

2016年量子保密通信暑期学校

面向量子信息的超导纳米线单光子探测技术

Superconducting Nanowire Single Photon Detector
for Quantum Information

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中国科学院上海微系统与信息技术研究所

2016/07

目 录

■ 量子信息与单光子探测SPD

■ 超导纳米线单光子探测 (SNSPD) 原理

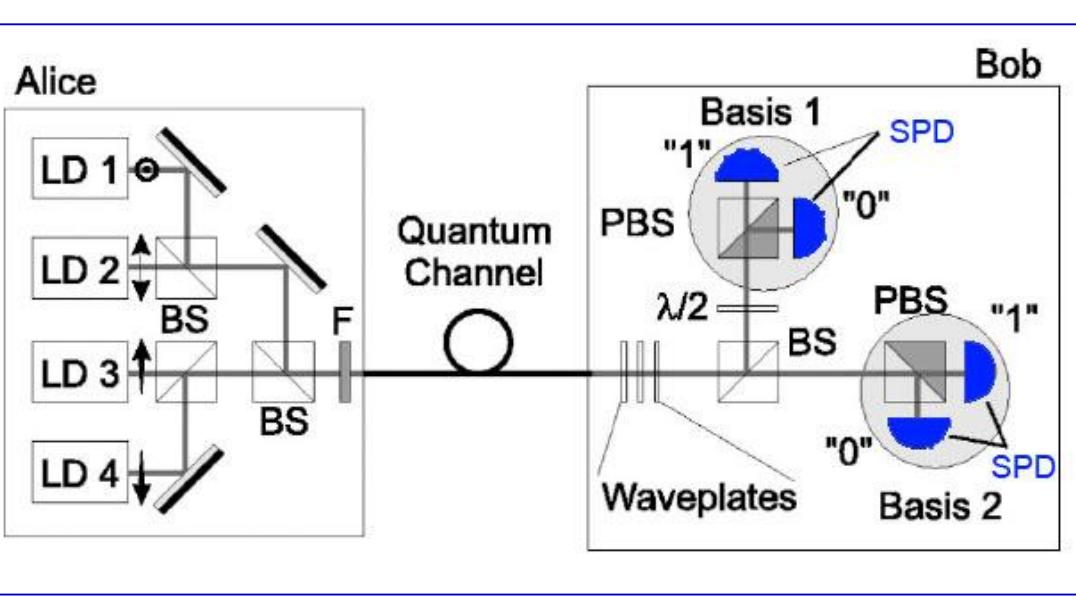
■ SNSPD特性研究

- ✓ 探测效率 (从近红外到可见光)
- ✓ 低暗计数SNSPD
- ✓ 低抖动SNSPD
- ✓ SNSPD极化调控

■ SNSPD应用

- ✓ 量子信息应用
- ✓ 其它应用

量子通信与单光子探测



核心技术:

- 单光子源
- 编码、算法
- 存储转发
- 单光子探测

BB84 (4-state)

- 单光子探测技术是量子密钥分发的主要技术瓶颈之一；
- 单光子探测技术永远是量子密钥分发的核心技术。

量子通信对SPD需求

应用需求

K_u (成码率) $\propto f$ (频率) · μ (光子数) · L (链路损失) · DE(效率)

K_e (误码率) $\approx R_{dc}$ (暗计数)/ K_u (成码率)

器件性能及发展需求

探测效率：近理想探测效率 (~100%)；

器件噪声：极低噪声，零噪声；

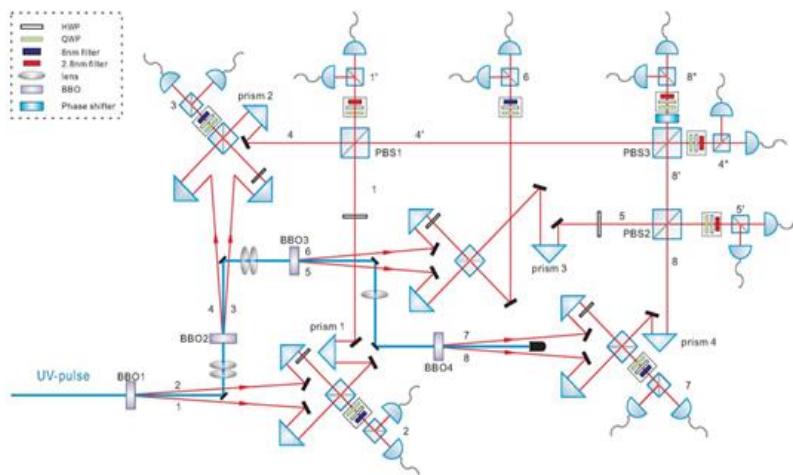
工作速度：越快越好 (GHz)；

能量分辨：光子数分辨，光子能量分辨；

用户友好：低成本、高可靠、7/24全时工作

量子通信应用及发展需要探索高性能单光子探测解决方案

光量子模拟/计算与SPD



核心技术:

- 高质量纠缠源
- 单光子探测

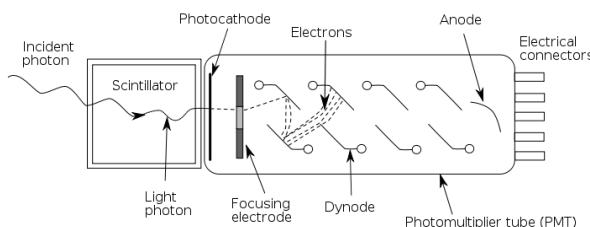
a n -photon coincidence count rate: $R \sim \eta^n$

Current Si SPD : 探测器效率 $\sim 20\%$ @940 nm, 系统效率 $\sim 50\%$;
10光子纠缠（频率=10MHz）的符合计数率达到 0.001 Hz。

*If we could improve η to 60%,
the coincidence count rate can improved by 4-5 orders of magnitude.
Measurement Time can be suppressed from 1 year to 10 min.*

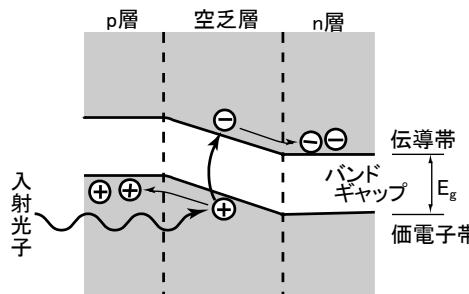
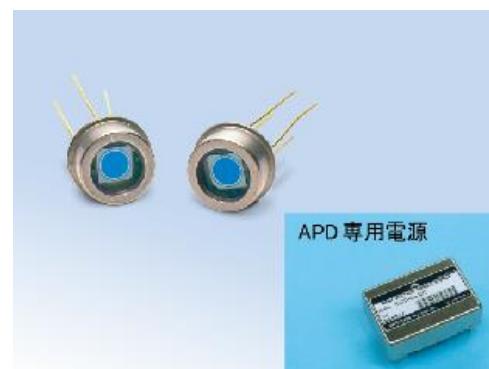
单光子探测器(SPD)

光电倍增管(PMT)



电压偏置 : 数百 ~ 1000V

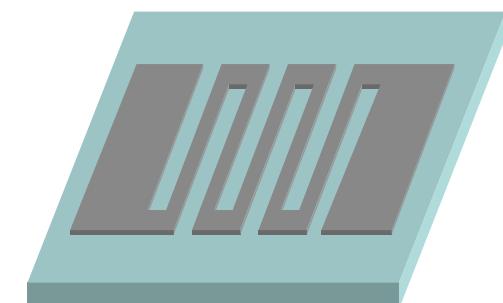
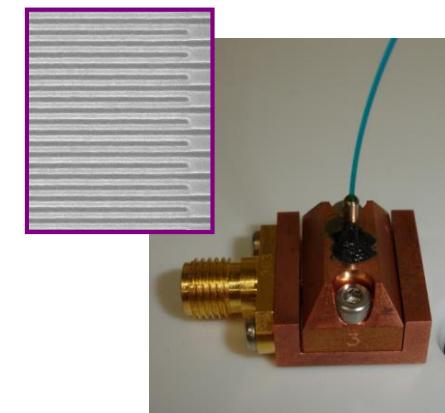
雪崩光电二极管(APD)



电压偏置 : 数十 ~ 100V

超导纳米线单光子探测器(SNSPD)

Since 2001



电流偏置 : 数十 μ A

超导探测器

热探测器

- 探测声子温度上升
- 极高能量分辨率 ($\sim \text{eV}$)
- 低速 (ms)
- 工作温度 ($< 0.1\text{K}$)

超导转变边探
测器 (TES)

ETF-TES

非热探测器

- 探测电子激发状态
- 高能量分辨率 (数eV)
- 高速 ($\mu\text{s} - \text{ns}$)
- 工作温度 ($0.1 - 4.2\text{K}$)

超导隧道结
(STJ)

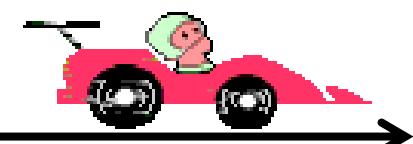
超导纳米线单光
子探测(SNSPD)

响应時間

ms

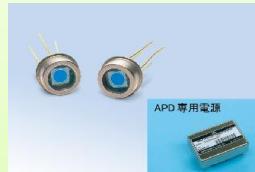
μs

ns



SPD性能比较@1550 nm

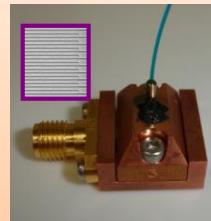
SPD	计数率 (Hz)	效率 (%)	暗计数 (s ⁻¹)	时间抖动 (ps)	工作温度 (K)
SNSPD (NbN)	>100 M	> 80	<1	<20	~ 2.2 K
STJ (Al)	5 K	60	N/A	N/A	< 1K
TES (W)	100 K	95	~ 0	100 ns	0.1 K
InGaAs APD	100 M	20	16K	55	200 K
IR PMT	10 M	2	200 K	300	室温



APD器件



APD模块

SNSPD
15 x 15 x 10 mm1350 x 400 x 450mm
功耗: 1.3 kW600(H) x
φ260mm

SNSPD Applications

- Photon counting optical telecommunications at 1550nm

E. A. Dauler, et al *Proc. SPIE* 6372, 637212 (2006)

- Interplanetary optical communications

B. S. Robinson et al., *Optics Letters* 31, 444-446 (2006)

- Quantum key distribution

H. Takesue, et al, *Nature Photonics* 1, 343-348 (2007)

- Single-photon source validation

R. H. Hadfield, *Opt. Express* 13, 10846 (2005)

- Noninvasive testing of LSI circuit design failure

J. Zhang et al , *Electronics Letters* 39, 1086-1088 (2003)

- Laser radar (or LIDAR) remote sensing: ranging and imaging

M. J. Stevens, *Appl. Phys. Lett.* 89, 031109 (2006)

- Fault location inspection of optical fiber

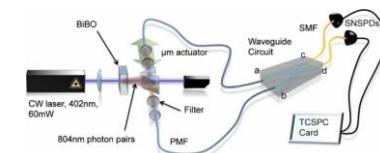
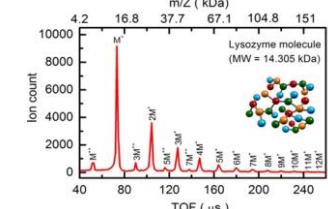
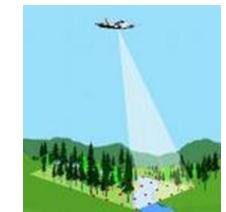
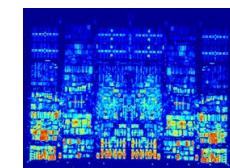
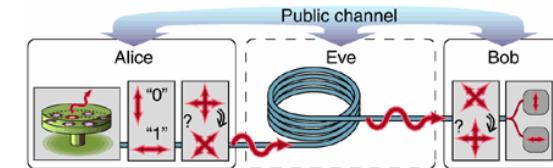
M. Fujiwara et al, *Opt. Exp.*, 18, 22199 (2010)

- Molecules detectors for time-of-flight mass spectrometry

N. Zen, et al. *Appl. Phys. Letts.* (2009)

- Fundamental experiments in quantum optics

M. Halder, et al, *Nature Physics* 3, 692-695 (2007)



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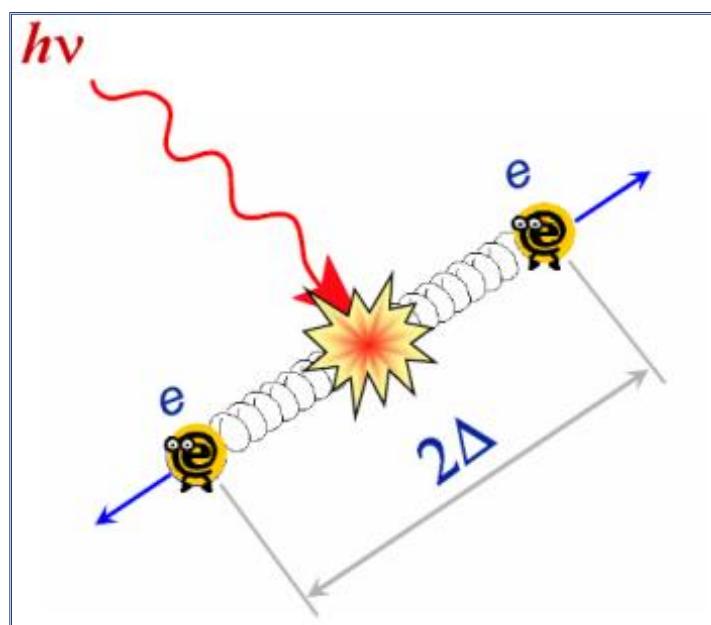
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■ SNSPD应用

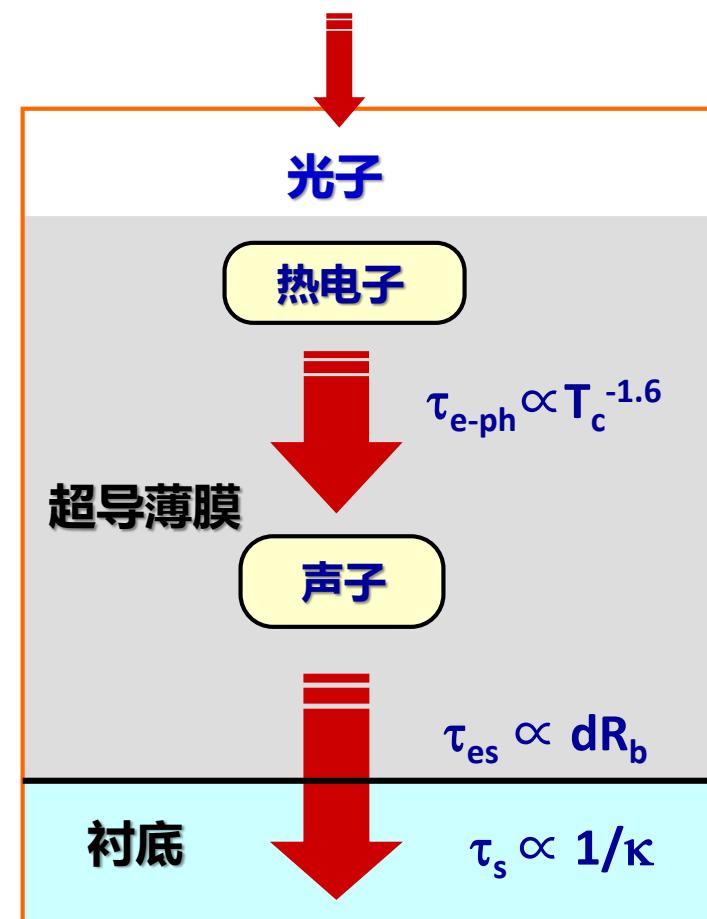
- ✓ 量子信息应用
- ✓ 其它应用

探测机理-微观

利用超导量子效应去探测光量子



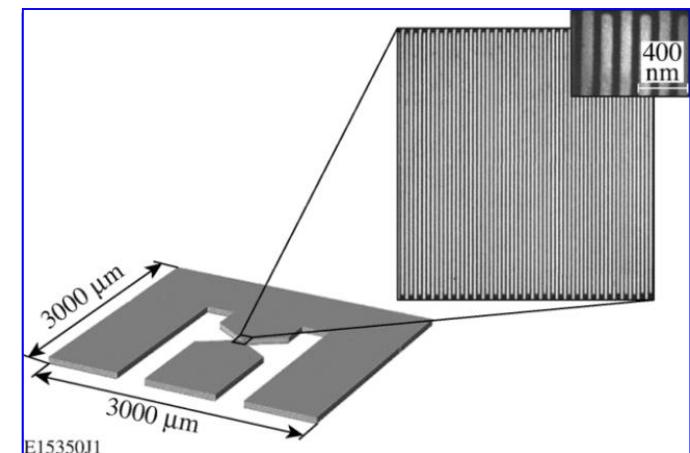
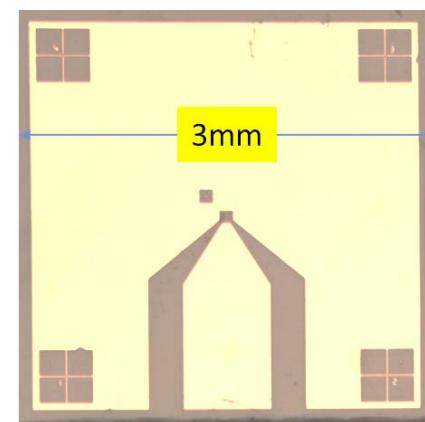
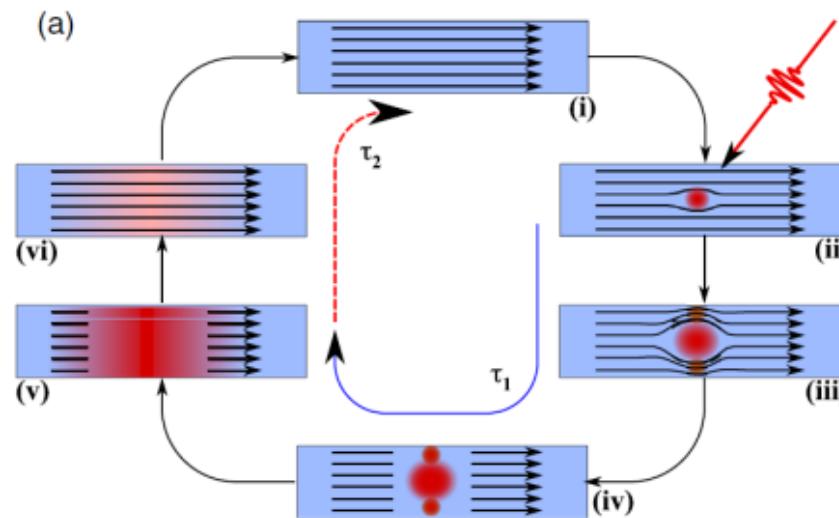
光子能量 vs 超导能隙/Cooper Pair 能量
 $h\nu$ (1eV) vs 2Δ (6.4 meV)



SNSPD热弛豫过程

探测机理-宏观

- 材料: 超薄 NbN 薄膜 ($\sim 5 \text{ nm}$)
- 结构: 纳米线 (宽度 $<= 100\text{nm}$)

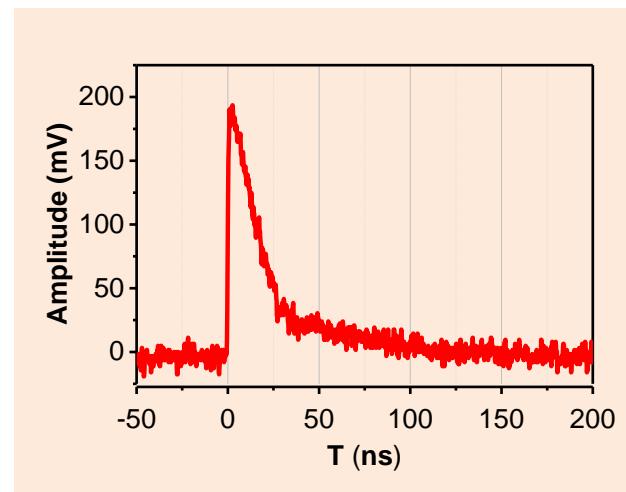
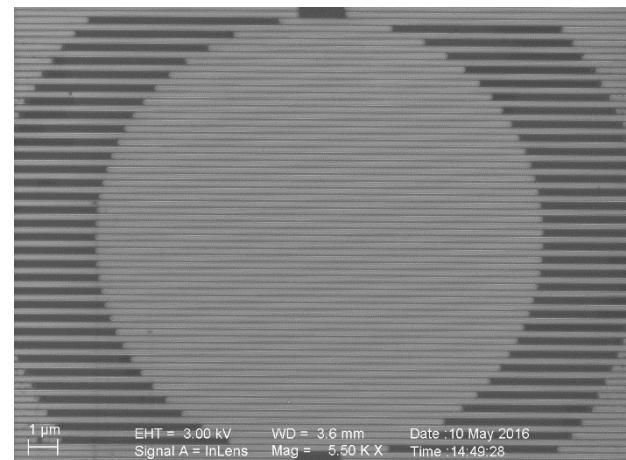
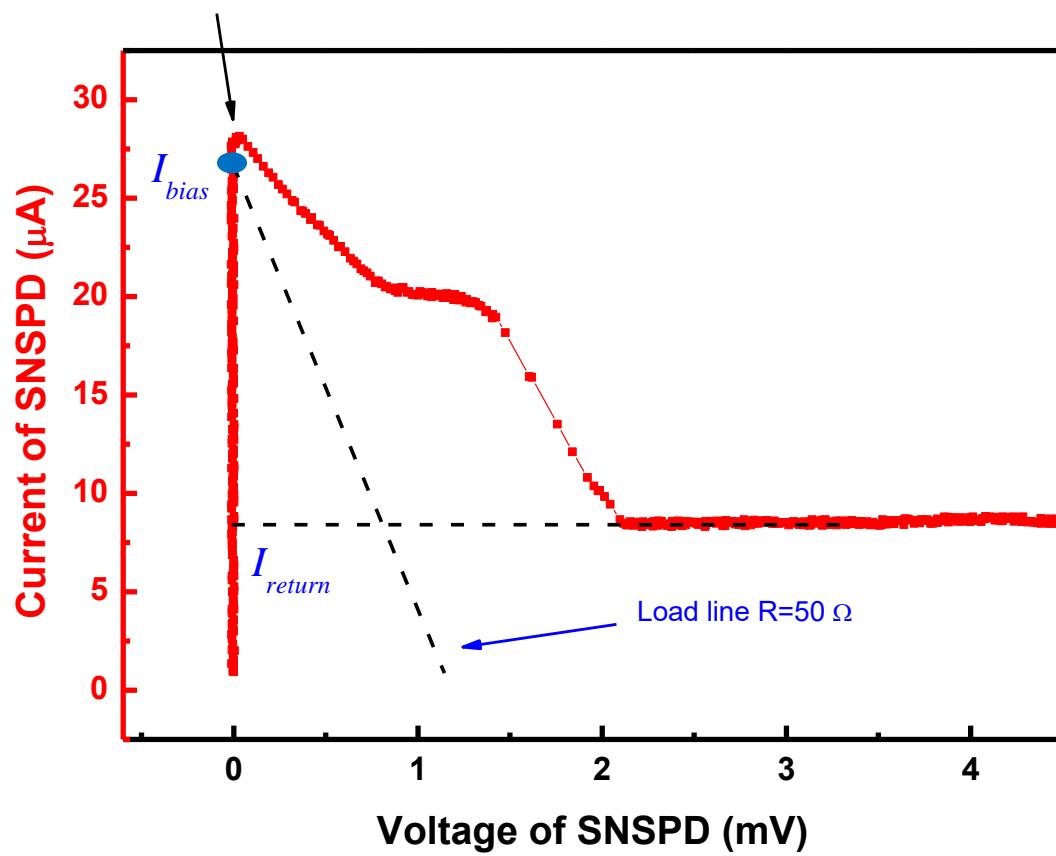


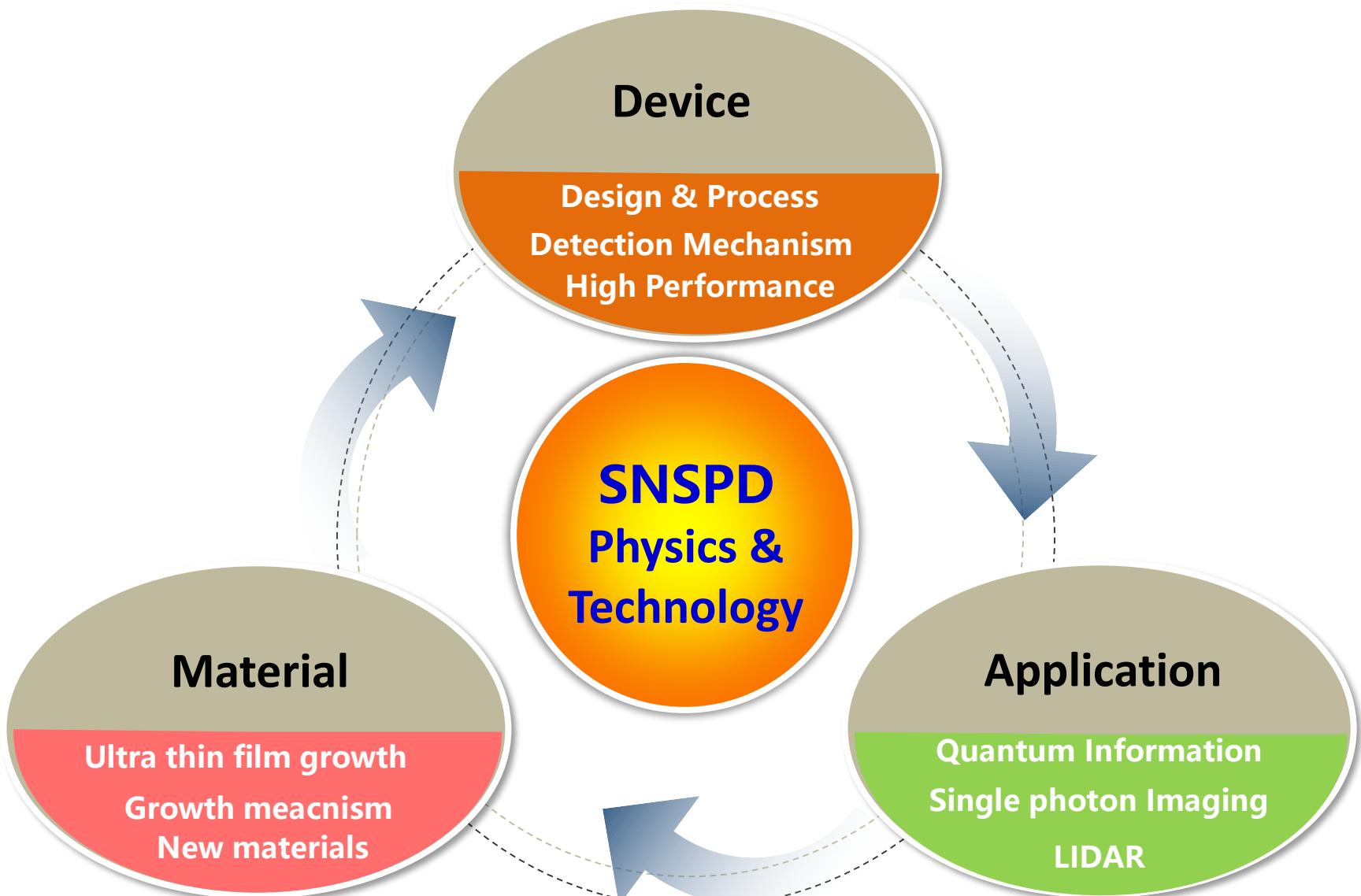
探测原理

器件结构

超薄超导薄膜的能量弛豫时间在几十皮秒量级。——》高速探测

探测机理-电学





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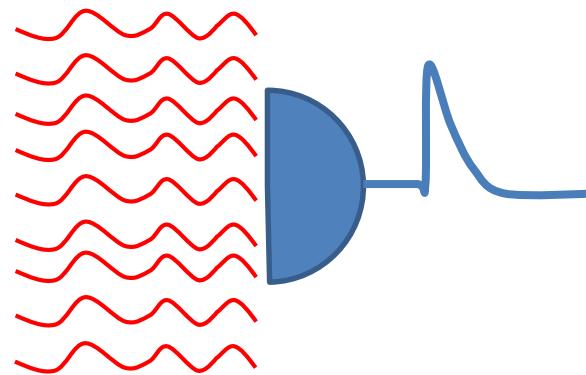
■ SNSPD应用

- ✓ 量子信息应用
- ✓ 其它应用

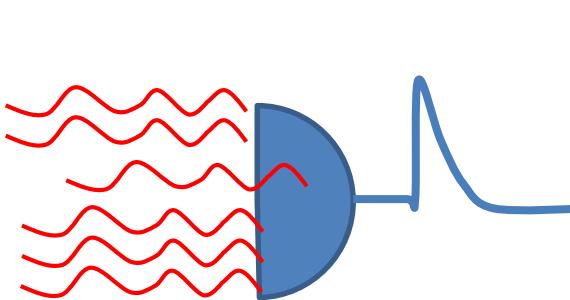
如何实现高探测效率?

System detection efficiency =

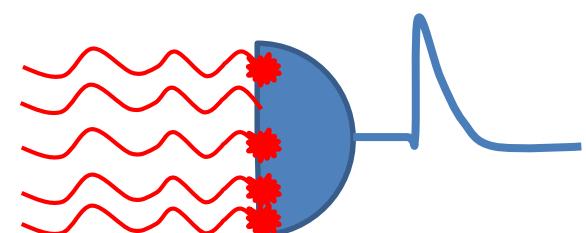
Coupling efficiency



Absorption



Intrinsic detection efficiency



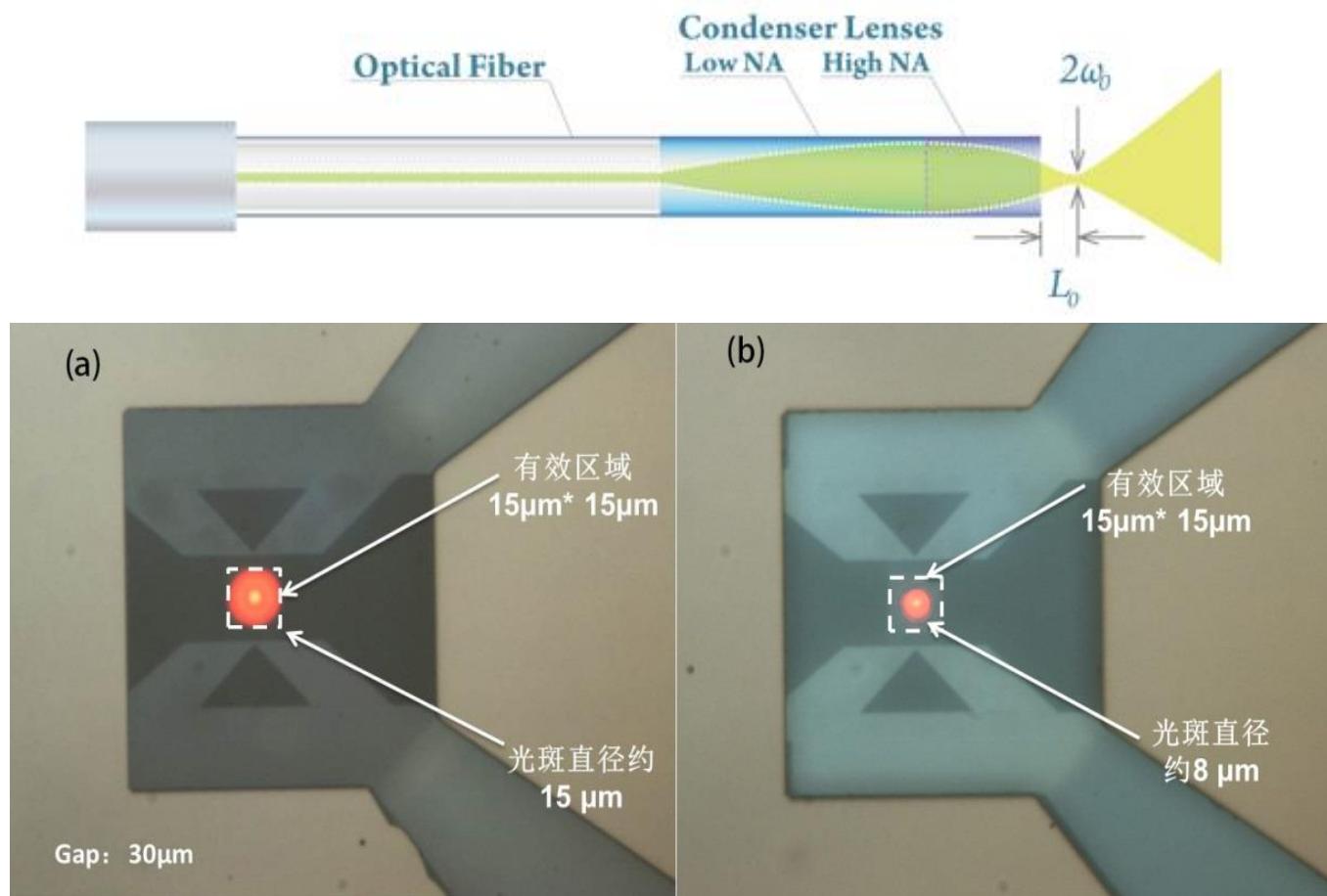
通常有效面积为 $15 \times 15 \mu\text{m}^2$
耦合效率 >95%

7 nm厚NbN对1550 nm光
子的吸收率~30%

IDE >80%

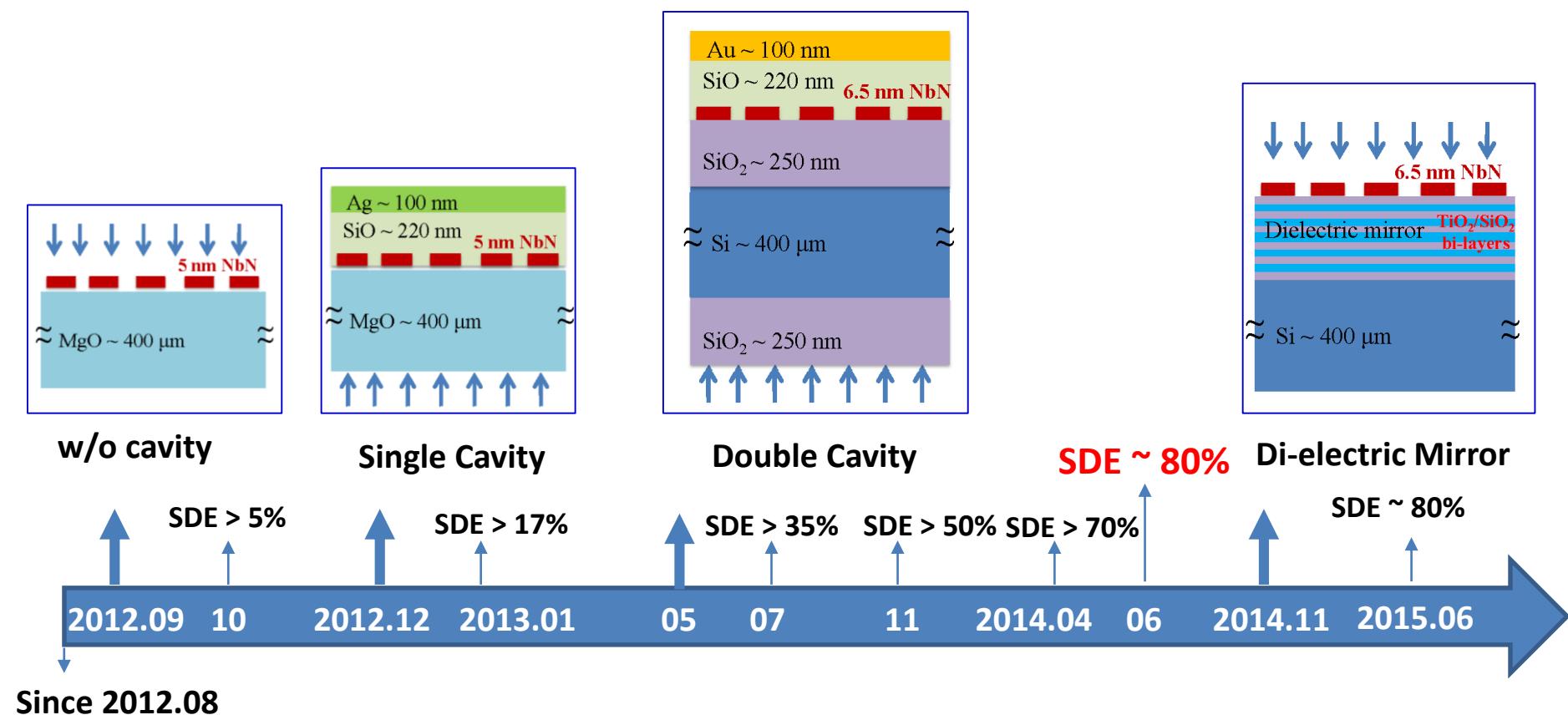
Challenges: 不要漏掉任何一个光子

光耦合技术



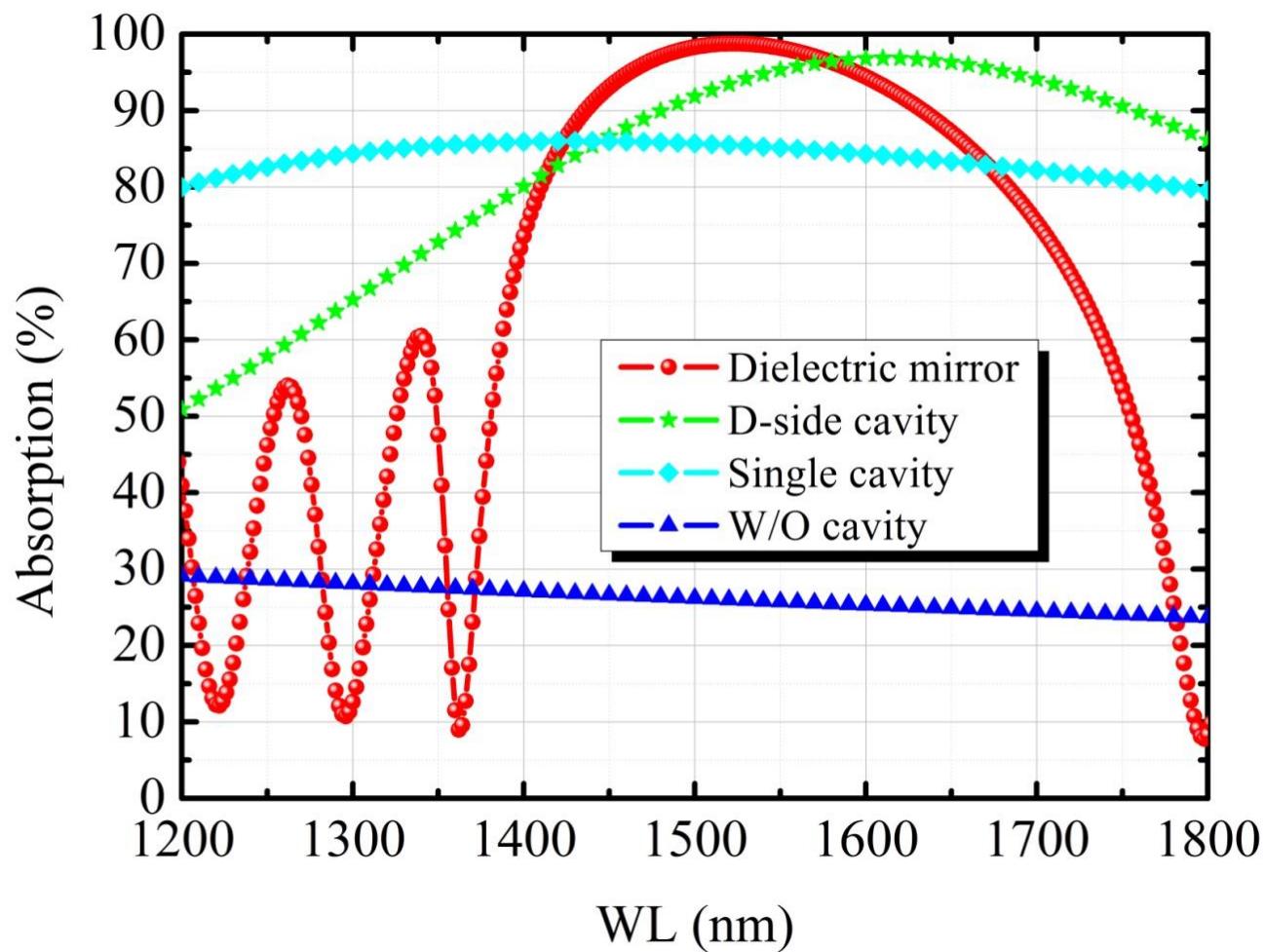
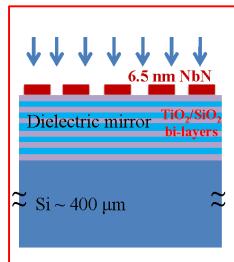
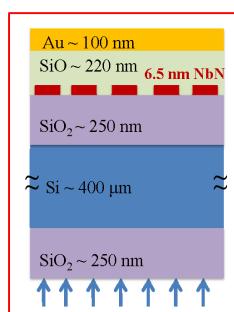
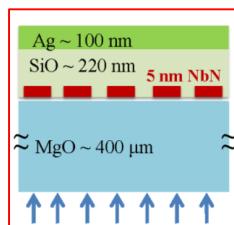
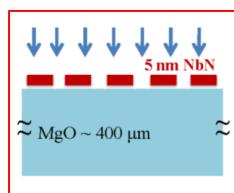
(a) 普通光纤光耦合; (b) 透镜光纤光耦合

Structure Development



The key is to improve the photon absorption of the superconducting nanowire

Improvement on absorption



Simulation of absorption for different structures

Fabrication Process

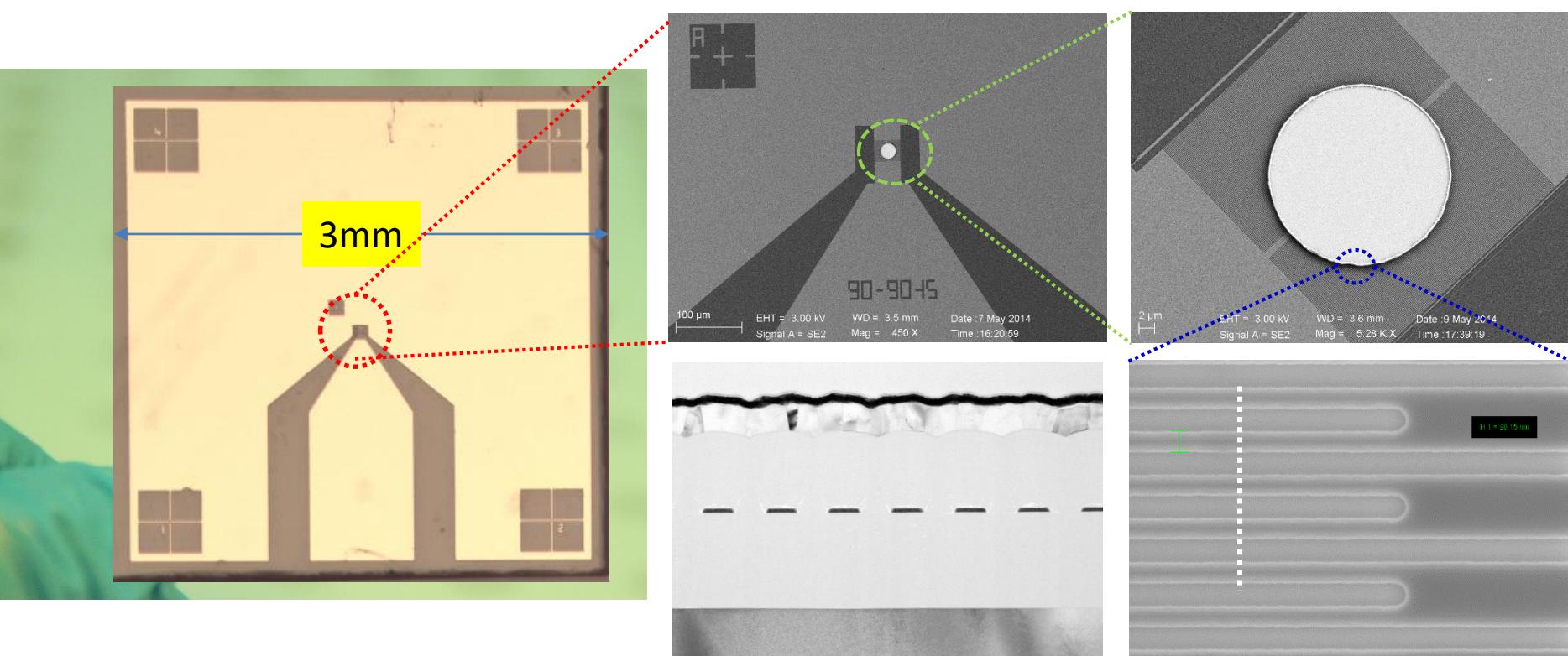
Electrode
and mark

Nanowire
pattern

Define
Active
area

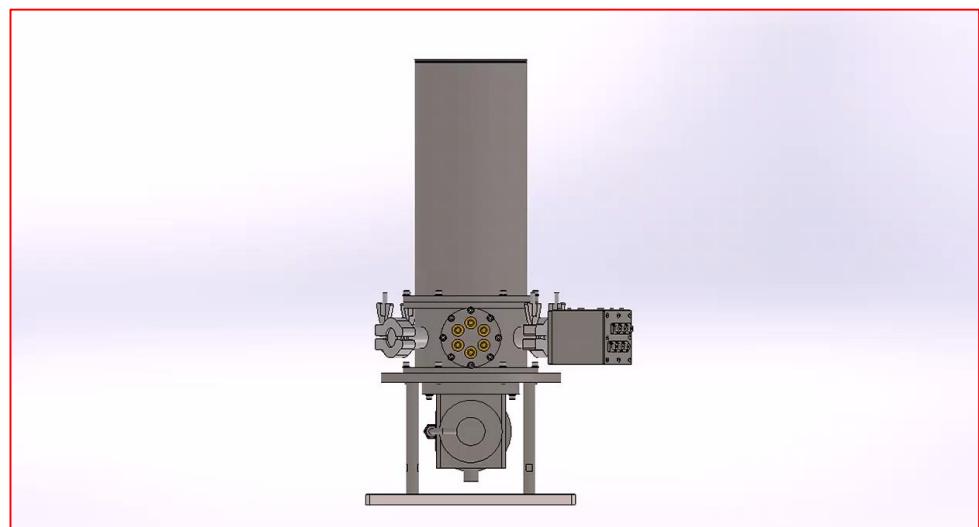
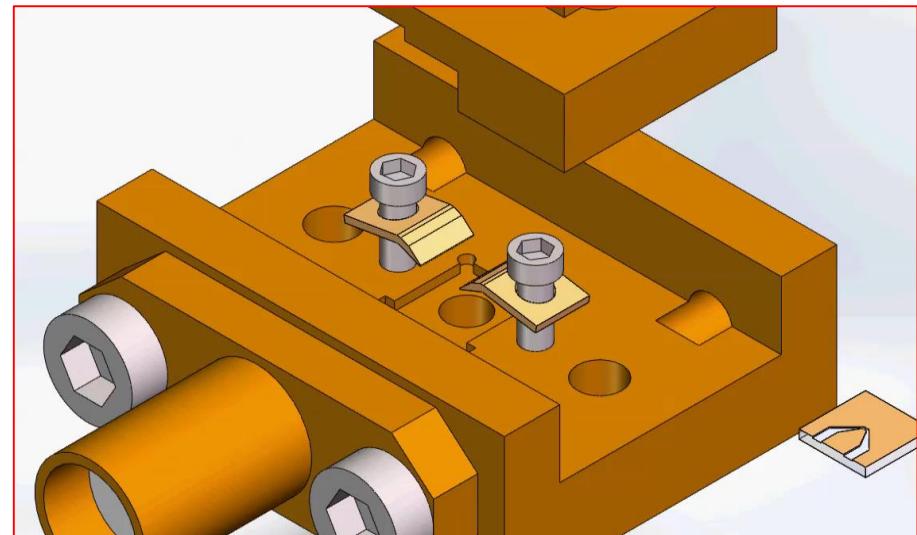
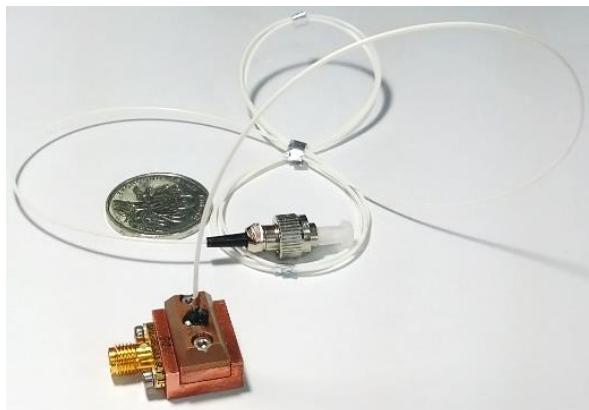
Optical
cavity

Dicing

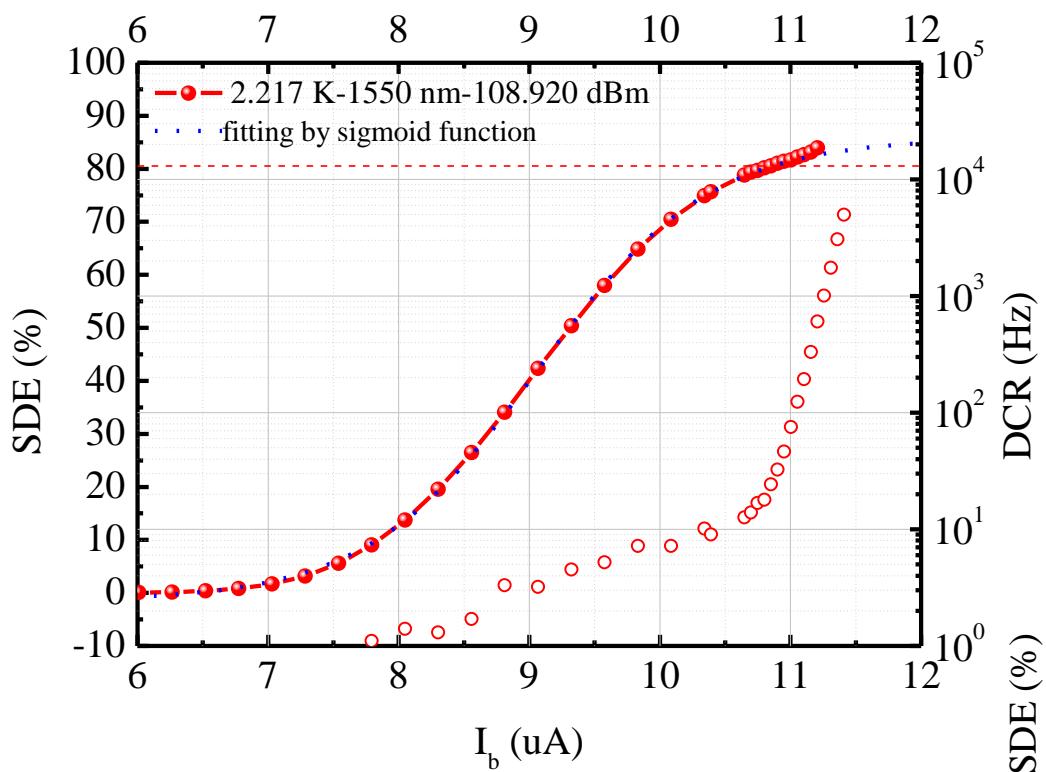


Cross section view

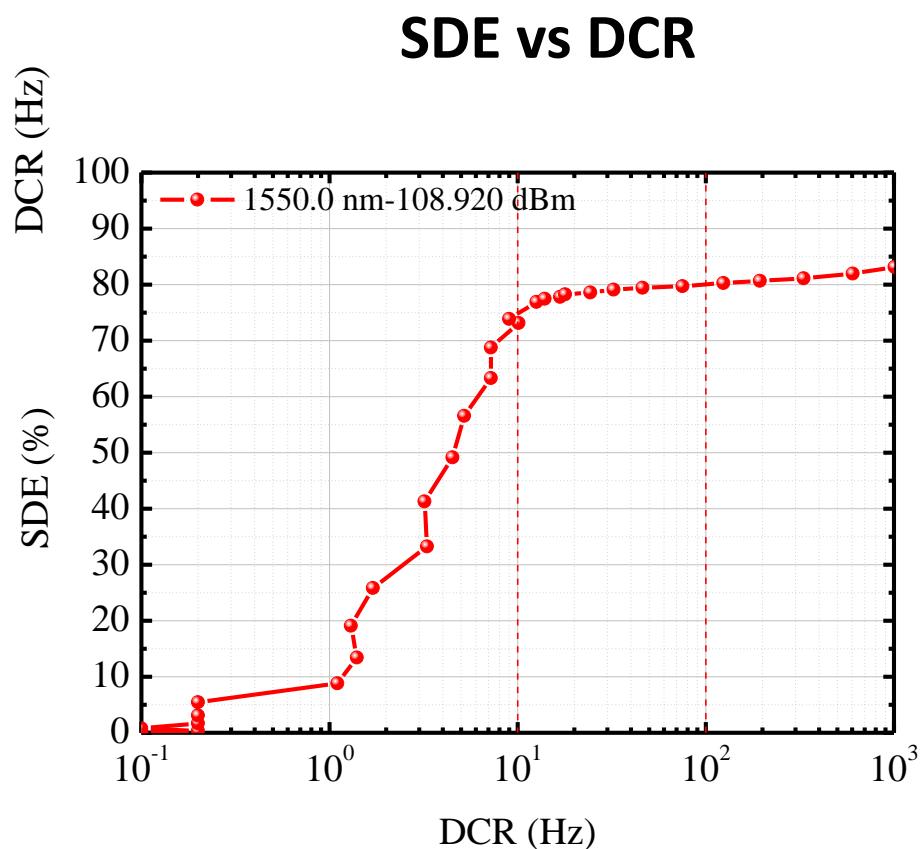
SNSPD System Performance



High DE SNSPD @1550 nm

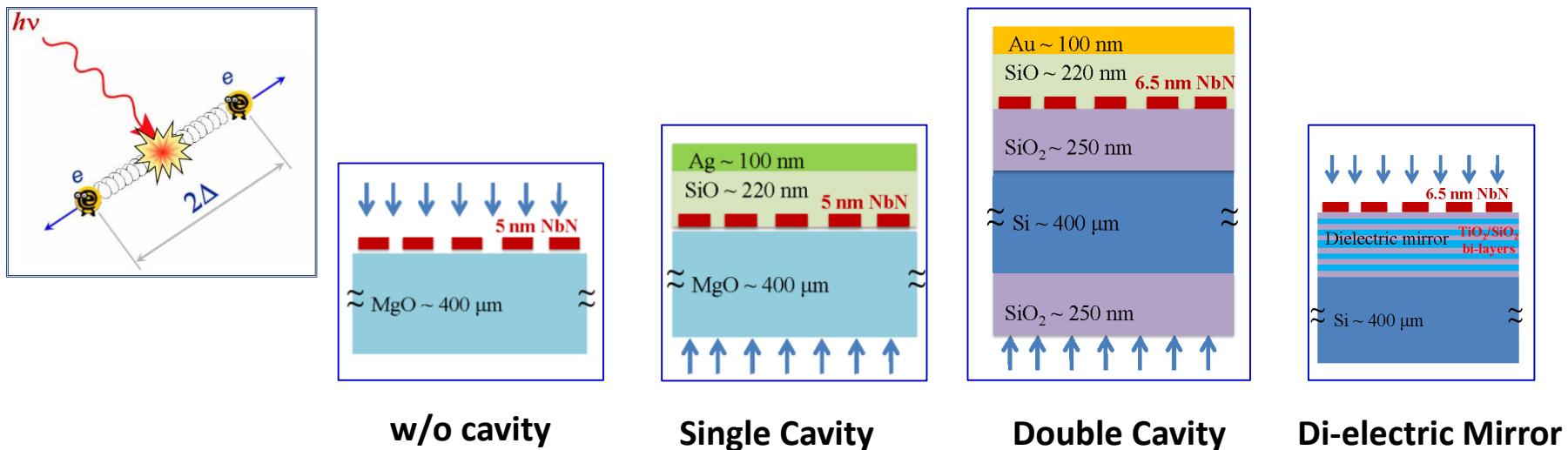


SDE & DCR vs I_b



SDE vs DCR

SNSPD : 从近红外到可见？



NIR



VIS



Absorption



Single Cavity

Double Cavity

Di-electric Mirror

	w/o cavity	Single Cavity	Double Cavity	Di-electric Mirror
NIR				
VIS				
Absorption				

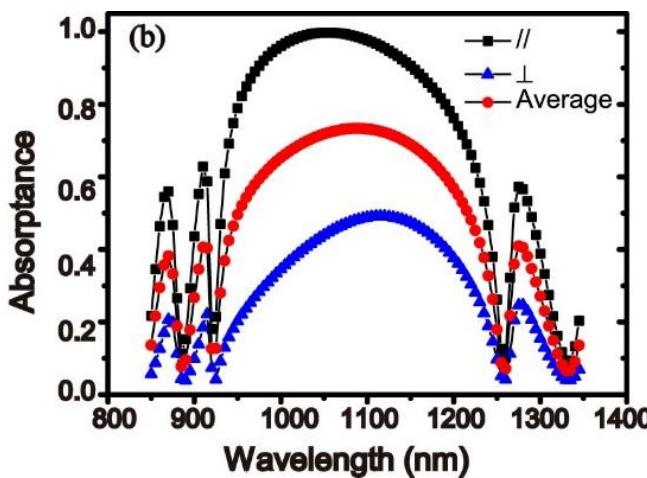
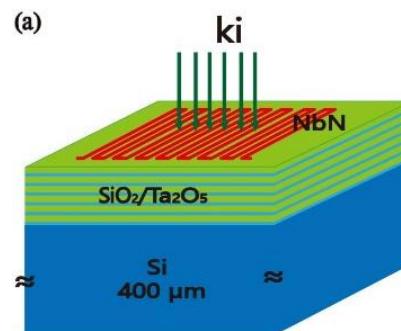
SNSPD at 1064nm

Why 1064nm?

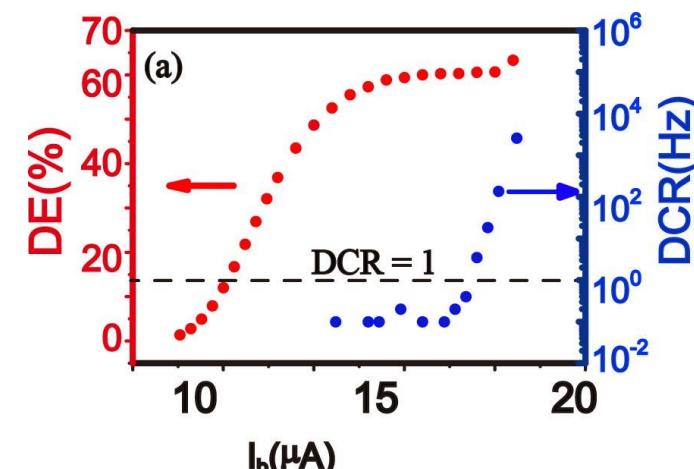
1. Potential applications for *quantum optics, satellite laser ranging, ghost imaging* and so on.
2. Semiconductor APDs have a limited DE < 30%.

Design of SNSPD

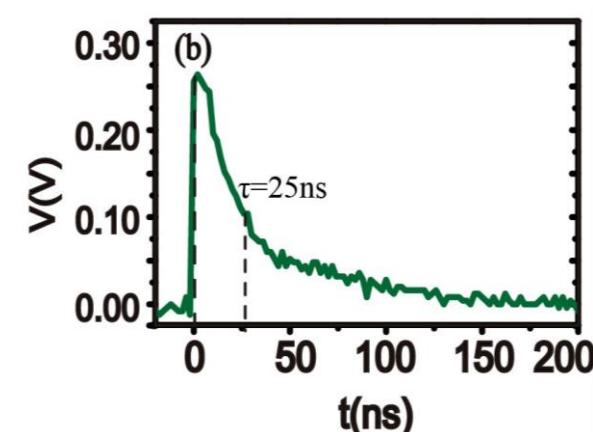
1. 13 bilayers with reflectivity>99%.
2. SMF e28/MMF($\phi=50\mu\text{m}$) coupled.
3. Width/pitch=100/220 (nm)
4. Sensitive area with $\phi=24 \mu\text{m}$



1. Average abs ~ 70%.
2. Abs ~1 is possible with PM photons



SDE & DCR vs I_b SDE=60% @ DCR < 1Hz



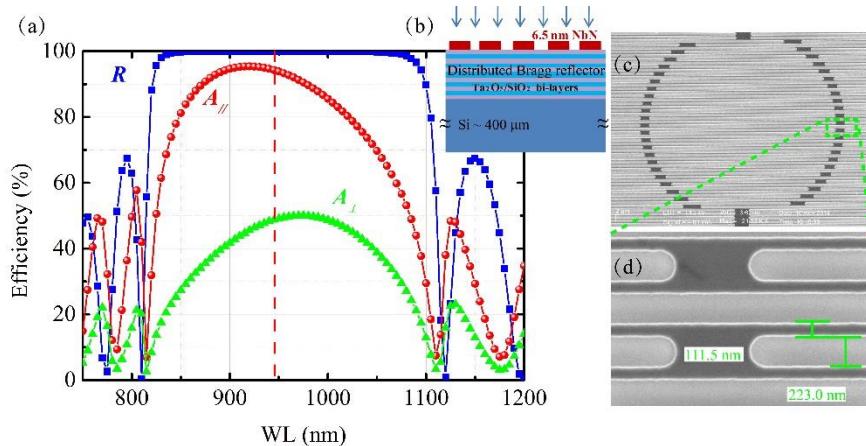
Response waveform

已提供给山西大学苏晓龙教授

SNSPD for 940 nm

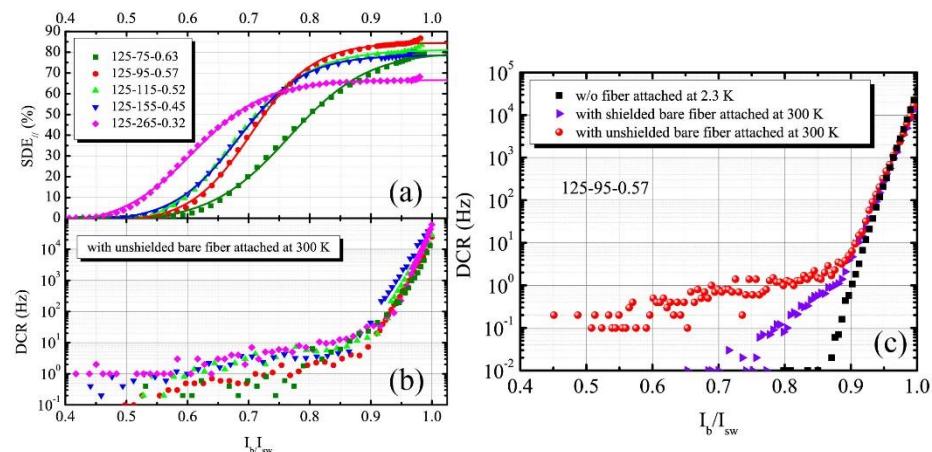
Why 940 nm?

- Best available QD at this wavelength
- Important platform for quantum information process

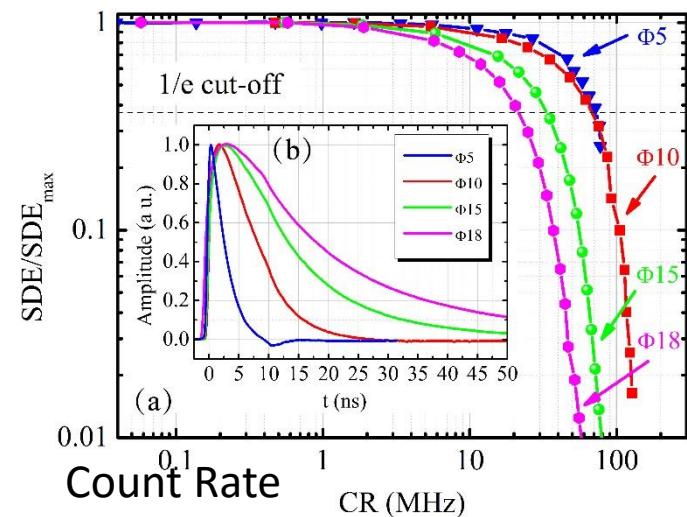


Detector	DE	Dead Time
Si APD	20-30%	45 ns
SNSPD	80%	12 ns

Ten-fold count rate will be improved by 10^{4-5}



SDE and DCR vs Bias current



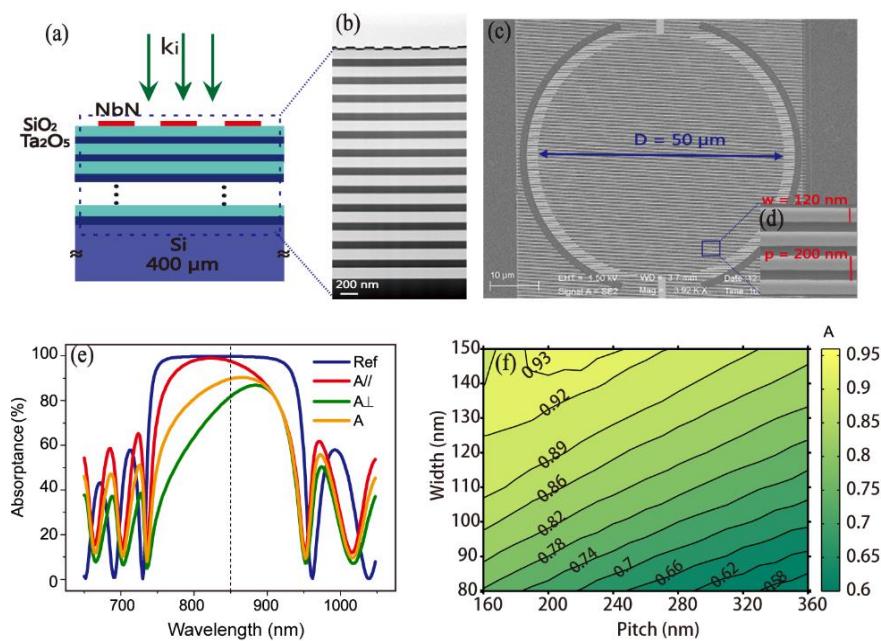
AIP Adv 5(6): 067129. (2015), IEEE J Photon 8(2): 1 (2016)

已提供给中科大陆朝阳教授

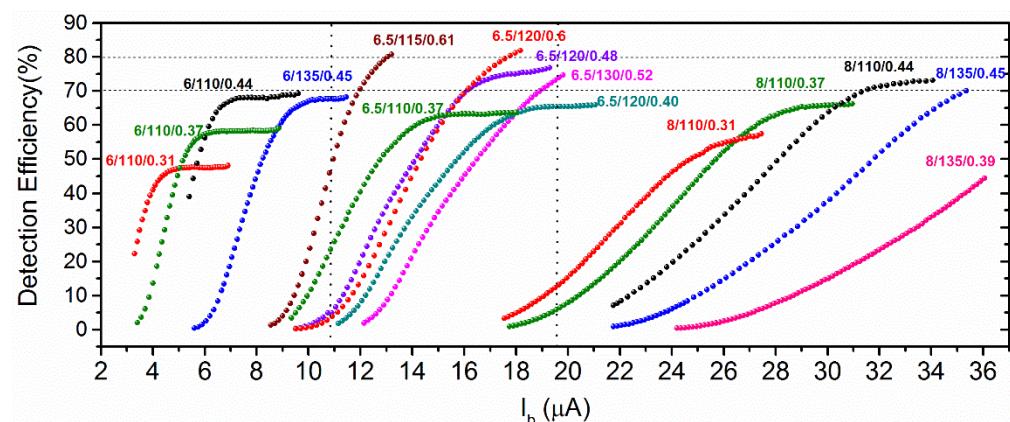
SNSPD for 850 nm

Why 850 nm?

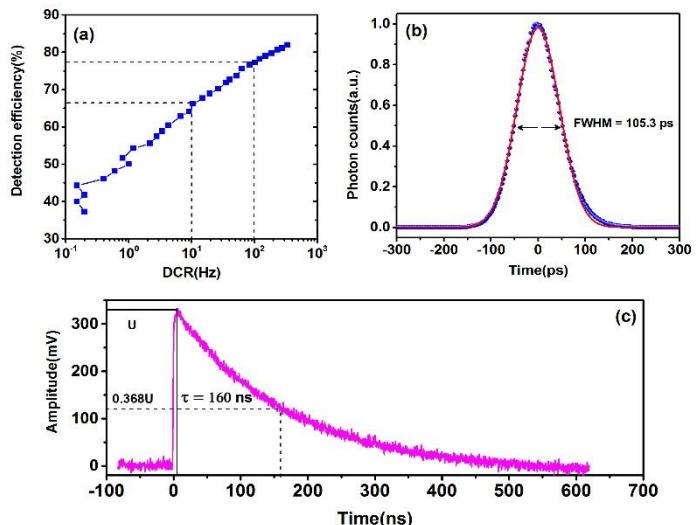
Detector	DE
Si APD	50%
SNSPD	80%



OE 23(13): 17301 (2015)

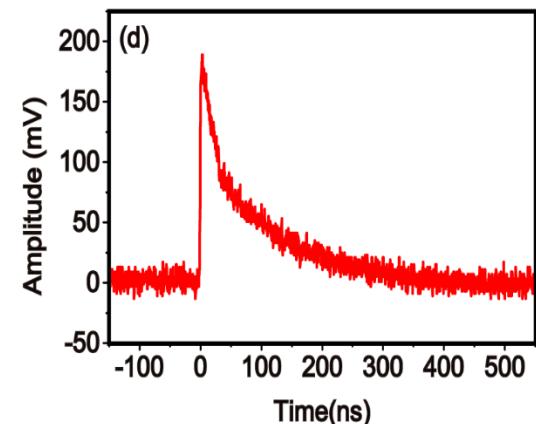
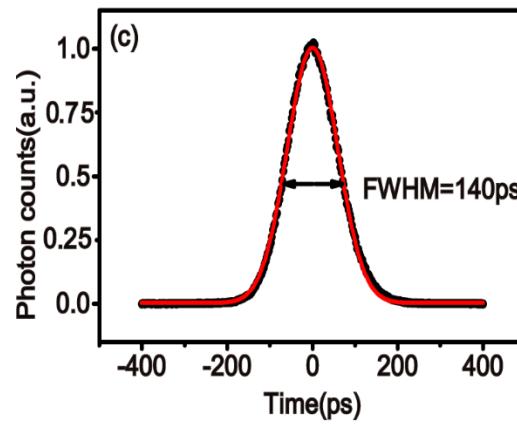
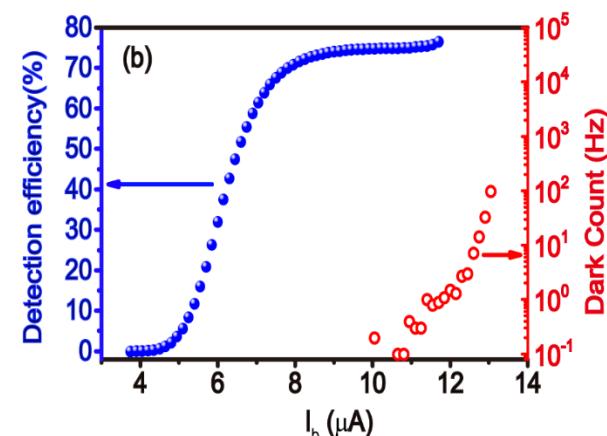
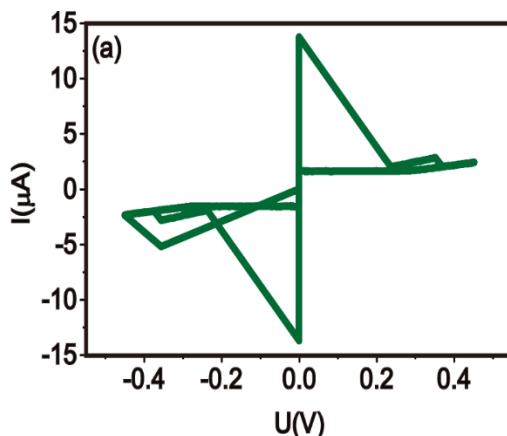
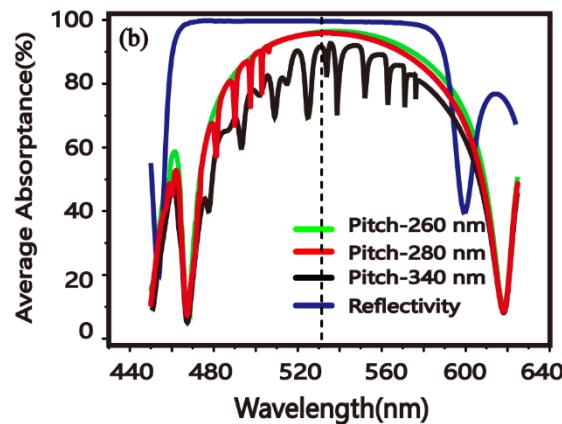
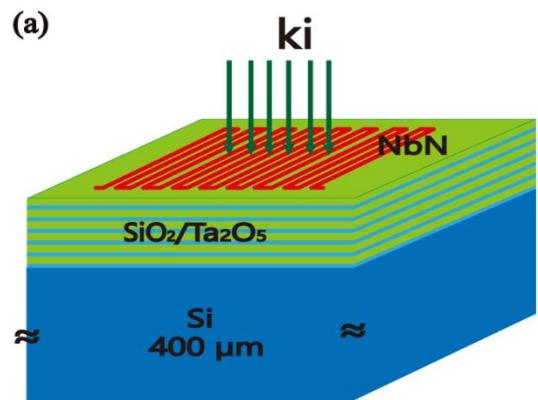


SDE ($> 80\%$) vs Bias current



Key performance

SNSPD at 532nm



1. HR based.

2. MMF($\phi=50\mu\text{m}$)

3. W/p=140/280 (nm)

4. $\phi=42 \mu\text{m}$

SDE=75%@DCR<1

Optics Express 24(4): 3535 (2016)

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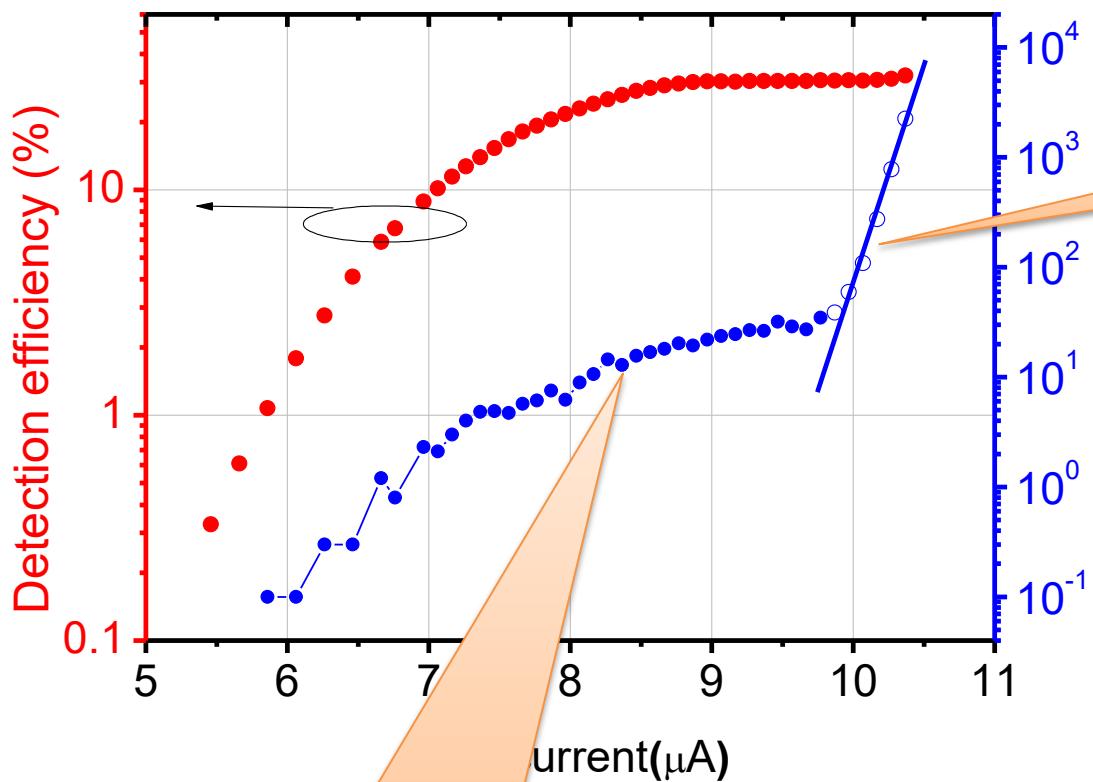
- ✓ 探测效率 (从近红外到可见光)
- ✓ 低暗计数SNSPD
- ✓ 低抖动SNSPD
- ✓ SNSPD极化调控

■ SNSPD应用

- ✓ 量子信息应用
- ✓ 其它应用

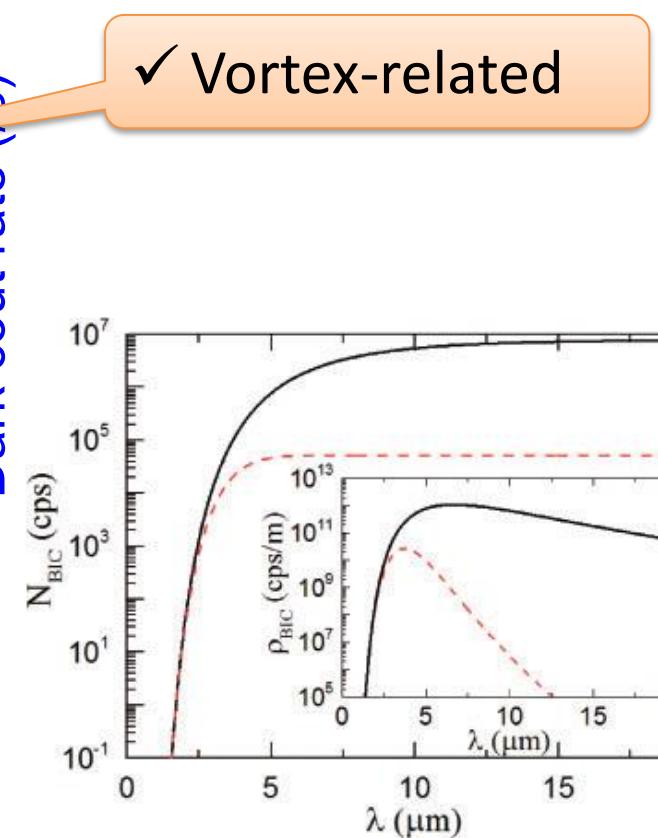
Origin of dark counts of SNSPD

DE & DCR vs Bias Current



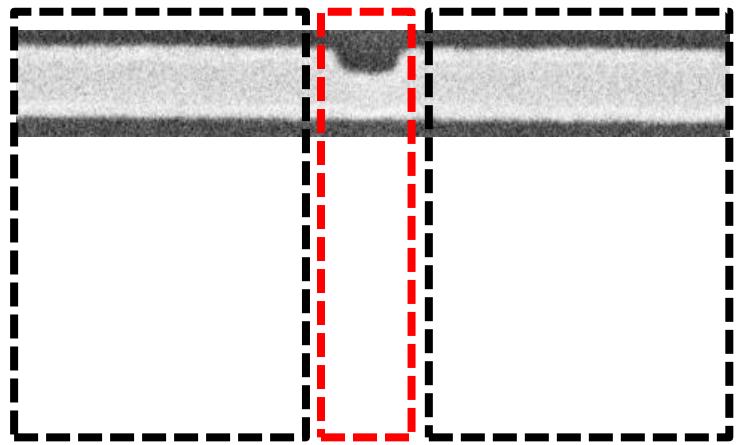
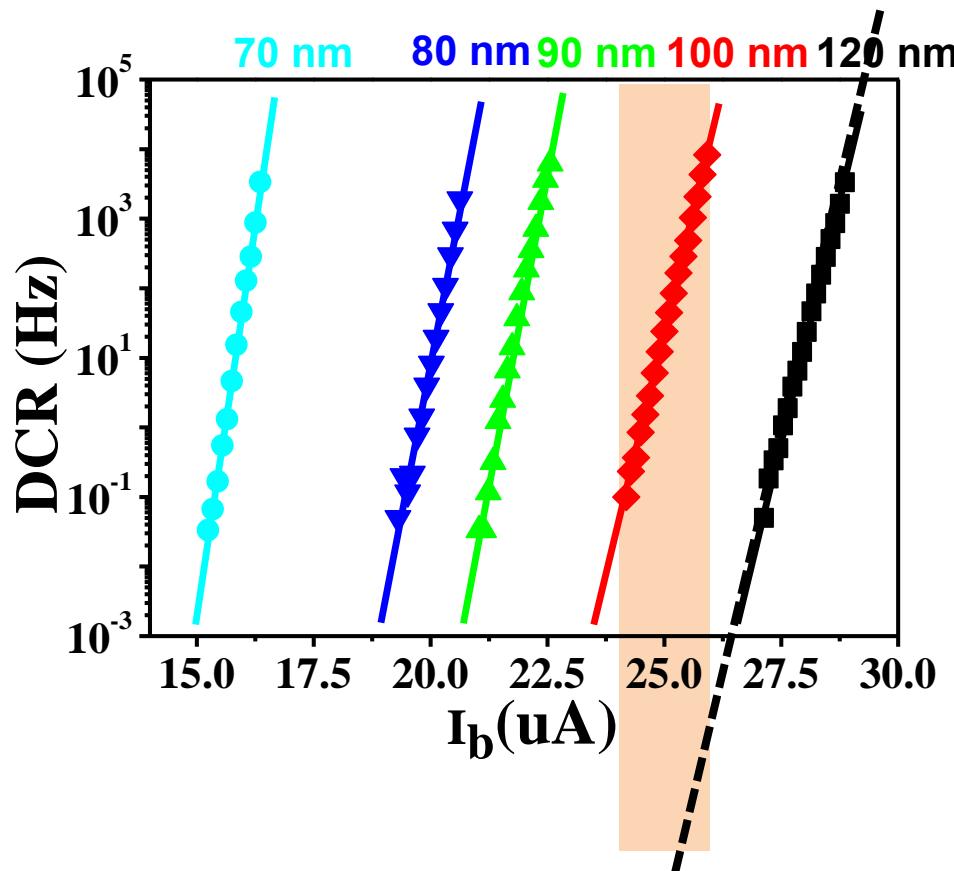
✓ Blackbody
Radiation of fiber

Origin of Dark Count Rate



Blackbody radiation

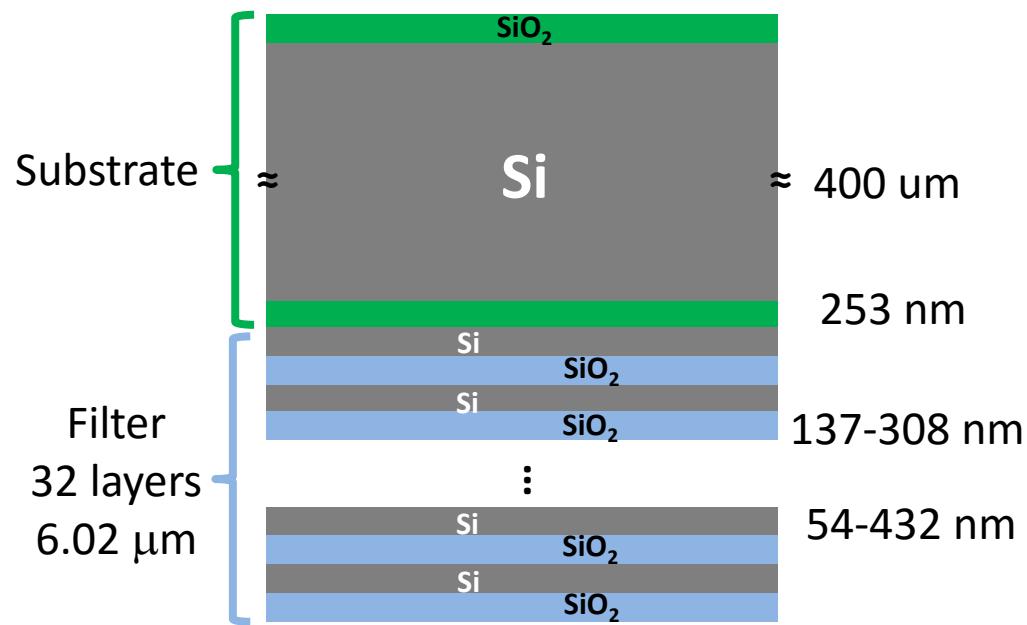
Intrinsic Dark count



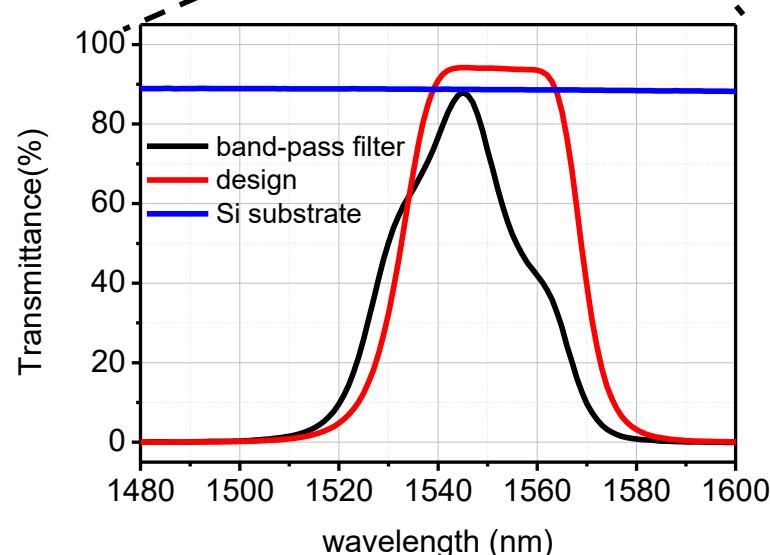
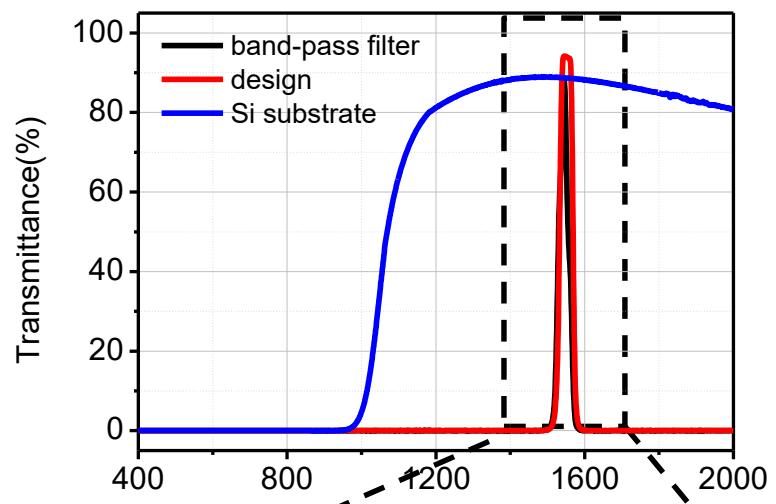
Origin of DC (VAP, Hopping, quantum tunneling) is unclear

DCR is contributed by the single smallest constriction.

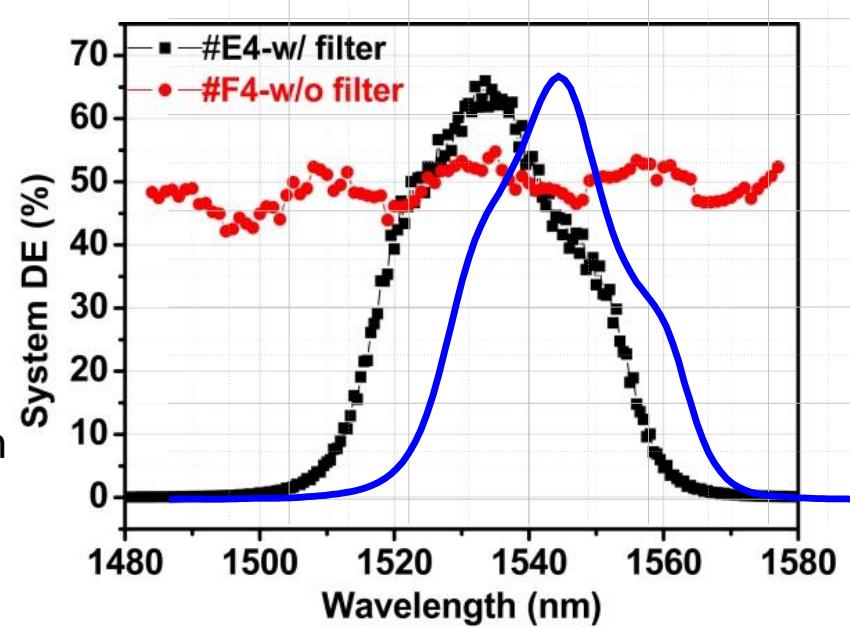
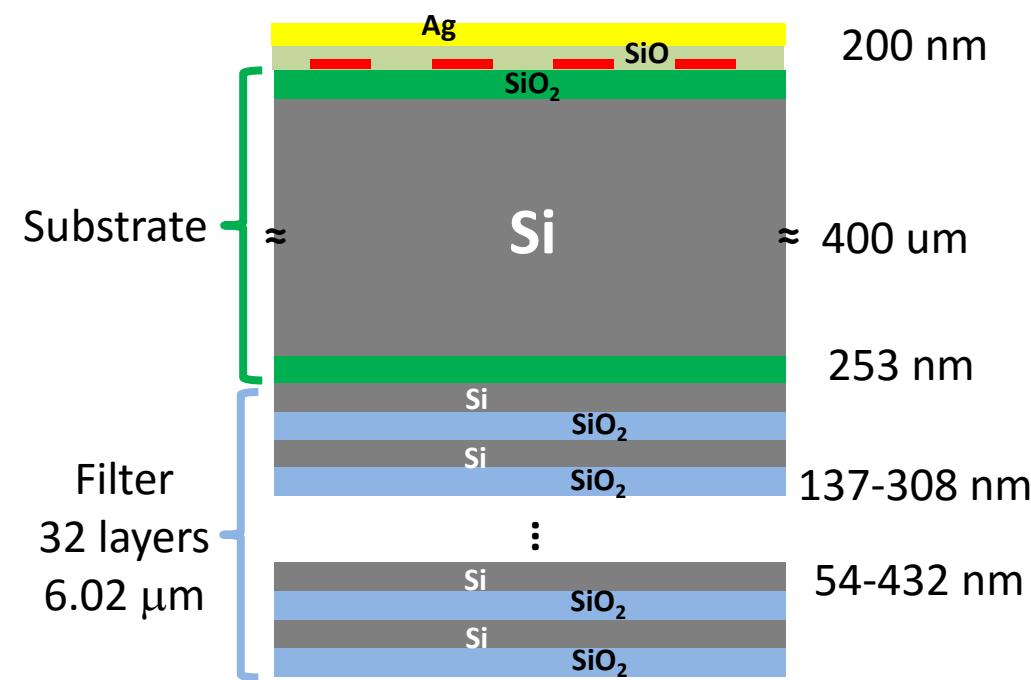
On-chip Bandpass Filter



	<i>Pass-band</i>	<i>transmittance</i>
<i>Substrate only</i>	>1000nm	88.7%
<i>Calculation</i>	1545-1555nm	94%
<i>Experiment</i>	1542nm	88%



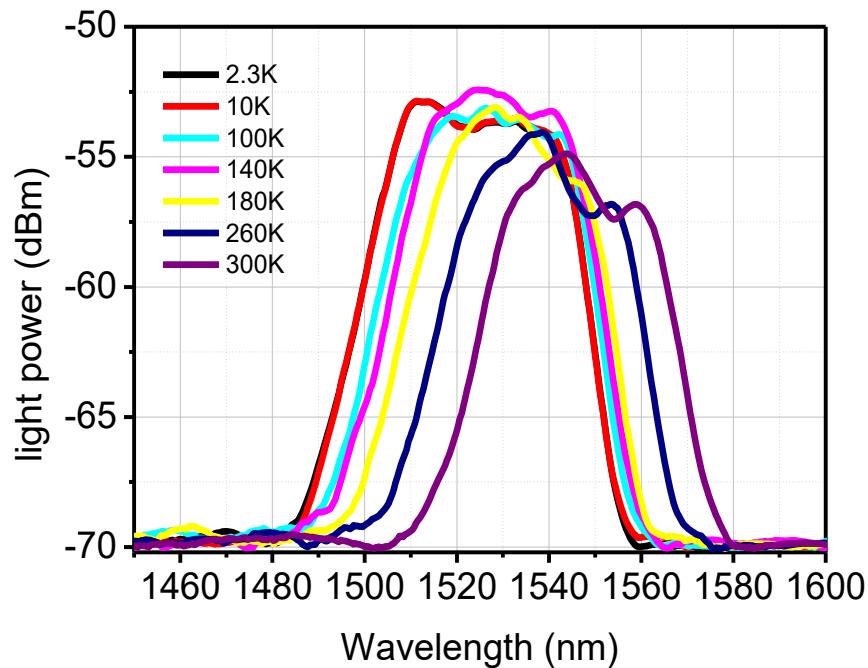
SNSPD with bandpass filter



SDE vs Wavelength

- System DE shows an evident wavelength dependence consistent to the property of bandpass filter
- The central wavelength is shifted to lower value (1545 nm to 1532 nm)

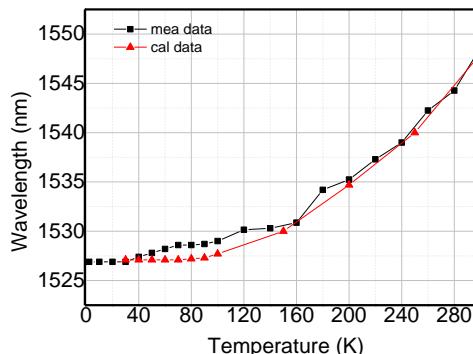
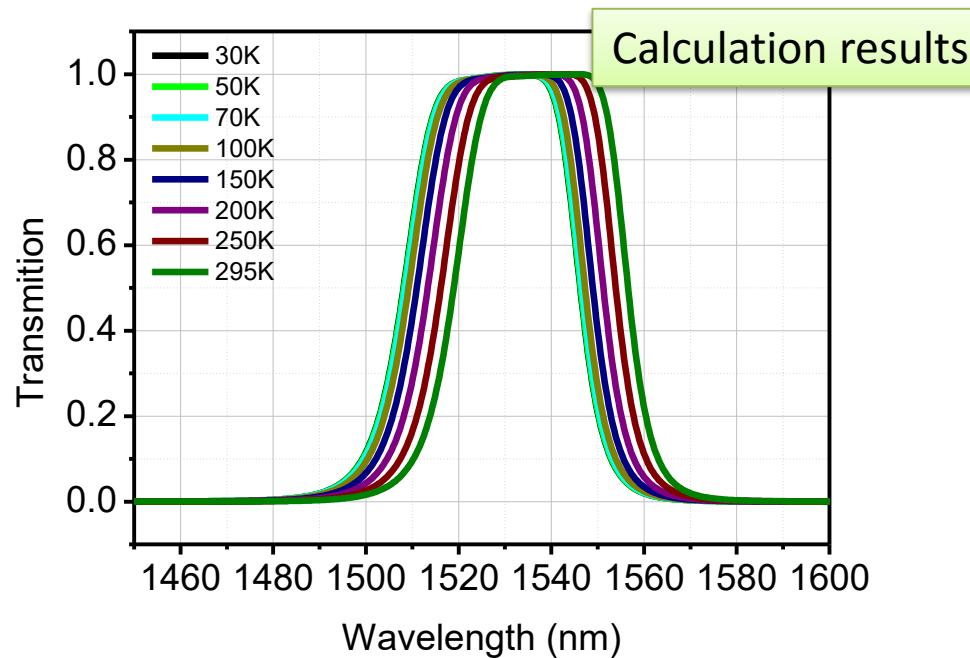
Temperature dependence of filter



Experimental results

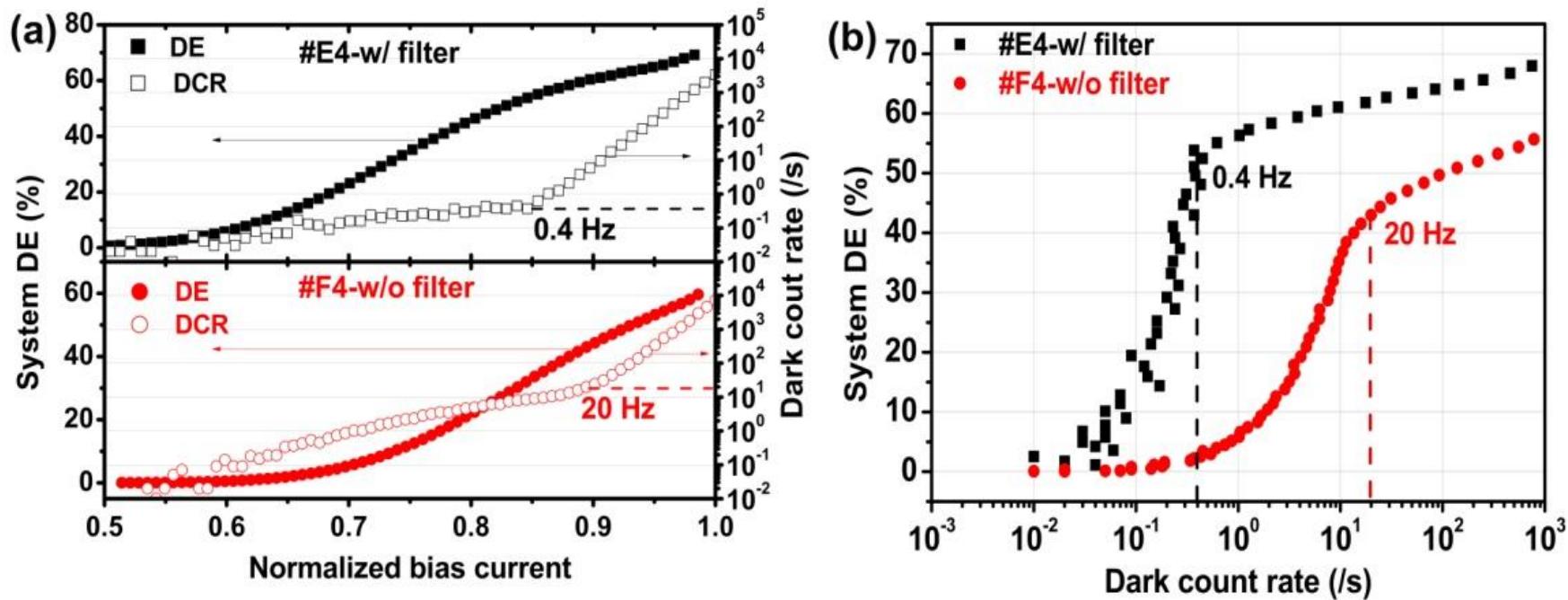
- Central wavelength moves from : 1549 nm (300K) to 1527 nm (2K), which can be explained by the changes of refractive index of Si

Si data from Bradley J. Frey Proc. SPIE 6273, Optomechanical Technologies for Astronomy, 62732J (July 06, 2006)



SiO₂ data from C.Z. Tan et.al. Journal of Physics and Chemistry of Solids 61 (2000) 1315–1320

Low-DCR SNSPD



DCR (Hz)	0.1	0.4	1	10	100	
SDE (%)	#E4	16.8	52.4	56.2	61.2	64.2
	#F4	0.7	2.6	6.0	36.4	50.2
NEP (W/Hz ^{1/2})	#E4	3.7×10^{-19}	2.0×10^{-19}	3.0×10^{-19}	8.8×10^{-19}	2.6×10^{-18}
	#F4	6.7×10^{-18}	4.4×10^{-18}	2.8×10^{-18}	1.6×10^{-18}	3.6×10^{-18}

$$NEP = h\nu \cdot \sqrt{2DCR} / DE$$

X. Yang et al Opt. Express 22, 16267-16272 (2014)

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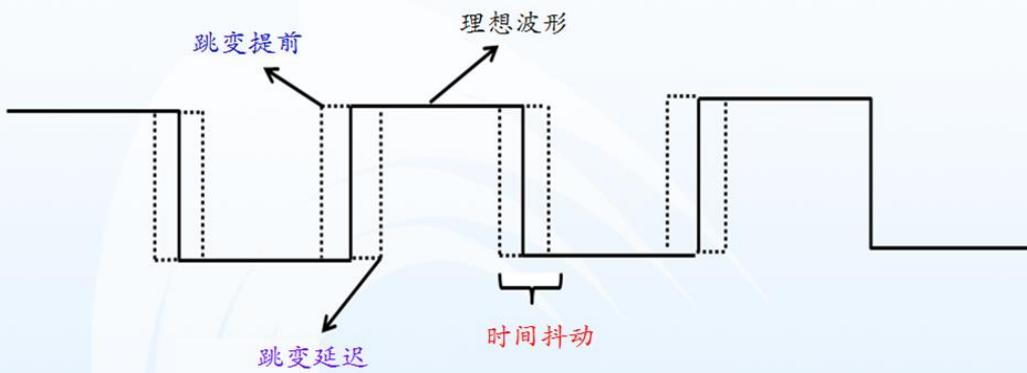
- ✓ 探测效率 (从近红外到可见光)
- ✓ 低暗计数SNSPD
- ✓ 低抖动SNSPD
- ✓ SNSPD极化调控

■ SNSPD应用

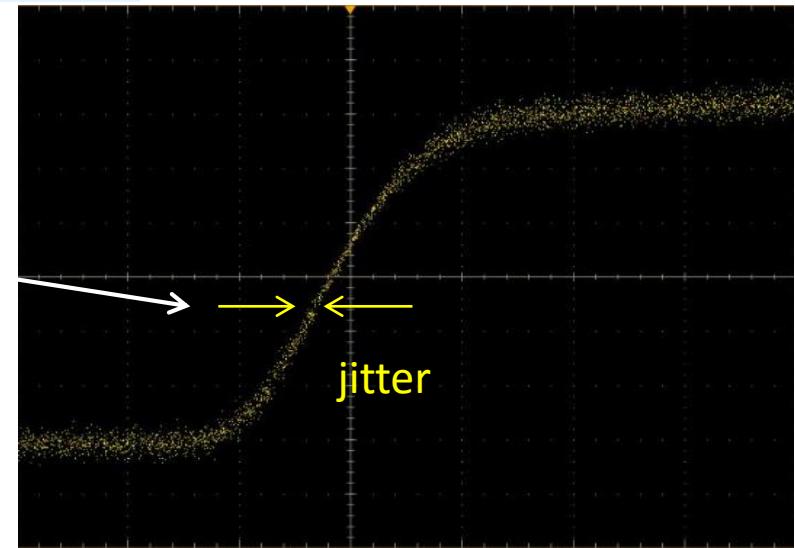
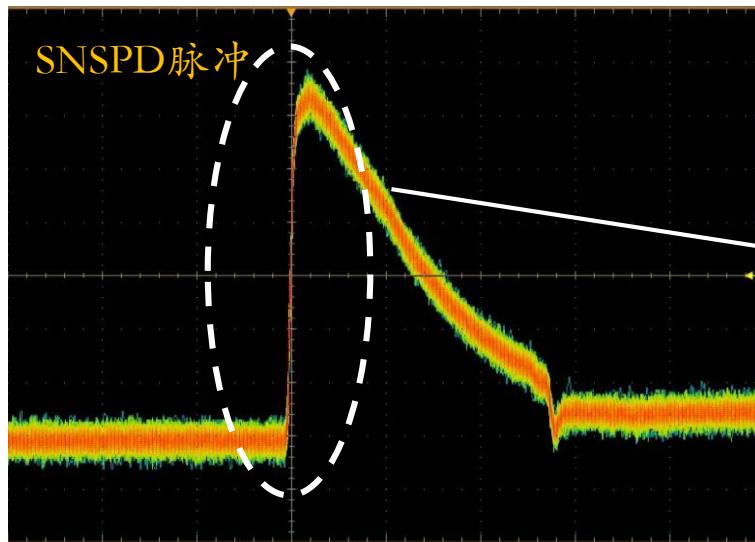
- ✓ 量子信息应用
- ✓ 其它应用

What is jitter

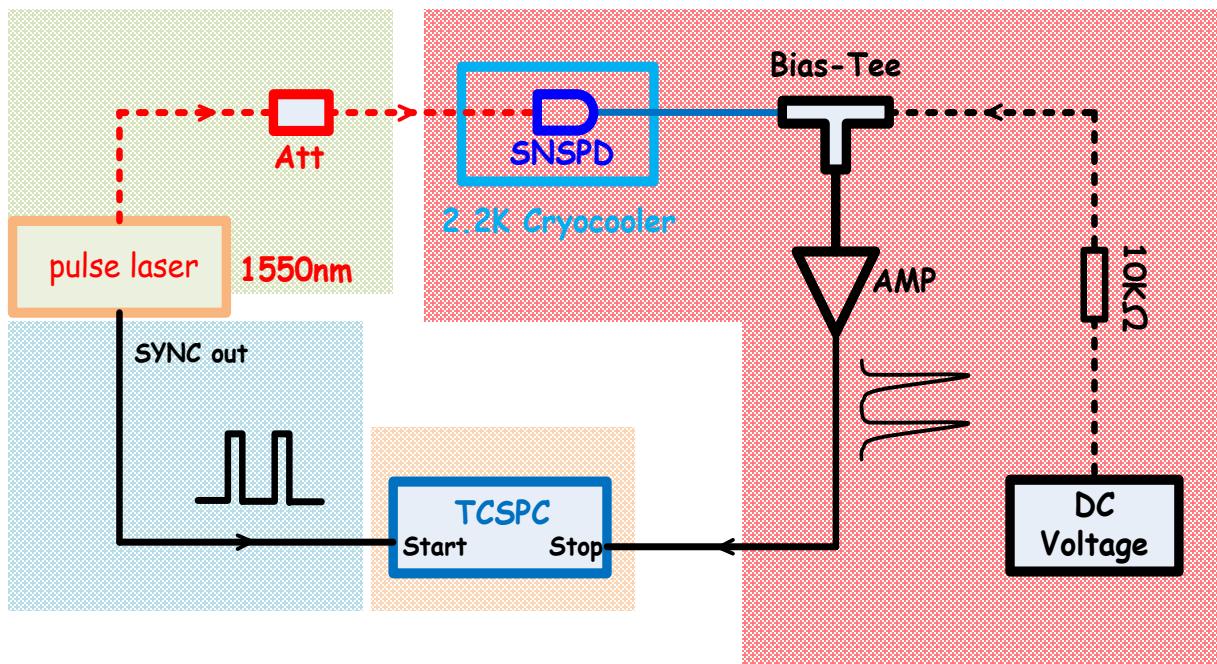
Timing Jitter: the timing deviation from an ideal periodic single-photon-response voltage pulse



- Laser ranging
- SP imaging
- High speed communication



TCSPC system for jitter measurement

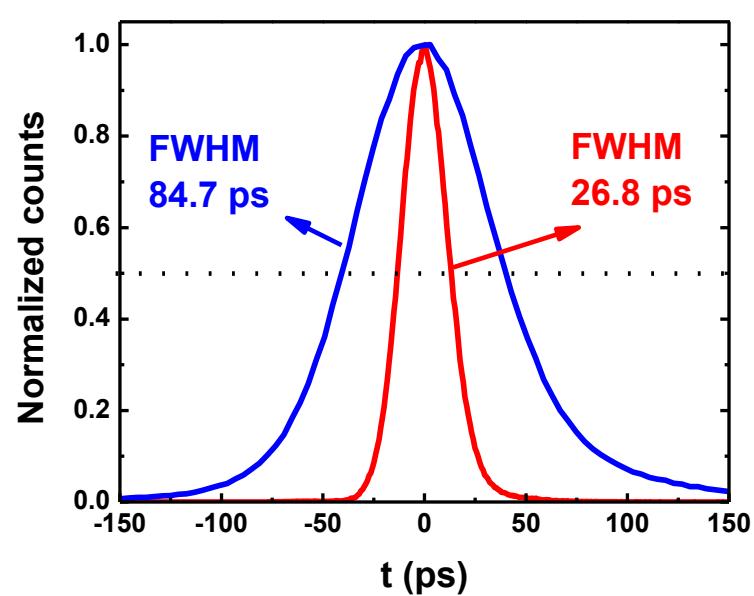
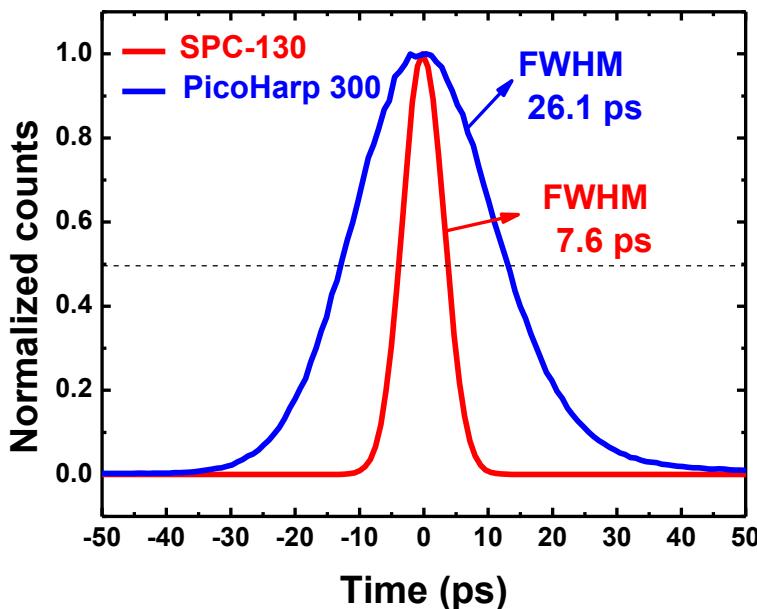


Items	Typical values (ps)
j_{APD}	> 50 ps
j_{SNSPD}	~30
j_{IRF}	20~30
j_{SYNC}	<10

$$j_{total} = \sqrt{j_{SNSPD}^2 + j_{laser}^2 + j_{sync}^2 + j_{IRF}^2}$$

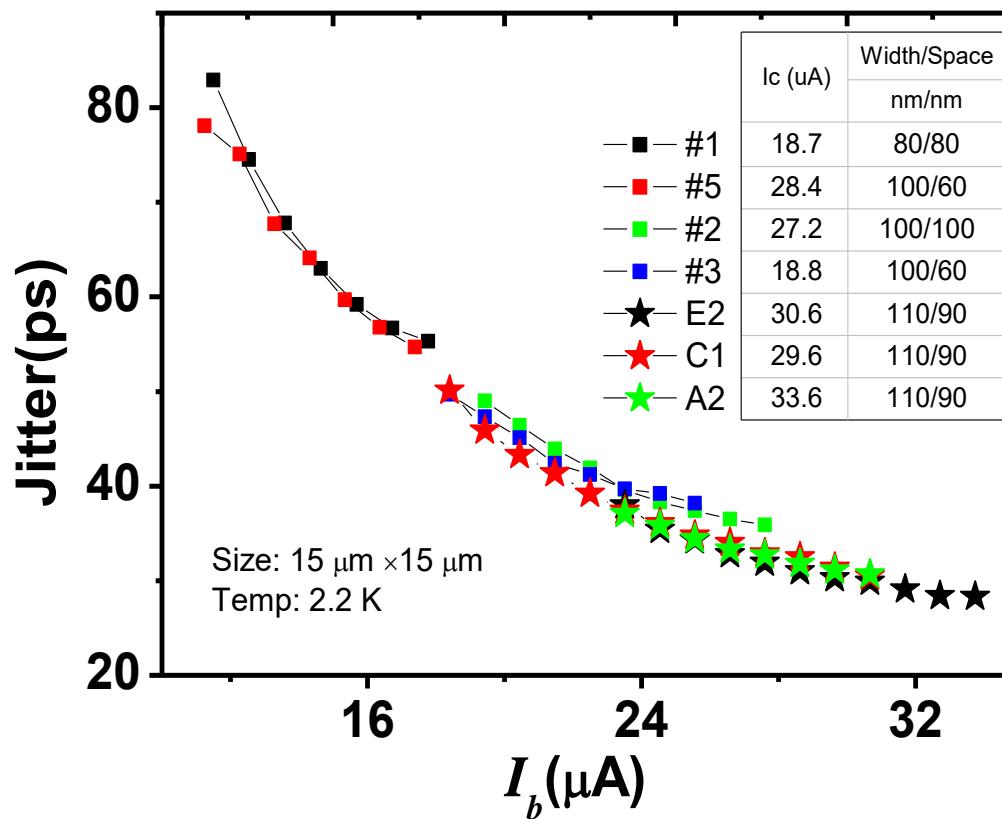
Jitter analysis of parts

Jitter compositions	popular components	Jitter (ps)	Optimized components	Jitter (ps)
j_{laser}	Hamamatsu C10196	68.7	Calmar FPL-01CAF	0.06
j_{sync}		16.2		4.0
j_{TCSPC}	PicoQuant PicoHarp 300	26.1	bh SPC-130	7.6
j_{NSPND}	LNA Phillips-6954	39.6	LNA-650	25.4
j_{total}	×	84.7	×	26.8



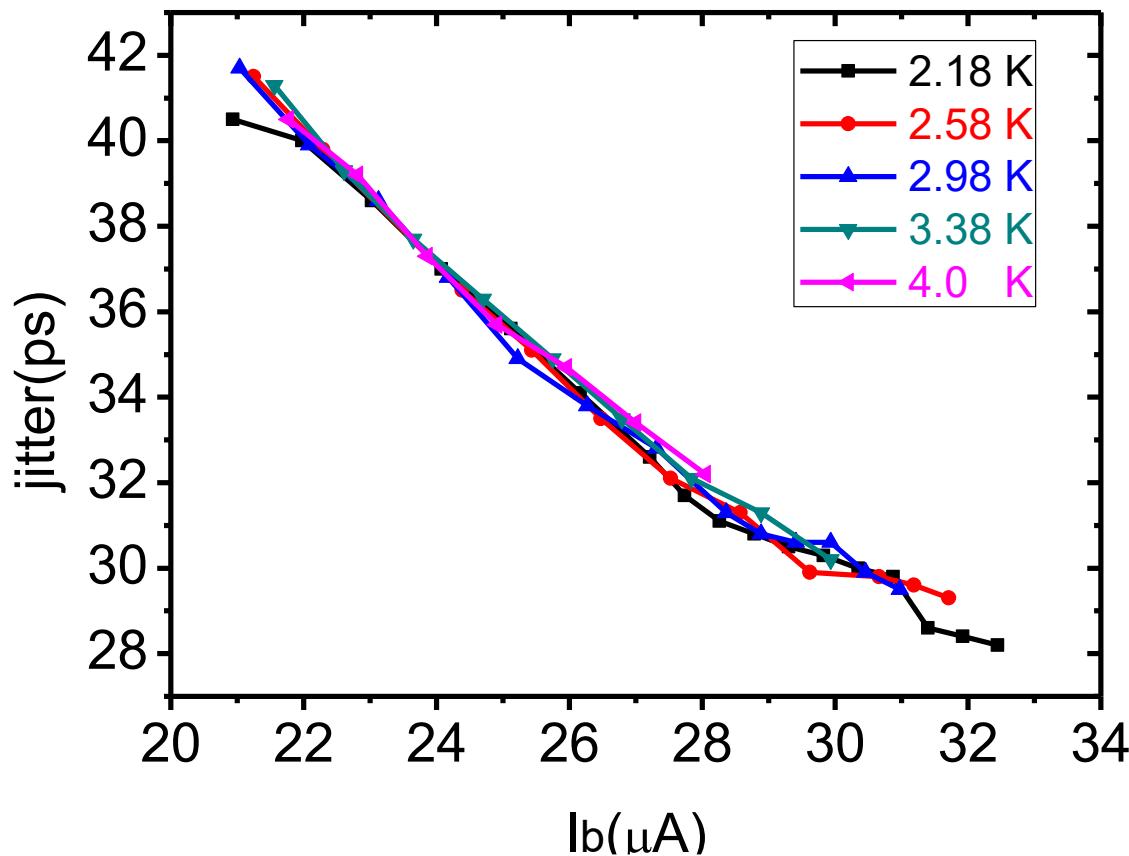
Jitter analysis of SNSPD

What determines the jitter of SNSPD?



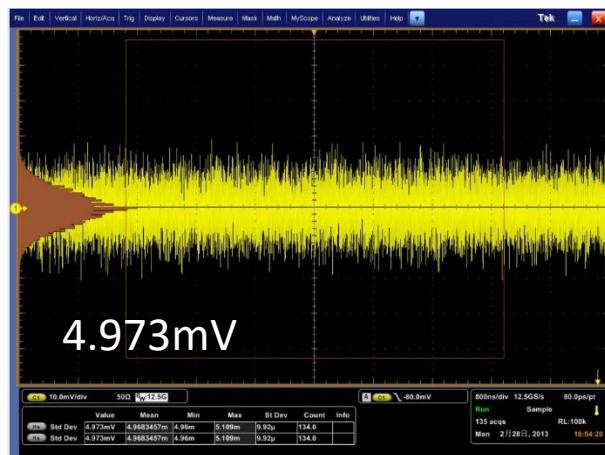
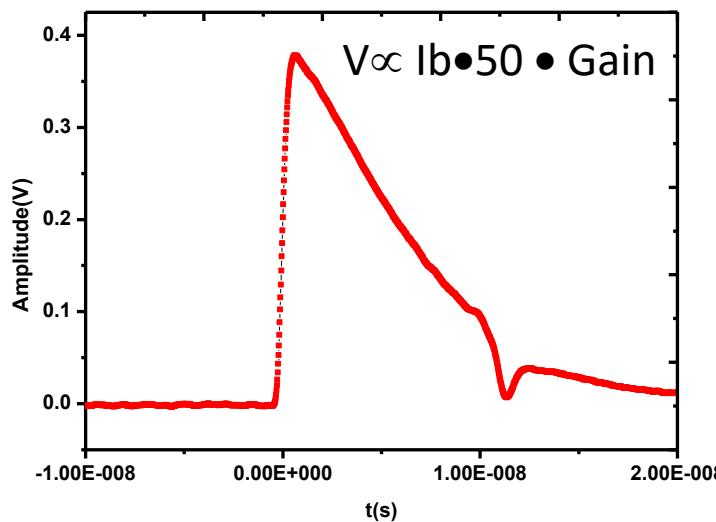
Jitter vs I_b

Jitter analysis of SNSPD

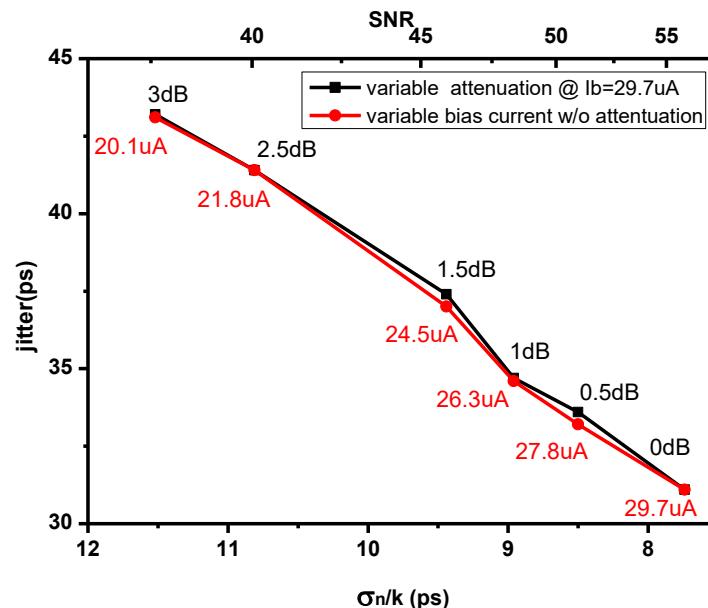
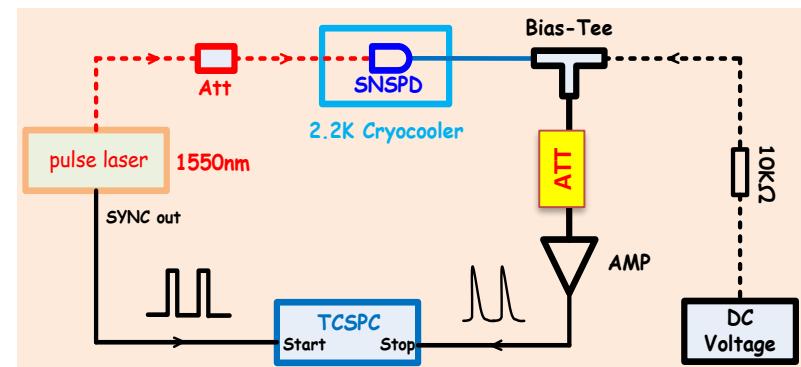


Jitter vs I_b at different temperature

Jitter analysis of SNSPD

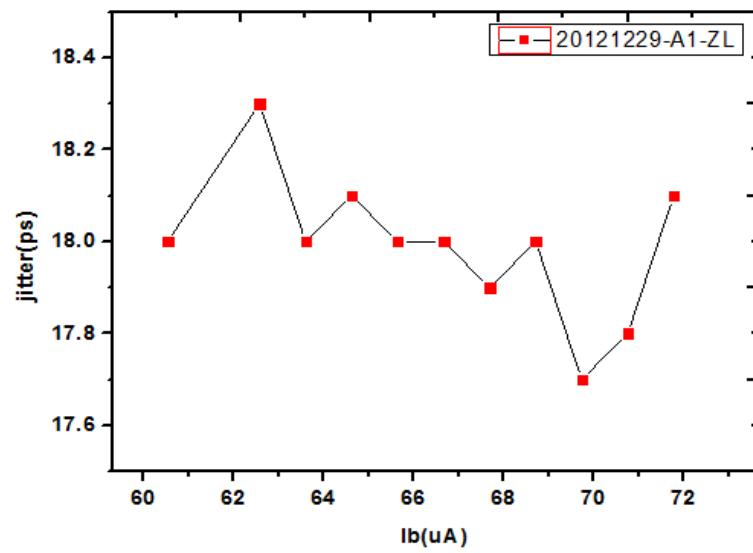
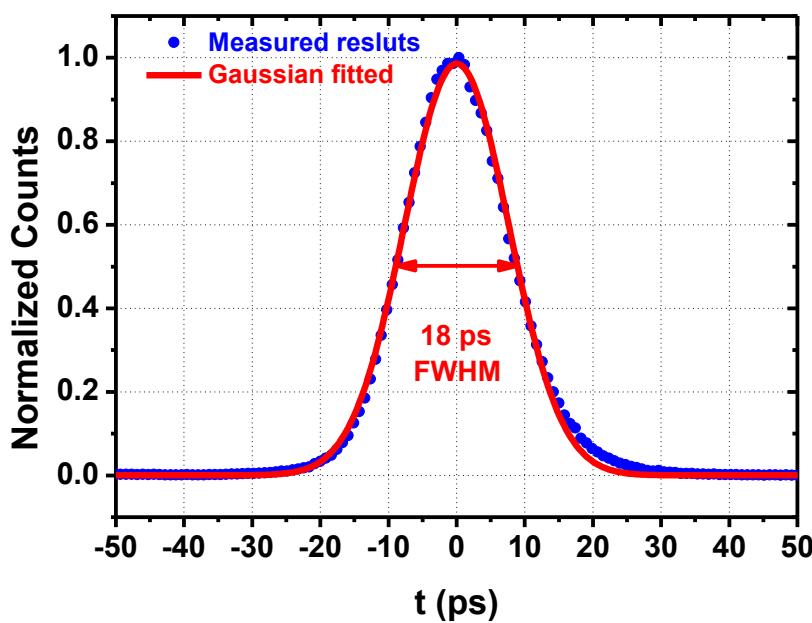


You, L et al AIP Advances 3: 072135, 2013



Jitter vs σ_n/k and SNR

Jitter analysis of SNSPD



Jitter of SNSPD with high SNR

$$j_{SNSPD} = \sqrt{j_{intrinsic}^2 + j_{noise}^2}$$

器件	探测效率	临界电流/ μA	偏置电流 (@100DCR) / μA	薄膜厚度/nm
A1	1%	32.0	27.5	4
201229-A1-ZL	0.8%	73.0	70.0	7

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- ✓ 低抖动SNSPD
- ✓ SNSPD极化调控

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- ✓ 量子信息应用
- ✓ 其它应用

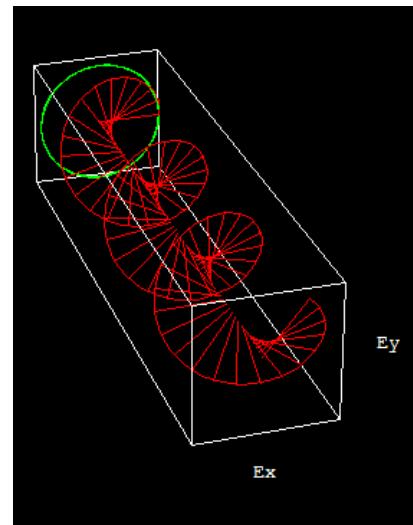
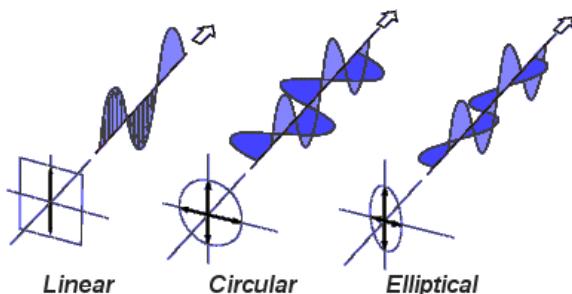
Polarization and applications

Light parameters:

- Frequency/Wavelength
- Intensity
- Phase
- Polarization



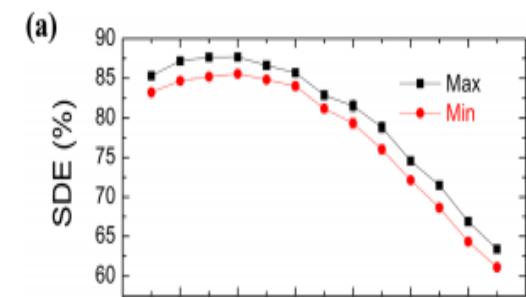
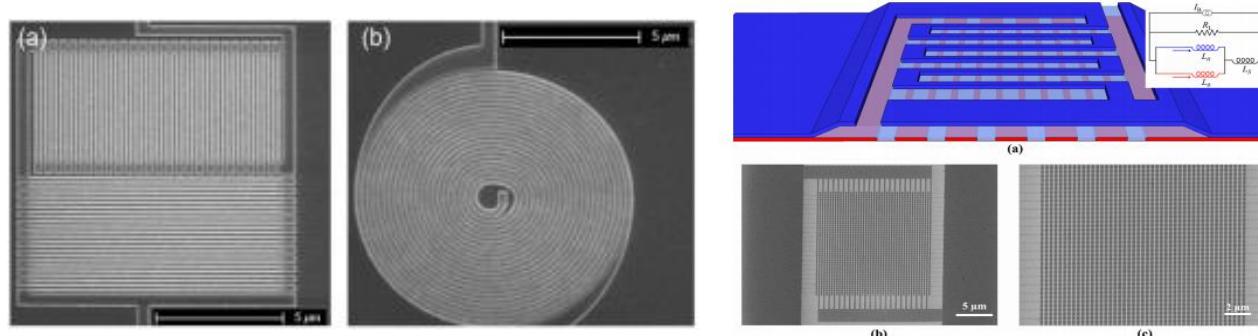
Polarization of electromagnetic waves



Applications:

- Sunglass
- LCD
- 3D video
- Remote sensing
- Biological imaging
- Quantum Info (QKD)
-

SNSPD 极化特性



Dorenbos S N, et al. Applied Physics Letters, 2008, 93: 161102

Verma V B et al, Applied Physics Letters, 2012, 101: 251114

$$QE_{//} \approx QE_{\perp}$$

Polarization-insensitive SNSPD

SNSPD with high polarization sensitivity

$$QE_{//} \gg QE_{\perp}$$

Play with the geometric parameters: linewidth, pitch

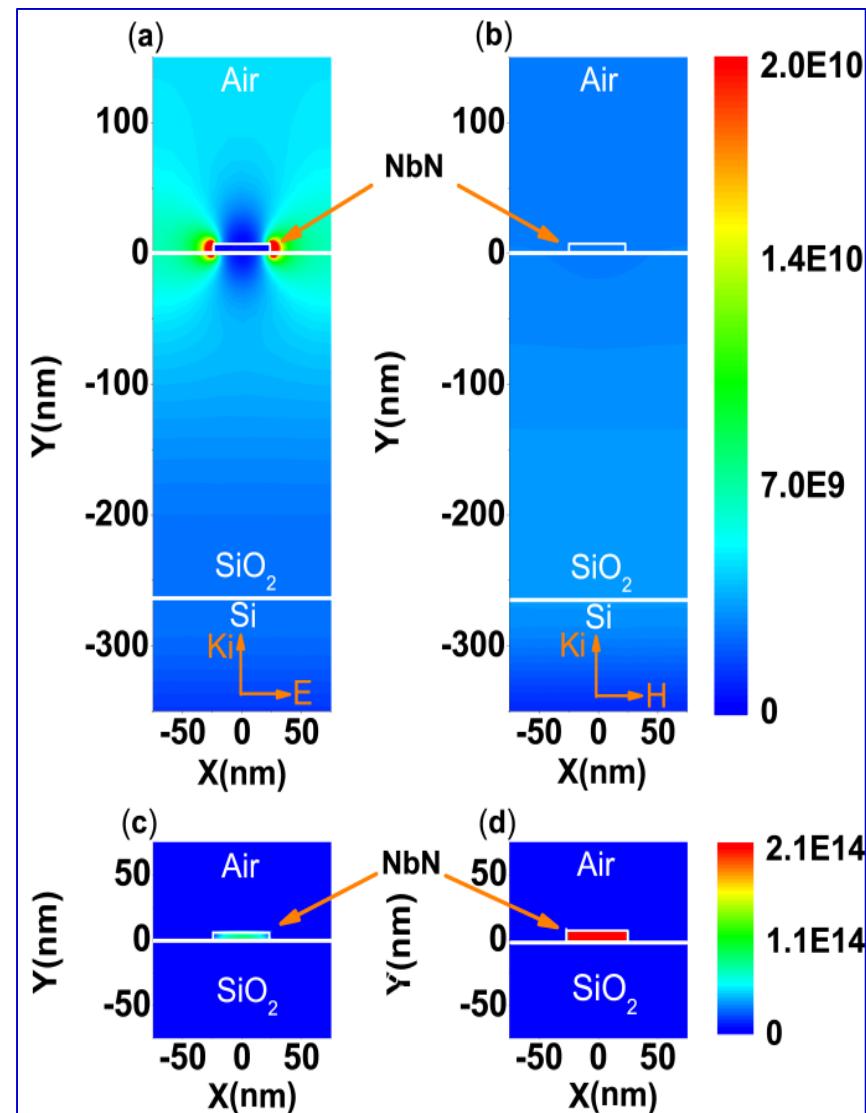
高度极化敏感 SNSPD

The factors we may play:

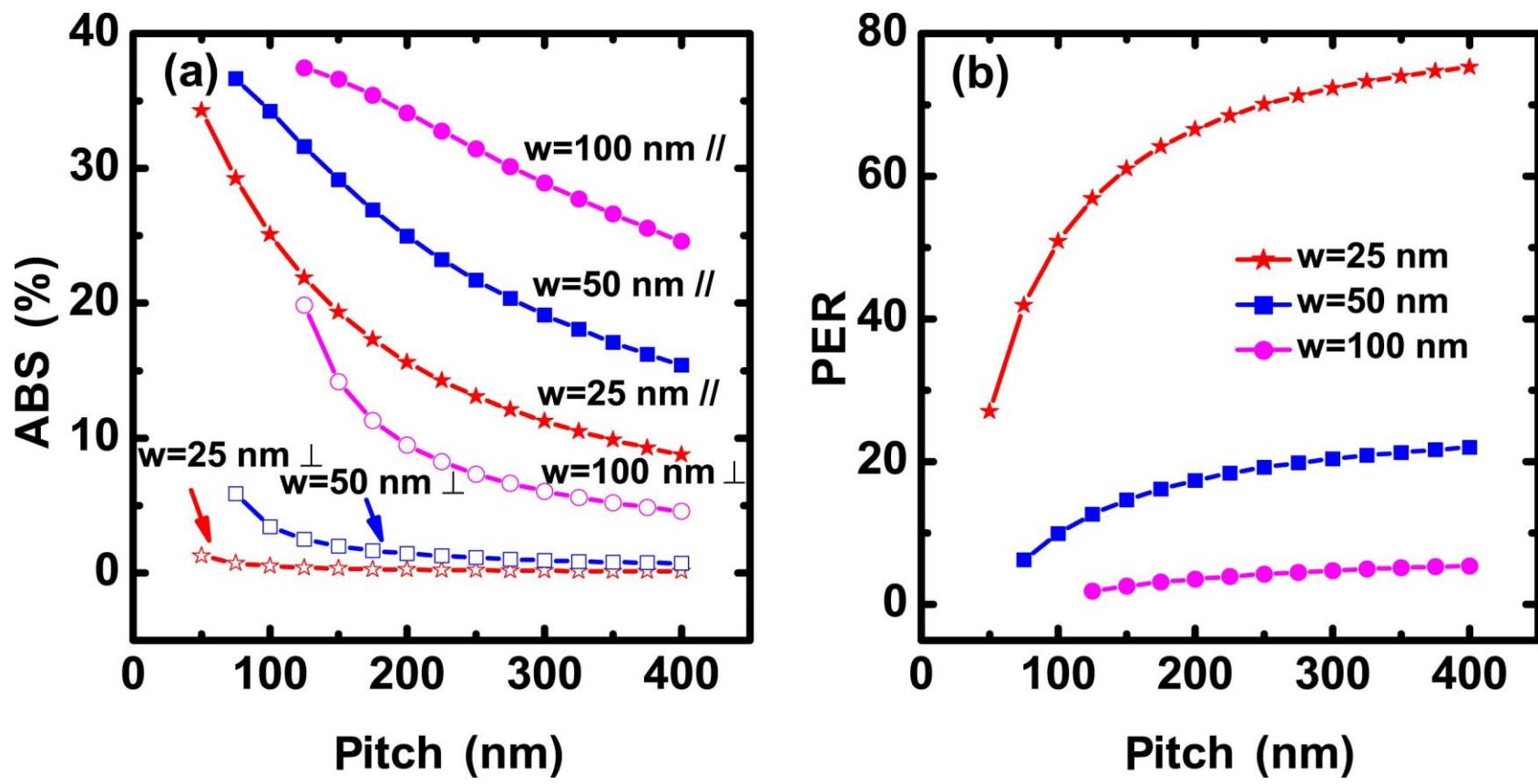
- ✓ width
- ✓ pitch
- ✓ thickness of NbN
- ✓ cavity

- Software: Comsol
- Method: FEM with periodic boundary condition

- NbN SNSPD on SiO_2/Si substrate
- Backside illumination
- Linewidth/pitch: 50/100 nm



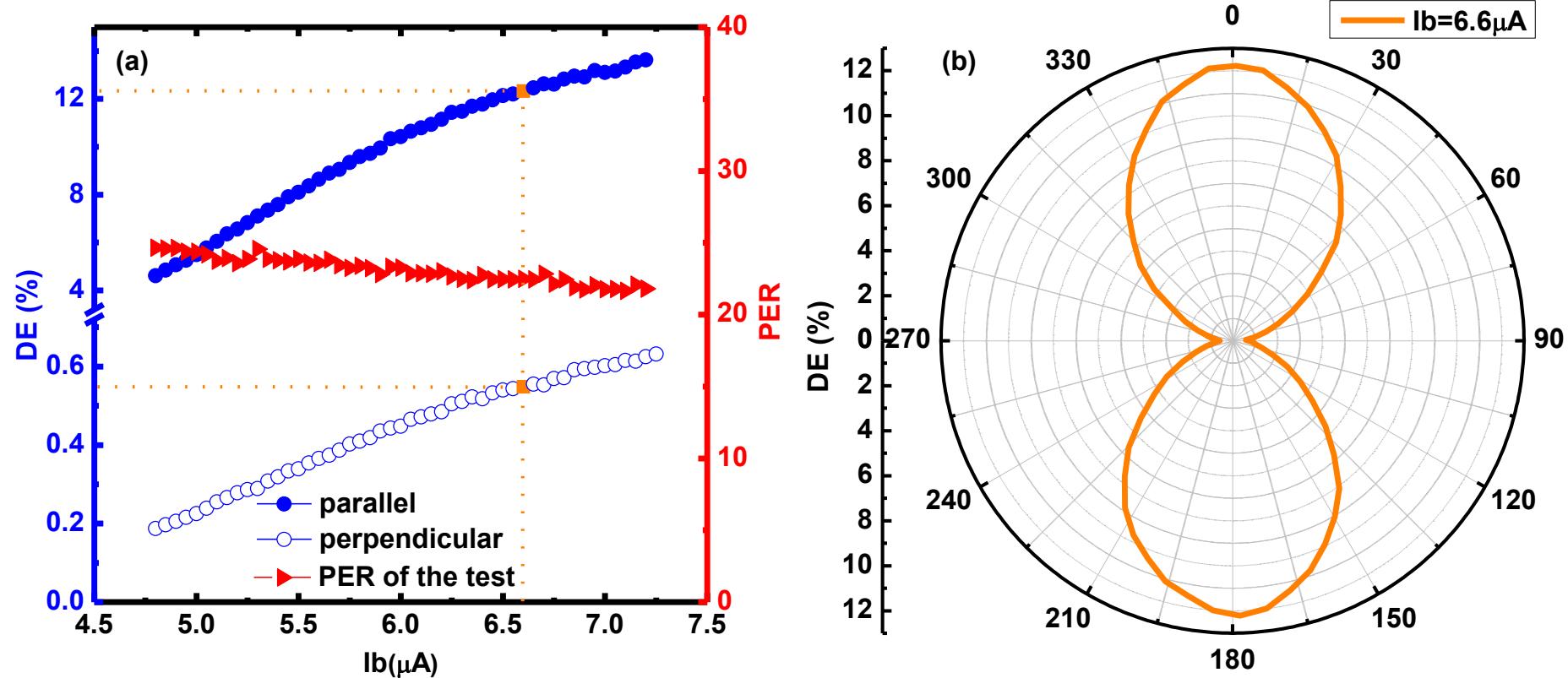
高度极化敏感 SNSPD



ABS & PER vs pitch

- Higher filling ratio → higher absorptance, but
- Trade-off between DE and PER

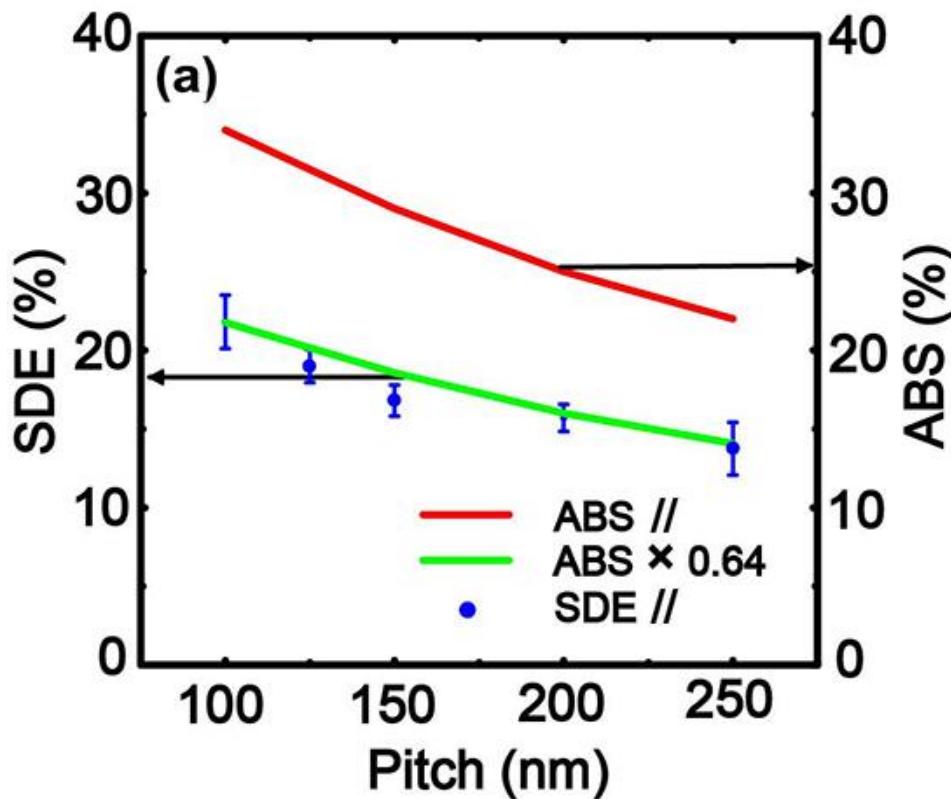
高度极化敏感 SNSPD



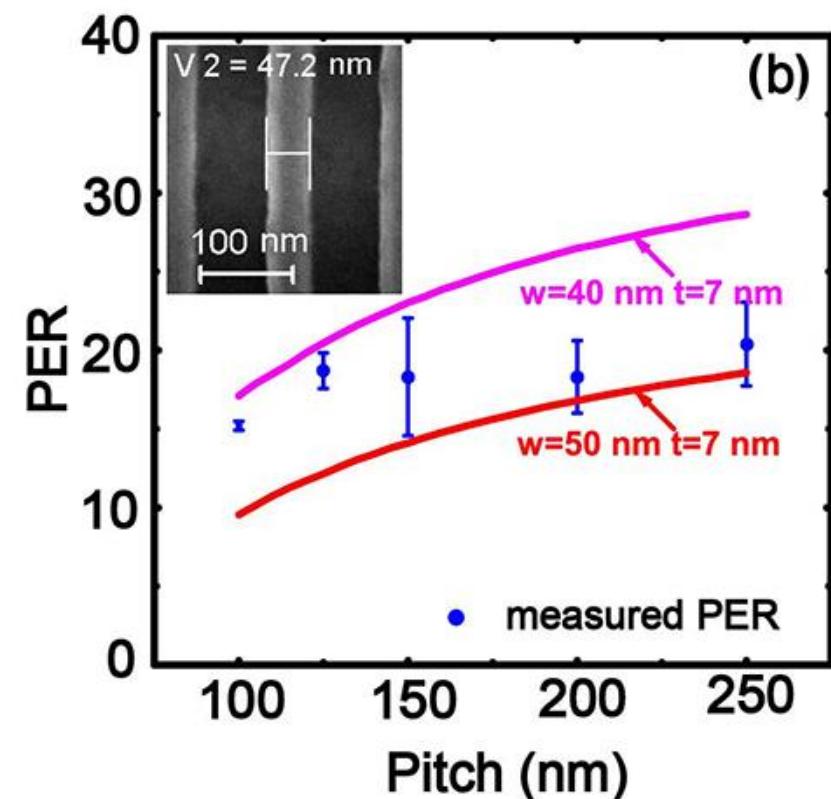
Linewidth/Pitch: 50 nm/250 nm

$SDE_{max} = 12\%$ with $PER > 21$

高度极化敏感 SNSPD



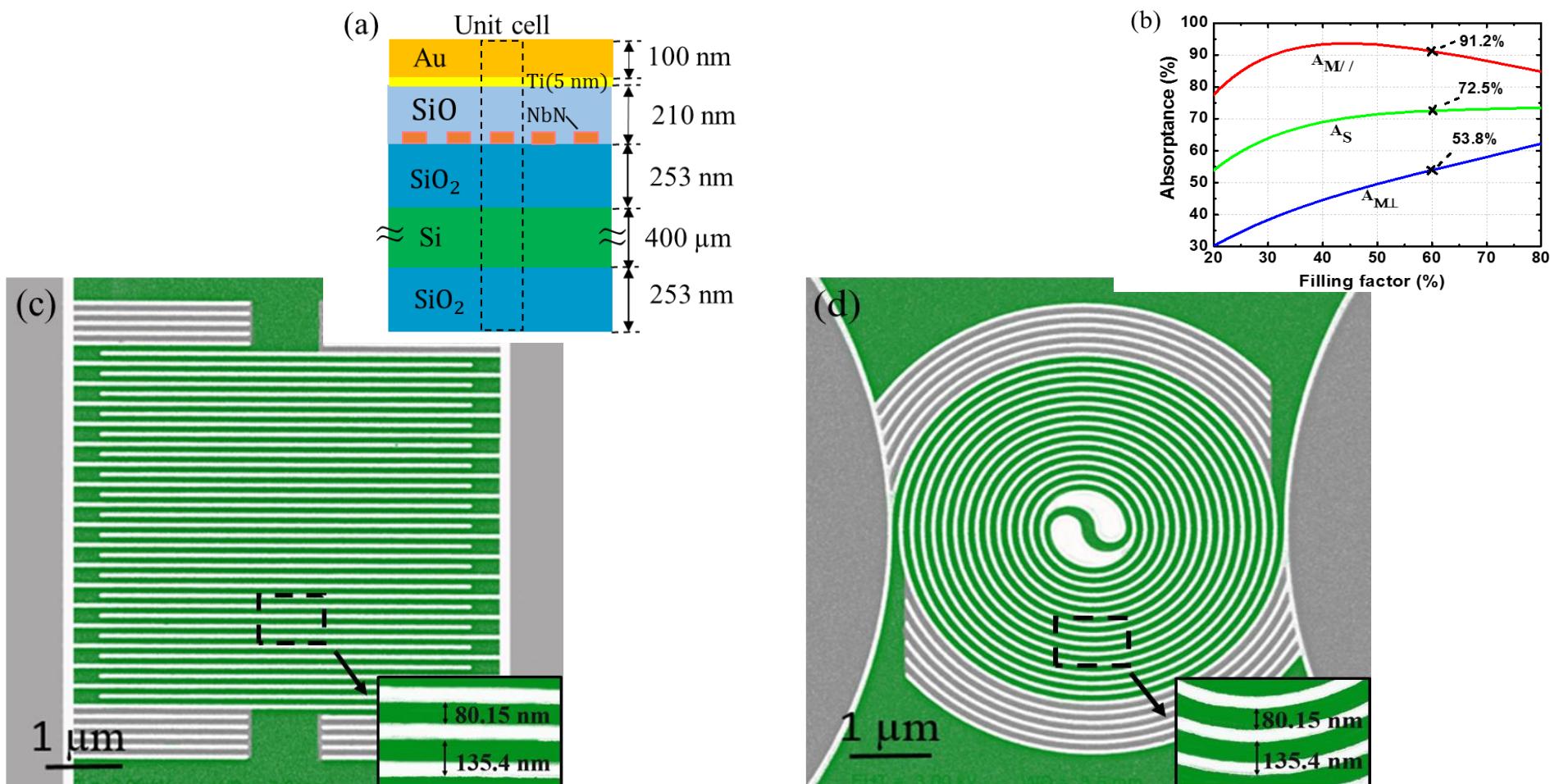
SDE & ABS vs pitch



PER vs pitch

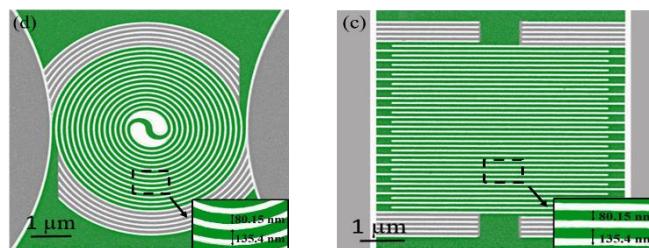
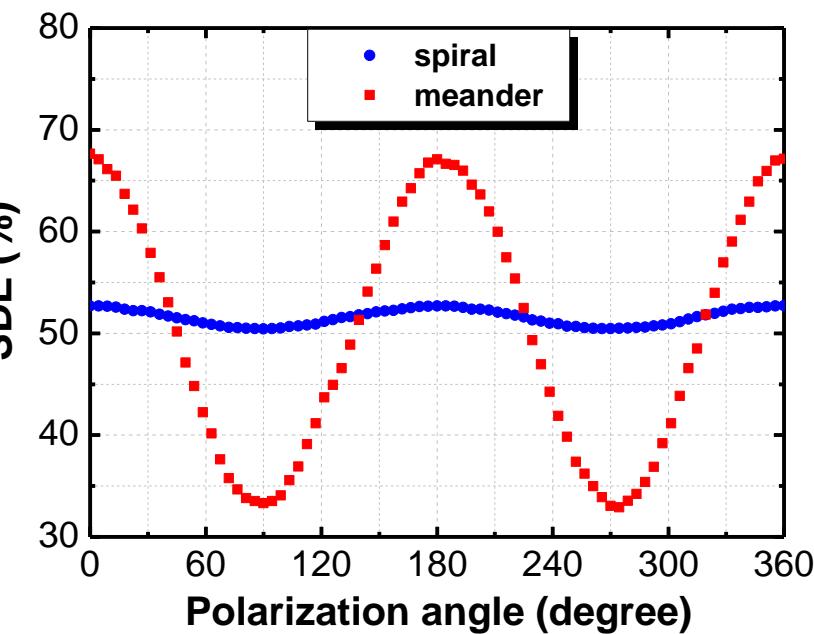
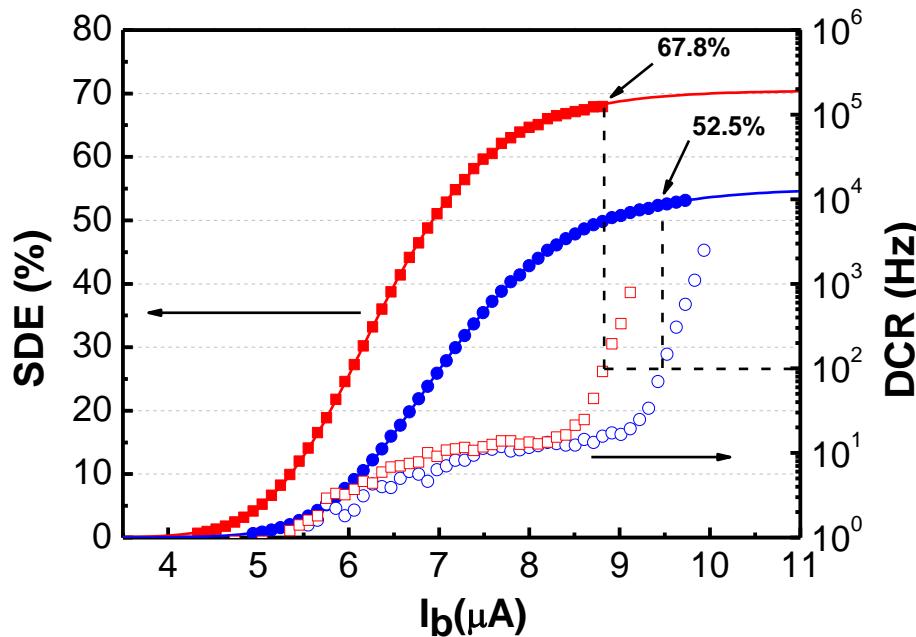
Scientific Reports 5: 9616. (2015)

极化不敏感SNSPD



极化不敏感器件结构设计

极化不敏感SNSPD



简单螺旋线结构器件可以实现计划不敏感性
优于4%，探测效率大于50%。

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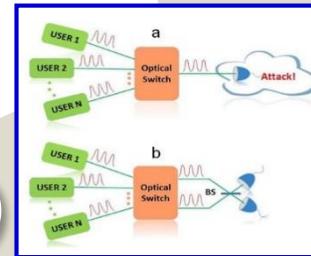
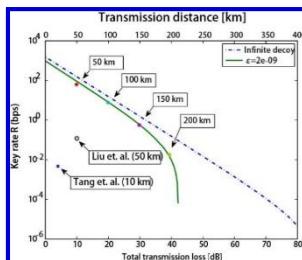
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- ✓ SNSPD极化调控

■ SNSPD应用

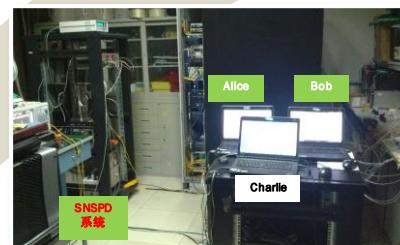
- ✓ 量子信息应用
- ✓ 其它应用

全自主系统应用于量子通信

13-14年
200 km MDI-QKD
2014年度
“中国十大科技进展”



15-16年：
200 平方公里星型拓扑结构MDI-QKD网络



13年10月，
4通道全自主系统效率~50%
分别安装于北京和合肥两地QC实验



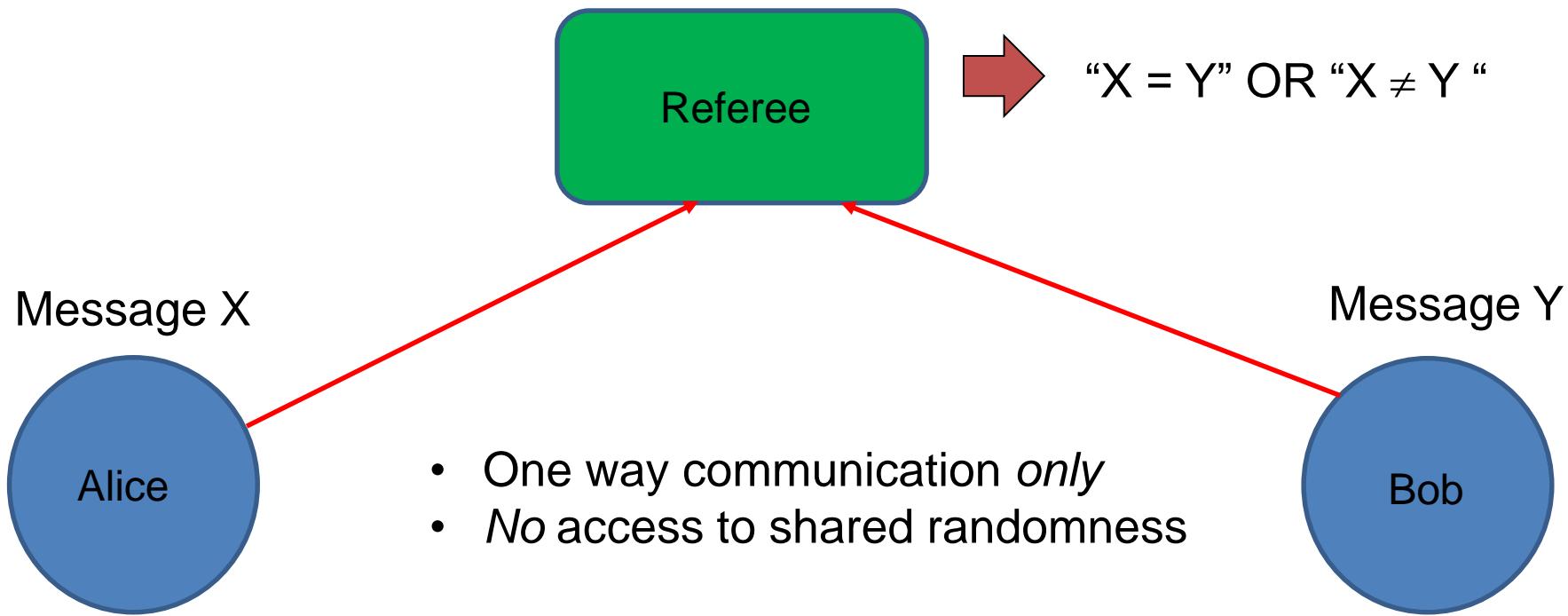
百公里城际QKD网络实验
DE (4% , NICT)
12年5月 , 合肥 - 六安 - 舒城



室内100km QKD实验
DE (4%, NICT)
11年8月,合肥

Collaborated with JW Pan's Group in USTC
Y. L. Tang et al. PRL 113(19): 190501. (2014)
Y. L. Tang et al. IEEE STQE 21(3): 1 (2015)
Y. L. Tang et al. PRX 6, 011024 (2016).

Fingerprinting model (simultaneous message passing)



Given two n-bit strings, what is the *minimum* amount of information that must be transmitted to the referee?



A. C.-C. Yao, in Proceedings of the 11th Annual ACM Symposium on Theory of Computing, pp. 209-213, 1979.

Why quantum fingerprinting?

Proven classical bound*:

$$O(\sqrt{n}) - \text{bits}$$

Proven quantum bound**:

$$O(\log_2 n) - \text{qubits}$$

An *exponential* gap between classical and quantum!

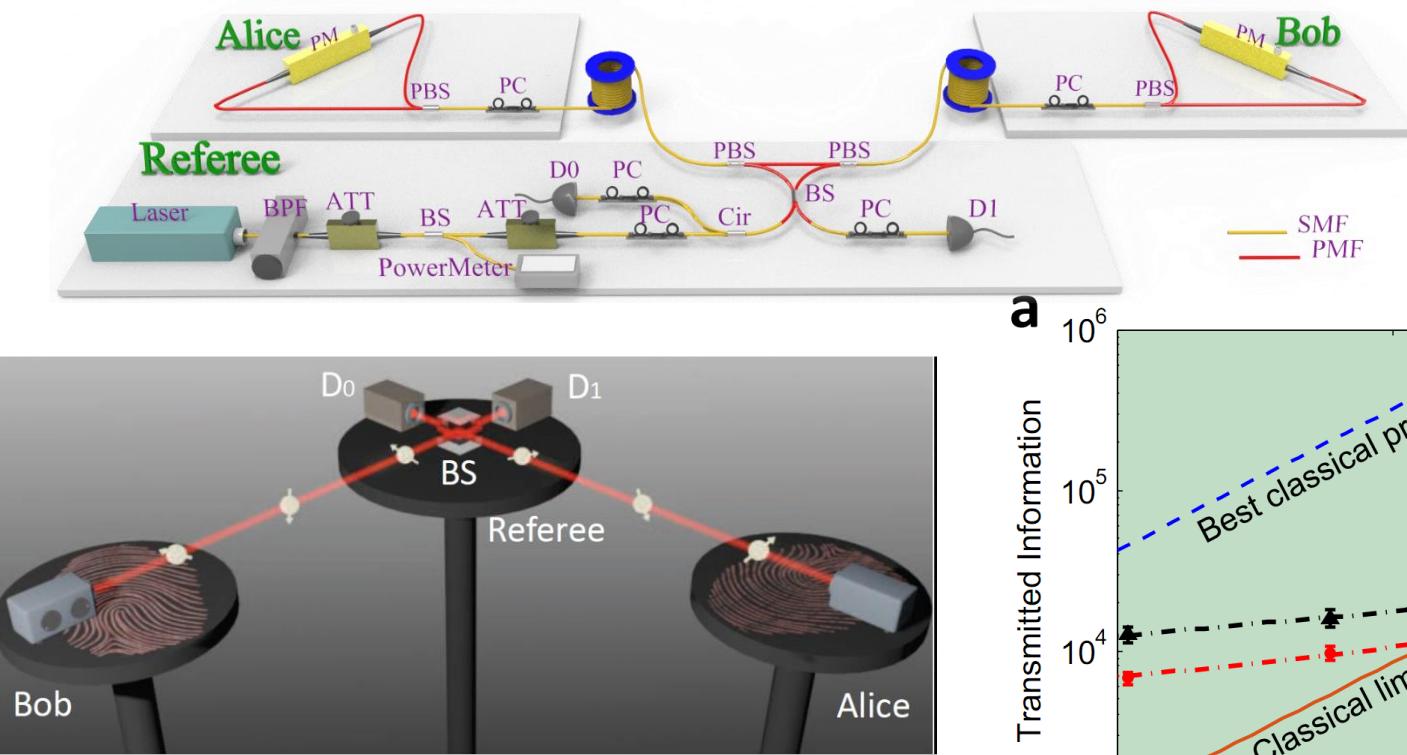
But, it requires $\log_2(n)$ highly entangled qubits ...



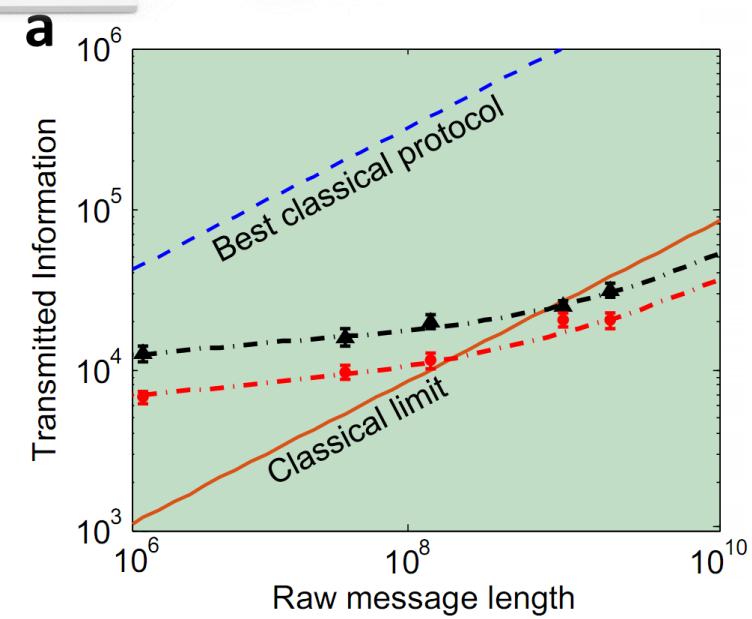
* A. Ambainis, Algorithmica **16**, 298 (1996).

** H. Buhrman, R. Cleve, J. Watrous, R. Wolf , Phys. Rev. Lett., **87**, 167902 (2001).

量子指纹突破经典极限



SNSPD: DE of ~45% @DCR of 0.1 Hz



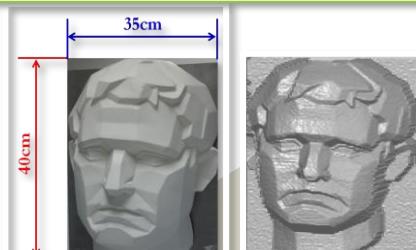
- 2 orders of magnitude lower than best classical protocol
- Beat the classical limit by 84% (19%) at 0 (20) km

PRL 116(24): 240502. (2016)

应用研究 - 激光测距和成像实验室研究

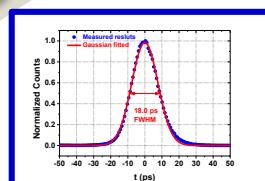
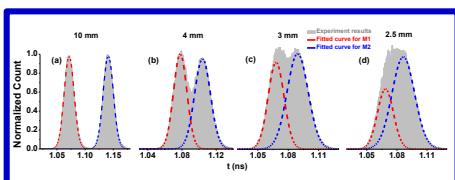
2014年，少数几个光子成像

像素：200*220，步长：3mm, 时间：50 ms/pixel



2013年中，成像精度提升

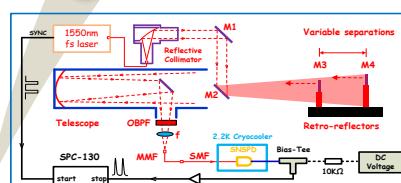
像素：80*120，步长：3mm, 时间：5 h



2013年初，优化器件抖动(~ 18ps)，
TOF测距 精度优于3mm，为国际最好结果

2012年底，首次利用SNSPD实现单光子统计成像

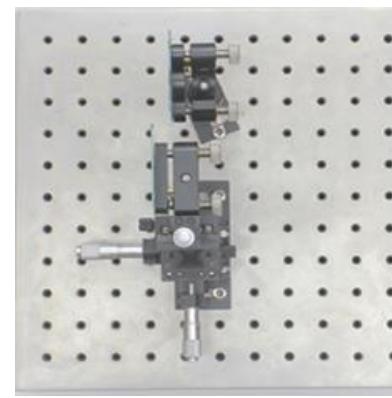
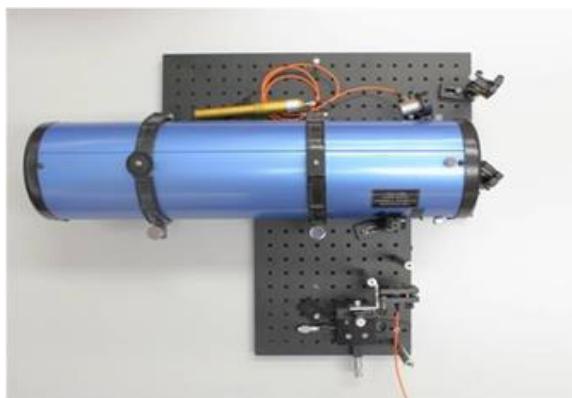
像素：29*35，步长 1cm, 时间 8 h



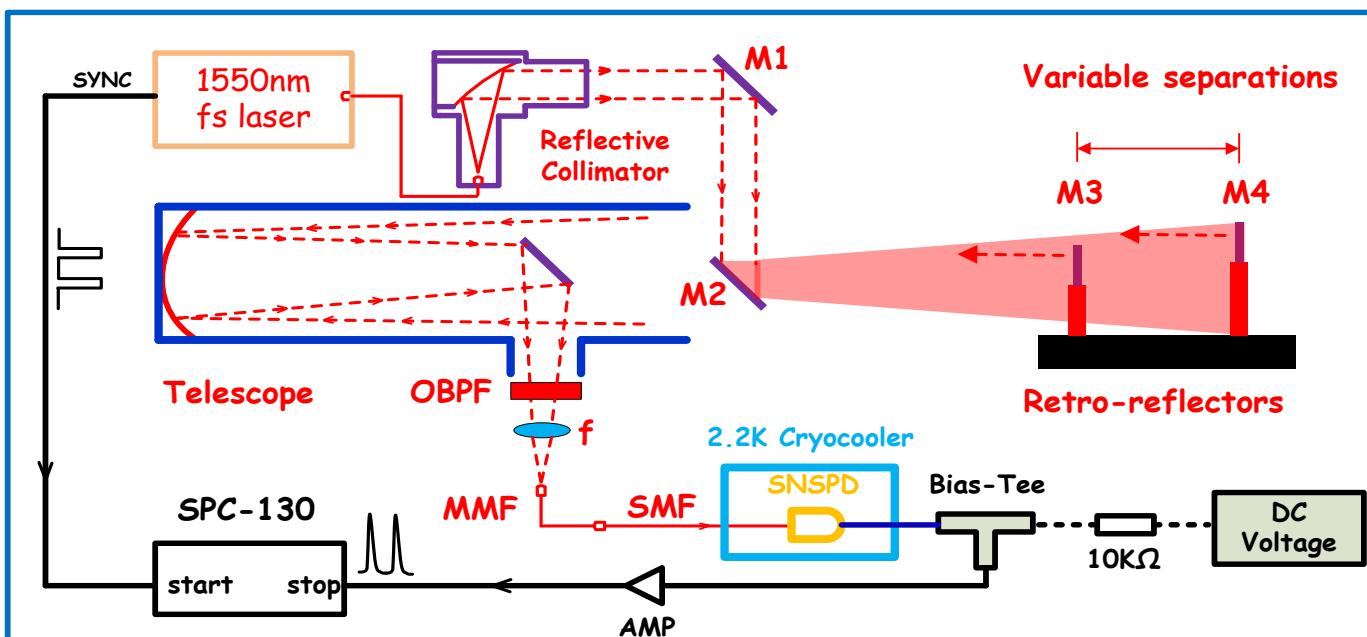
2012年，优化系统抖动(~ 27 ps)，实现TOF测距

距离：115米，波长：1550 nm, 精度优于4mm

激光测距系统



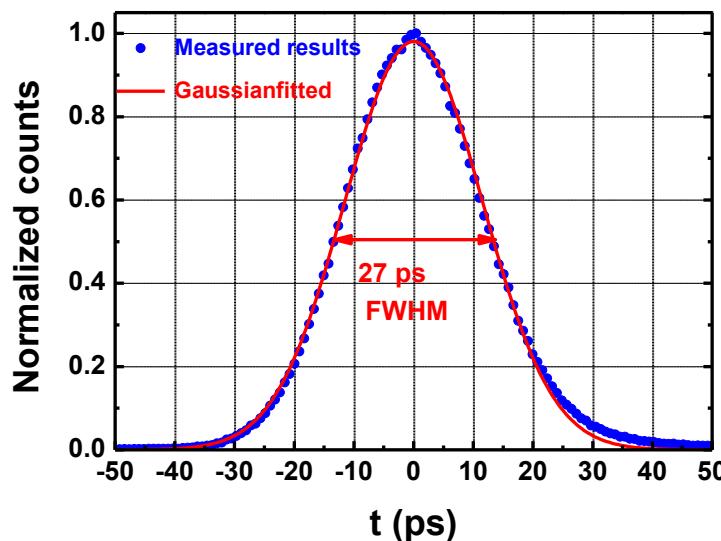
System Jitter: 27 ps;
Distance: 115 m
fs pulsed Laser:
 $\lambda=1.55 \mu\text{m}$
repetition: 20 MHz ;
energy: 0.1 nJ/pulse



TOF system

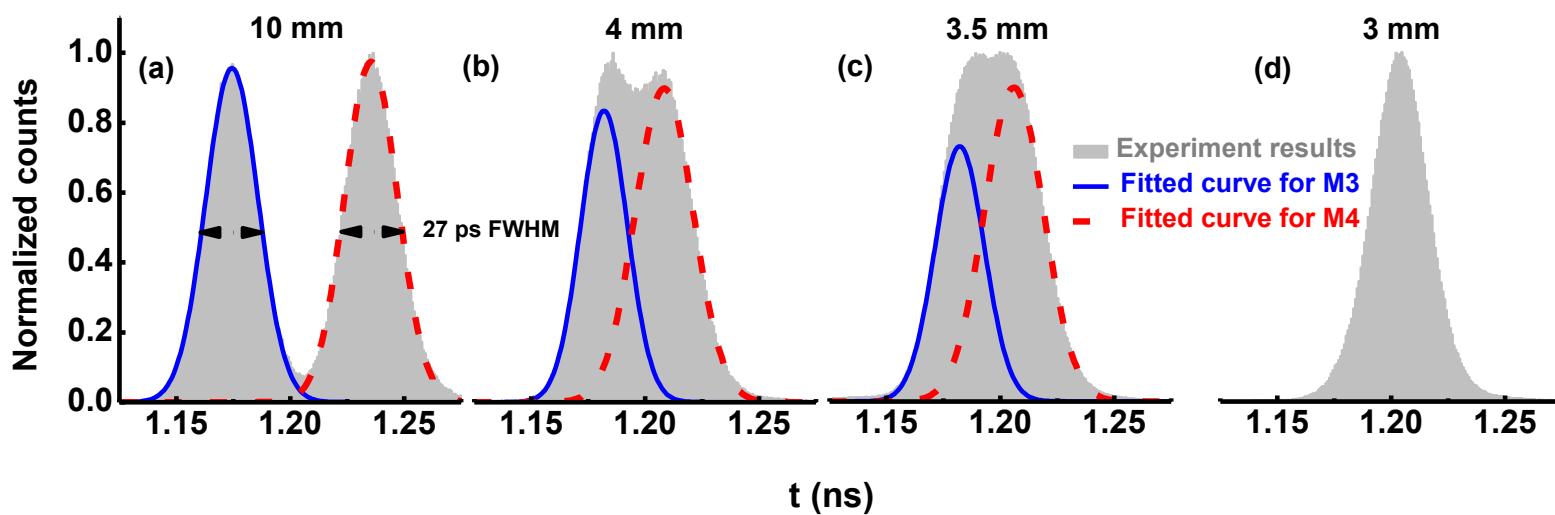
M1, M2: Protected gold mirrors
M3, M4: Gold-plated mirrors
OBPF: Optical band-pass filter
MMF: Multimode fiber
SMF: Single mode fiber
SPC-130: TCSPC card

测距实验结果

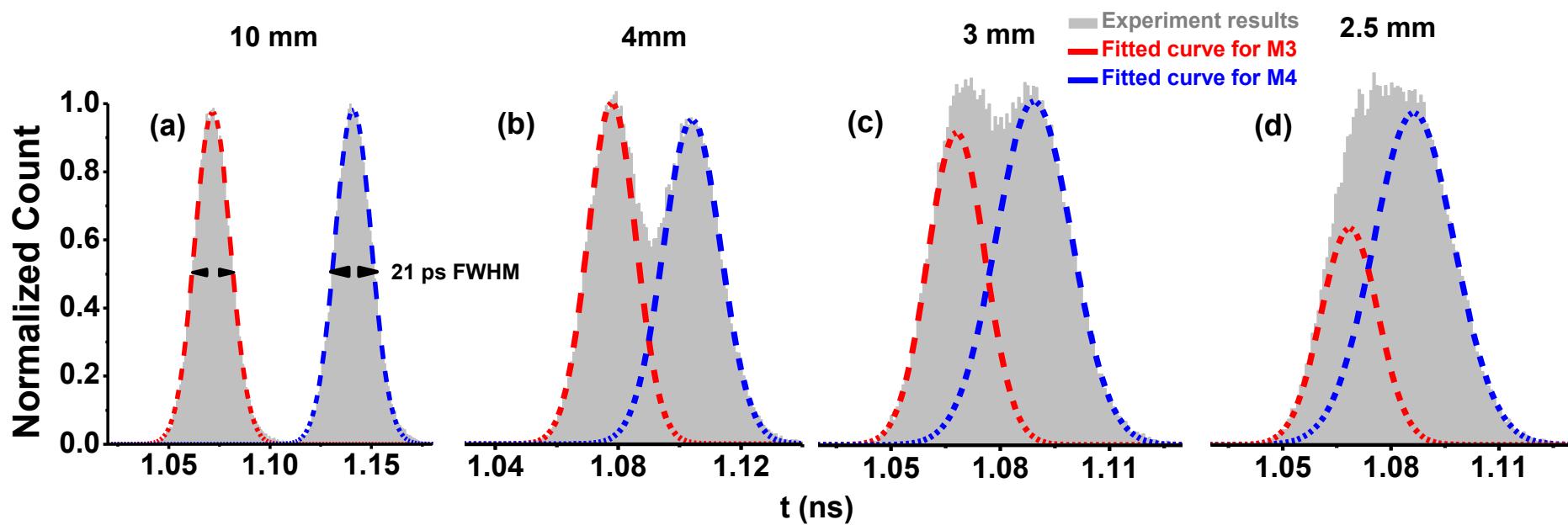


System Jitter: 27 ps @ QE=3%
Depth resolution: 3.5mm @1550 nm
Distance: 115 m

$$R_d = j \cdot c / 2$$



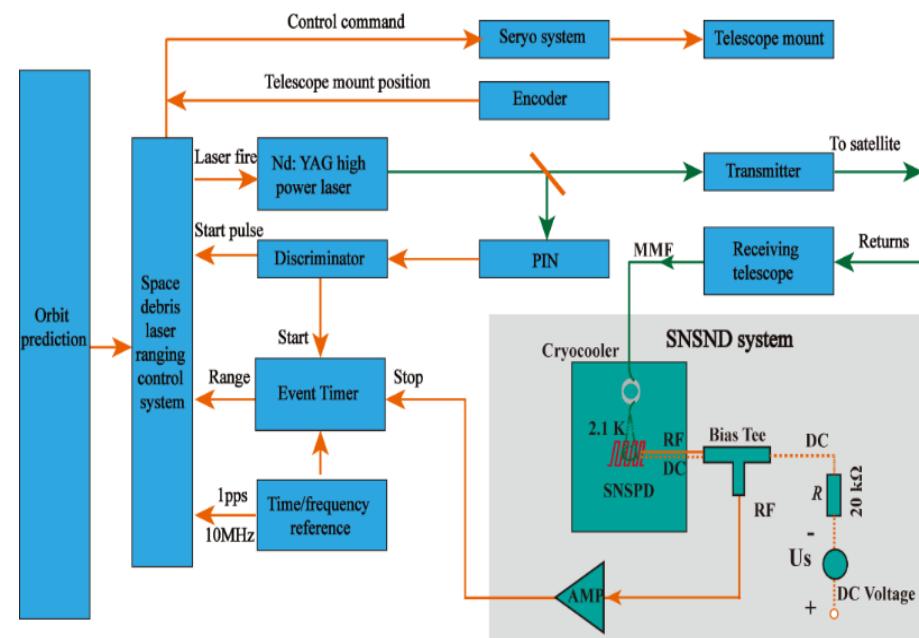
测距实验结果



System Jitter: 18 ps, QE=1% with $I_c \sim 70 \mu\text{A}$
Depth resolution: 3 mm @1550 nm
Distance: 115 m

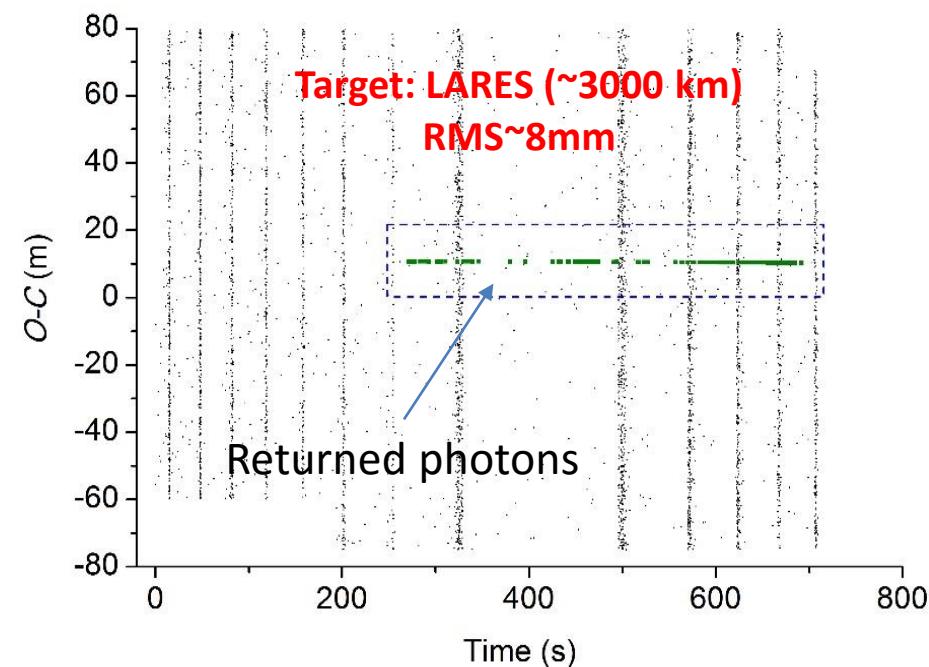
$$R_d = j \cdot c / 2$$

SNSPD at 532nm aiming to SLR



SLR measurement setup

2015年：实现532nm工作波长，3000公里卫星LARES的测距，精度达8mm；
 2016年：实现近2万公里的俄罗斯Glonass卫星，精度约2cm



SLR results of LARES

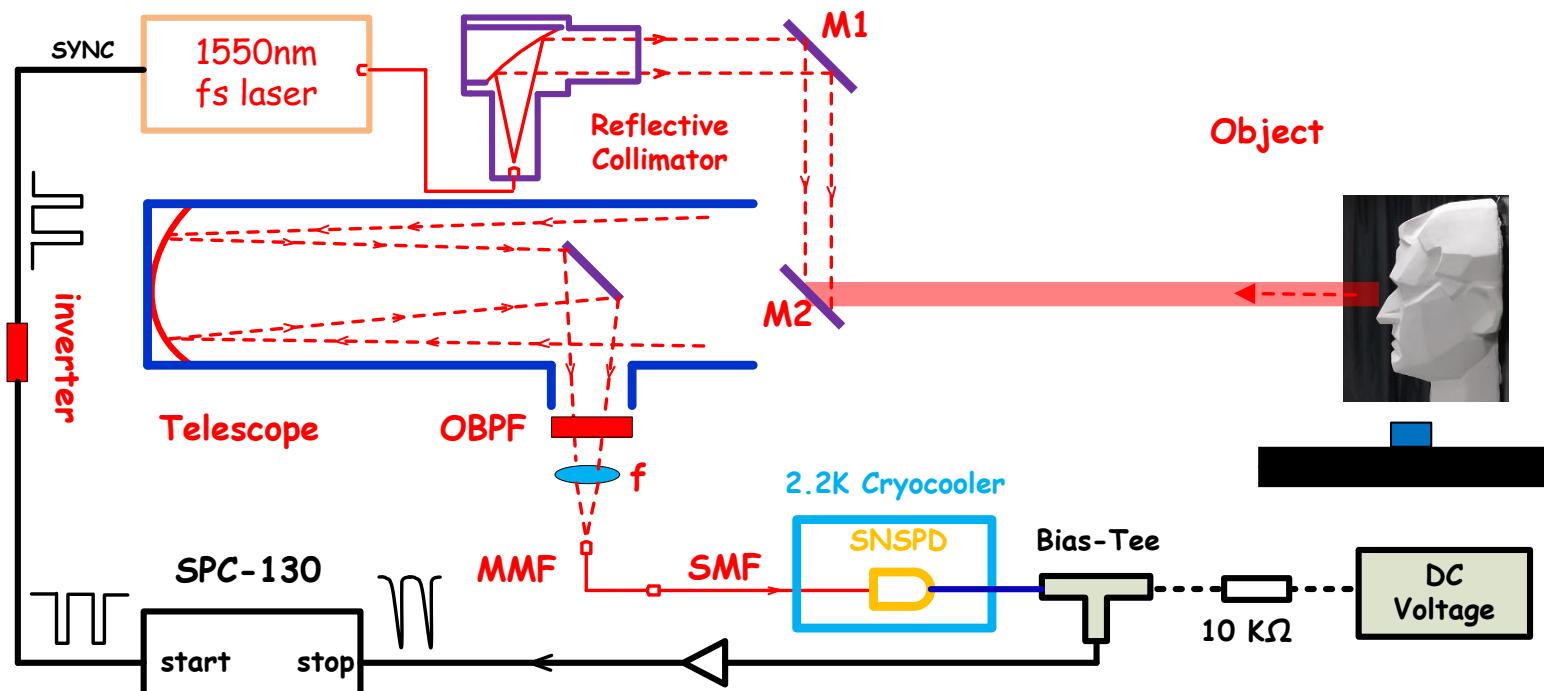
Opt. Express 24, 3535 (2016)



飞行时间光子计数成像

System Jitter: 30 ps; Imaging distance: 2.5 m

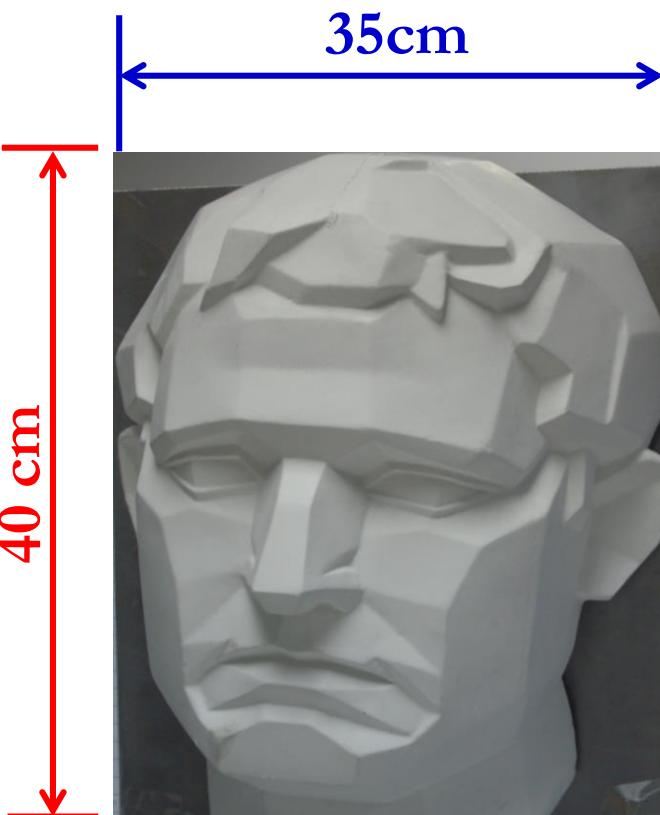
R_{DC}: 200-500 Hz (Daytime)



System schematics

Laser Depth Imaging using SNSPD system

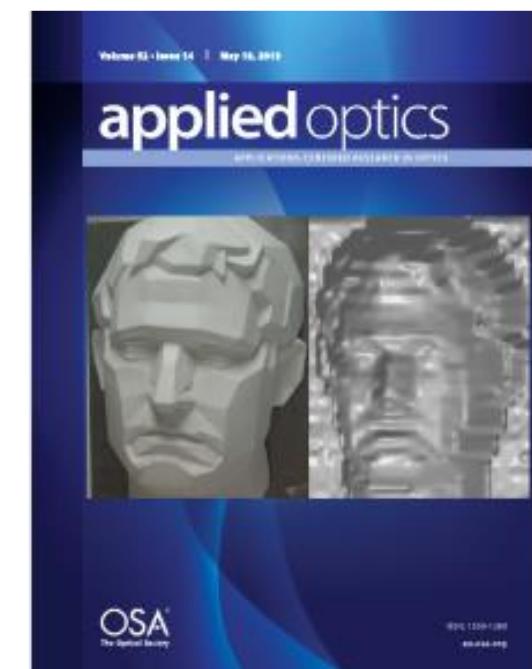
Resolution: 29(Y)×35 (Z)=1015; Step=1 cm



(a) cast



(b) Image



Cover Image of AO 52(14) 2013

Laser Depth Imaging using SNSPD system

Resolution: 85 (Y) × 120 (Z)=10K;

Step= 3 mm

Time: ~ 5 hours

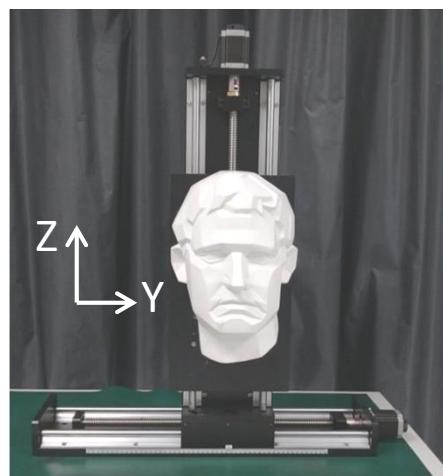
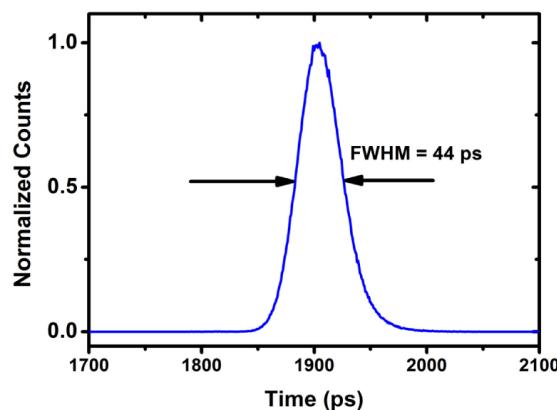


Image Scanner

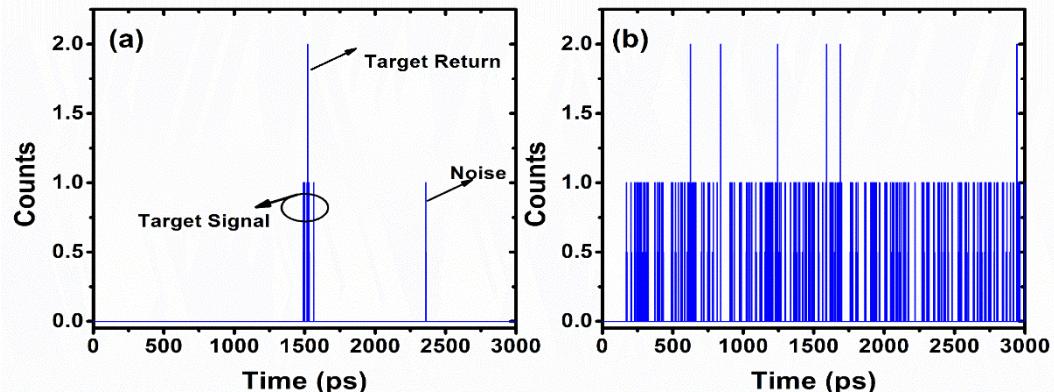


Imaging improvement by adopting a scanner

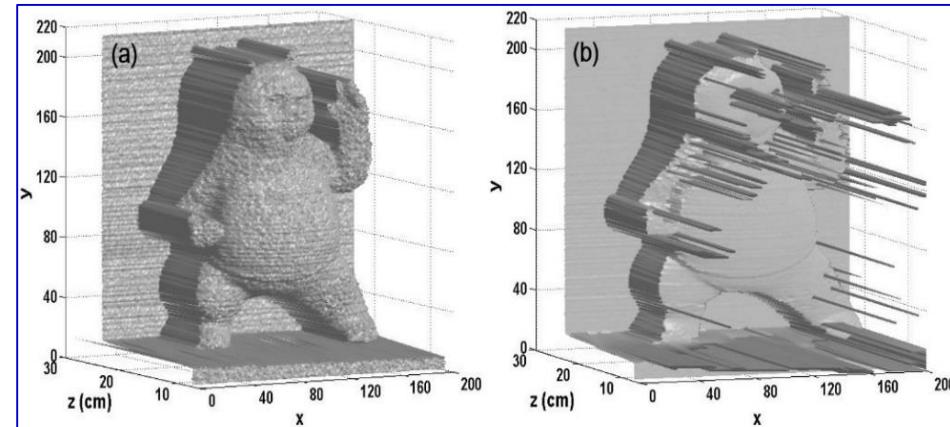
弱光条件下的激光测距成像



大量光子计数的统计分布

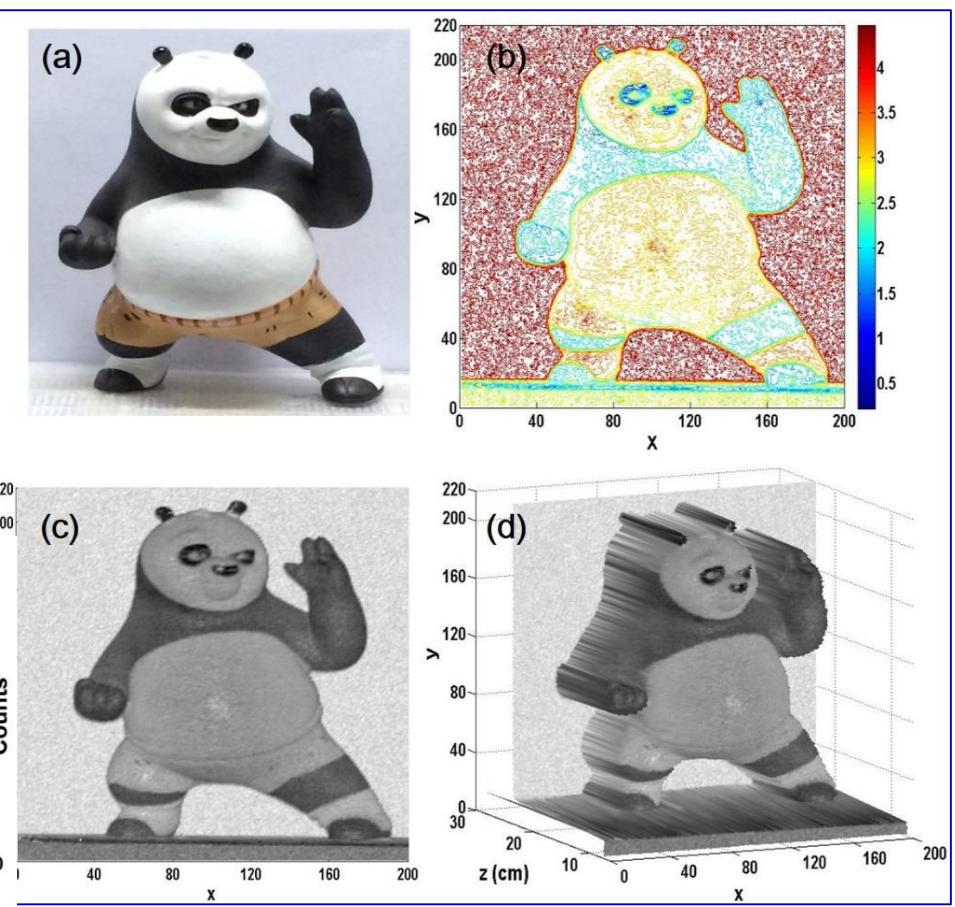
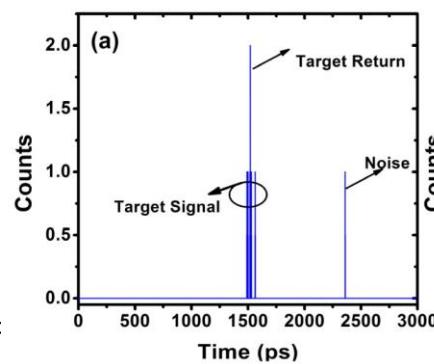
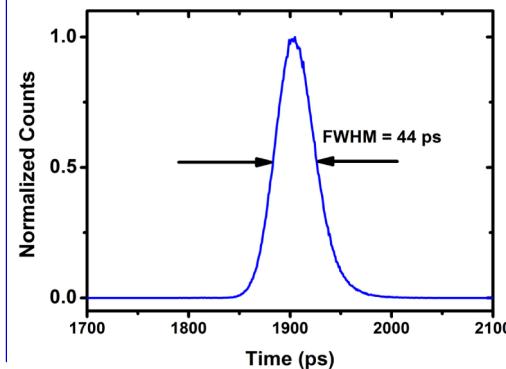
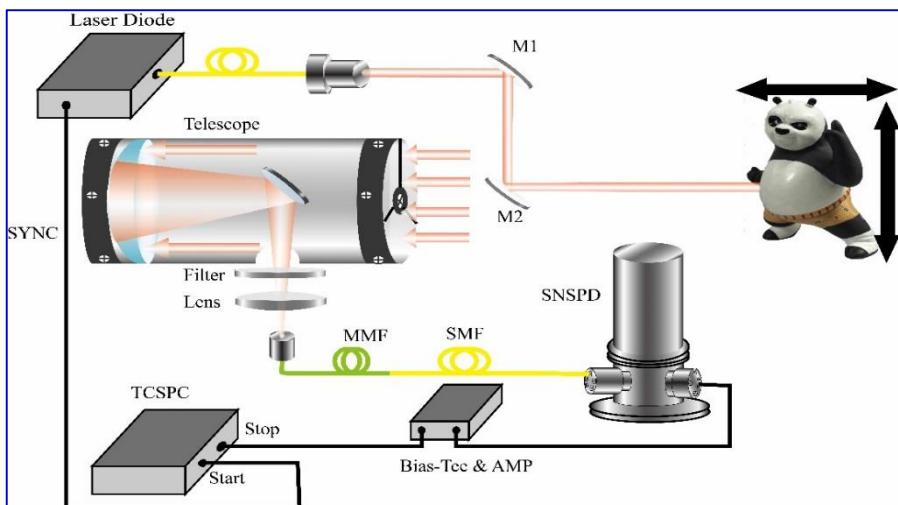


少量计数情况（白天实验室/白天户外）



44-ps TJ SNSPD with sub-ps time-bin enables few photon imaging w/o fitting and algorithm

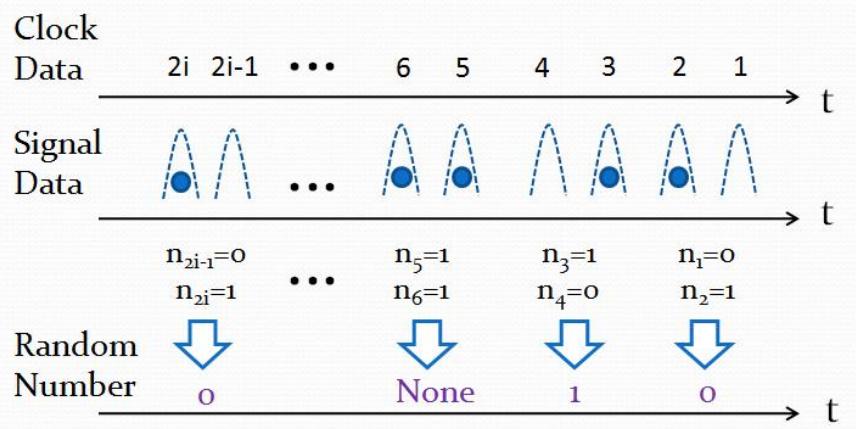
强度/深度符合成像



44-ps TJ SNSPD with sub-ps time-bin enables few photon imaging w/o fitting and algorithm

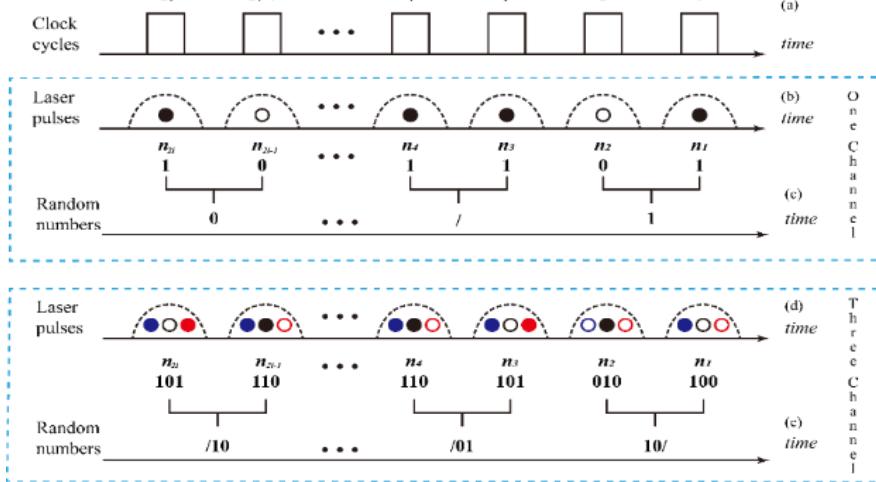
Zhou H et al, Optics Express 23(11): 14603 (2015)

基于SNSPD的量子随机数发生器

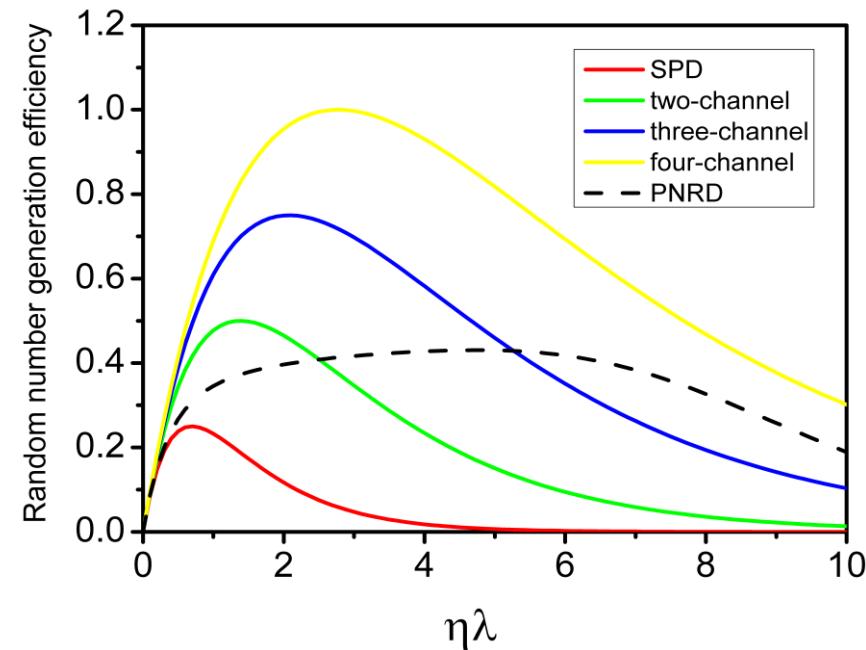


基于SPD的QRNG

H. Guo. OL 34 1876 (2009)

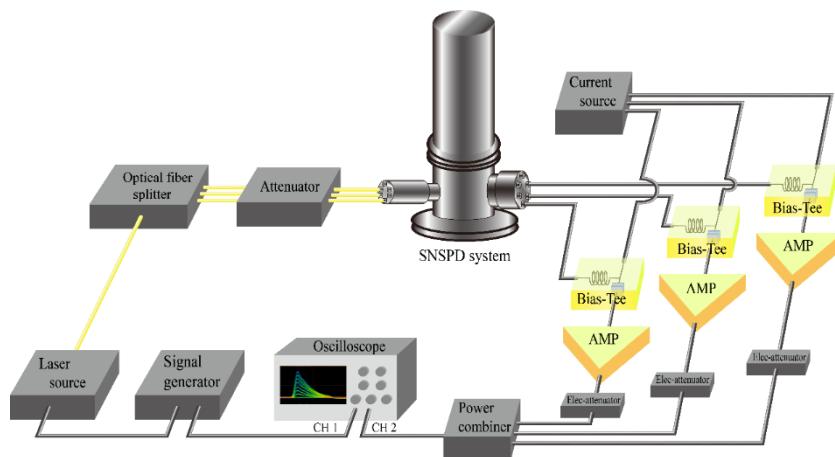


升级版QRNG H. Zeng. PRA 83(2). 023820(2011)

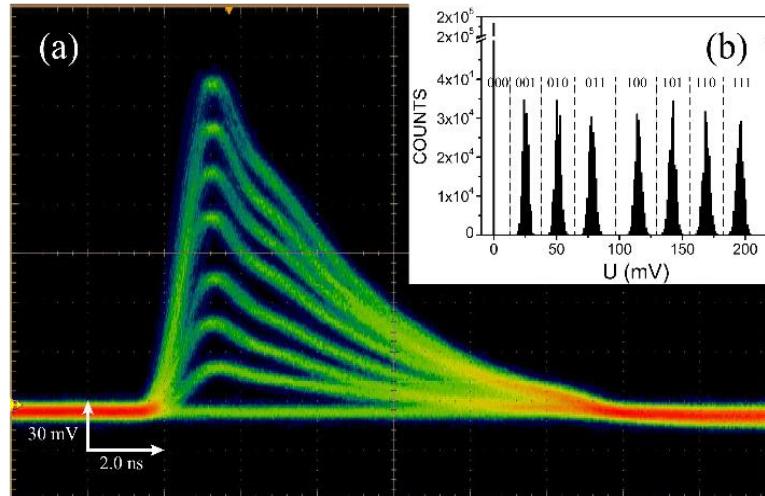


随机数产生效率和探测效率/光强的关系

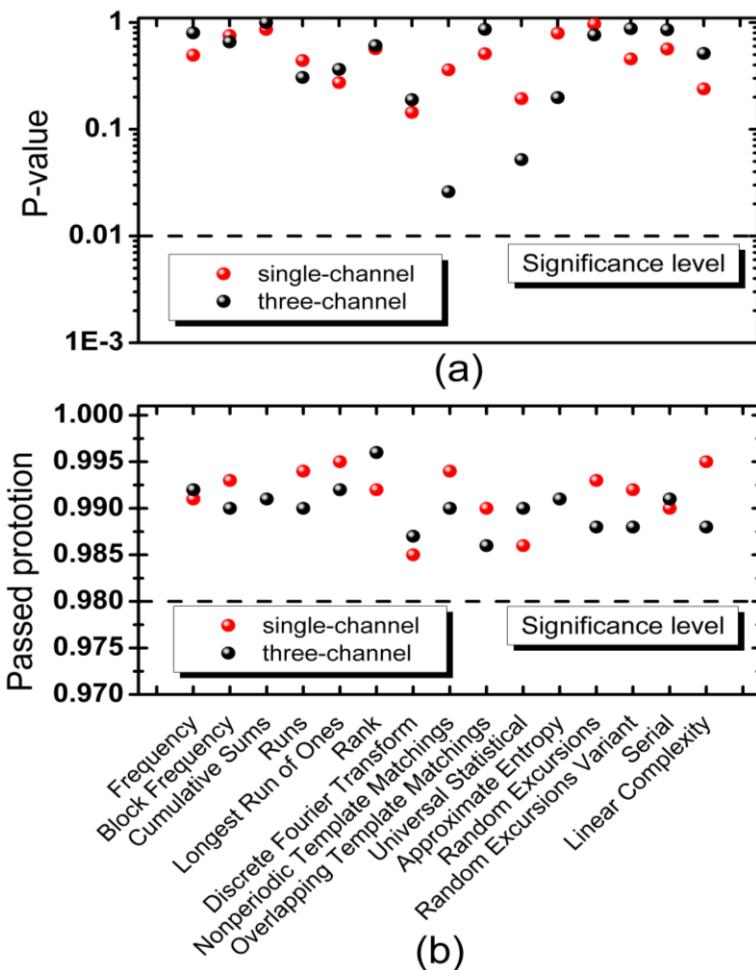
基于SNSPD的量子随机数发生器



基于3-ch SNSPD的QRNG



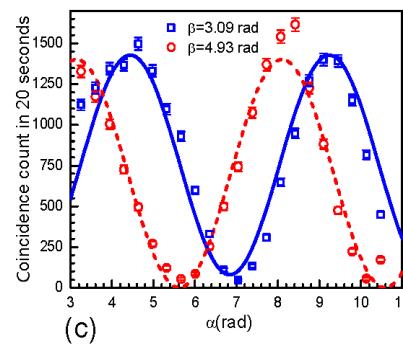
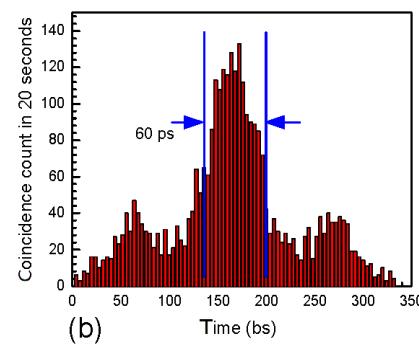
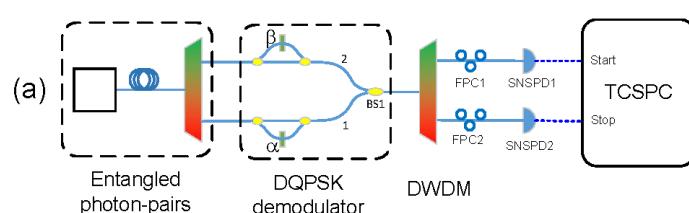
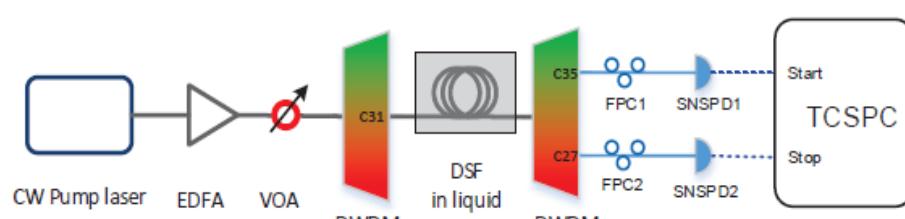
多通道响应脉冲波形种类



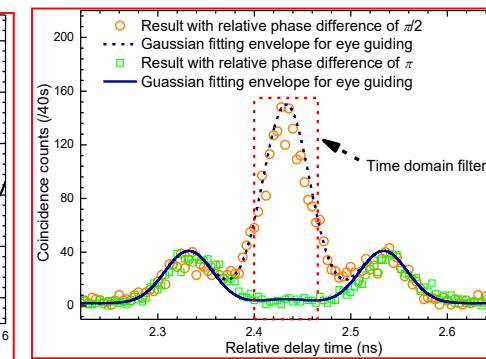
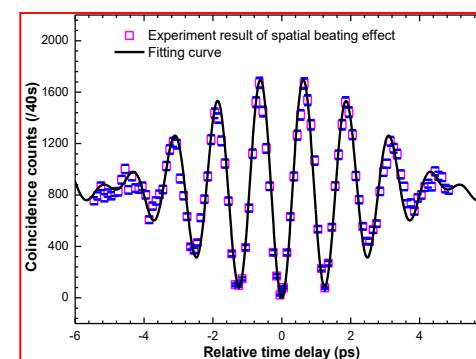
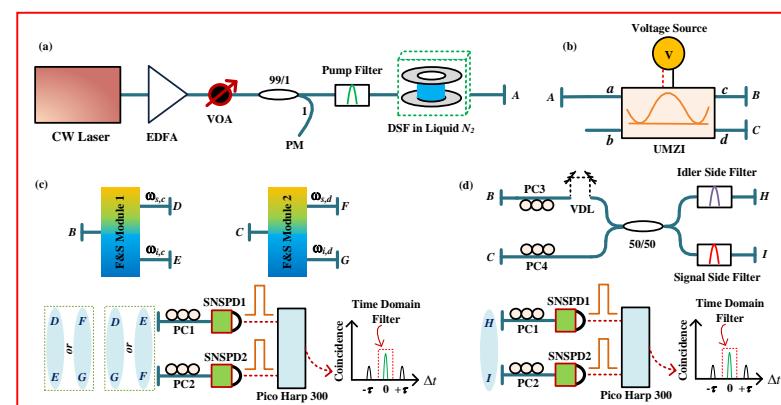
7.5 M 成码率，通过NIST RN随机性认证

SUST 29: 085005. (2016)

量子光源表征



Collaborated with W Zhang in Tsinghua Univ.

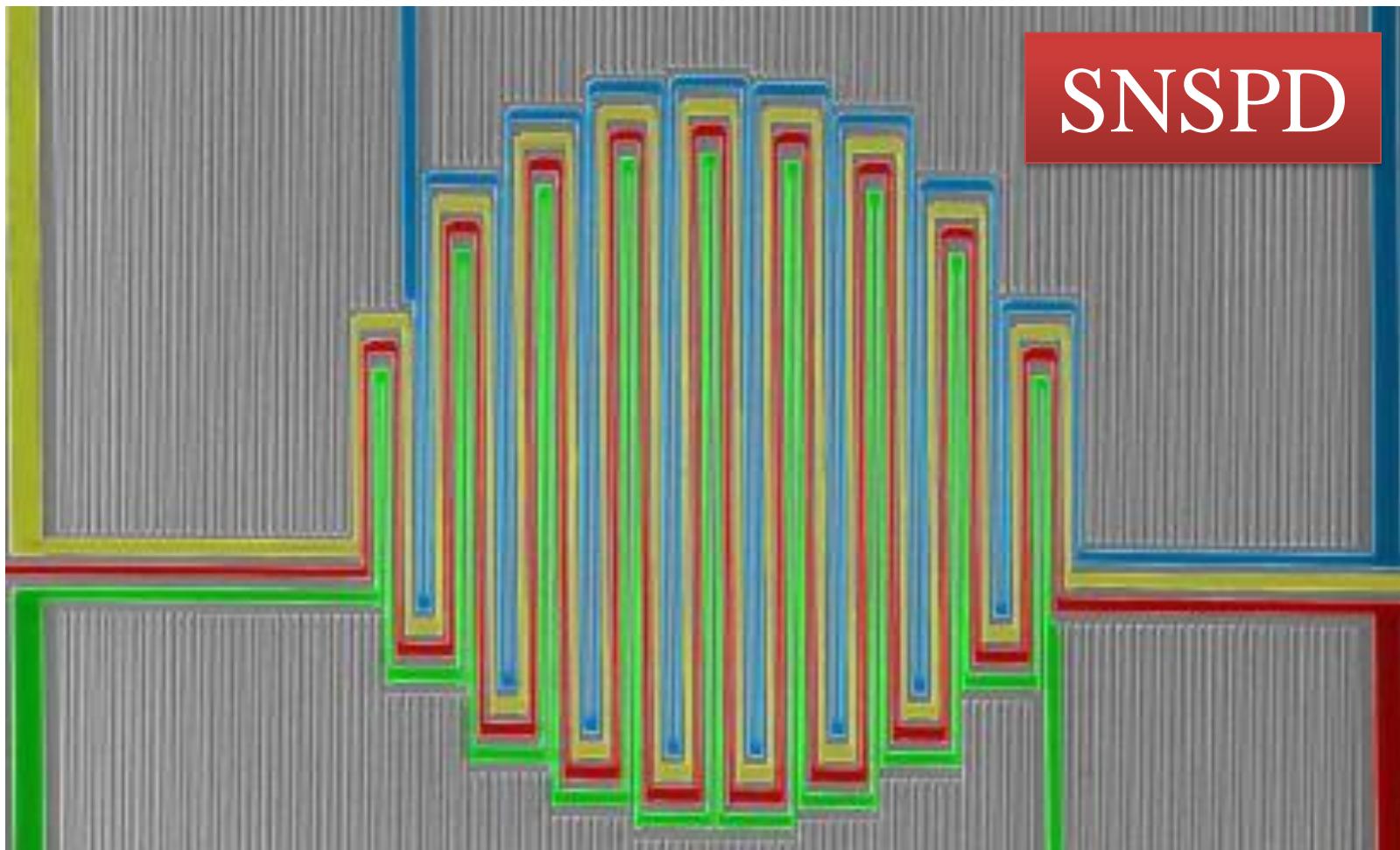


Energy-time entanglement using low jitter SNSPD

- Optics Express 22 000359 (2014)
- J. Opt. Soc. Am. B **31** (8), 1801-1806 (2014)

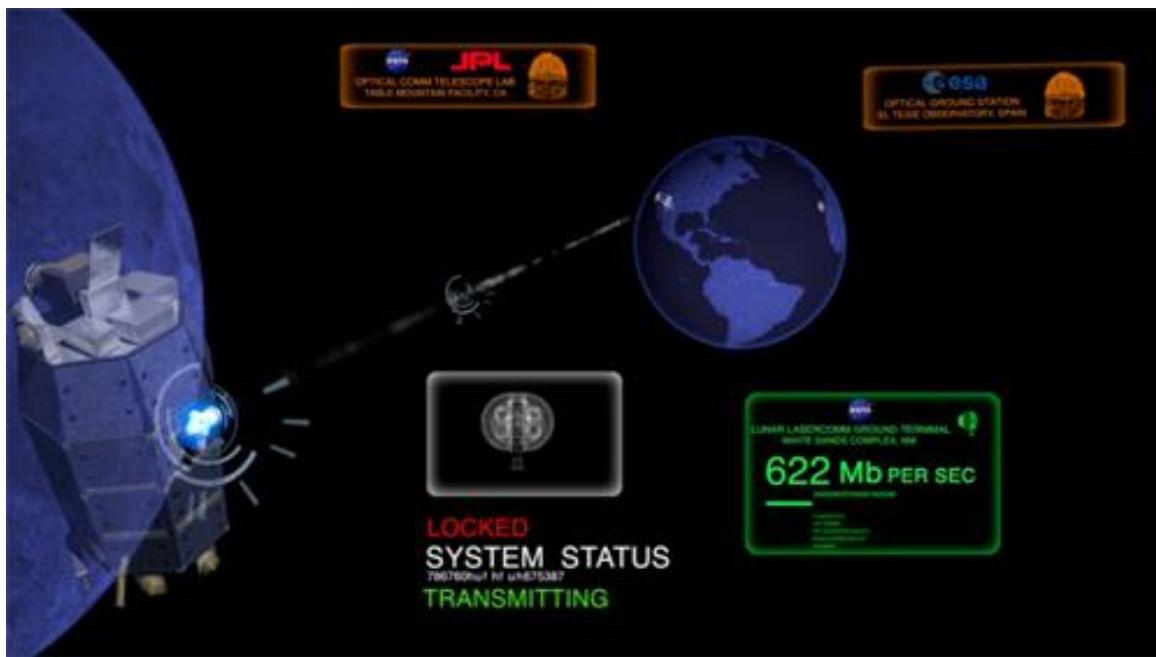
- Sci Rep 5: 9195. (2015)

高速SNSPD和深空激光通信

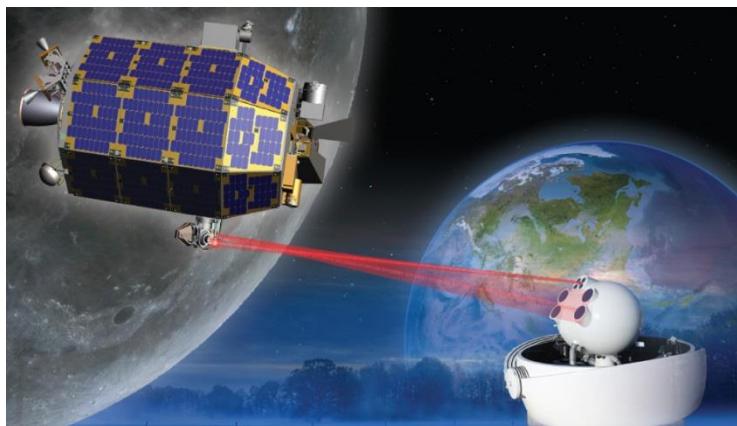


四根纳米线并行SNSPD

深空激光通信/测距



- ✓ 2013年，9月6日发射LADEE，
- ✓ 10月18日，月球轨道-地面高速激光通信成功验证



月—地（38万公里）通信新记录

- 下行：上行速率：622 Mbps vs 20 Mbps
- 月球卫星到地球测距精度：优于 0.5 英寸

Conclusion

□ SNSPD with outstanding performance

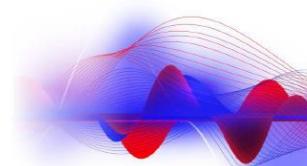
- ✓ High SDE from VIS to NIR
- ✓ Low DCR
- ✓ Low jitter

□ Niche market available for SNSPD



SUPERCONDUCTING NANOWIRE SINGLE-PHOTON DETECTOR

ID280 SUPERCONDUCTING NANOWIRE WITH 50%
QUANTUM EFFICIENCY AND FASTEST ELECTRONICS



Other Companies:

- SconTel (Russia),
- Single Quantum (Netherlands)
- Quantum Opus (USA)
- Photon Spot (USA)

博士后招聘-超导单光子探测研究

拟开展的研究方向：

- SNSPD相关薄膜、器件与SNSPD系统集成研究；
- SNSPD器件机理和新型SNSPD器件研究；
- 单光子探测前沿应用探索；
- 片上集成量子光学。

岗位要求：

- 博士学位，超导电子学、量子光学、半导体器件等领域背景；
- 熟悉微纳器件工艺、微纳光学技术、低温实验技术者优先。

工作地点： 上海

待遇： 年薪15万元起，最高25万元/年。将根据资历和能力进行评估。