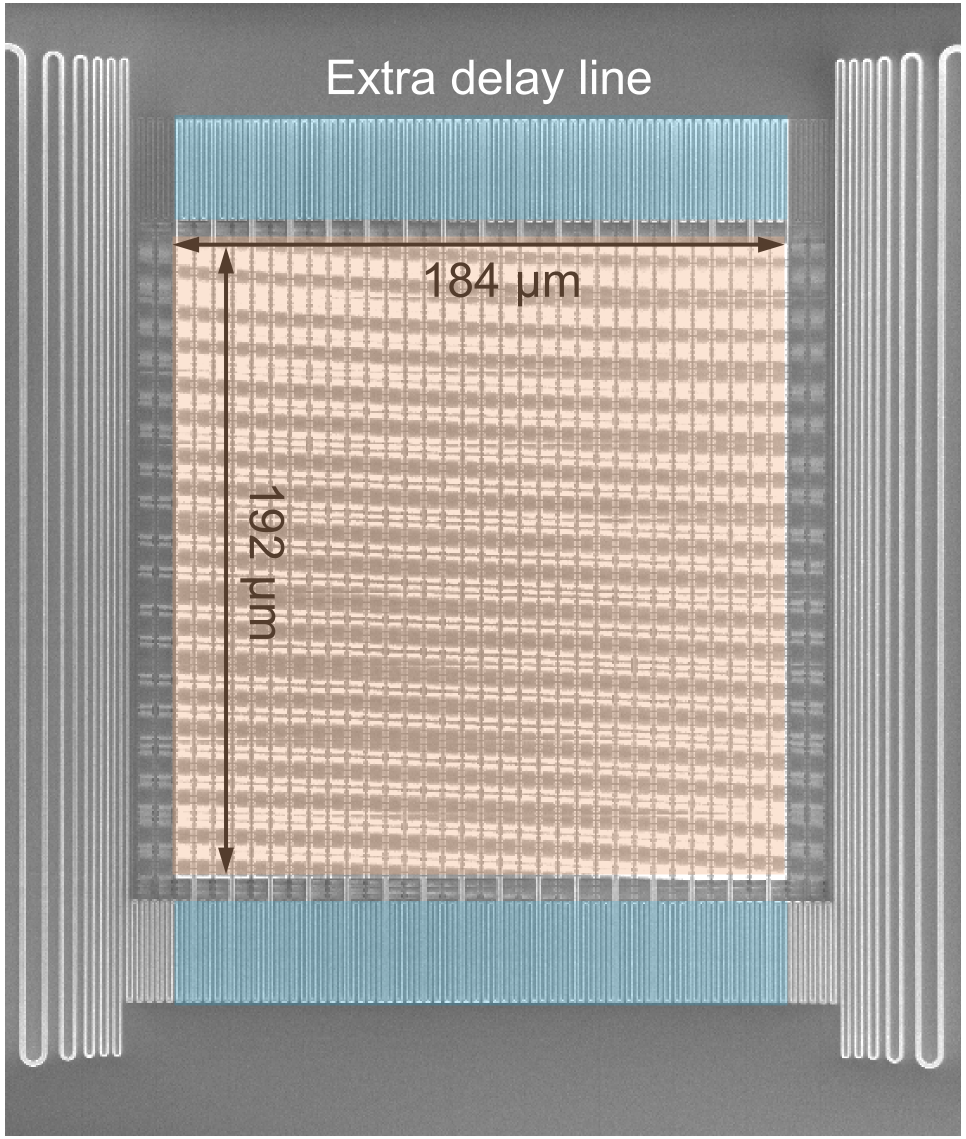
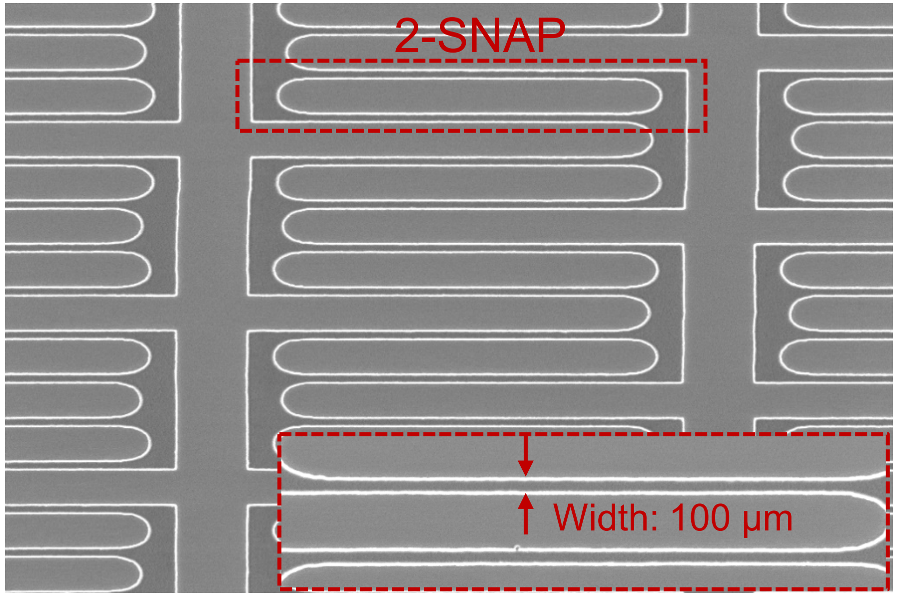
High-Efficiency Kilopixel Imager at 1550 nm



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



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

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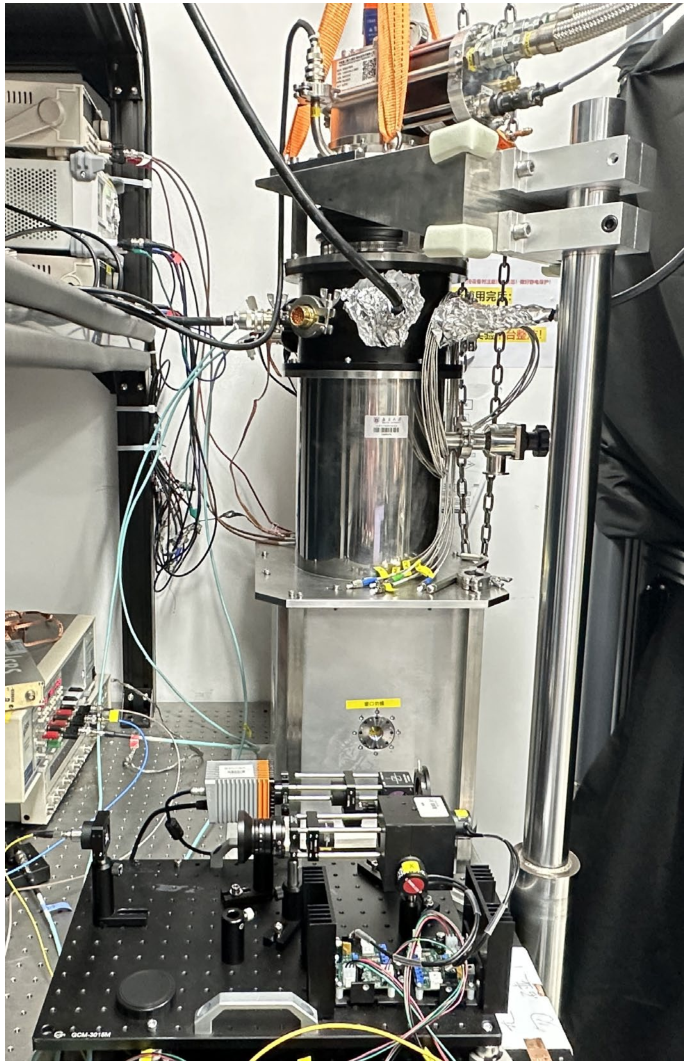
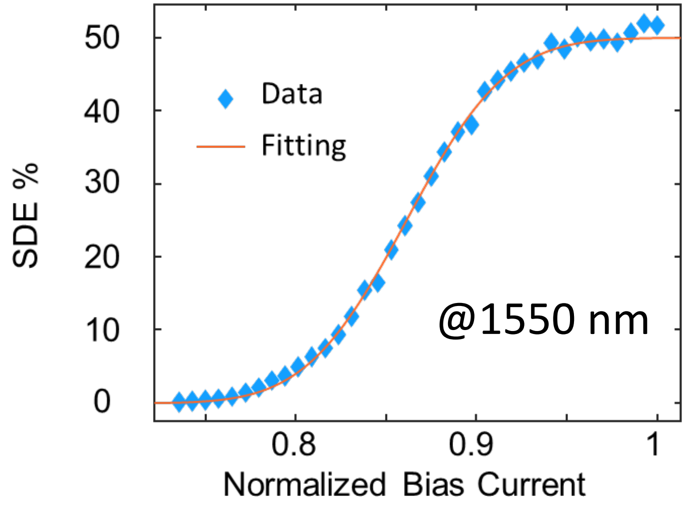
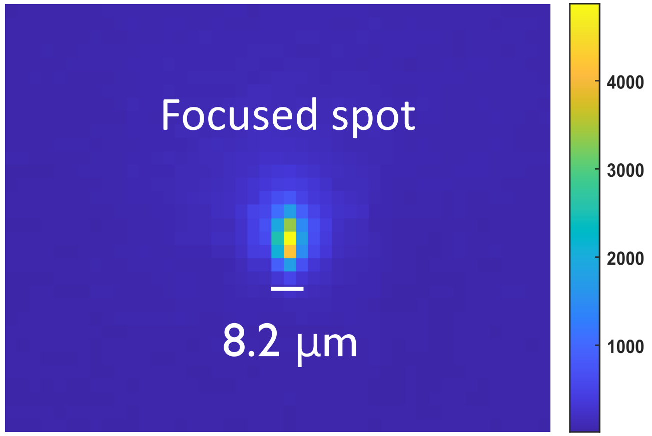
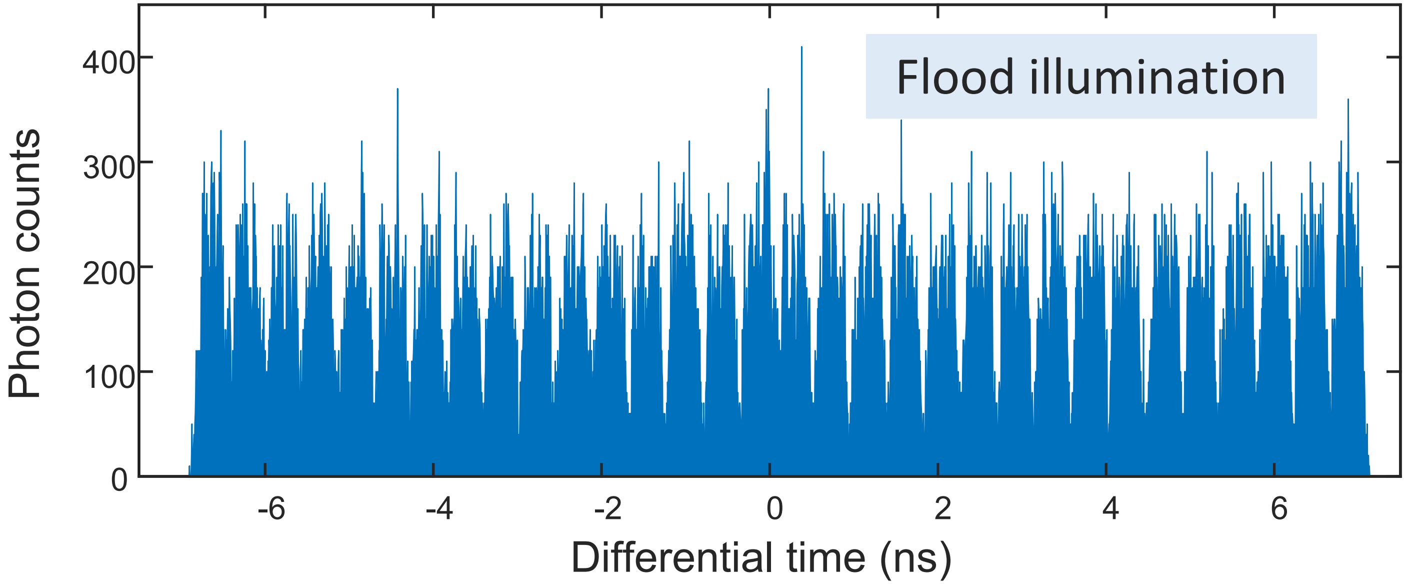
High-Efficiency Kilopixel Imager at 1550 nm

Free space imaging 1K system









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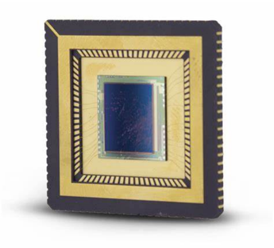
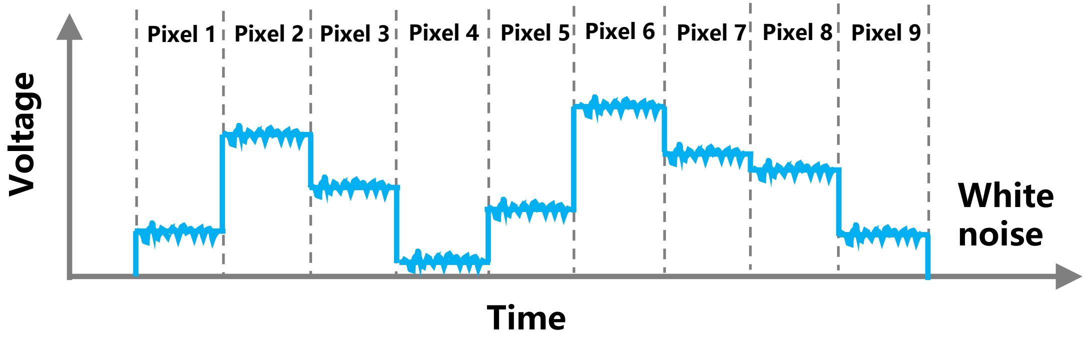
Single-photon event camera

CMOS

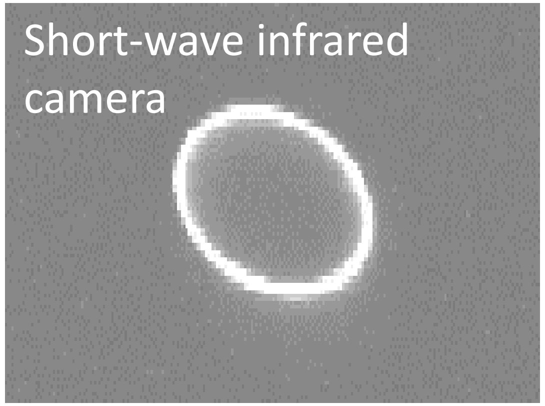


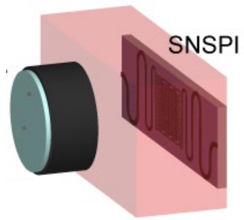
Conventional integral sampling

Frame determined by row-column sequence



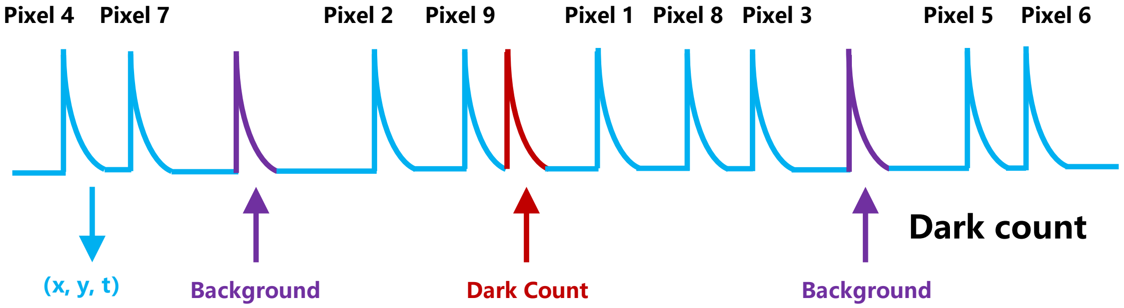
Spot moves at 500 Hz

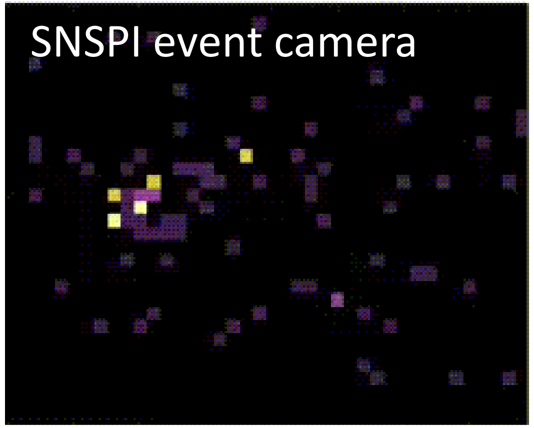




Photon event counting

No fixed frame, random pulse train

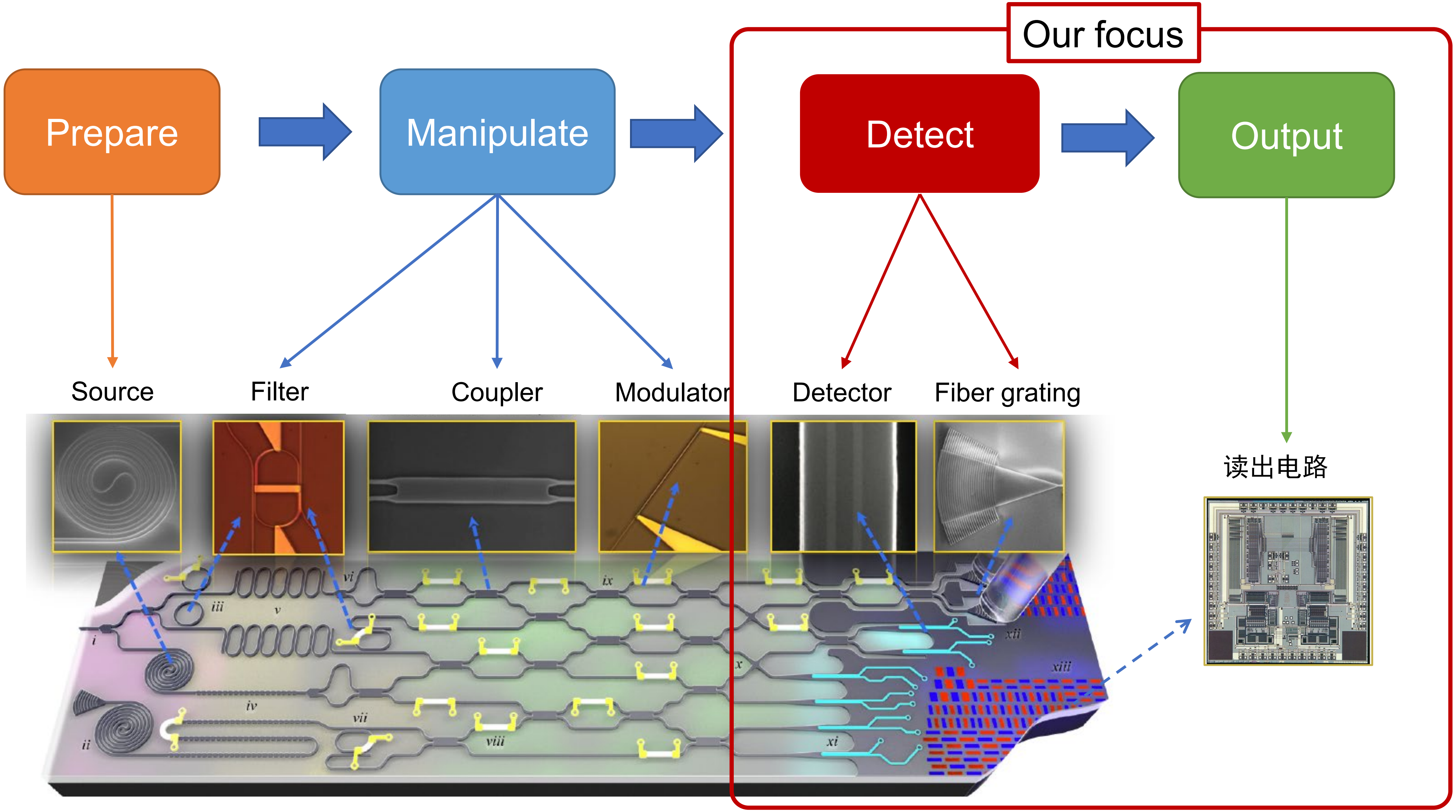




Every frame = 200 photons

Photon event synchronized, fast and low latency!

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).

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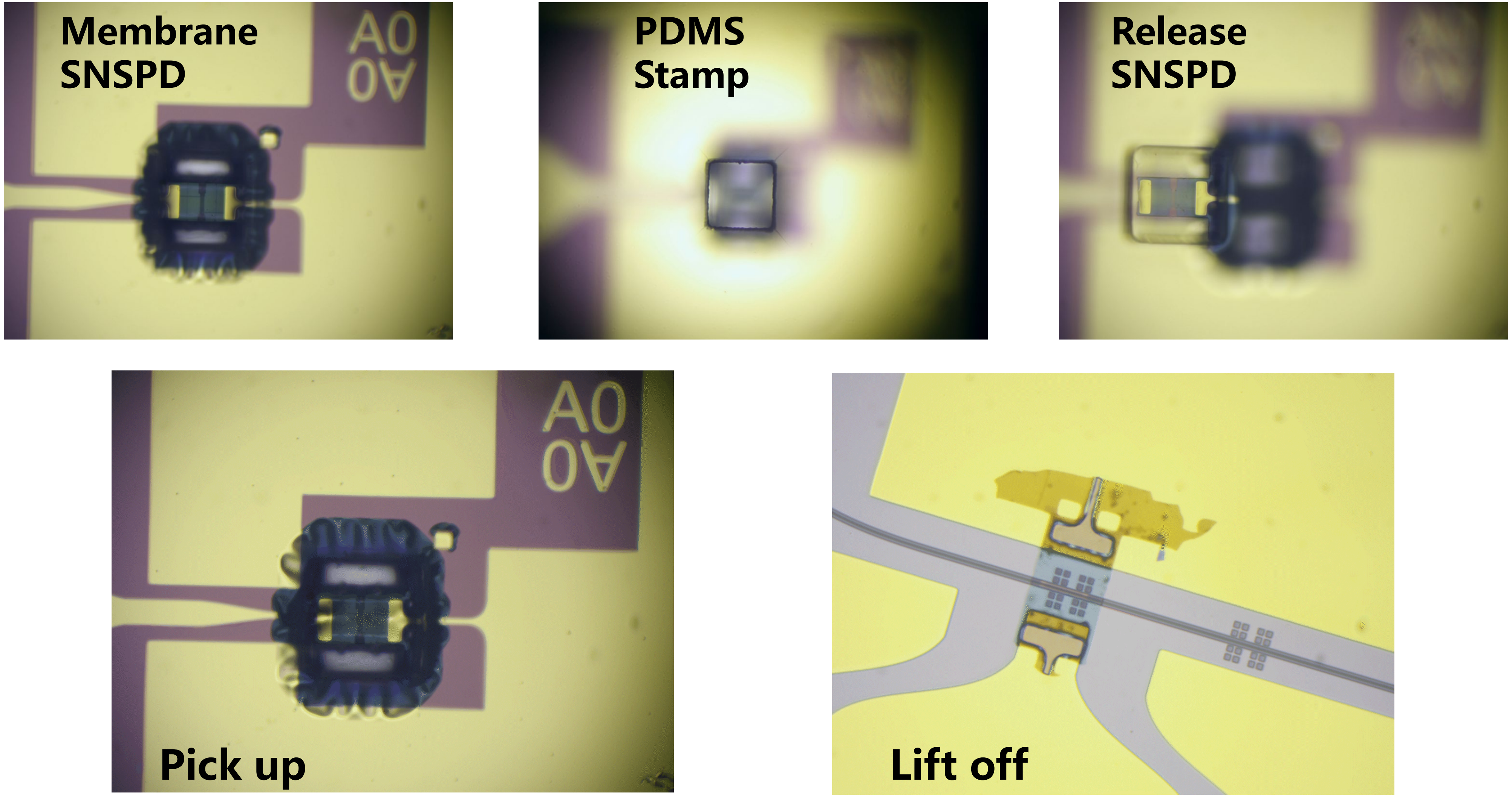
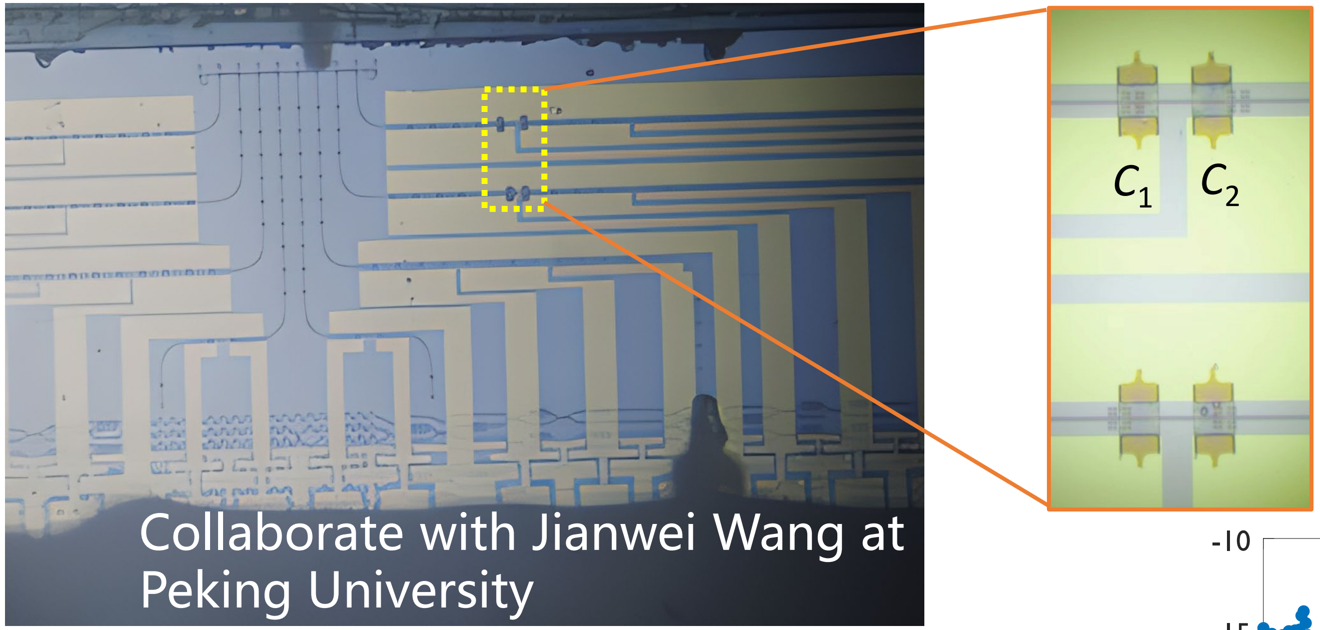
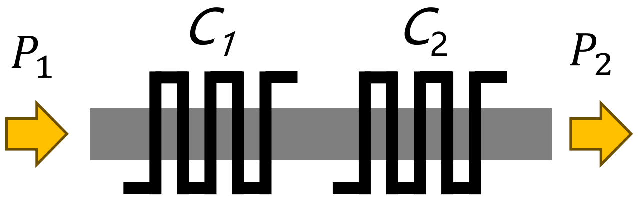
Hybrid integrated SNSPD on waveguides



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

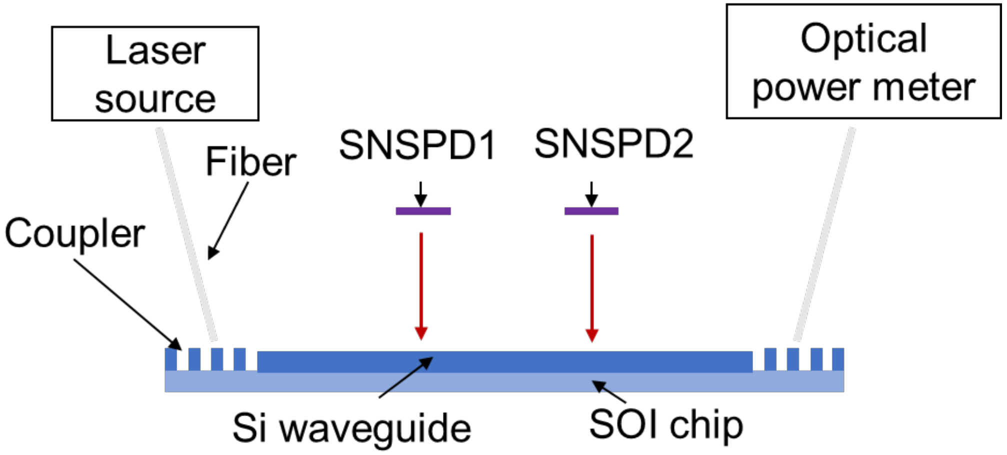
>99% on Si waveguide detection efficiency

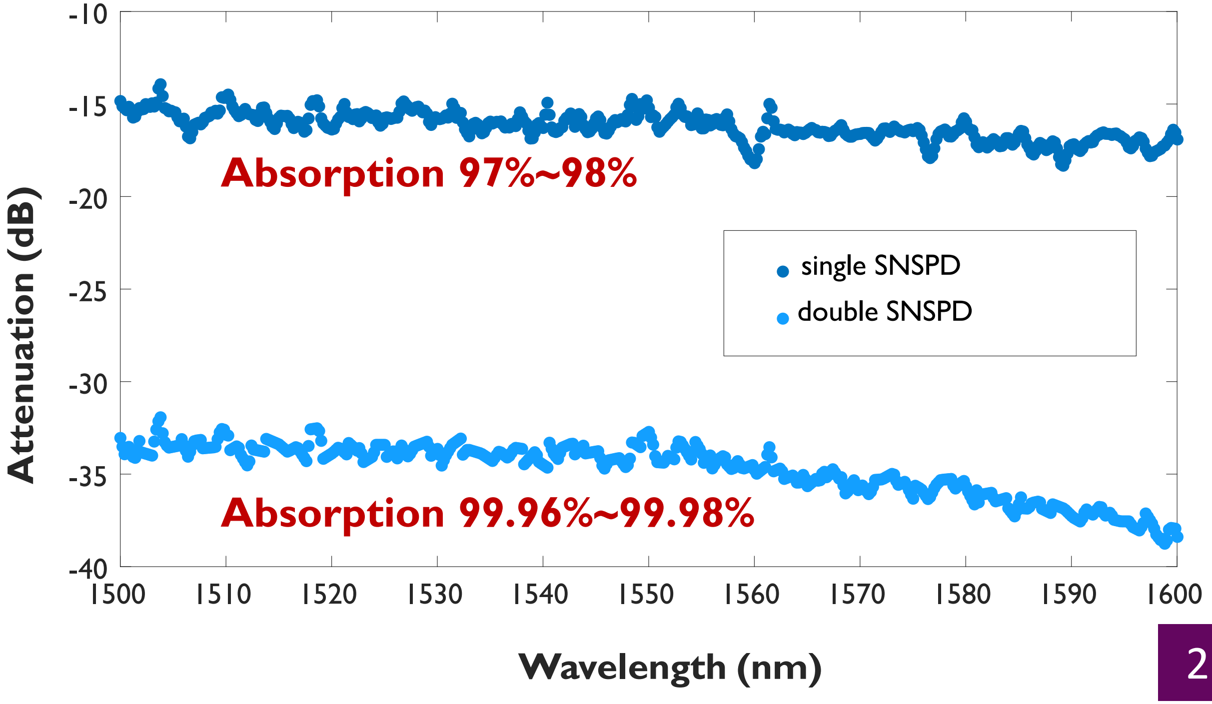




Single ODE： 98%

Double ODE： 99.96%

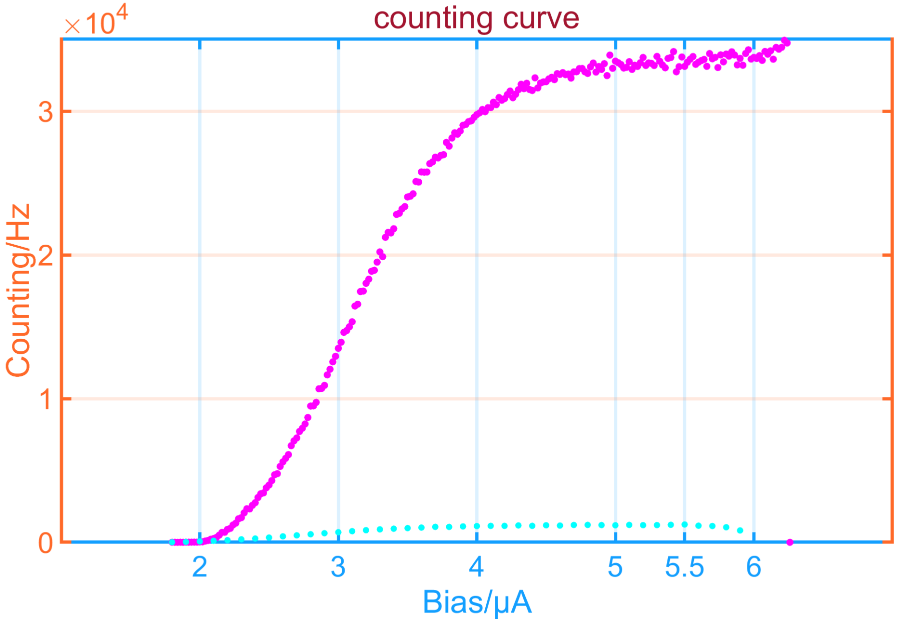




IEEE CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 58, Feb. 2025. Presentation given at ISS 2024, Kanazawa, Japan, Dec. 3-5, 2024.

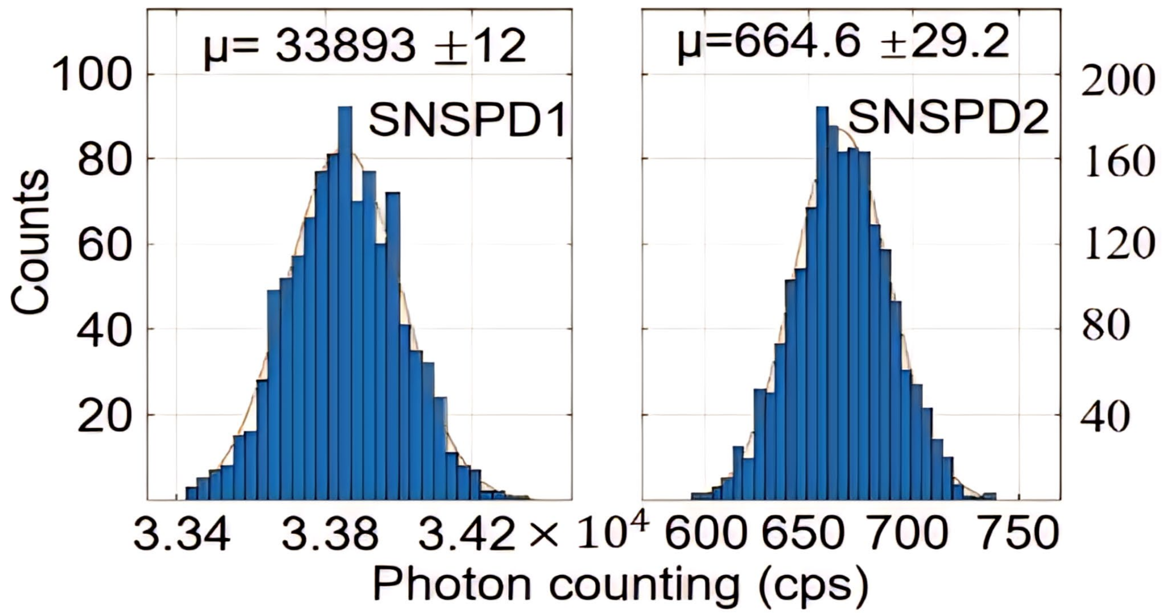
>99% on Si waveguide detection efficiency

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



Other losses: Reflection ≈ 0.2%, and waveguide loss

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



Detection coincidence of **100** photons

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

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

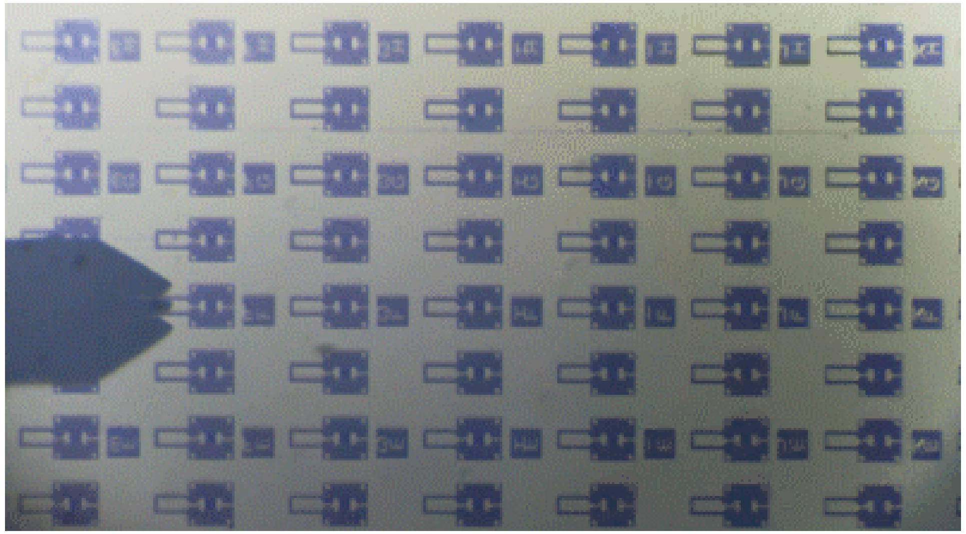
Detection coincidence of **1000** photons

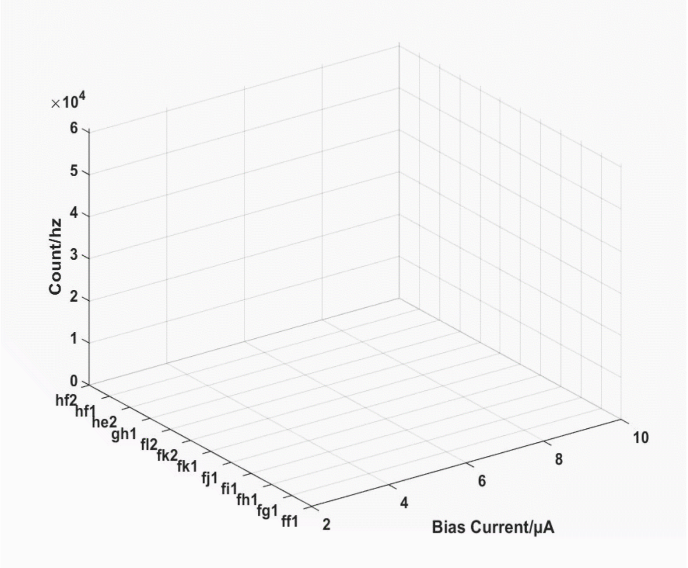
$98\%^{1000} = 1.68e - 9$

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

Large-scale chip production and automated testing

*与南京鹏力超低温联合研制





Probe Station

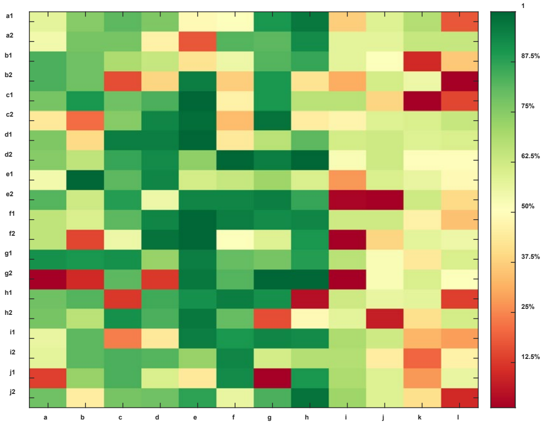
Minimal temp.: **1.3 K**

Vibration: **< 1 μm**

Chip size: **20 mm× 20 mm**

Nanopositioner: **4× 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…