Large-Area High-Speed SNSPDs for Laser Ranging

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SNSPDs: superconductor nanowire single-photon detectors

OUTLINE

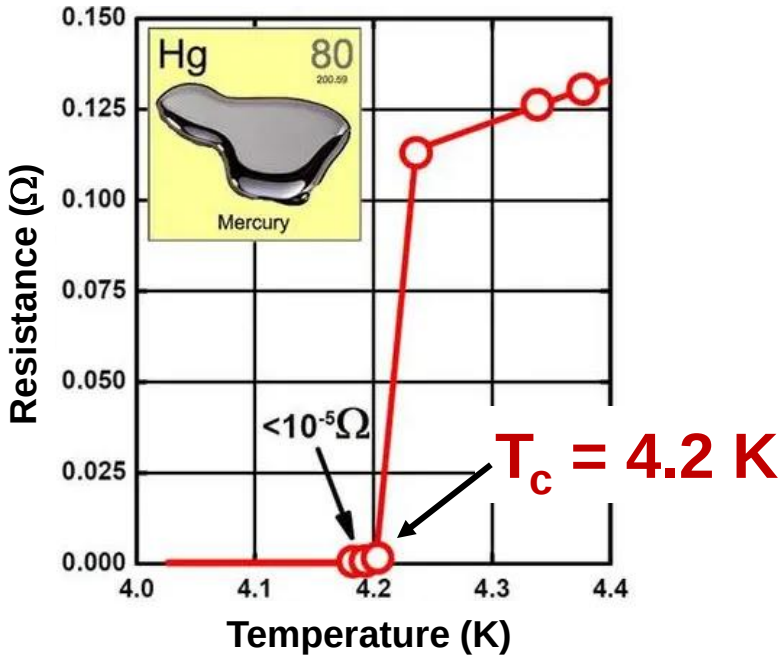
1. Introduction of SNSPDs
2. Large-area and High-speed SNSPDs
3. Application of SNSPDs in Laser Ranging
4. Summary and Perspective

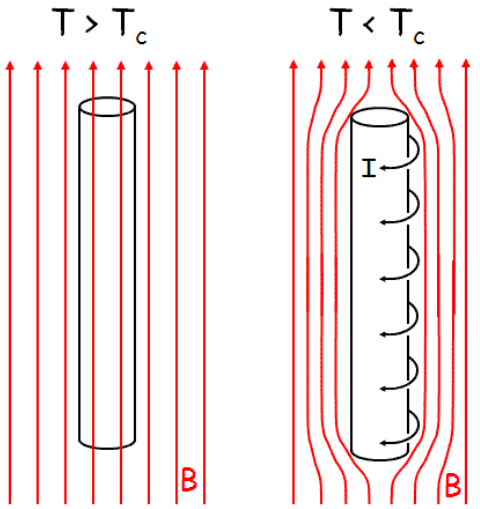
Superconductor

Definition

A superconductor is a type of material that conducts electricity with zero resistance (or energy loss) when cooled to a certain temperature.

superconductivity transition temperature, T_c





Meissner effect

H. K. Onnes, Commun. Phys. Lab. 12, 120, (1911)

Superconductor Changes Our World

Astronomy

Laser ranging

Information

Quantum computing

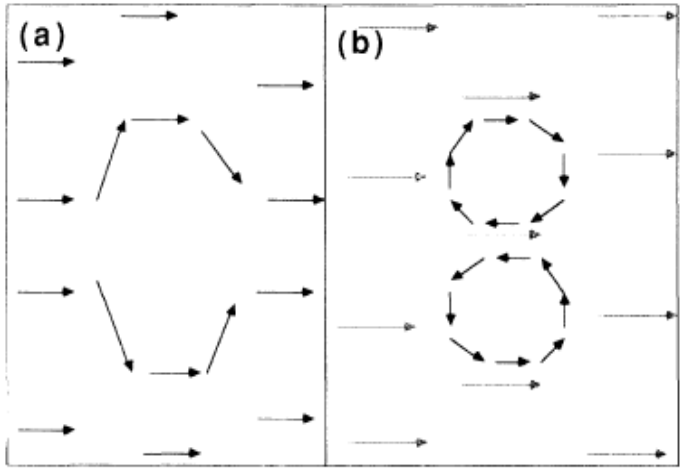
Energy

Power transmission

Health

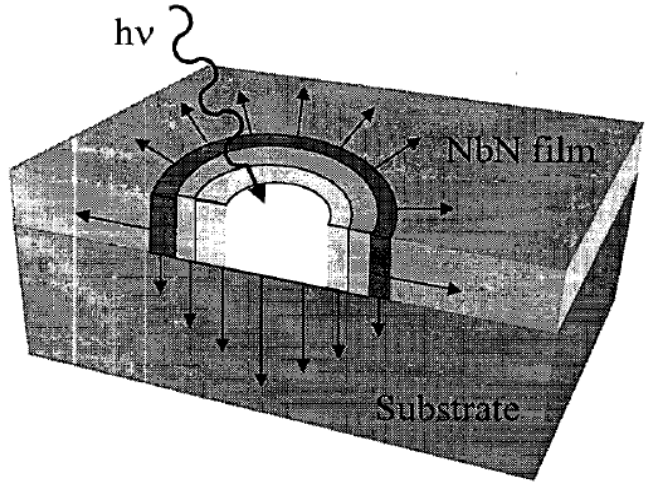
Magnetic Resonance Imaging (MRI)

Birth of SNSPDs



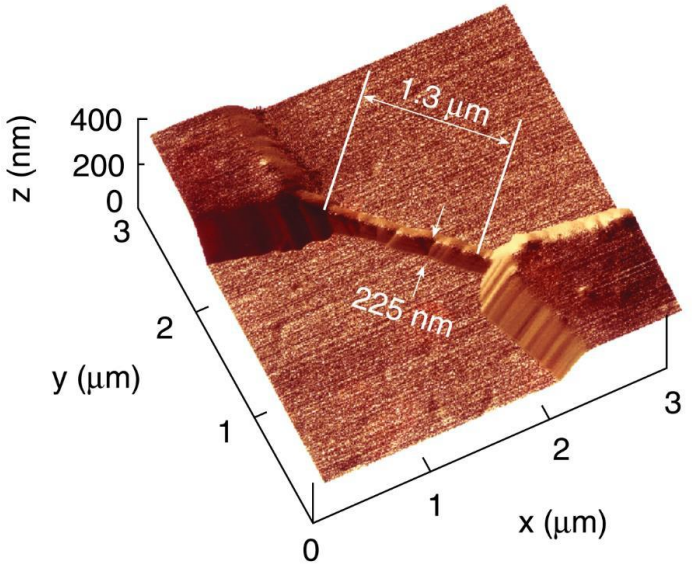
Kadin et al. PRL, 1990.

Single photon can **destroy the superconductivity** of a 2D superconductor.



Gupta et al. IEEE TAS, 1999.

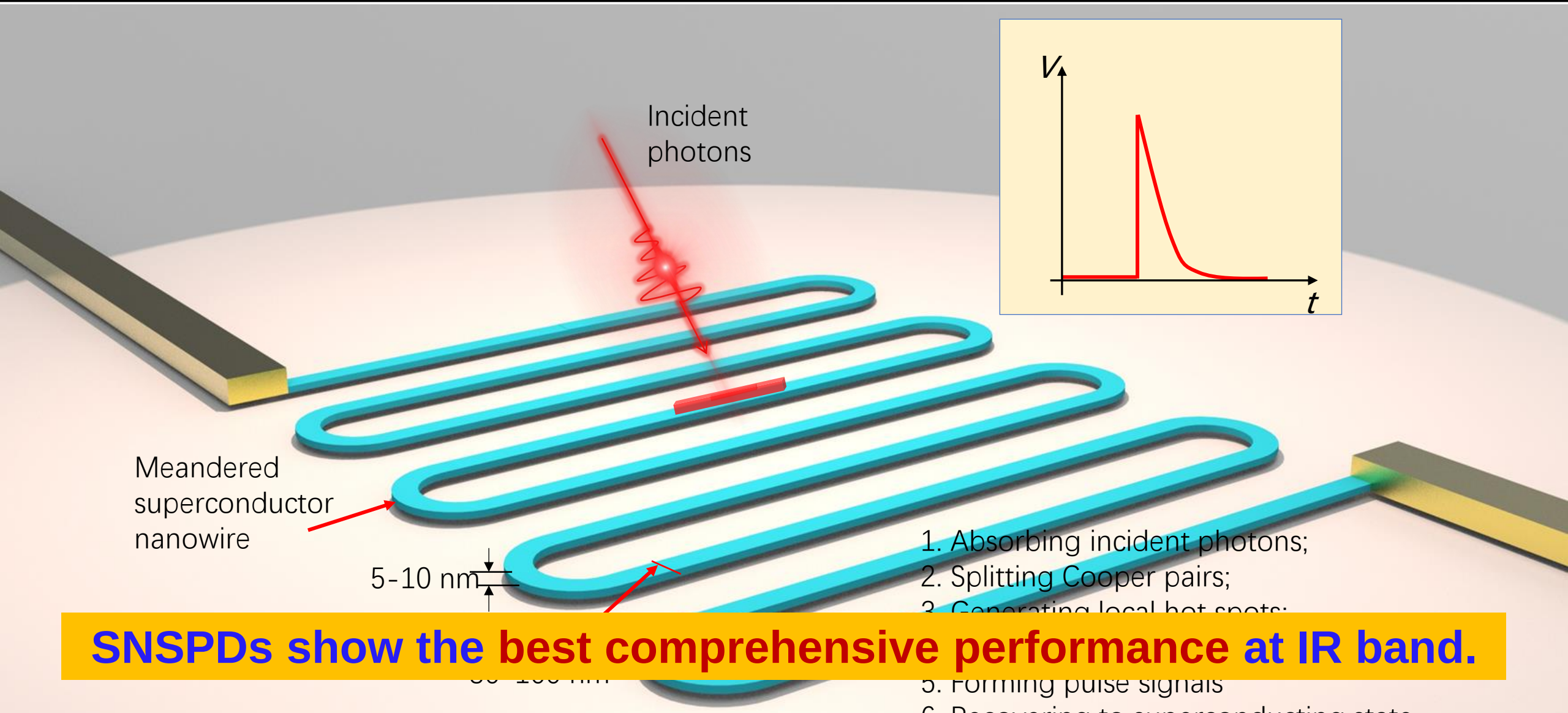
Hotspot can be formed in 1D superconducting NbN once absorbing a single photon



Gol'tsman et al. APL, 2001.

First SNSPD in the world

Detection Process of SNSPDs



1. Absorbing incident photons;
2. Splitting Cooper pairs;
3. Generating local hot spots;
5. Forming pulse signals
6. Recovering to superconducting state.

SNSPDs show the best comprehensive performance at IR band.

OUTLINE

1. Introduction of SNSPDs
2. **Large-area and High-speed SNSPDs**
3. Application of SNSPDs in Laser Ranging
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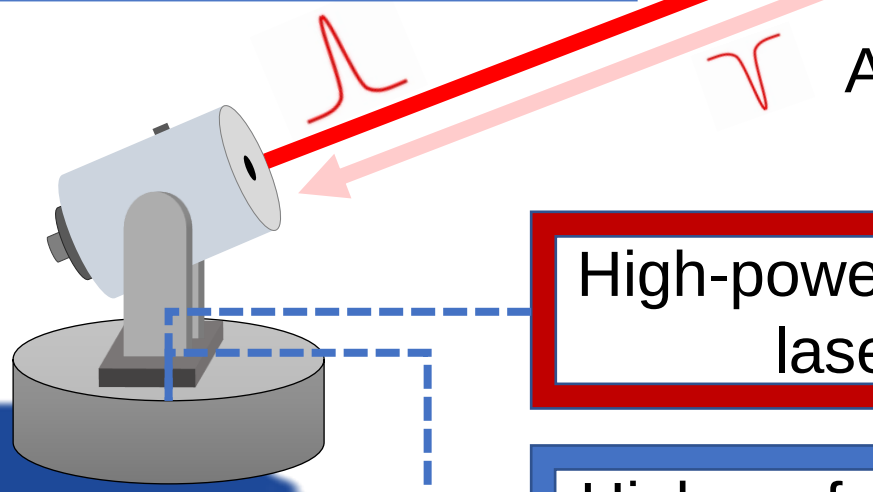
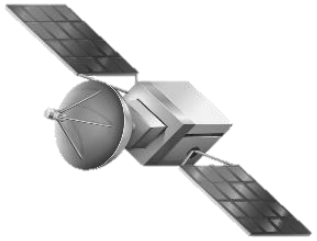
Laser Ranging

Large-aperture optical telescope



High-power pulsed laser

High-performance SPDs (SNSPDs)



Artificial satellites

Space debris

Moon

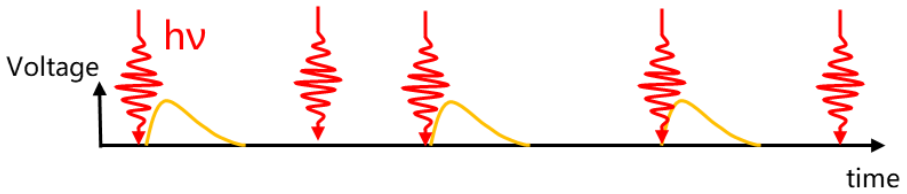
ToF Ranging: $D = \frac{c\Delta t}{2}$

Performance indicators

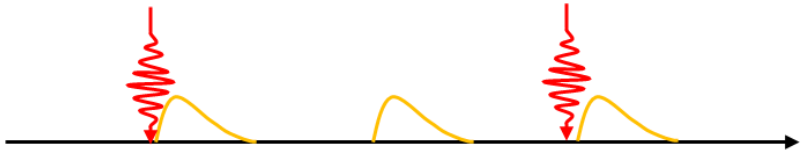
SNSPD

System

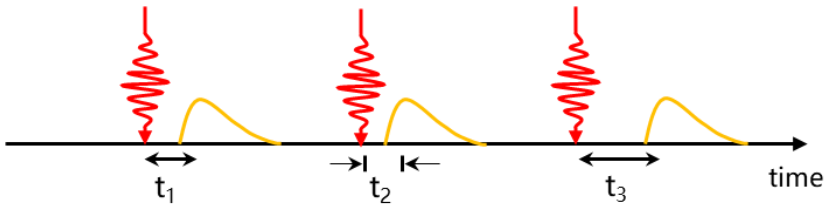
Detection efficiency $DE(\eta_d)$



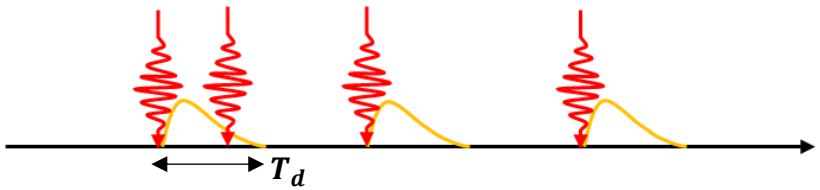
Dark count rate DCR



Timing jitter j_{total}



Recovery time



Signal-noise ratio

$$SNR = \frac{P_R \eta_d}{h\upsilon\sqrt{(DCR + N_b\eta_d)\Delta t}}$$

➡ **Detection range**

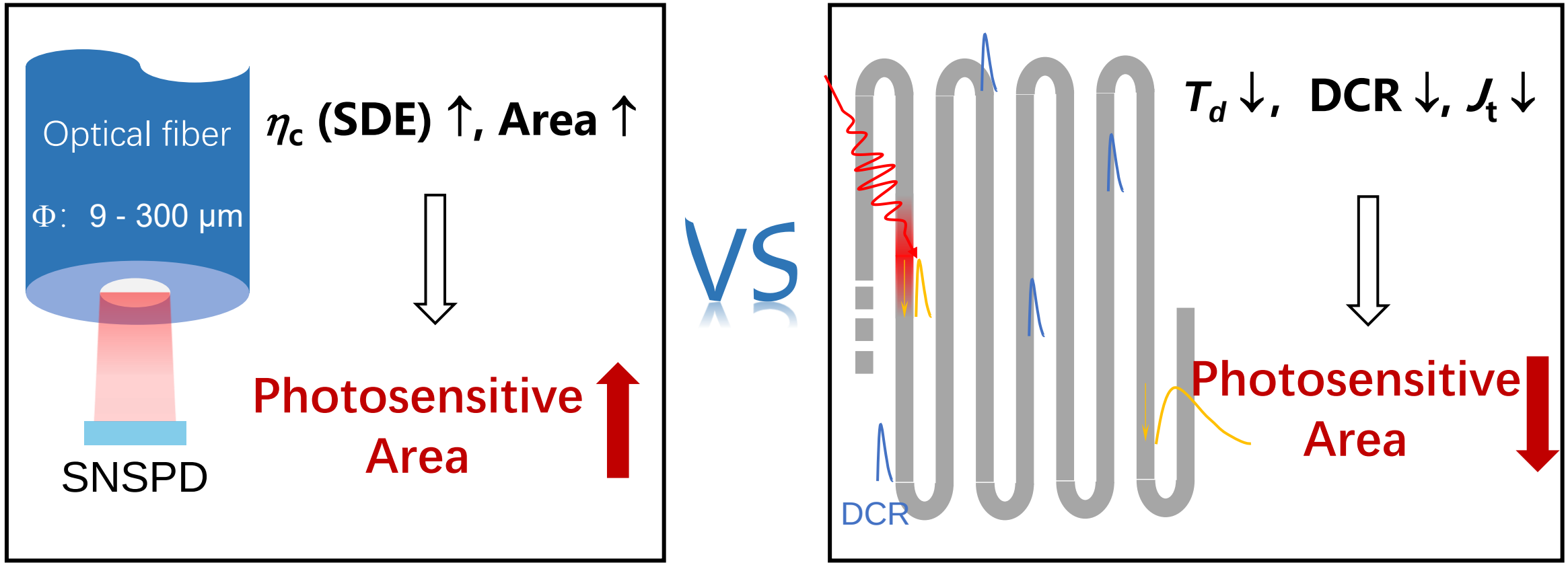
$$j_{total} = \sqrt{j_{SPD}^2 + j_{TCSPC}^2 + j_{laser}^2 + j_{sync}^2}$$

➡ **Depth accuracy**

$$T_d \propto L_k = \left(\frac{L}{w}\right)\frac{R_{sq}}{2\pi\Delta(T)}\tanh\left(\frac{\Delta(T)}{2k_BT}\right)$$

➡ **Acquisition time**

Contradictory between Area and Speed



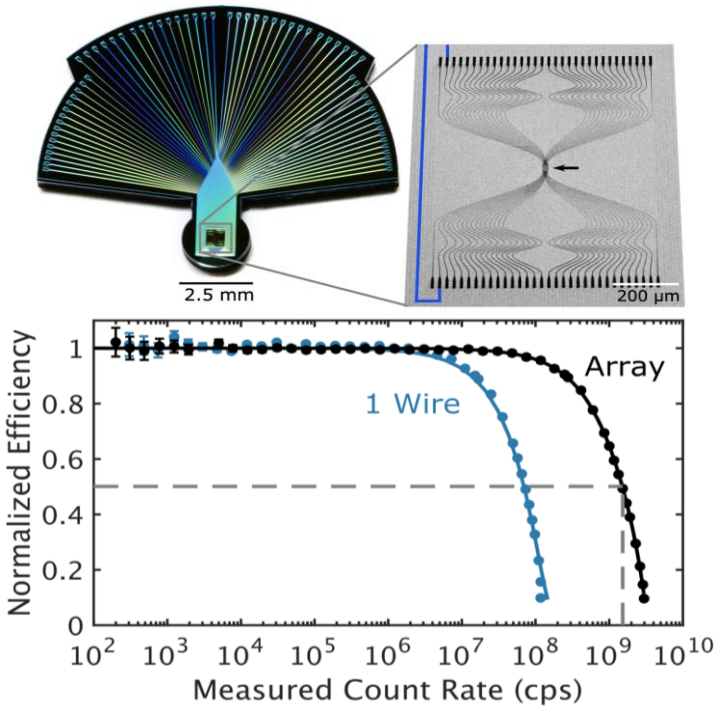
Challenge: Synchronizing large area and high speed of SNSPD

Latest status of high-speed SNSPD

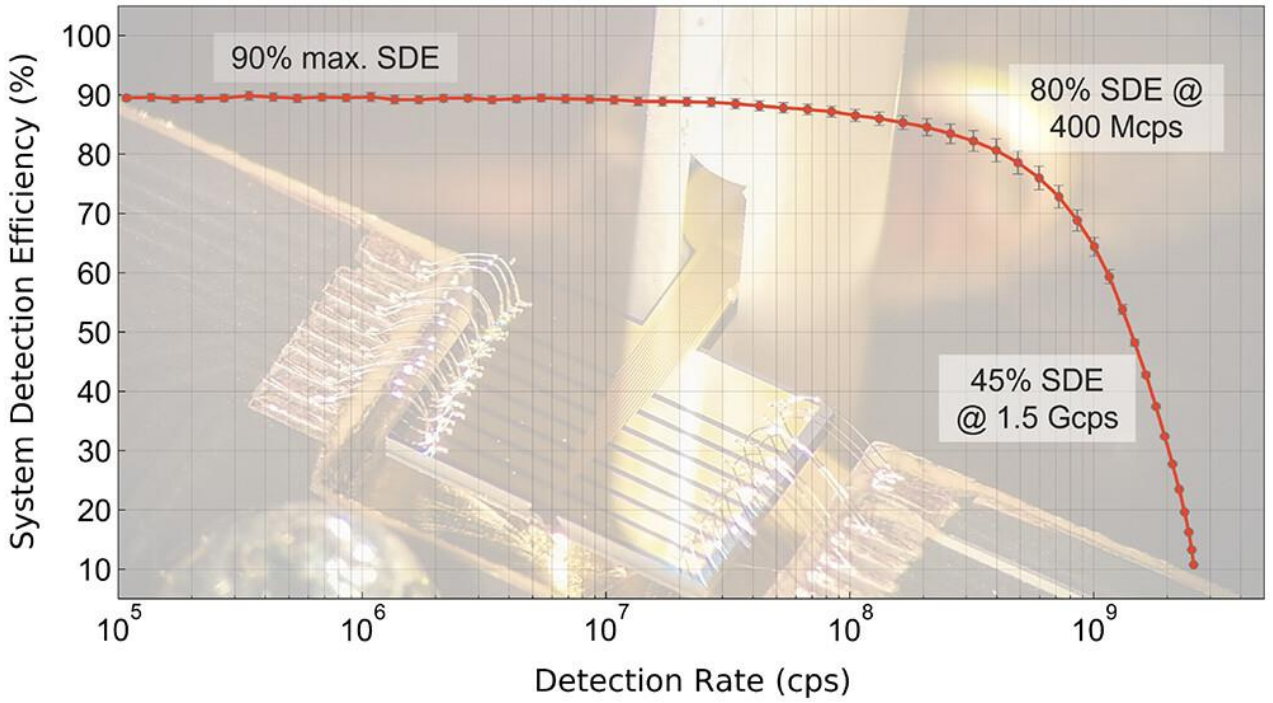
Current gigahertz (GHz) SNSPDs remain two issues:

1) Single-mode fiber is **incompatible** with most large-aperture telescopes,

2) **Uneven distribution** of nanowires limits the system performance.



Craiciu et al. Optica 2023

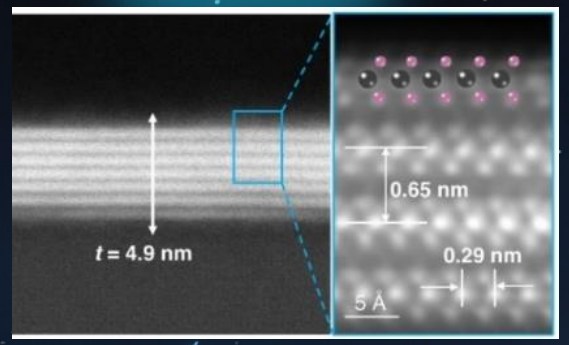


Resta et al. Nano Letters 2023

Our Lab: from fundamentals to applications

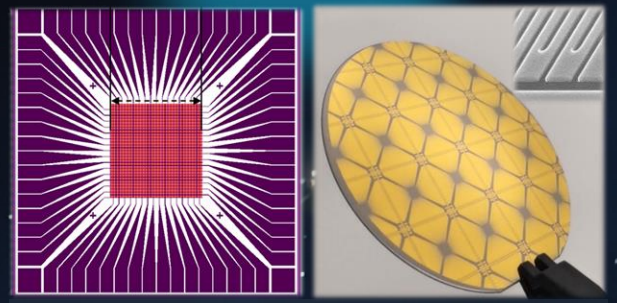
Full-link SNSPD research

Materials

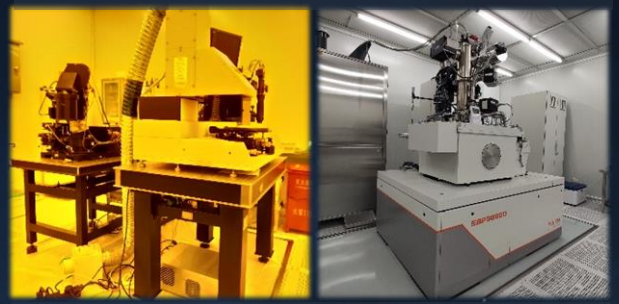


Thin film

Device

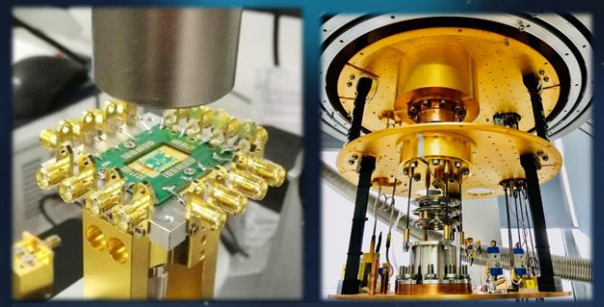


Structural design



Nano-fabrication

Integration

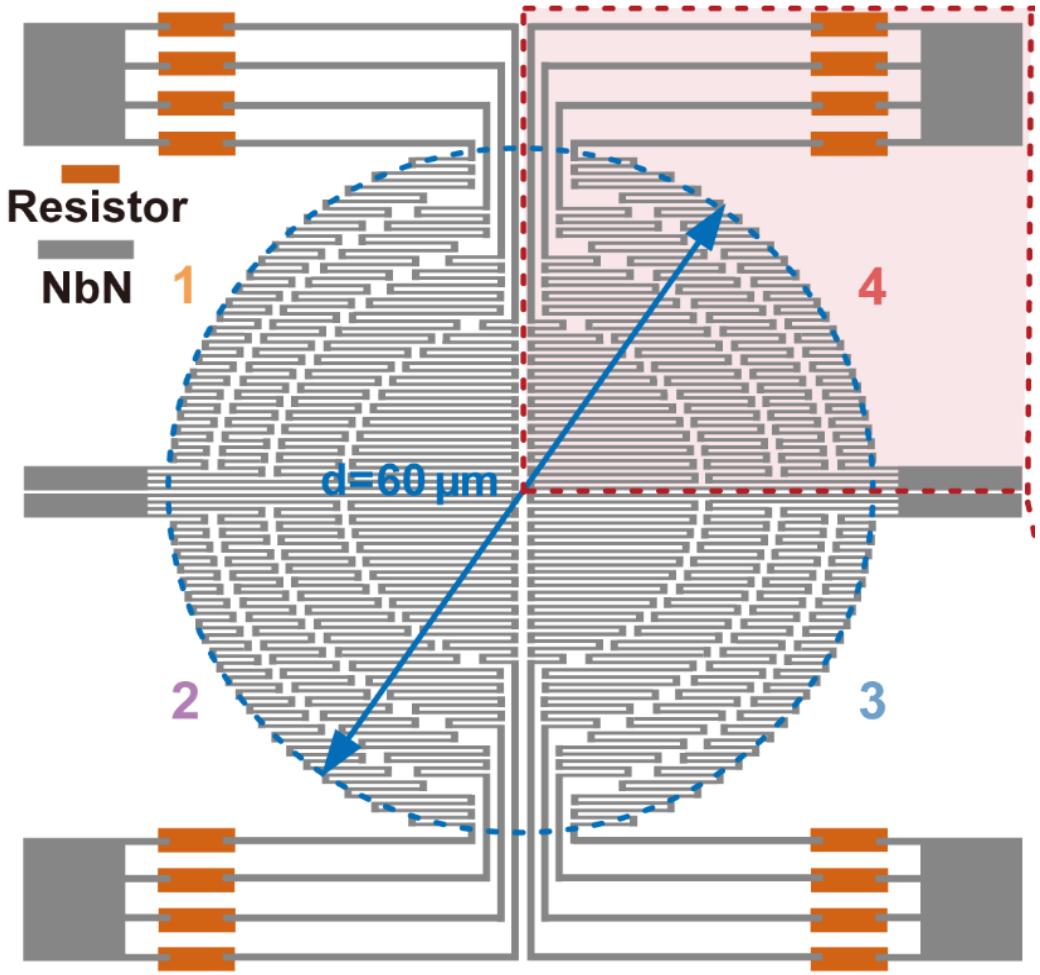


Platform

Optics and readout

System

Device Structure Design



- **Array with 4 pixels:**

  Rotation-symmetric structure

- **4 nanowires:**

  Concentric-circular parallel structure

- ✓ **A large detection area of ø60 μm**

  Coupling with ø200 μm MMF

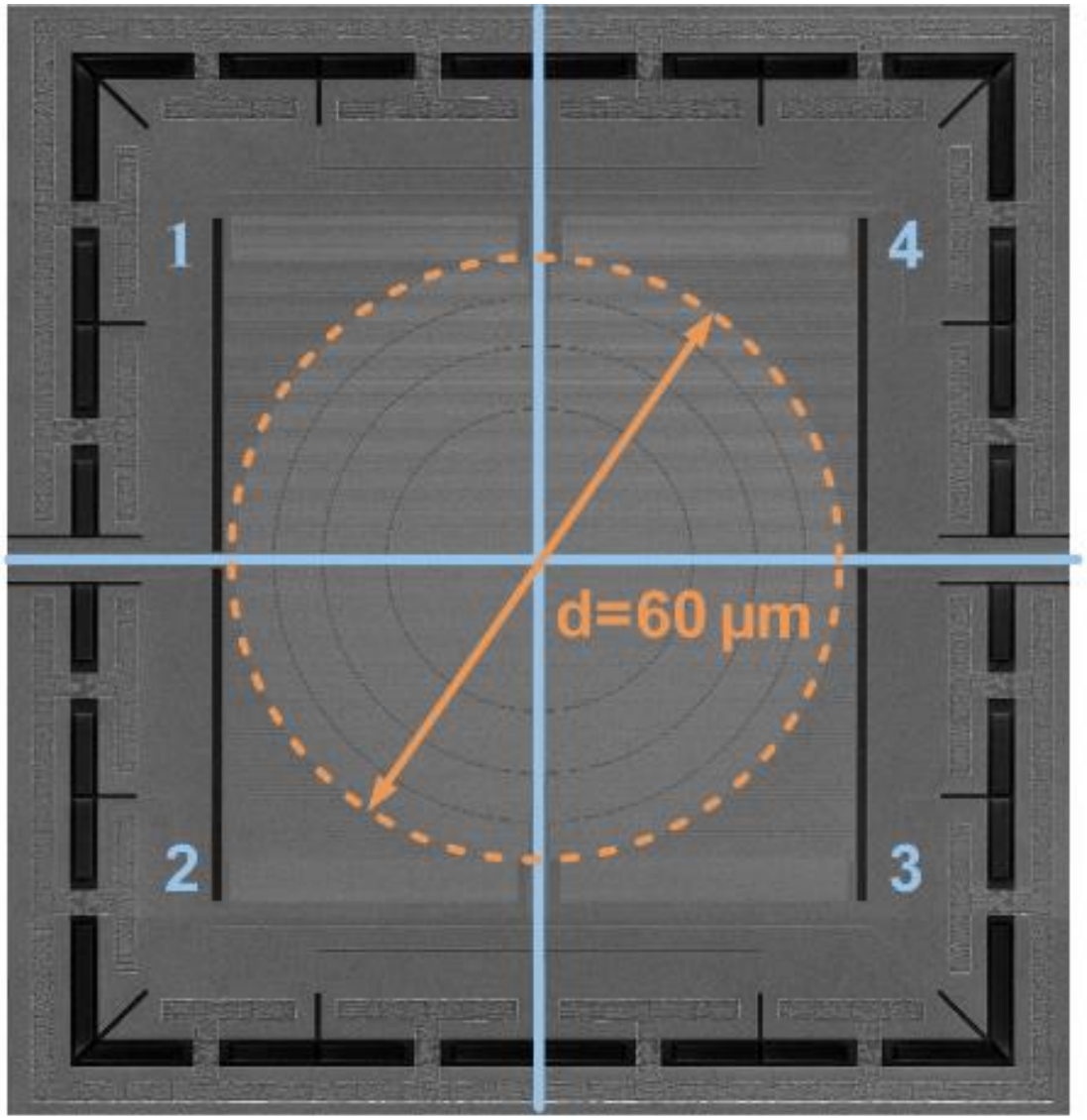
- ✓ **decreasing L_k by 16 times**

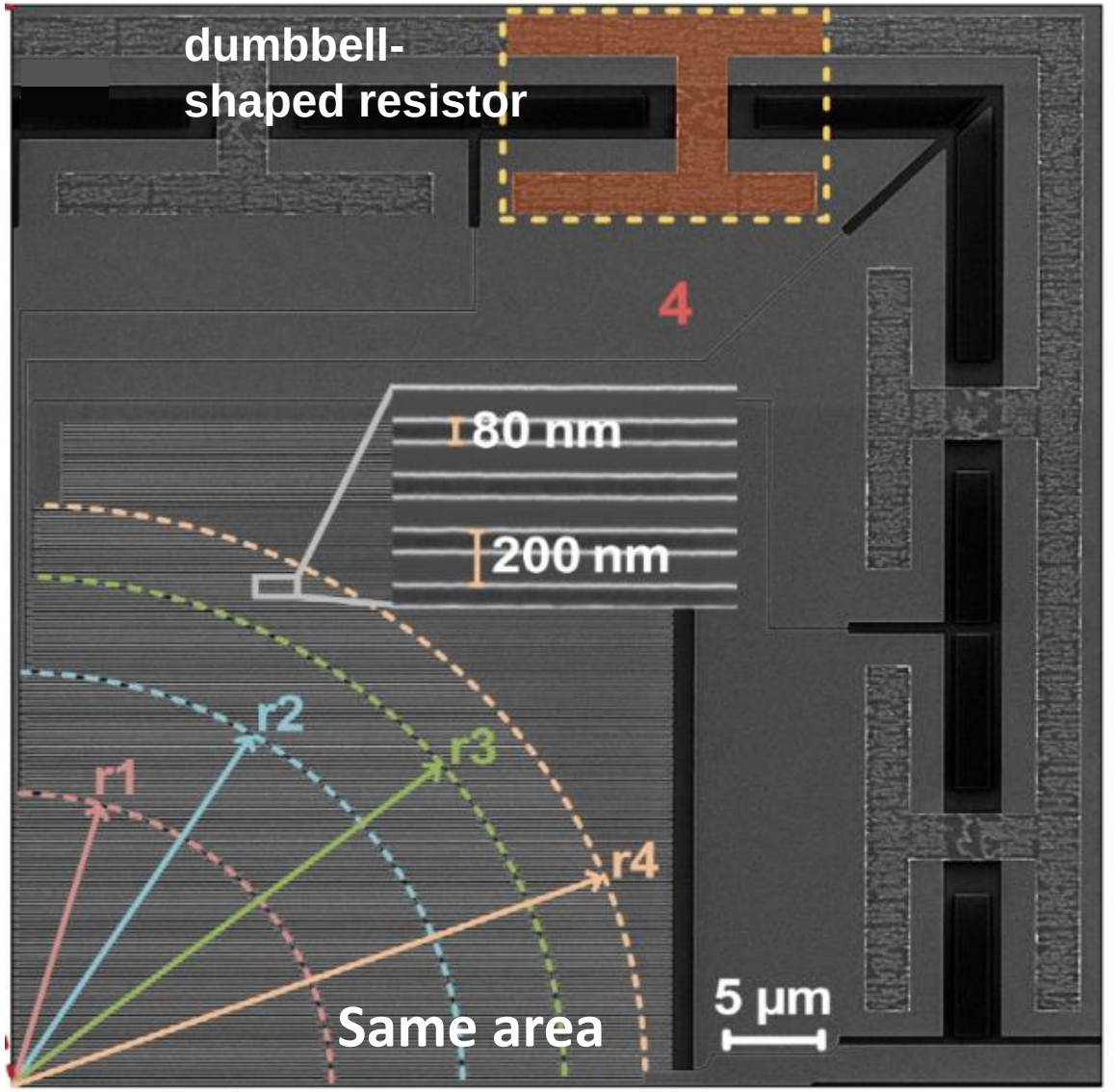
  Increase the detection speed

- **On-chip series resistors**

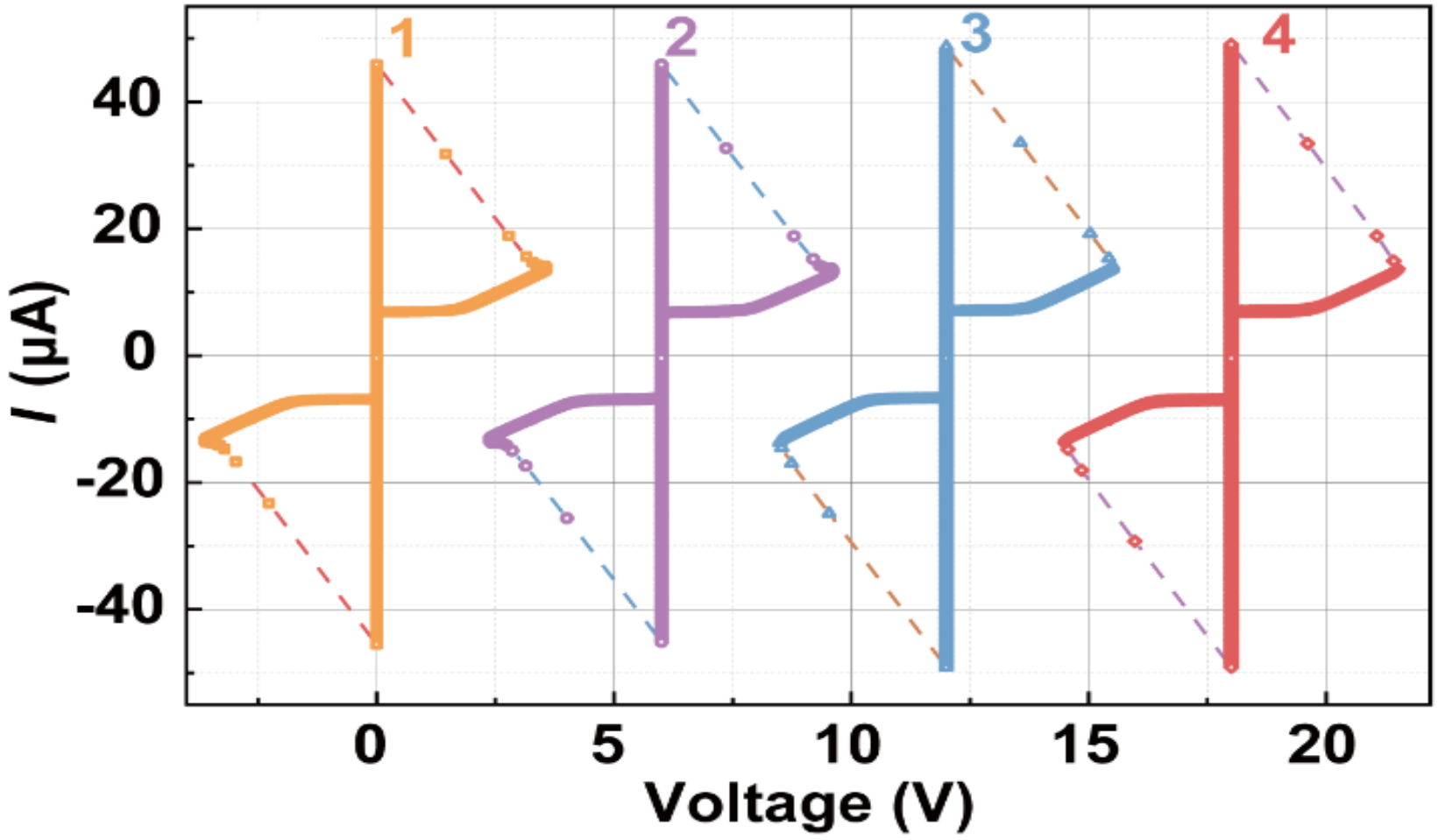
- ✓ Suppressing electrical crosstalk & Improving signal-noise ratio

Device fabrication based on layout design



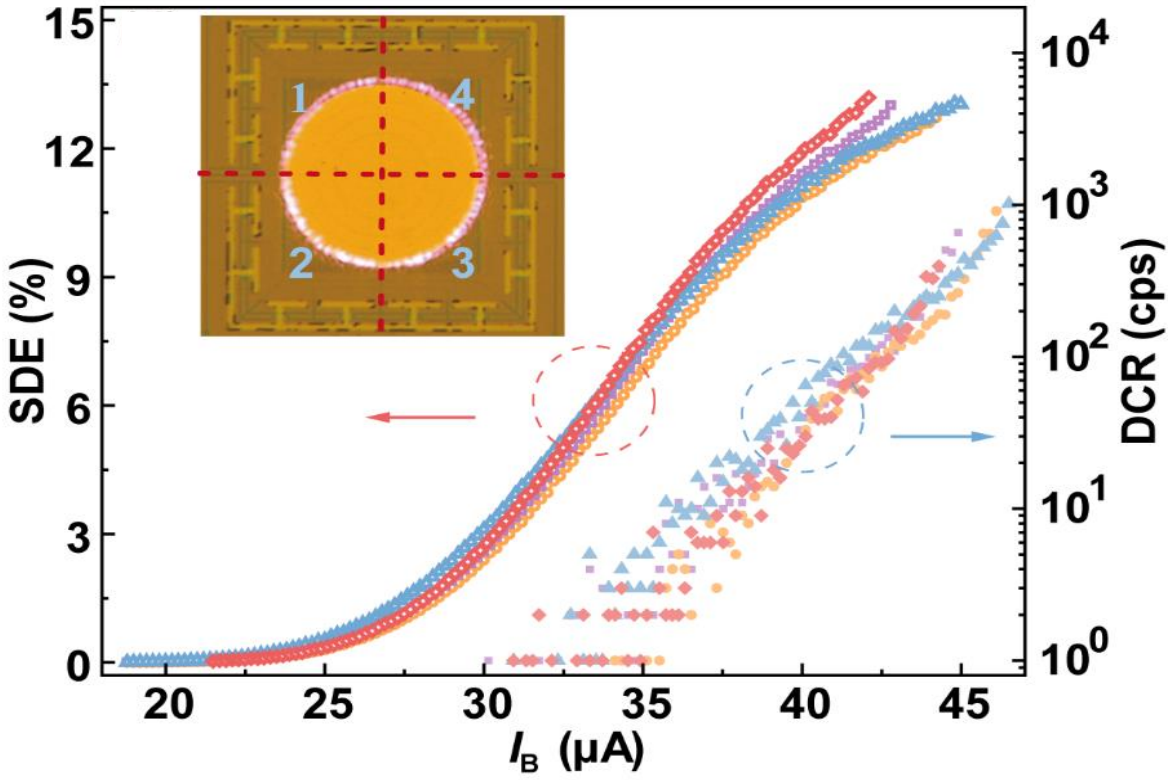


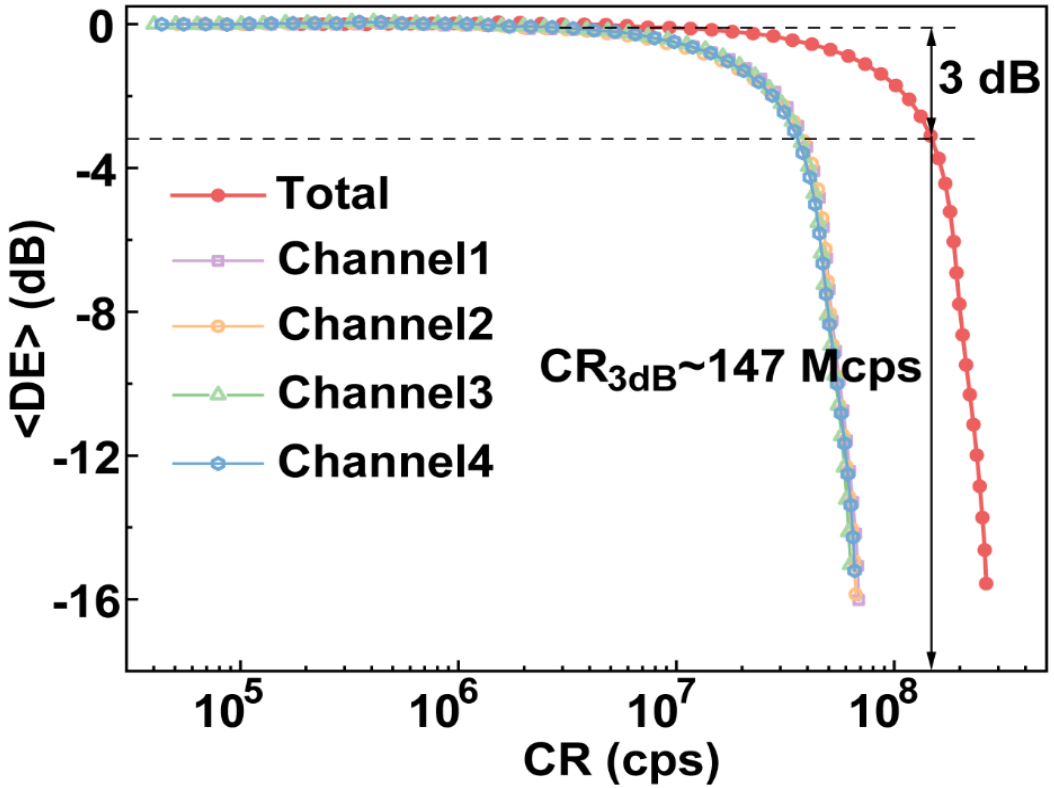
Uniform superconductivity of pixels



All the four pixels exhibit almost same I-V curves, proving the excellent high quality and uniformity of nanowires.

Realizing Large-area and High-speed SNSPD





- Coupling with ø200 μm multimode fiber, having a total SDE > 50% at 1064 nm
- Total count rate of four channels reaches ~147 Mcps@3dB DE drop

Comprehensive Performance

Institution	Year	N	A (μm^2)	f(CR@3 dB drop) (Gcps)	SDE(f)	P=(A·f)/N·SDE(f) (μm^2 Gcps)
SIMIT	2019	16	177	0.93	31%	3.2
JPL	2022	32	450	1.5	39%	8.2
UNIGE	2023	14	189	1.5	45%	9.1
NJU	**2023**	**4**	**2828**	**0.147**	**24%**	**24.9**

Highest comprehensive performance among the SNSPDs in the past 5 yrs.

More details refer to ***Appl. Phys. Lett. 123, 142601 (2023)***

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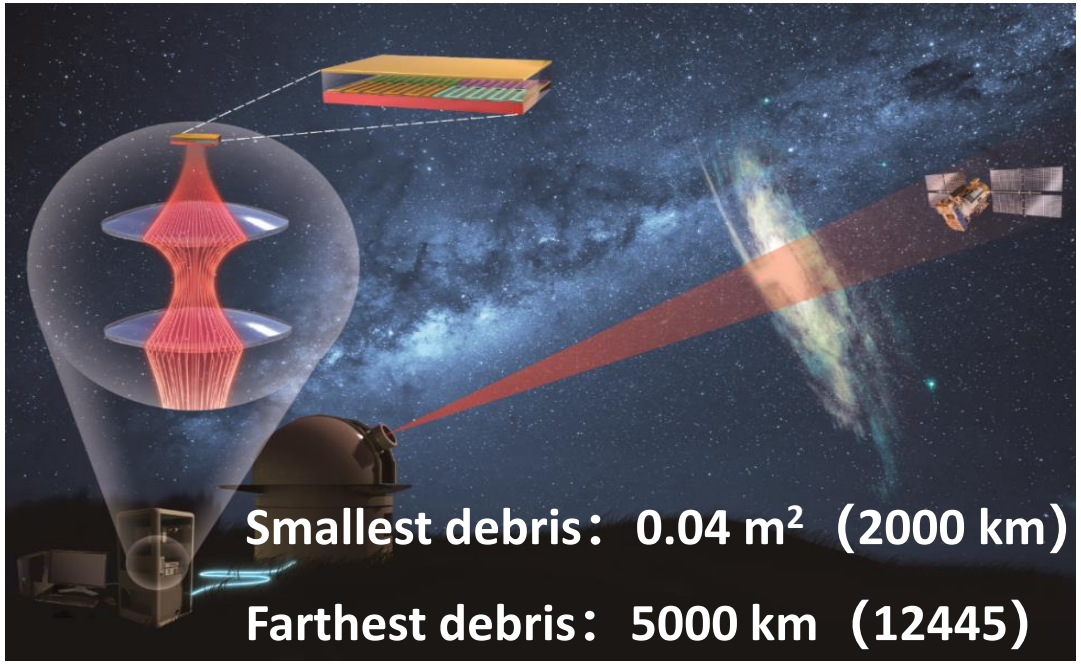
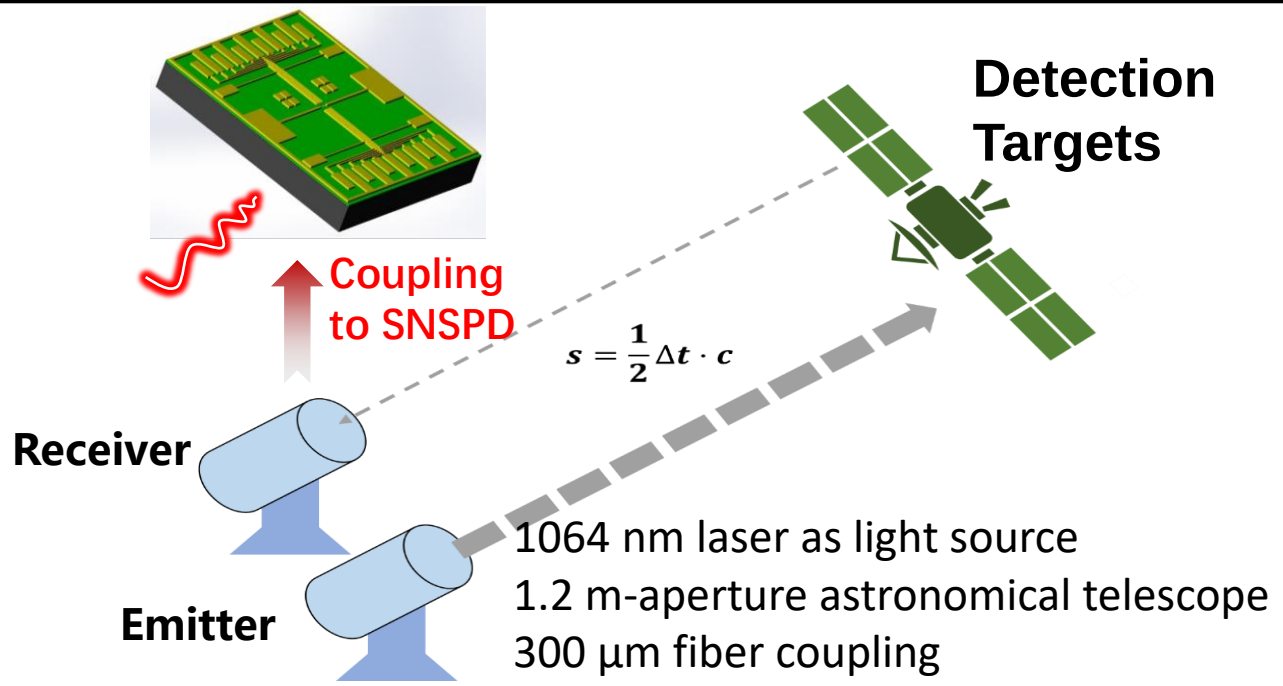
Daytime Satellite/Debris Ranging



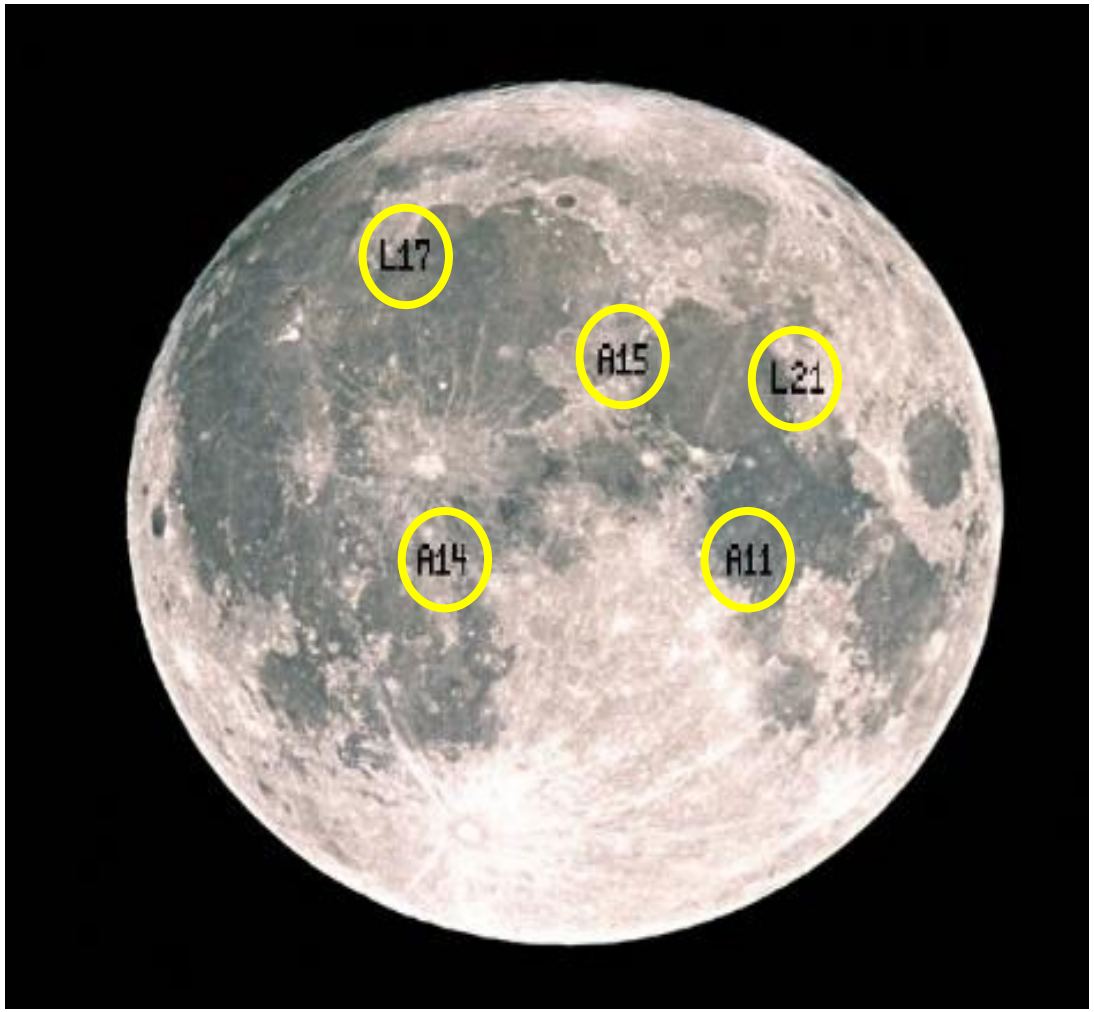


Target	Beaconc Satellite	Beidou Satellite	No.22803 Space Debris	Glonass134 Navigation Satellite	Hy2a Ranging Satellite
Height	~1,000 km	~36,000 km	~850 km	~20,000 km	~1,000 km
Condition	Night			Daytime	

✓ Overcoming strong background noise and promoting all-day satellite ranging technology

Cooperated with **Yunnan Observatories**, etc.

Moon-to-Earth Ranging

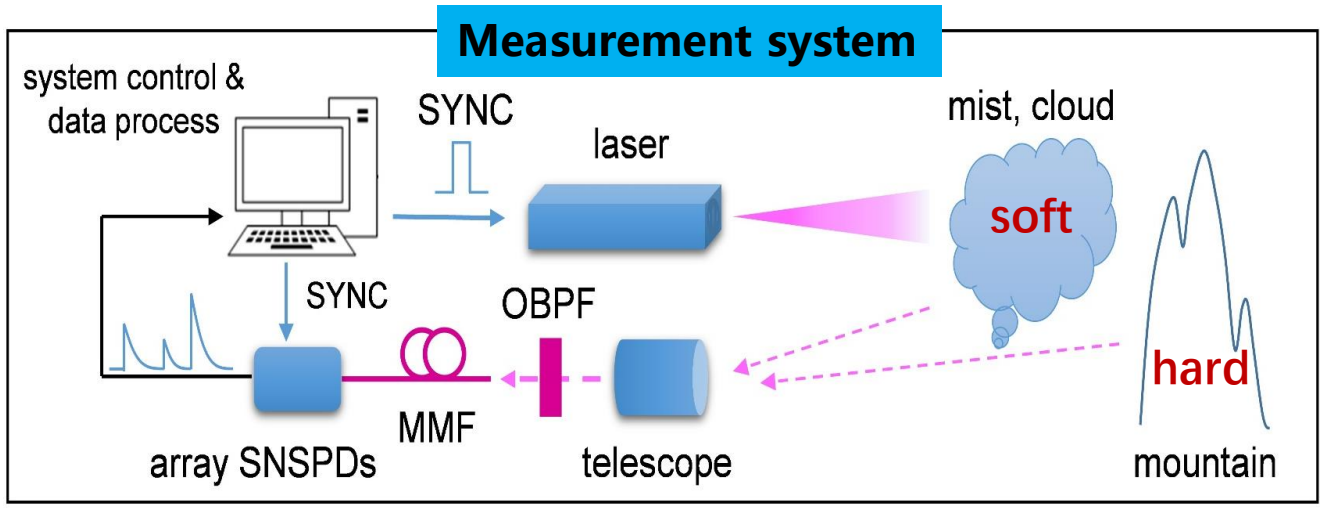


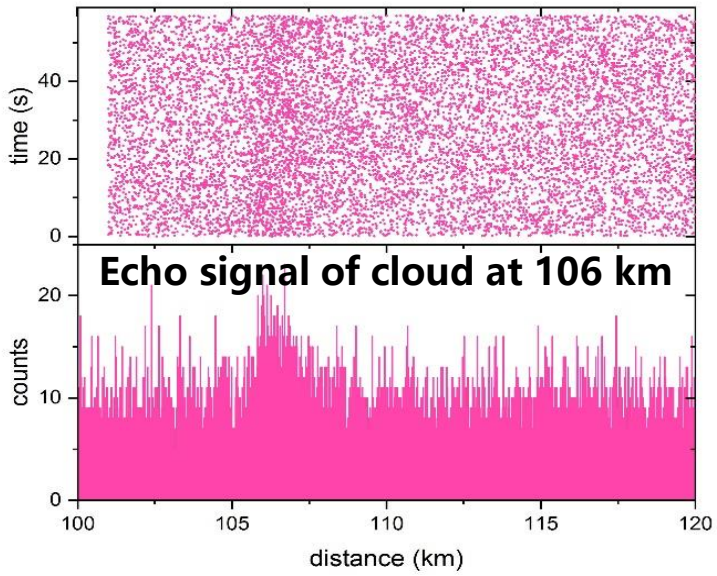
Reflector	Number (half year)
APOLLO 15	235
APOLLO 14	20
APOLLO 11	9
LUNA 17	25
LUNAR 21	21
Standard point/ Total echo point	310/17655

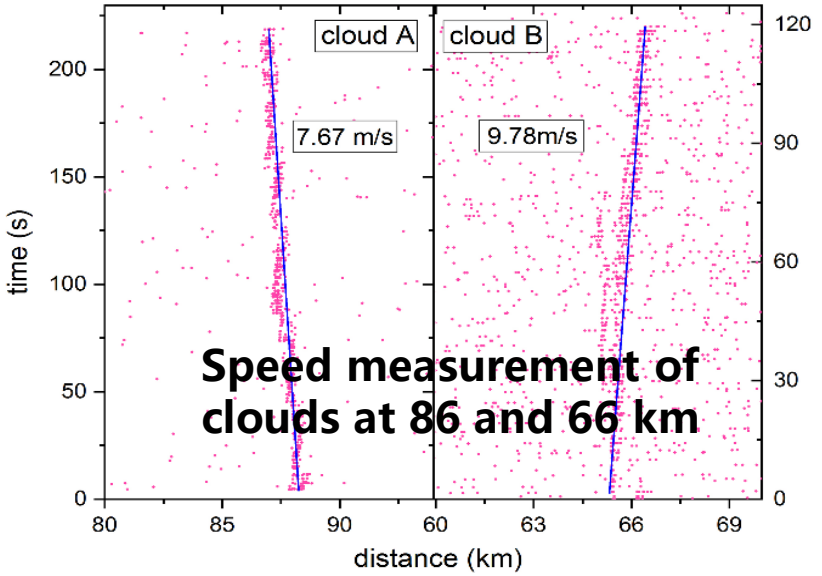
- ✓ **Applying SNSPD for MER for the first time;**
- ✓ **Achieving all 5 reflectors on the moon;**
- ✓ **Effective even at full-moon condition.**

Cooperated with **TianQin Center**, etc.

Soft target monitoring







All-day SNSPD-based laser ranging system can dynamically monitor clouds tens of kilometers away.

Superconductor Science and Technology 34, 034005, (2021)

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Summary and Perspective

✓ **Large-area high-speed SNSPDs are developed.**

Synergistic structure design overcomes the contradictory between area and speed, realizing the highest comprehensive performance (24.9)

✓ **As-developed SNSPDs have been successfully applied in laser ranging.**

Satellite/debris detection | Moon-to-earth ranging | Soft target monitoring

✓ **Fundamental research are ongoing toward advancing SNSPDs.**

Broader response band | Larger pixel scale | Extreme signal-noise ratio

Acknowledgment

Contributions from all the members in ZLB-lab and RISE, and other institutes.

Fundings: Innovation Program for Quantum Science and Technology,

National Natural Science Foundation of China,

Natural Science Foundation of Jiangsu Province, etc.

Thanks for your attention!

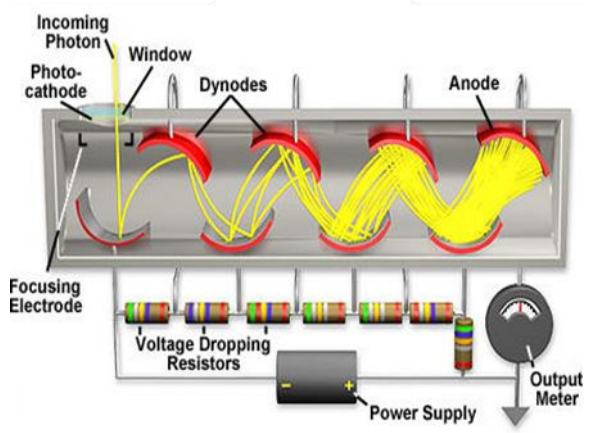
Nanjing University, Xianlin Campus

Single-photon detectors (SPDs)

Definition

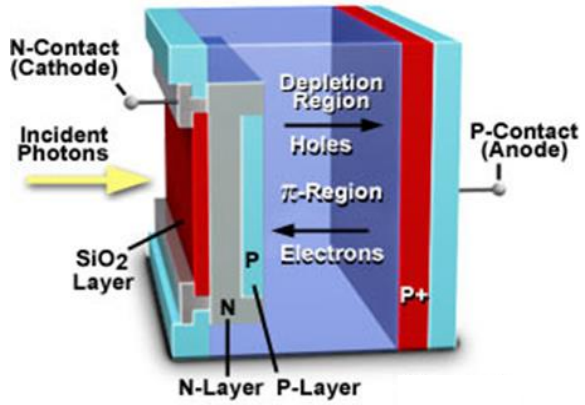
SPDs are ultra-sensitive devices that can detect and count individual photons.

Photomultiplier tube (PMT)



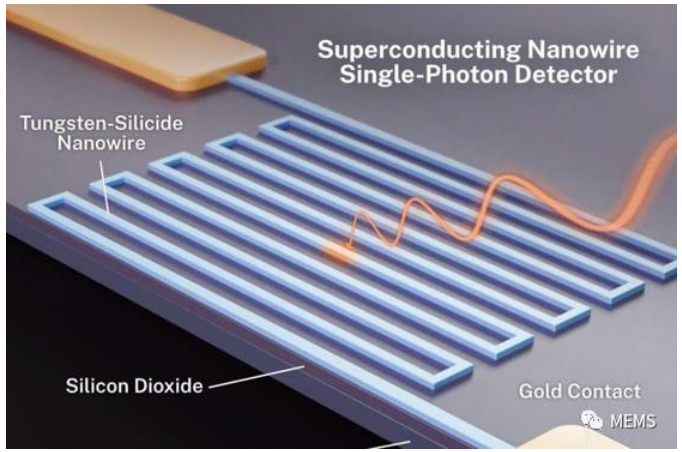
Opt. Lett. 2002, 27, 2076

Avalanche photodiode (APD)



Opt. Express 2018, 26, 23819

SNSPD

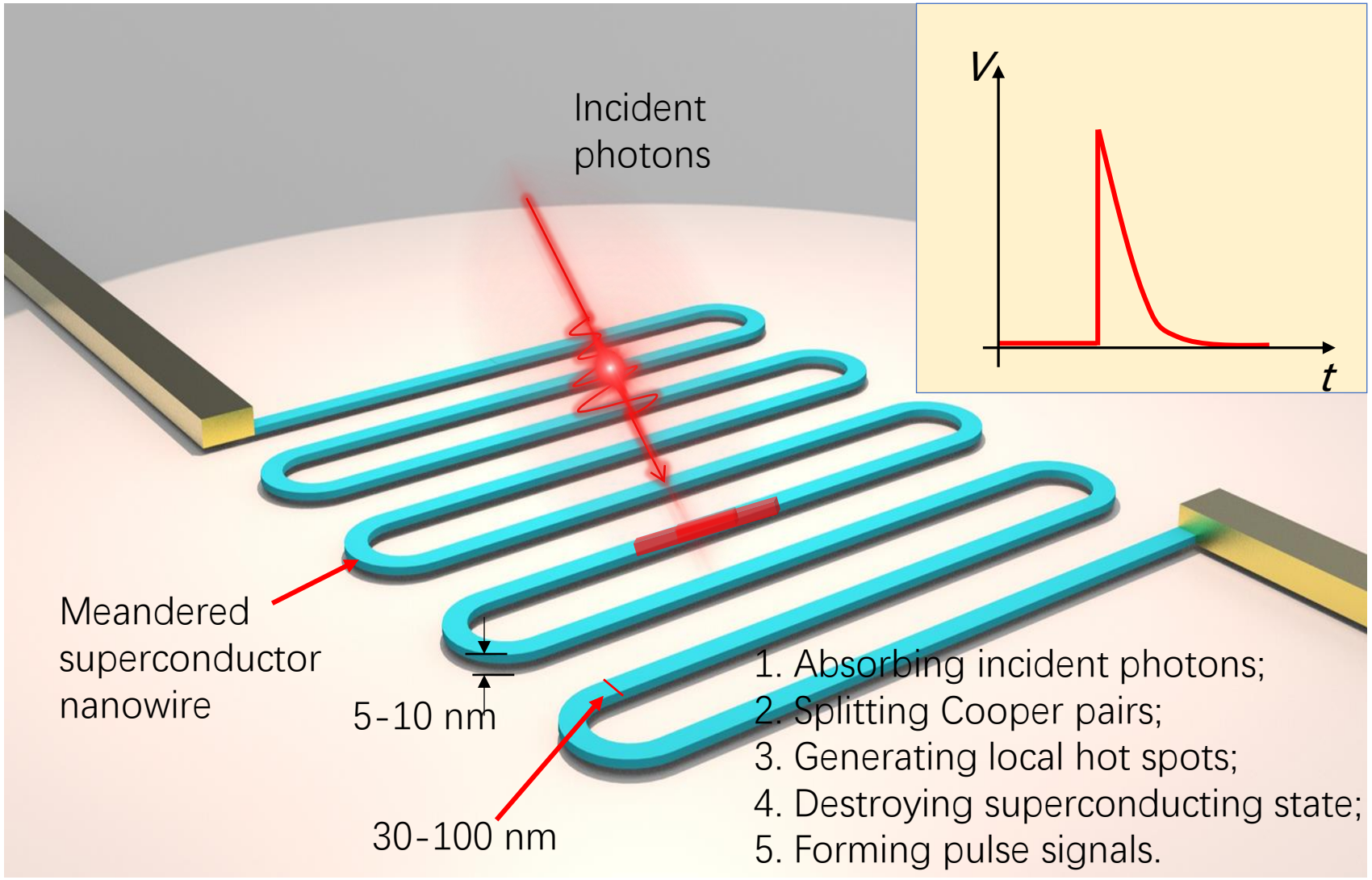


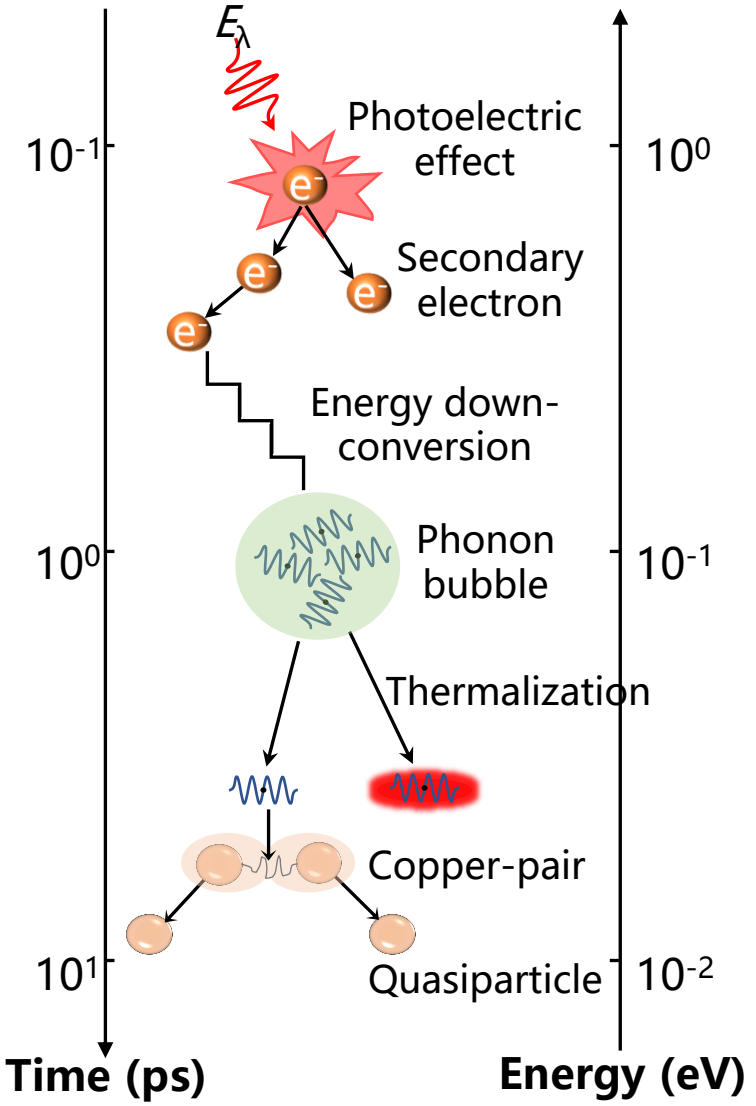
APL Photon. 2021, 6, 056101

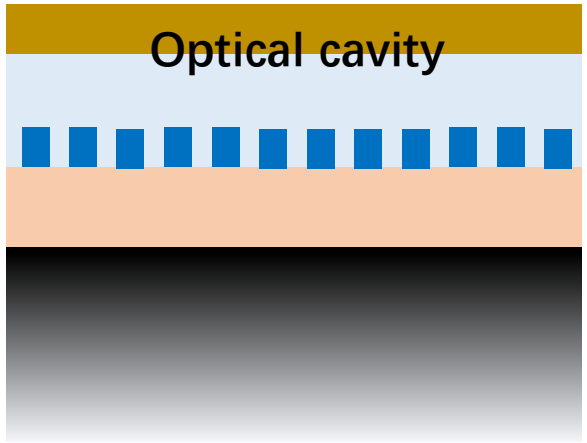
PMT、APD	Semiconductor	High detection efficiency at visible wavelength range; Bandgap limit
SNSPD	Superconductor	Extremely low superconducting gap, high DE, low DCR at infrared

SNSPDs show the best comprehensive performance at infrared band.

Our achievements in SNSPDs







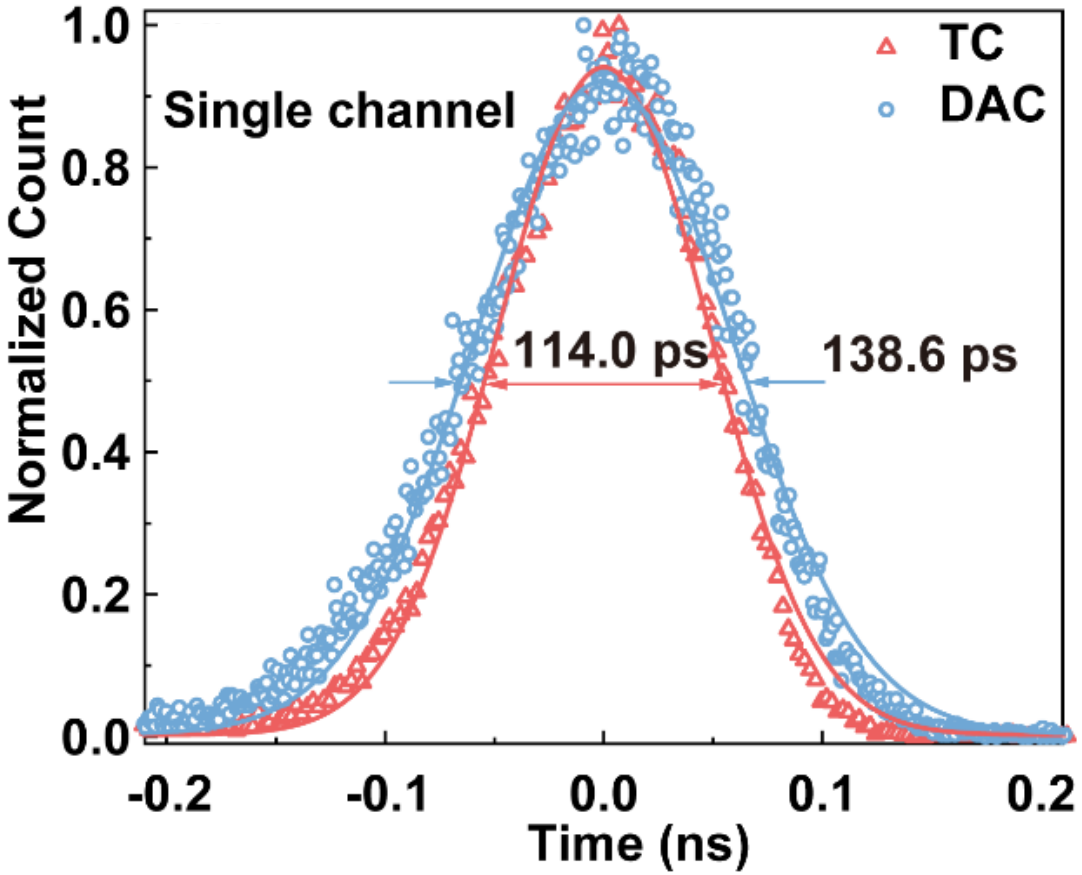
50 nm Golden layer

190 nm Silicon oxide

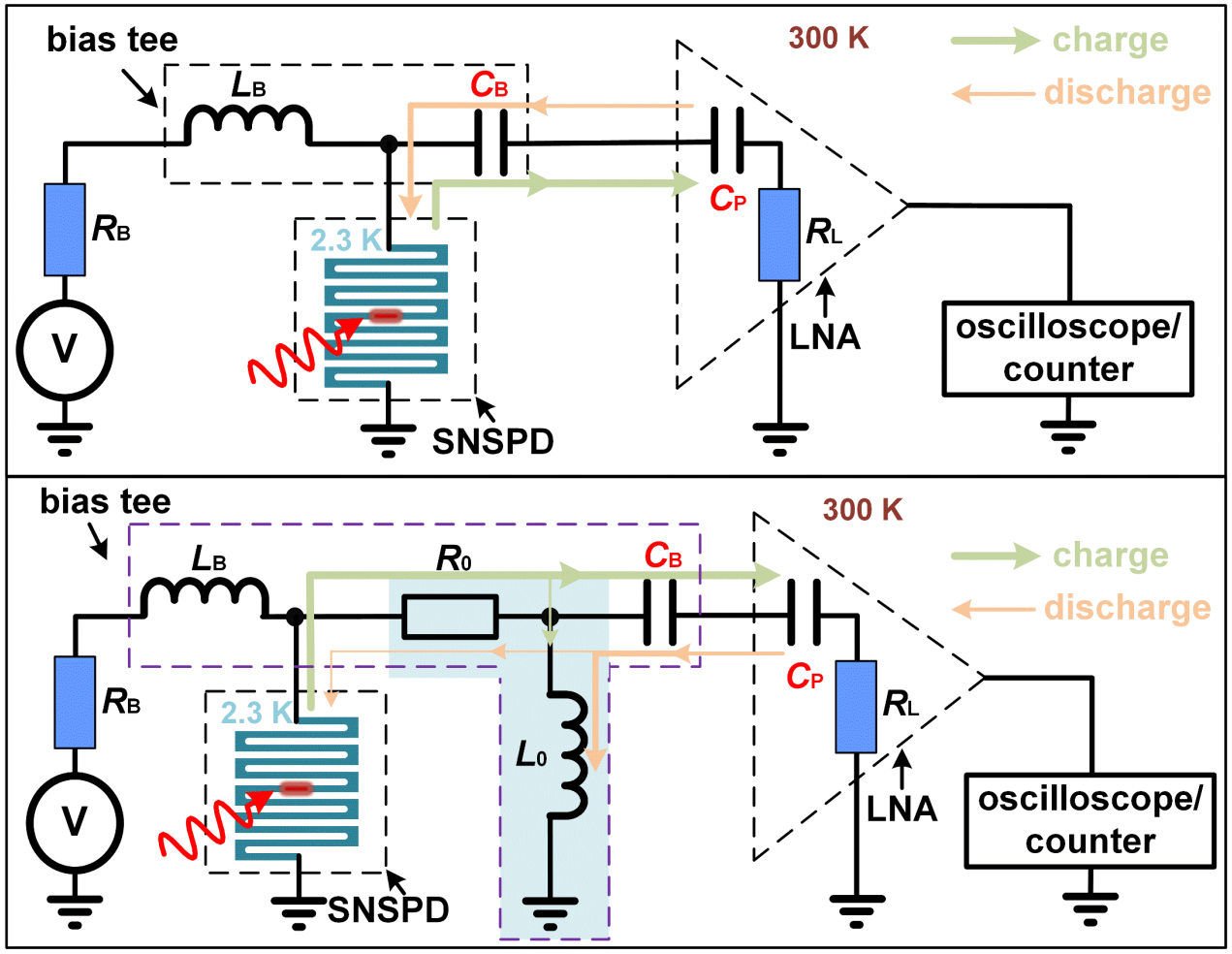
8 nm thick NbN nanowires

135 nm Silicon nitride

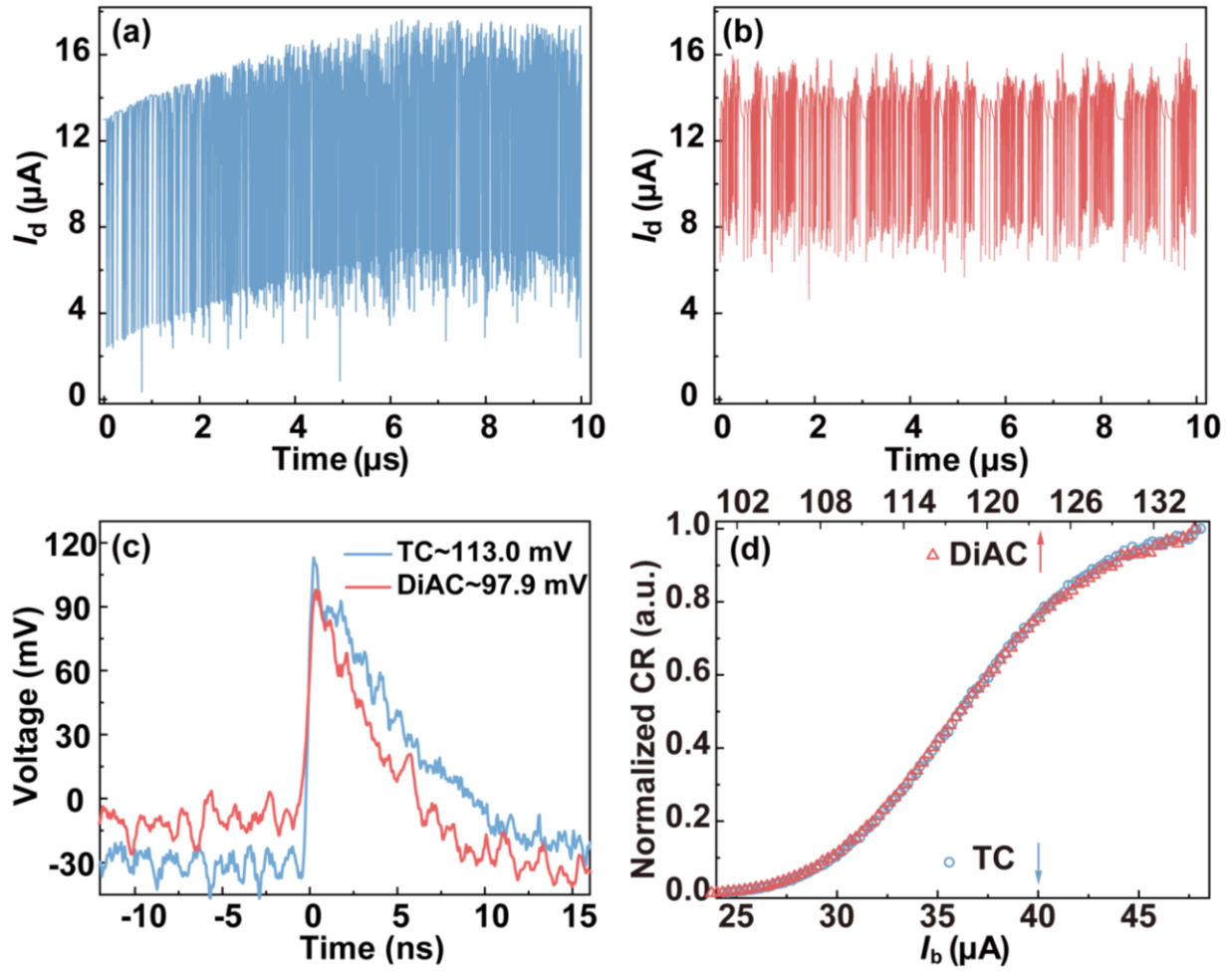
Silicon substrate



Readout optimization

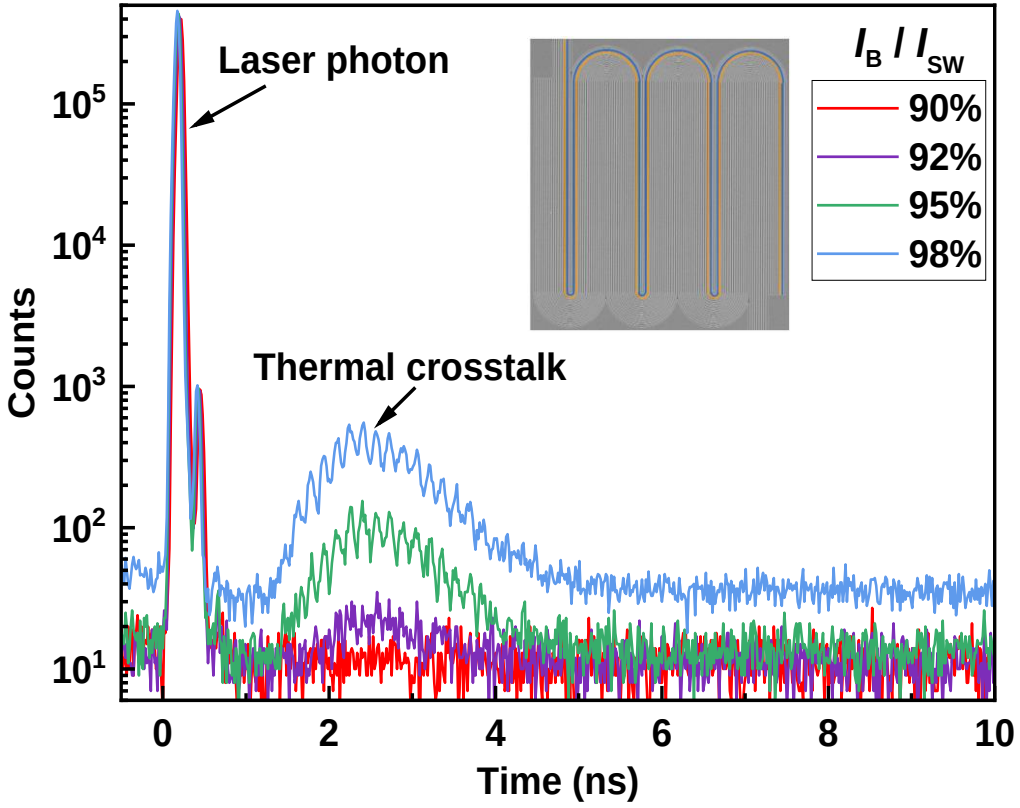


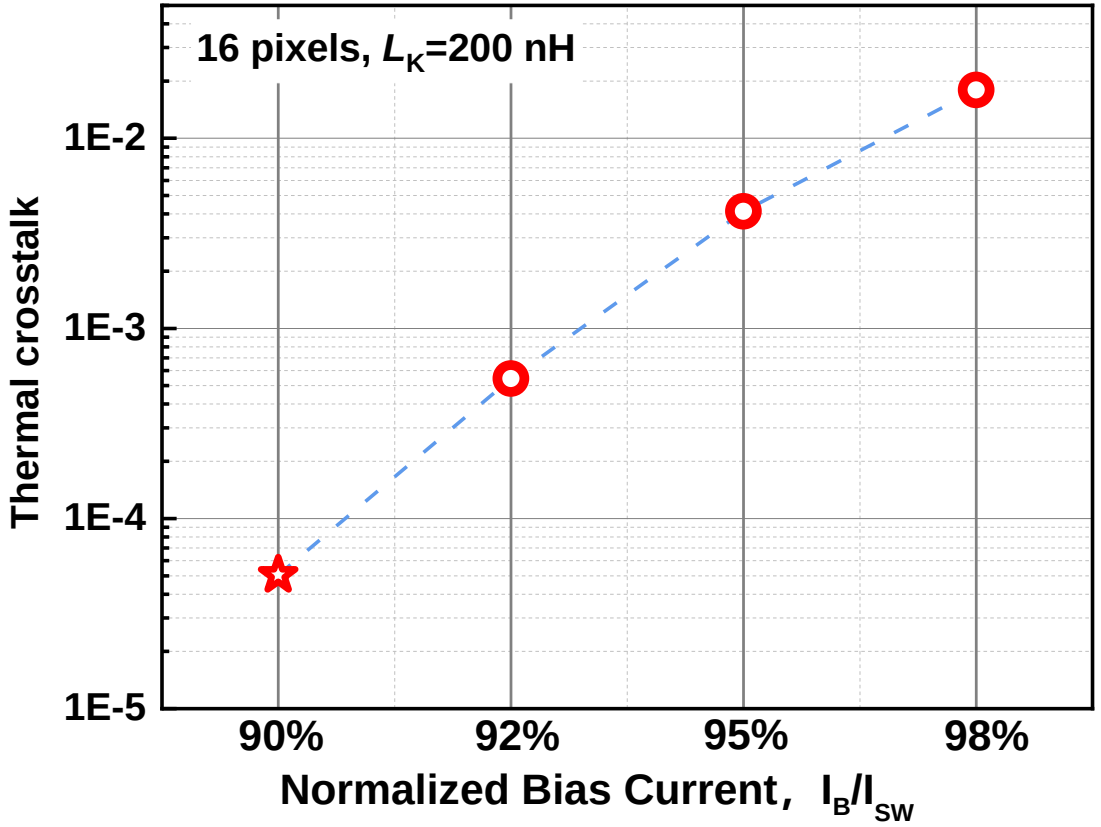
- Traditional circuit (TC)
- Discharge acceleration circuit (DiAC)



- The effect of DiAC

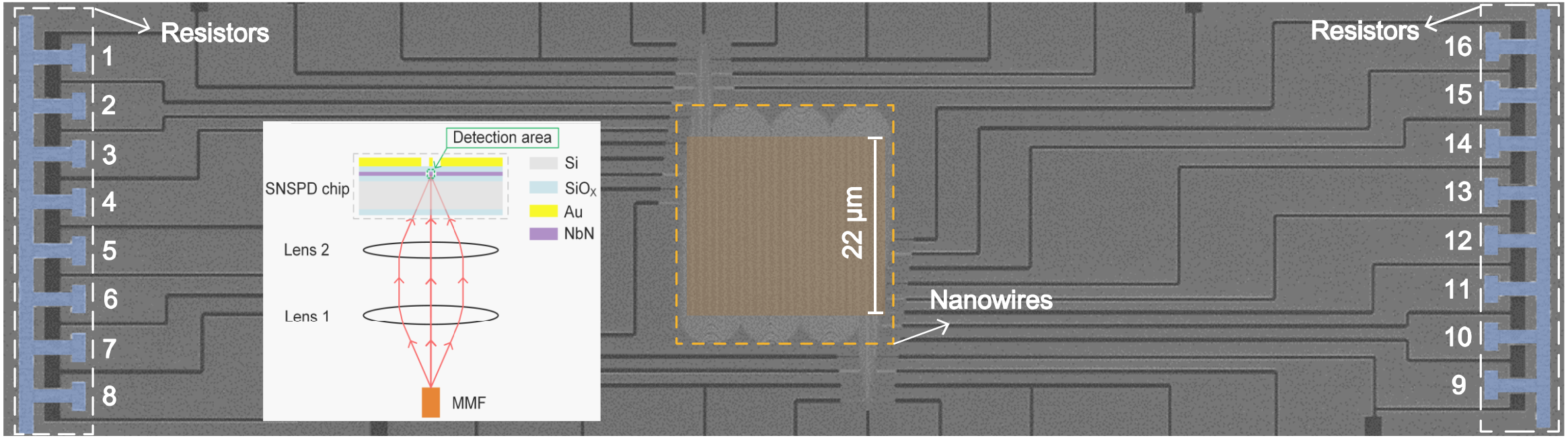
Thermal crosstalk analyses





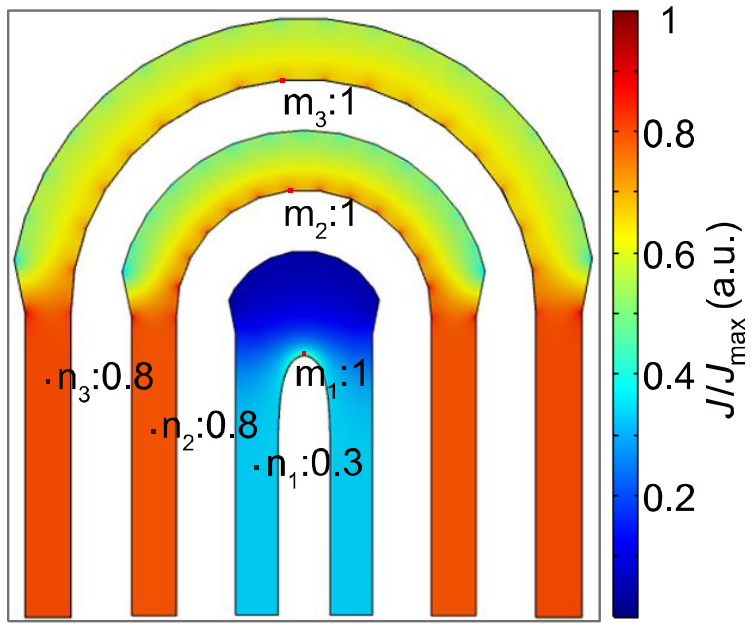
- I_B = 98%I_{SW}, thermal crosstalk~0.02
- I_B = 90%I_{SW}, thermal crosstalk~1.5×10^{-4} (negligible)

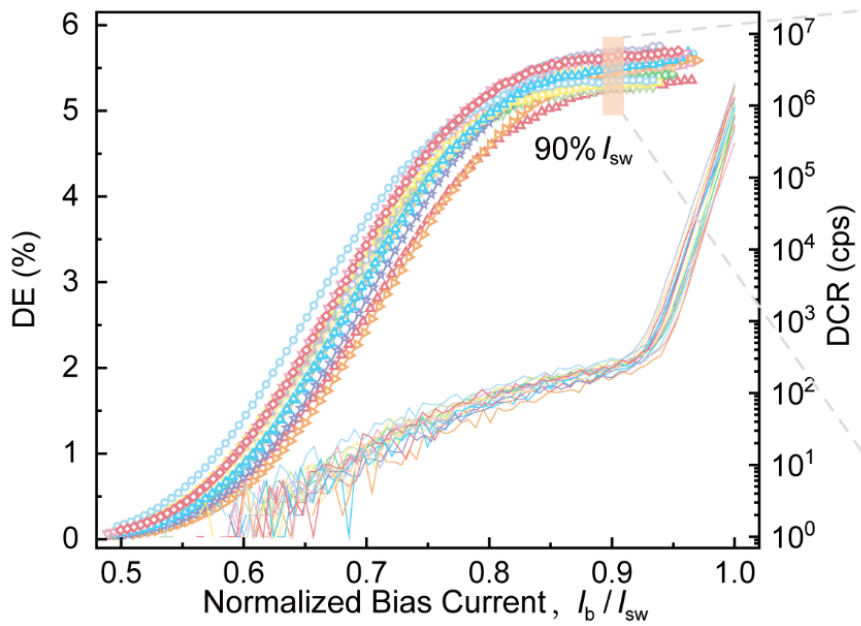
Towards higher speed in MMF-SNSPDs

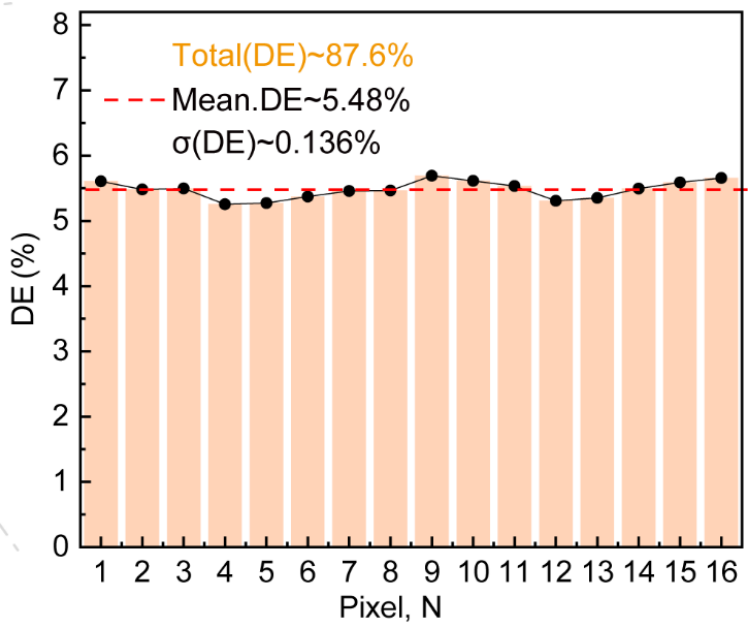


- ✓ 16 NbN nanowires in **fully wound structure** cover an area of 22×22 μm², which can be coupled with **a 62.6 μm multimode fiber (MMF)**
- ✓ On-chip series Ti resistors: suppress the electrical crosstalk and accelerate the recovery of the detector

High & Uniform Detection efficiency



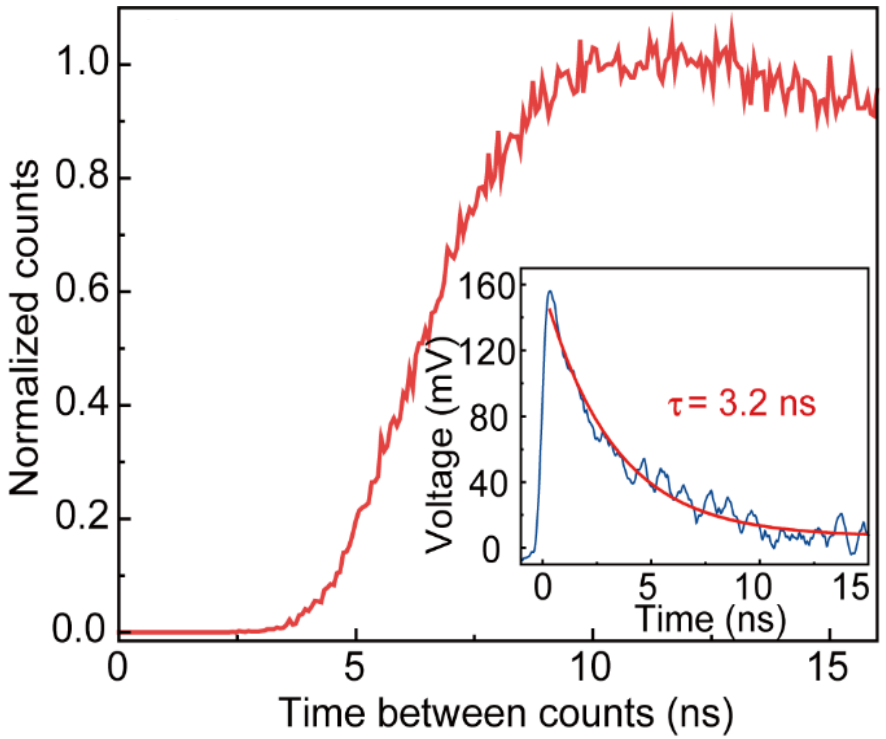




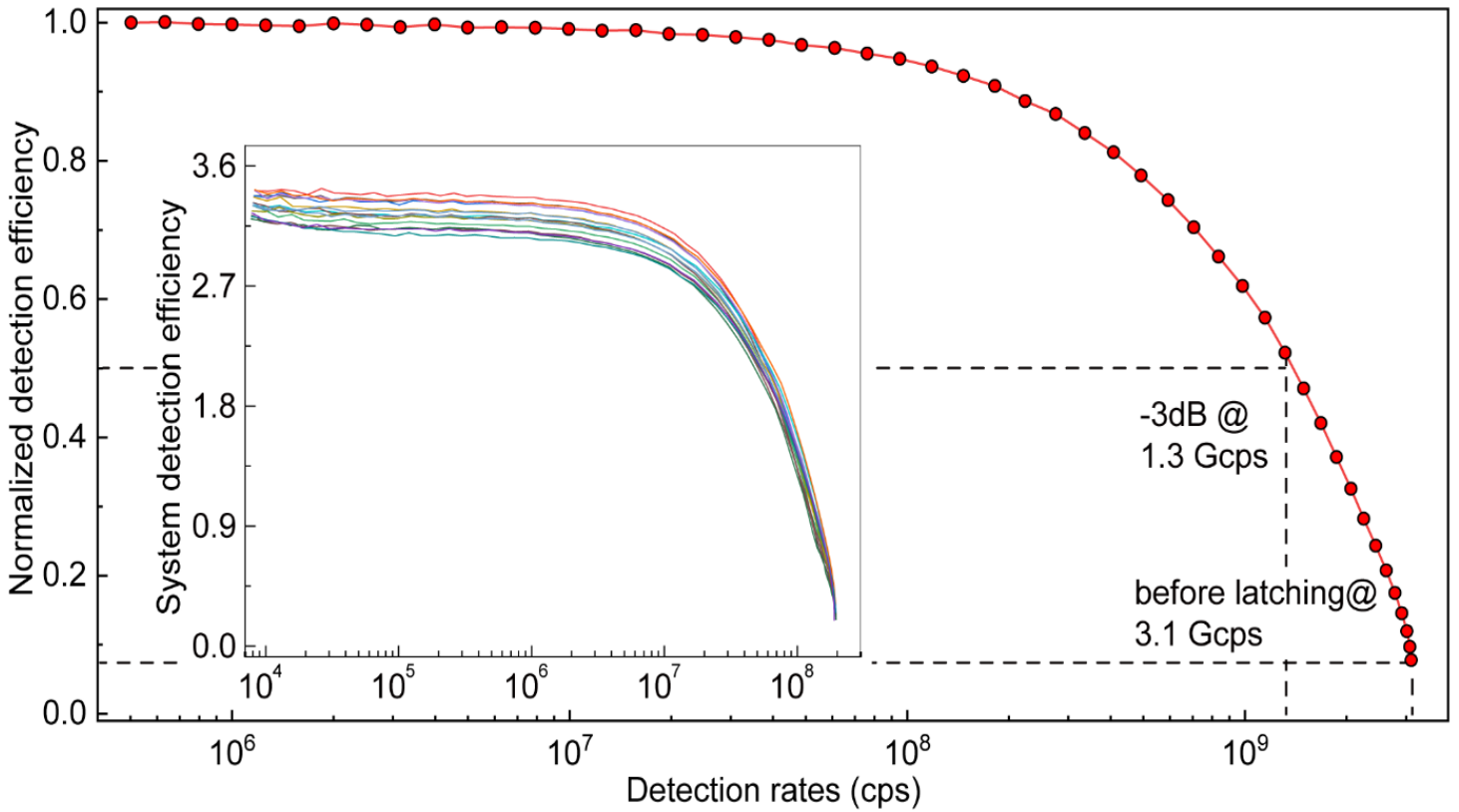
✓ The intertwined structure alleviates the current crowding effect at the corners

Quantum efficiency	Detection efficiency	Double-lenses module transmission	Fiber transmission	System detection efficiency
100%	87.6%	69.8%	85.5%	52.3%

High speed over GHz



- Recovery time: ~ **3.2 ns**

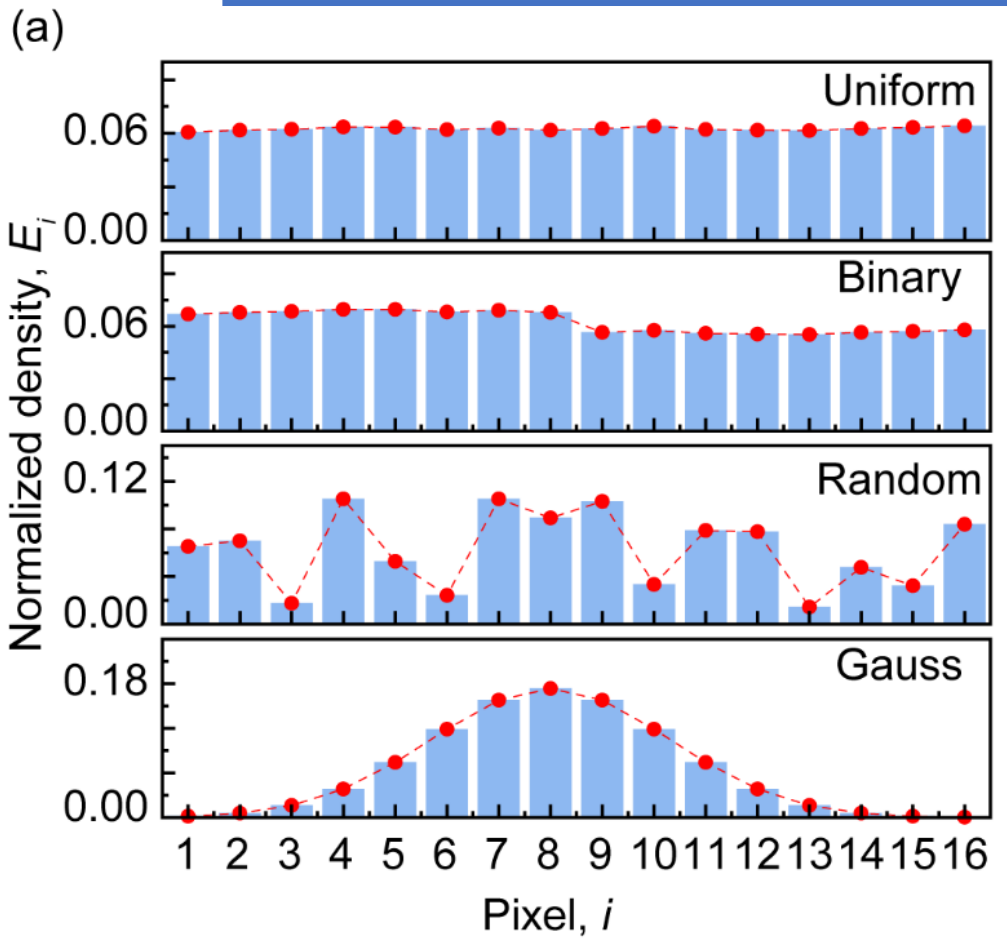


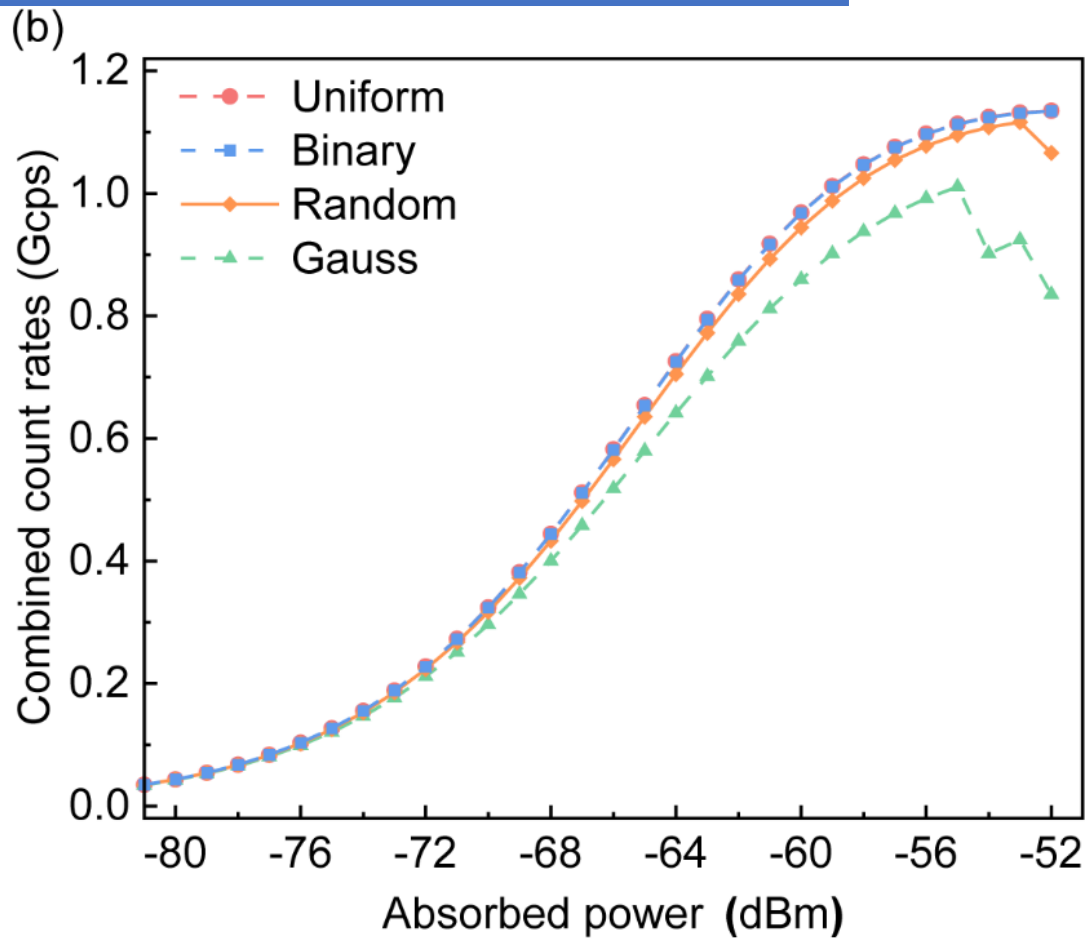
- Count rate~**1.3 Gcps** @-3 dB DE
- Count rate~**3.1 Gcps** @ before latching

***Laser & Photonics Reviews* (under review)**

Ultra high speed SNSPD with fully wound structure

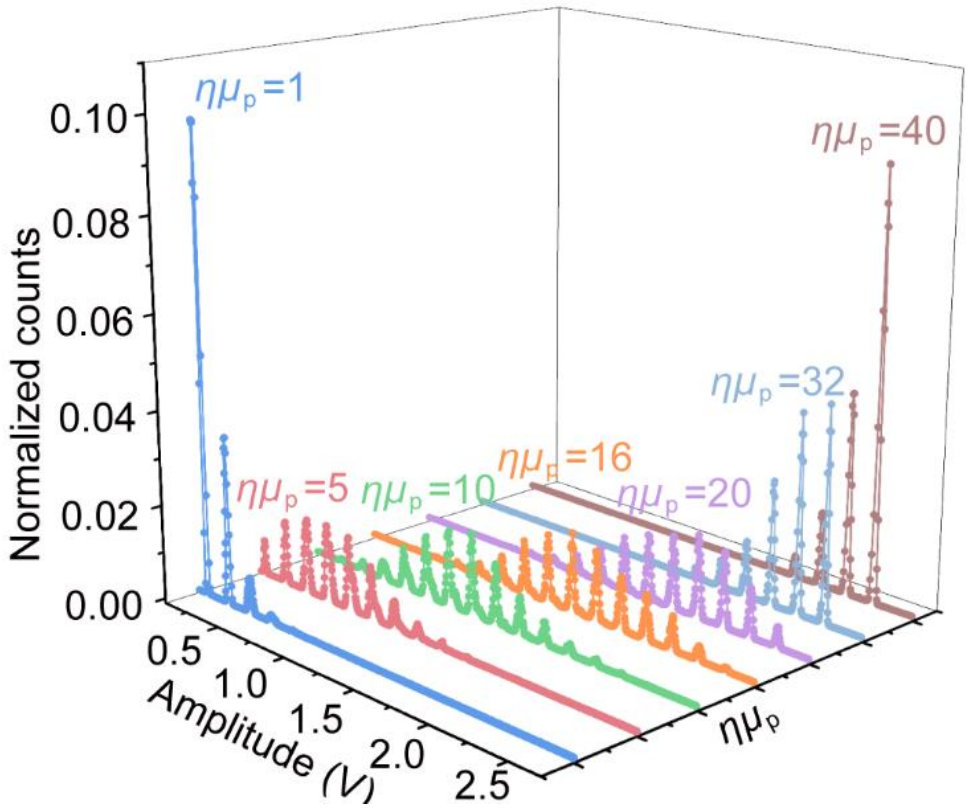
The combined count rates: $CR_{com} = f \times \left[1 - e^{\sum_{i=1}^{N} \ln\left(1-\frac{CR_i(P_i)}{f}\right)}\right]$

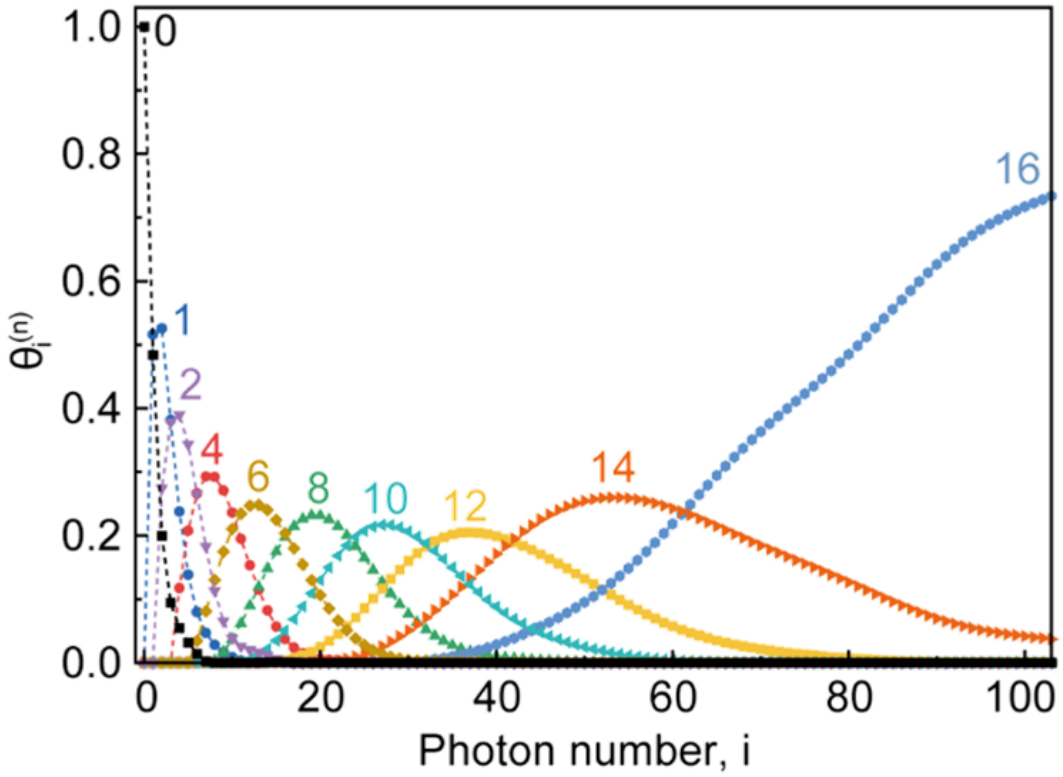




- Four types of light intensity distributions
- The **combined count rates** when the repetition frequency of the laser pulses is 1.2 GHz.

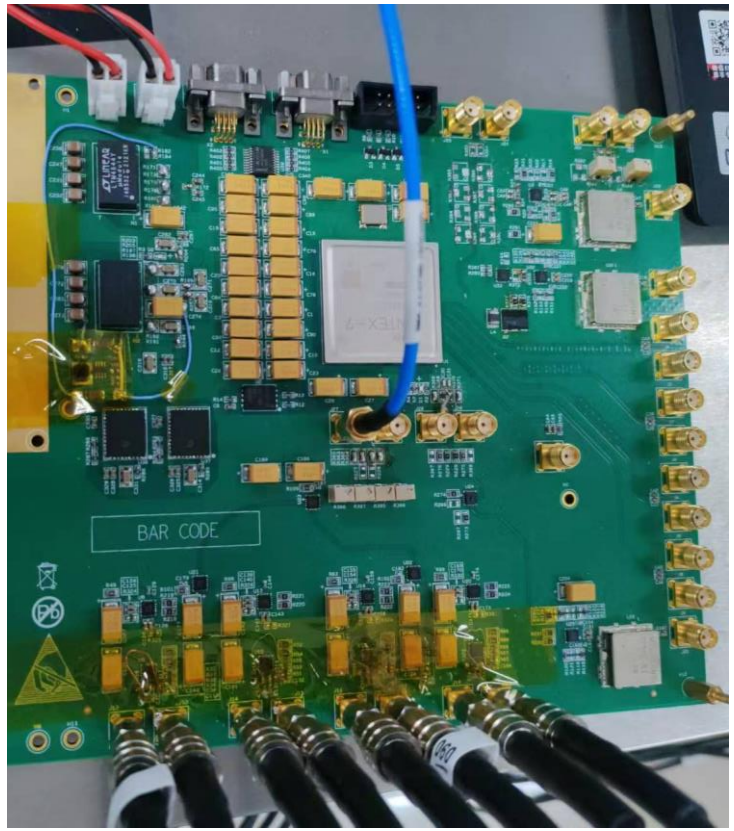
Photon number resolving



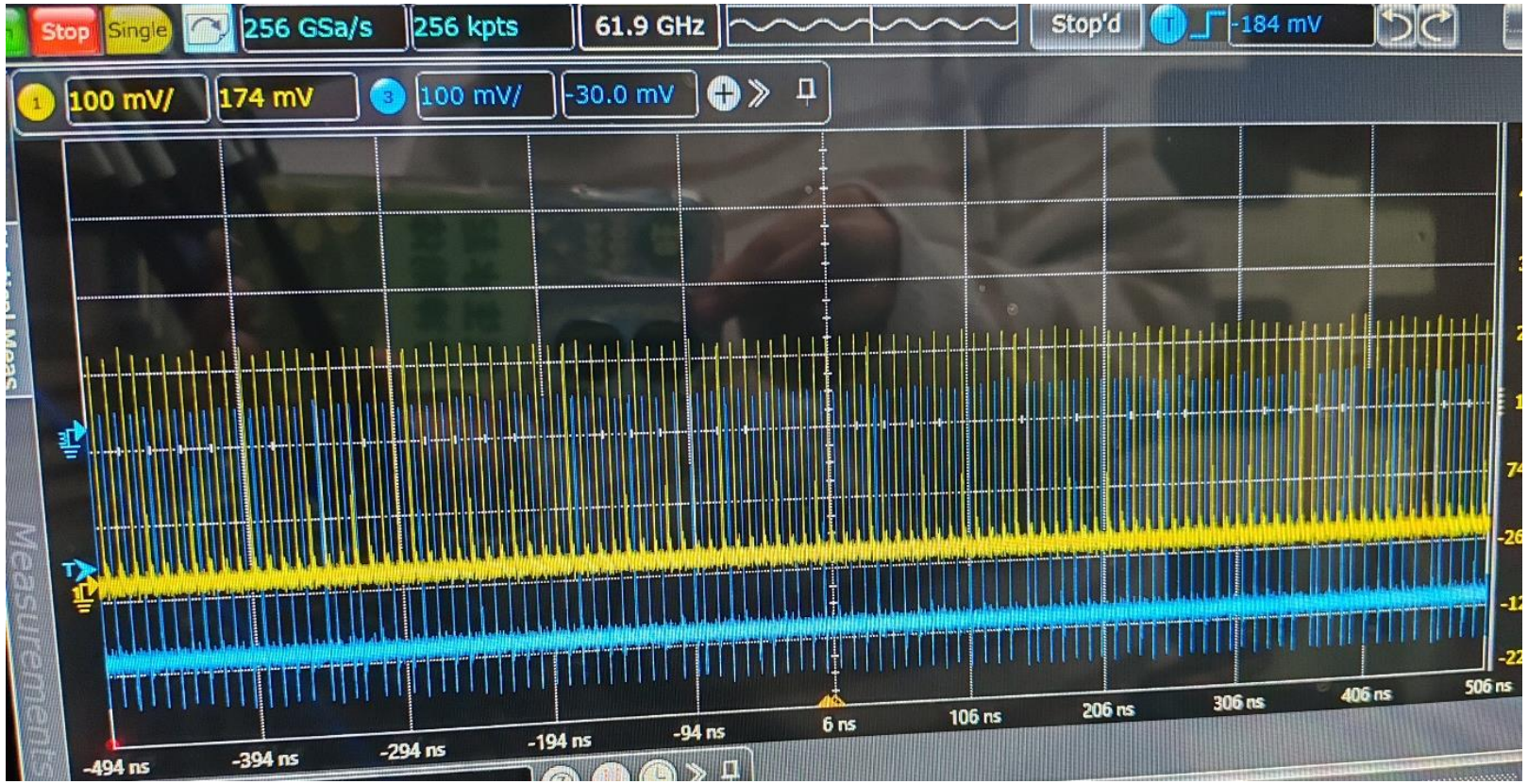


- **Quantum detector tomography** obtains the complete measurement **matrix** of the detector $\boldsymbol{P = l \times F\Pi}$

Ultra high speed SNSPD with fully wound structure



- Modulation and demodulation board



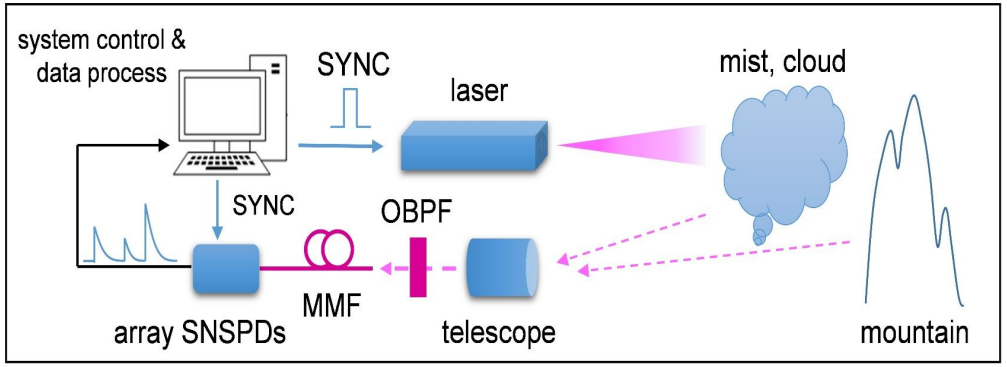
- Modulation signal (yellow) and recovery signal (blue)

Signal transmission verification： Successfully detect and restore **6.6 GHz** optical signal

2. All-day Atmospheric LiDAR

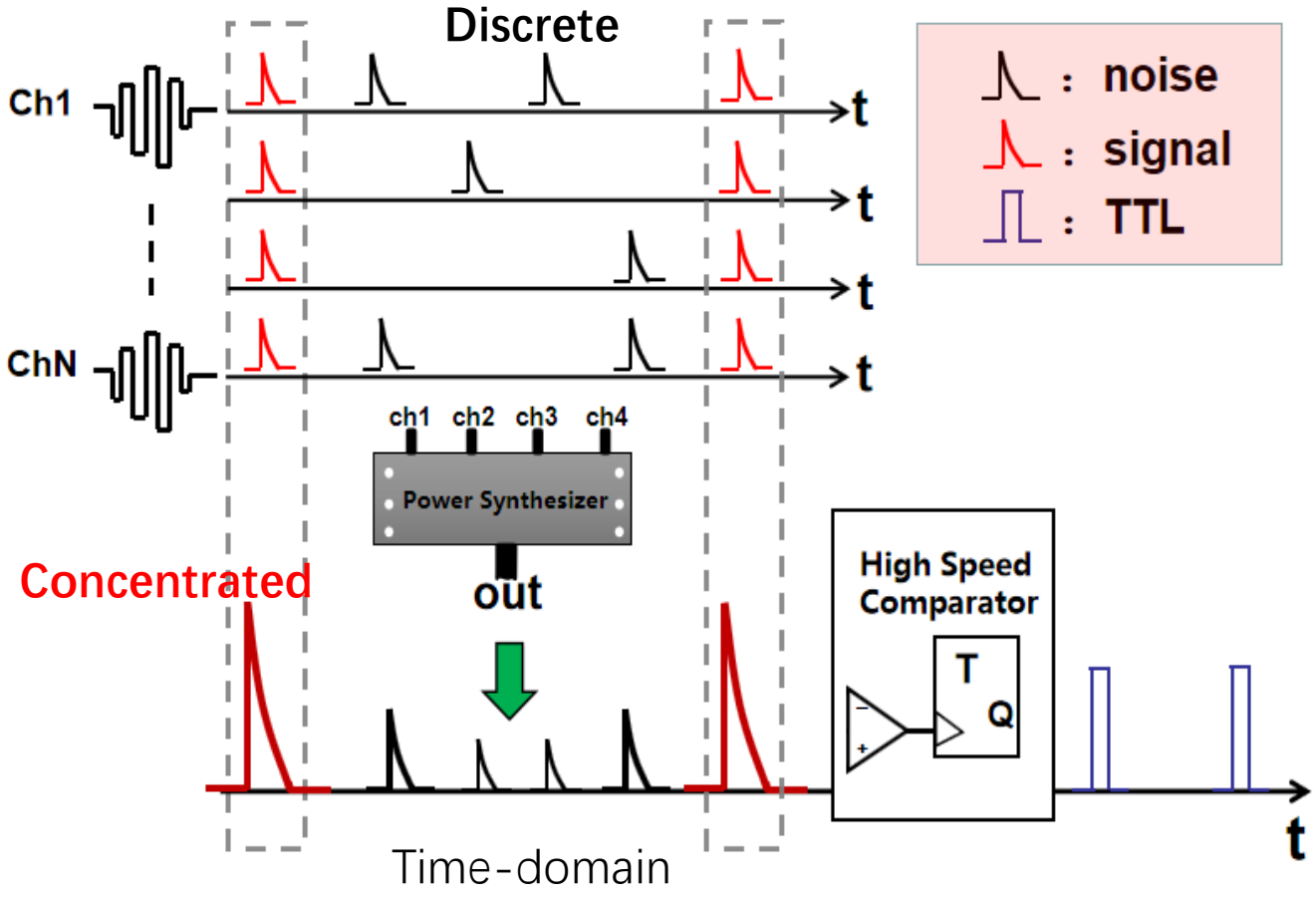
Challenges in daytime LiDAR:

- Strong backscattering
- Weak echo signal
- Strong background noise



Measurement system

PNR-enhanced measurement



The coherent superposition output in time domain improves both the SNR and detection distance.

南京大学超导电子学研究所
Research Institute of Superconductor Electronics

Photon number chromatography processing

Hard

$$n_h = \frac{\lambda E_{out}}{hc}\cdot\frac{\mu_t\mu_r\rho D^2}{8L^2}\cdot\exp\left[-2\int_0^L\left(\alpha_1(\lambda,R)+\alpha_2(\lambda,R)\right)\right]$$

Laser energy | Aerosol backscattering coefficient | Extinction coefficient

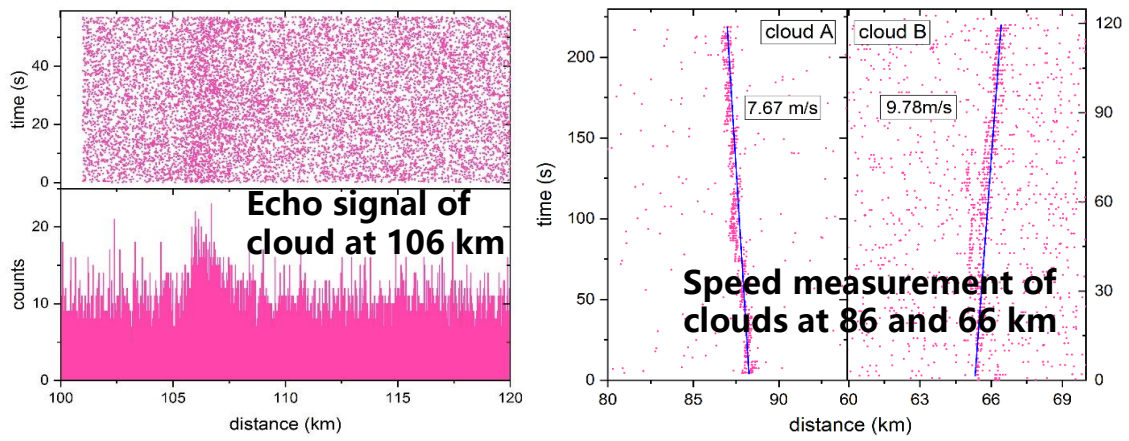
Soft

$$n_s = \frac{\lambda E_{out}}{hc}\cdot\frac{c\tau\mu_t\mu_r\pi D^2}{8L^2}\cdot\left(\beta_1(\lambda,R)+\beta_2(\lambda,R)\right)\exp\left[-2\int_0^L\left(\alpha_1(\lambda,R)+\alpha_2(\lambda,R)\right)dR\right]$$

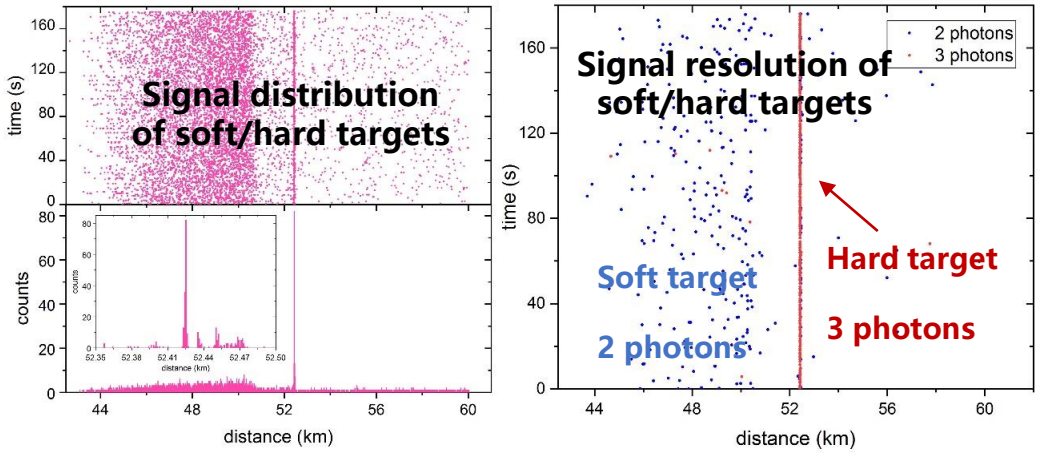
Echo signals

n_h=2.89 ~3 photons

n_s=2.16 ~2 photons



Daytime cloud echo signal



Daytime soft/hard target resolution