Single-photon imager based on a superconducting nanowire delay line

Journal club

2017/05/29

Oh Seunghoon

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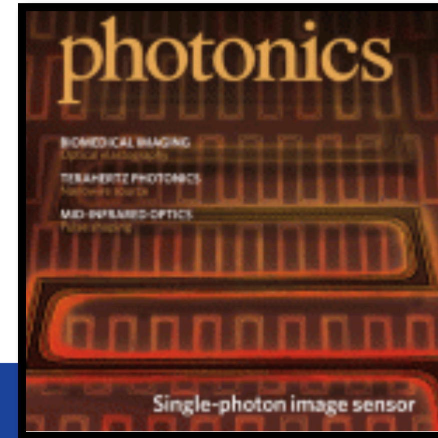
Paper publishment



nature photonics

PUBLISHED ONLINE: 27 MARCH 2017 | DOI: 10.1038/NPHOTON.2017.35

Single-photon imager based on a superconducting nanowire delay line

Qing-Yuan Zhao[1], Di Zhu[1], Niccolò Calandri[1,2], Andrew E. Dane[1], Adam N. McCaughan[1], Francesco Bellei[1], Hao-Zhu Wang[1], Daniel F. Santavicca[3] and Karl K. Berggren[1]*

Detecting spatial and temporal information of individual photons is critical to applications in spectroscopy, communication, biological imaging, astronomical observation and quantum-information processing. Here we demonstrate a scalable single-photon imager using a single continuous superconducting nanowire that is not only a single-photon detector but also functions as an efficient microwave delay line. In this context, photon-detection pulses are guided in the nanowire and enable the readout of the position and time of photon-absorption events from the arrival times of the detection pulses at the nanowire's two ends. Experimentally, we slowed down the velocity of pulse propagation to ~2% of the speed of light in free space. In a 19.7 mm long nanowire that meandered across an area of 286 × 193 μm^2, we were able to resolve ~590 effective pixels with a temporal resolution of 50 ps (full width at half maximum). The nanowire imager presents a scalable approach for high-resolution photon imaging in space and time.

Group information

Karl K. Berggren

Professor of Electrical Engineering, *Electrical Engineering and Computer Science (EECS)*

"The frontier of information processing lies in nanoscience and nanotechnology research"

- homepage (http://www.rle.mit.edu/qnn/)

Selected Publications

04.10.2017
Single-photon imager based on a superconducting nanowire delay line

01.09.2015
On-chip detection of non-classical light by scalable integration of single-photon detectors (Nature Communications)

12.15.2014
Universal scaling of the critical temperature for thin films near the superconducting-to-insulating transition (Physical Review)

Introduction

Quantum information & Quantum key distribution

SPD & SPD arrays (TES & MKID)

PMT & SP-APD

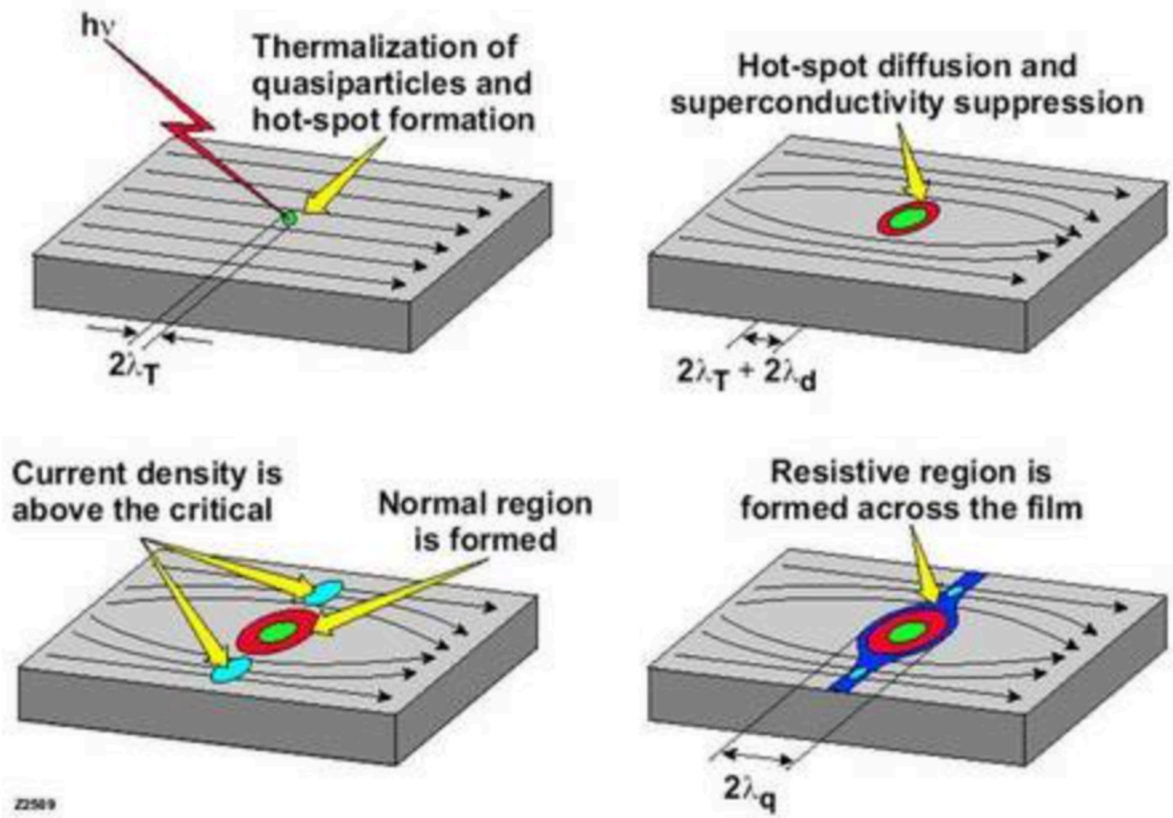
SNSPD

- Attempts to create arrays of SNSPDs have had limited success
- Current state-of-the-art SNSPD array is limited to ~100 pixels
- Lacks spatial sensitivity (modelled as lumped-element inductor)

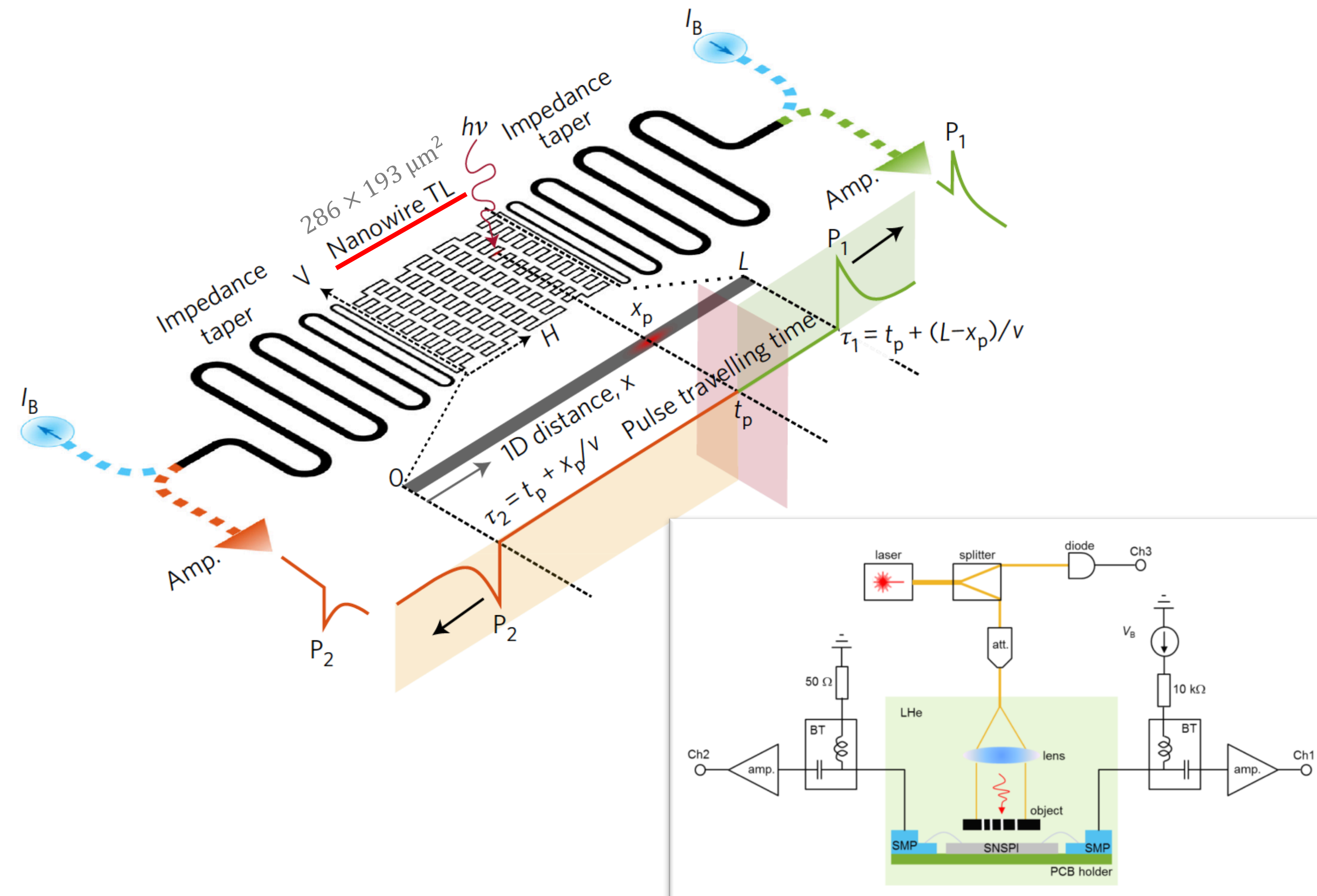
SNSPI

Position & Time arrival

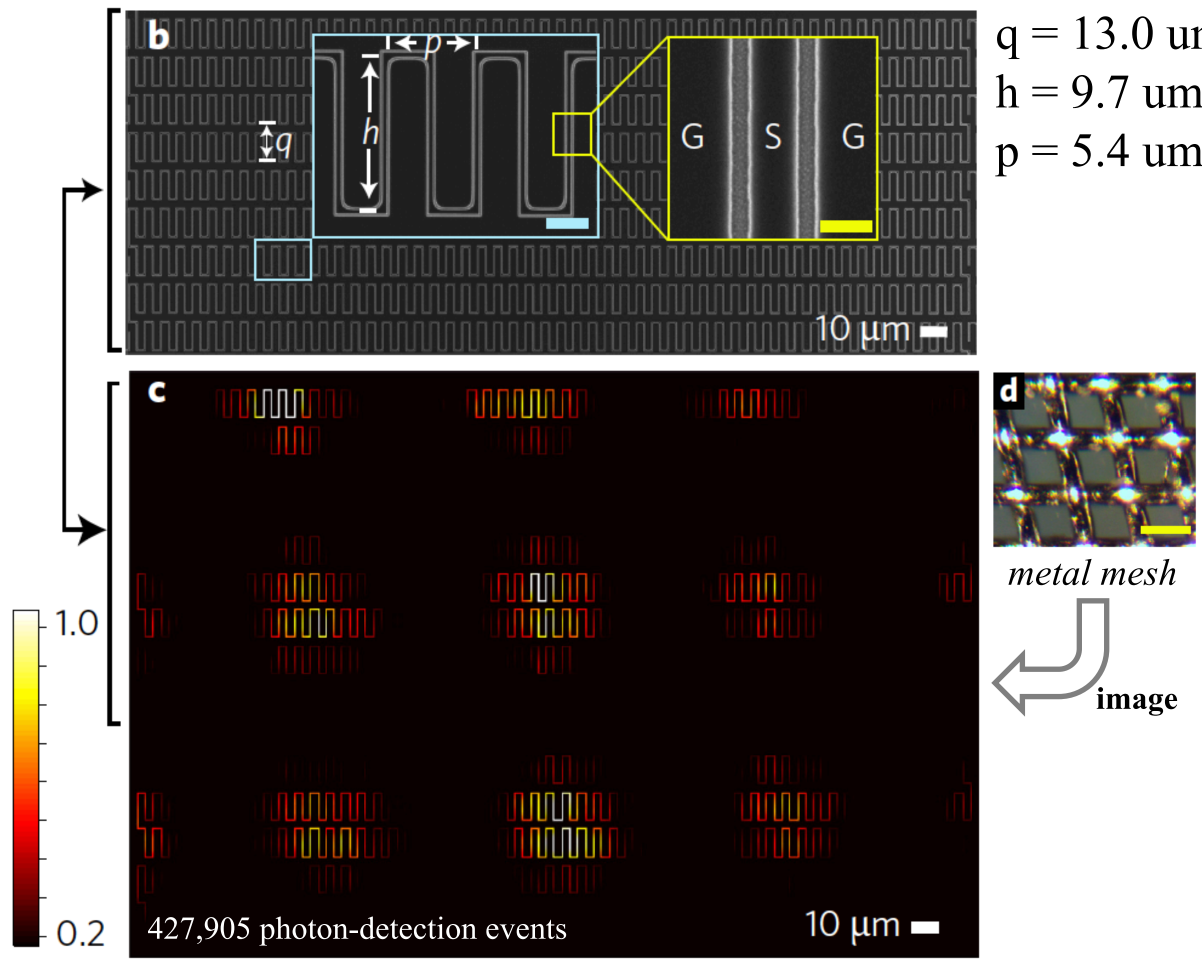
SNSPD


hν
Thermalization of quasiparticles and hot-spot formation
$2\lambda_T$
Hot-spot diffusion and superconductivity suppression
$2\lambda_T + 2\lambda_d$
Current density is above the critical
Normal region is formed
Resistive region is formed across the film
$2\lambda_q$

The experimental setup



The experimental setup



q = 13.0 um
h = 9.7 um
p = 5.4 um

Two fluid model

- Superconducting current (w/ electron density, n_s)
- Normal current (w/ electron density, n_n)

$$\frac{1}{2} n_s m v_s^2$$

n_s : superconducting electron density
m : electron mass
v_s : velocity of the Cooper pair

$$\mathcal{L}_k = \frac{m}{n_s e^2} = \mu_0 \lambda_L^2$$

e : elementary charge
λ_L : London penetration depth
μ_0 : permeability

In this experiment

- 7nm thick niobium nitride film (superconducting nanowire patterned on it)
- $\mathcal{L}_k = 3.43 \times 10^{-19}$ Hm

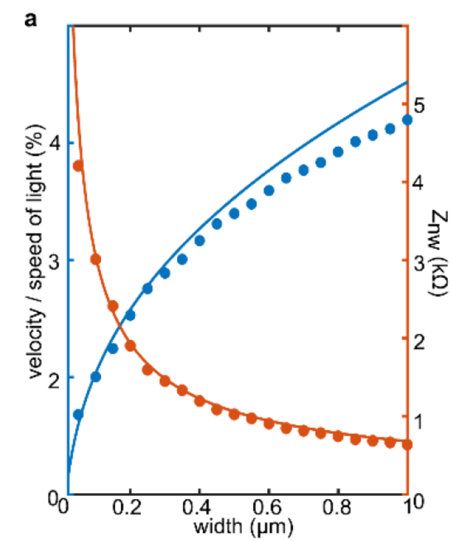
Guiding microwaves

High kinetic-inductance of thin superconducting nanowire

➔ Low signal-propagation velocity in an SNSPI

In a superconducting nanowire,

- Kinetic inductance ≫ Faraday inductance
- Reduction of v_s + increase of Z (compare to normal metal)

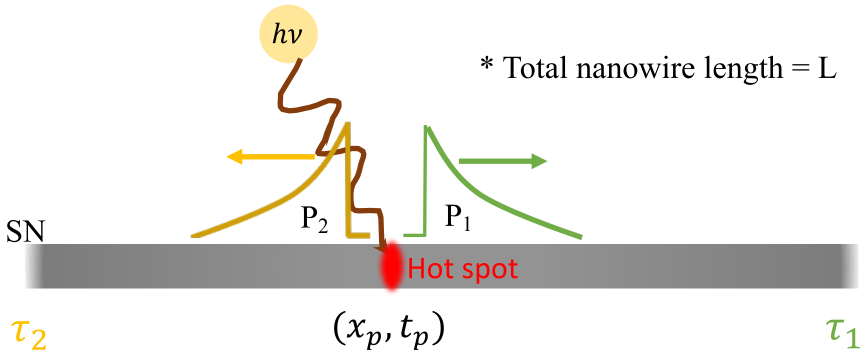


Guiding detection pulses

- Signal propagation velocity$(v) = 1/\sqrt{L_s C_s}$
- Characteristic impedance$(Z) = \sqrt{L_S/C_S}$
- L_S : inductance per unit length, C_S : capacitance per unit length

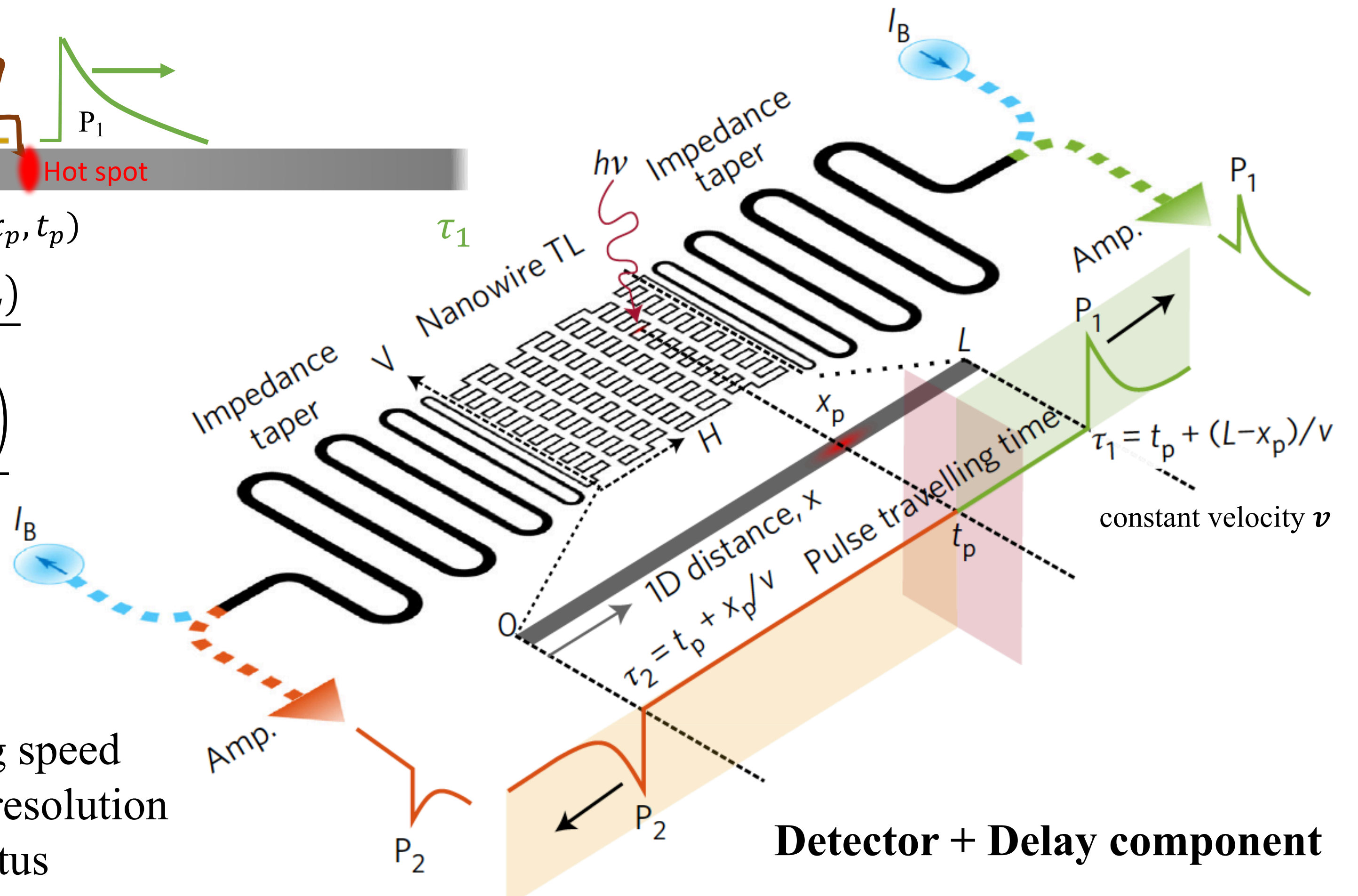
The measured velocity in this experiment ➔ 5.56 μm/ps

Superconducting nanowire single photon **imager** (SNSPI)



$$x_p = \frac{((\tau_2 - \tau_1)v + L)}{2}$$

$$t_p = \frac{\left((\tau_2 + \tau_1) - \frac{L}{v}\right)}{2}$$



- Higher imaging speed
- Higher spatial resolution
- Simpler apparatus

Spatial and temporal detection

Spatial resolution

- *Electrical noise* in the readout circuits
  → var. in the τ_1 & τ_2
- *Speed of signal propagation(v)* in the transmission line

Gaussian point-spread function ➔ estimate effective resolution

$$b(x) = e^{-\frac{x^2}{2h^2}} \text{ where } h = \frac{\delta}{\rho} \times \frac{v}{2}$$

$\frac{\delta}{\rho} = 4.3\ \text{ps} \rightarrow j_e$

δ : standard deviation of the Gaussian distribution of electrical noise
ρ : slope of the pulses at the discrimination threshold level

Substituting $v = 5.6\ \mu\text{m/ps}$, they got $h = 12.0\ \mu\text{m}$
Thus,

$$f_w = 28.4\ \mu\text{m (FWHM of } b(x))$$

The width determines the noise-limited spatial resolution

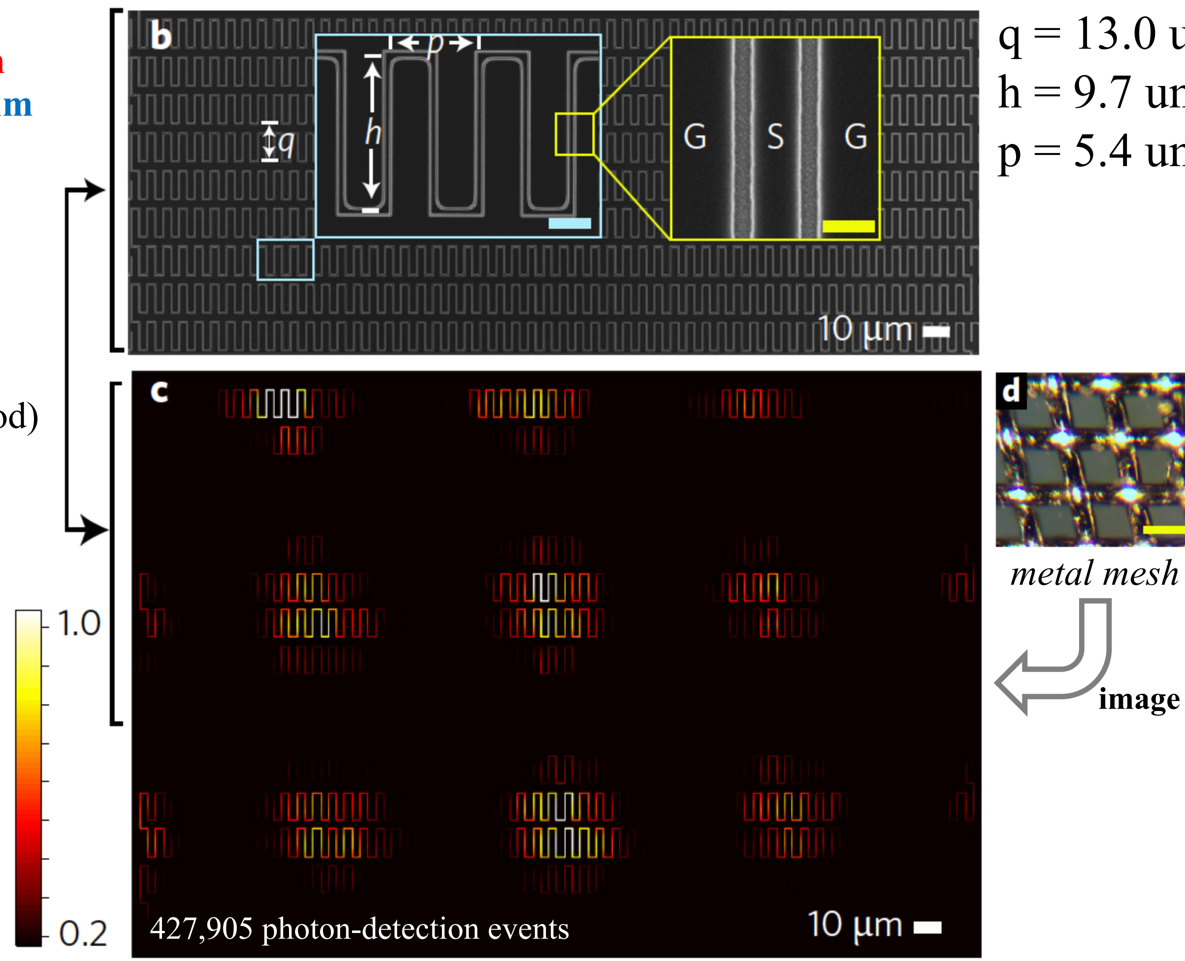
Spatial and temporal detection

Vertical spatial resolution : 13.0 um
Horizontal spatial resolution : 6.9 um

$$f_w \times \frac{p}{l_m} = 6.9\ \mu\text{m}$$

$$l_m = 22.24\ \mu\text{m}$$

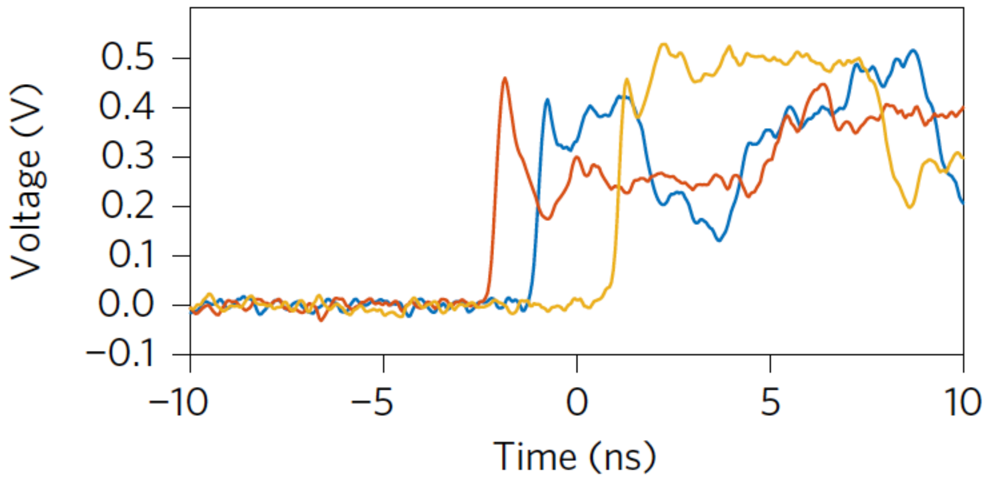
(effective length of one meander period)



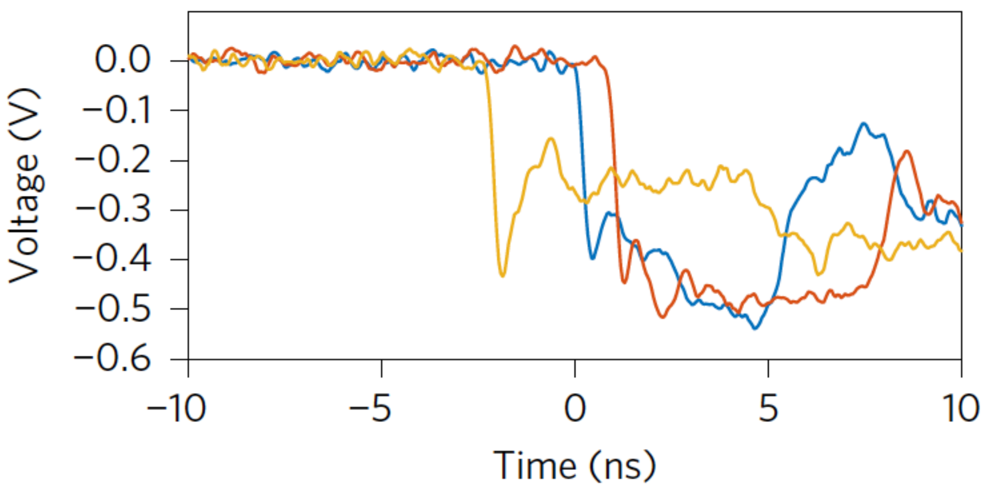
q = 13.0 um
h = 9.7 um
p = 5.4 um

Spatial and temporal detection

Three pulses(*ps* optical pulse) for three different detection locations



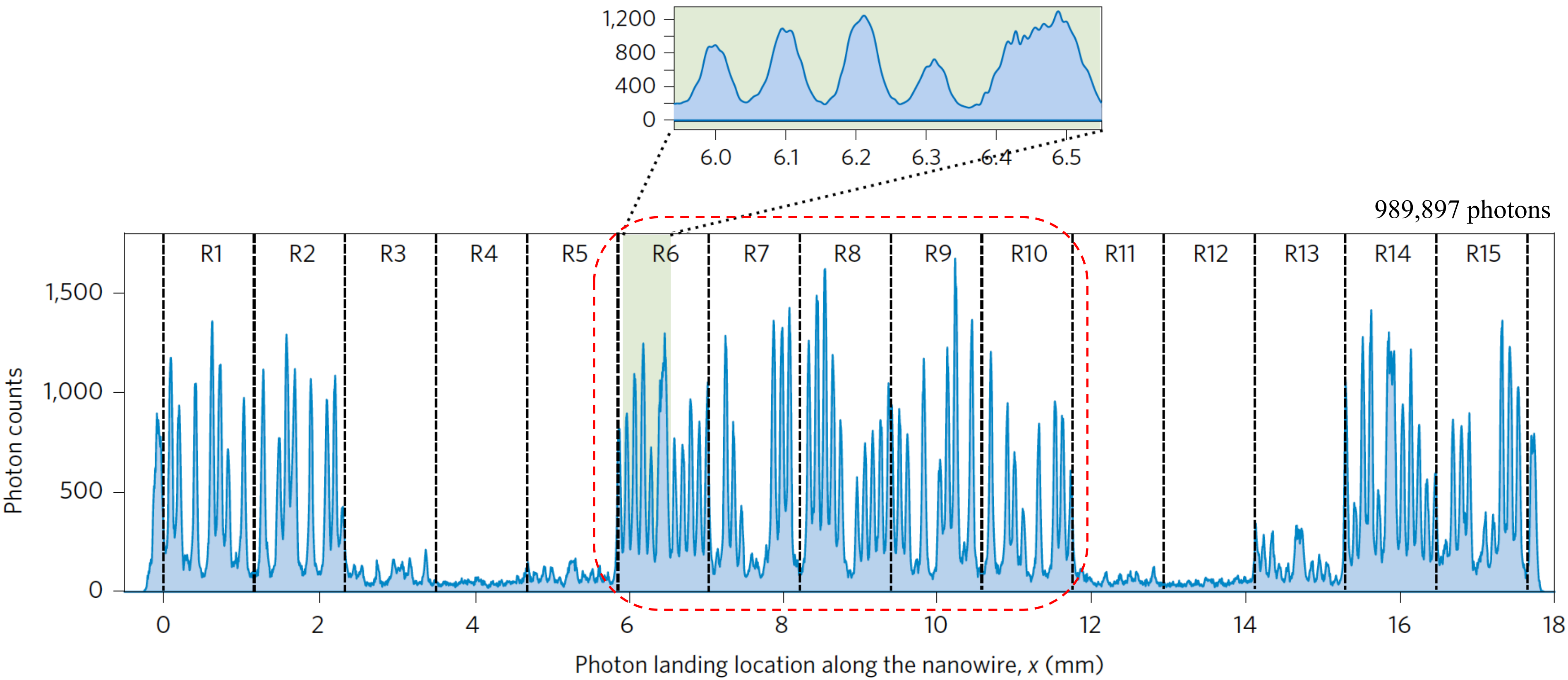
One end



The other end

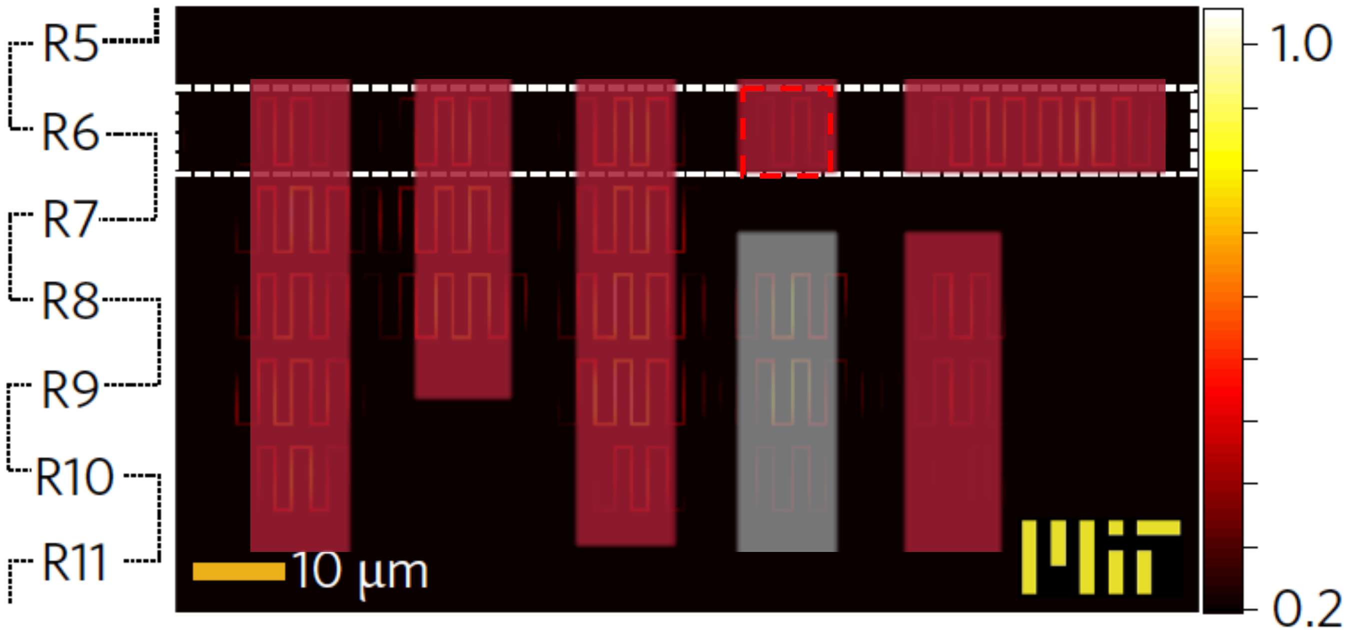
Spatial and temporal detection

Data signal along the superconducting nanowire



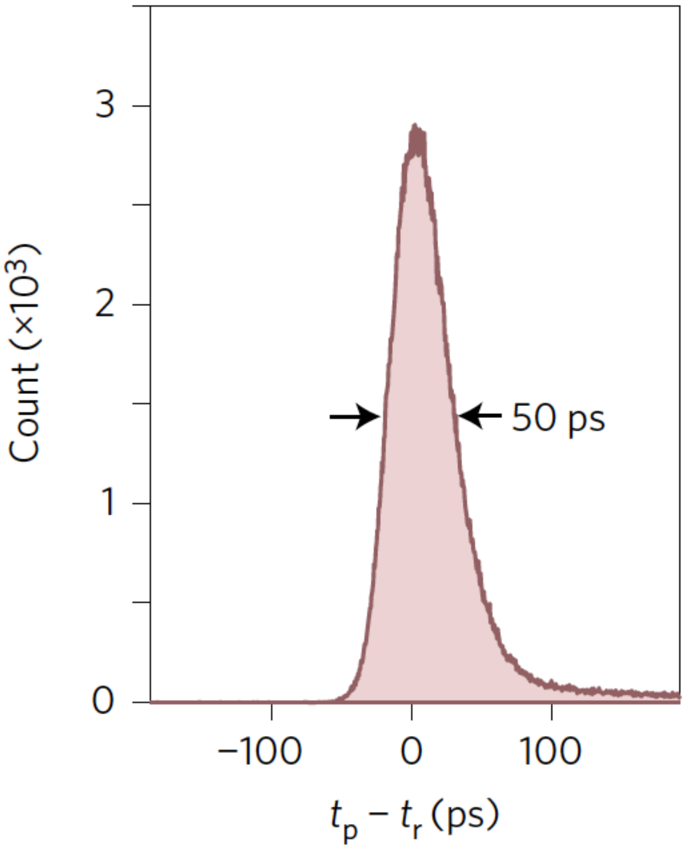
MIT logo

Spatial and temporal detection

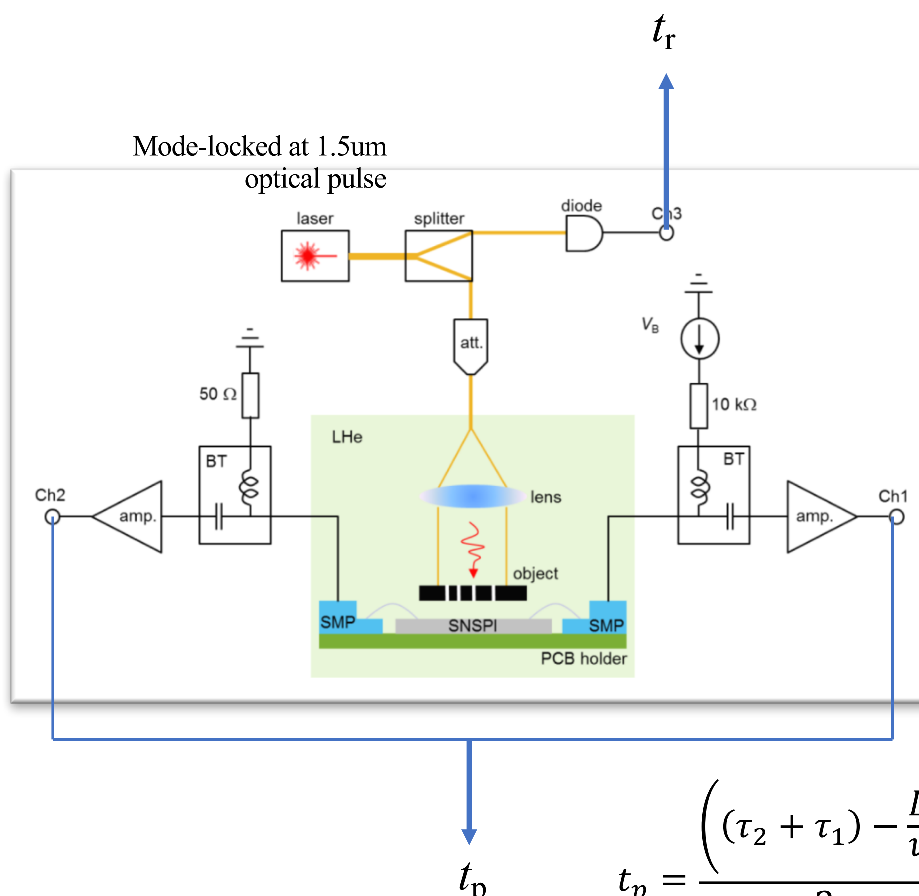


[redacted]

Spatial and **temporal** detection



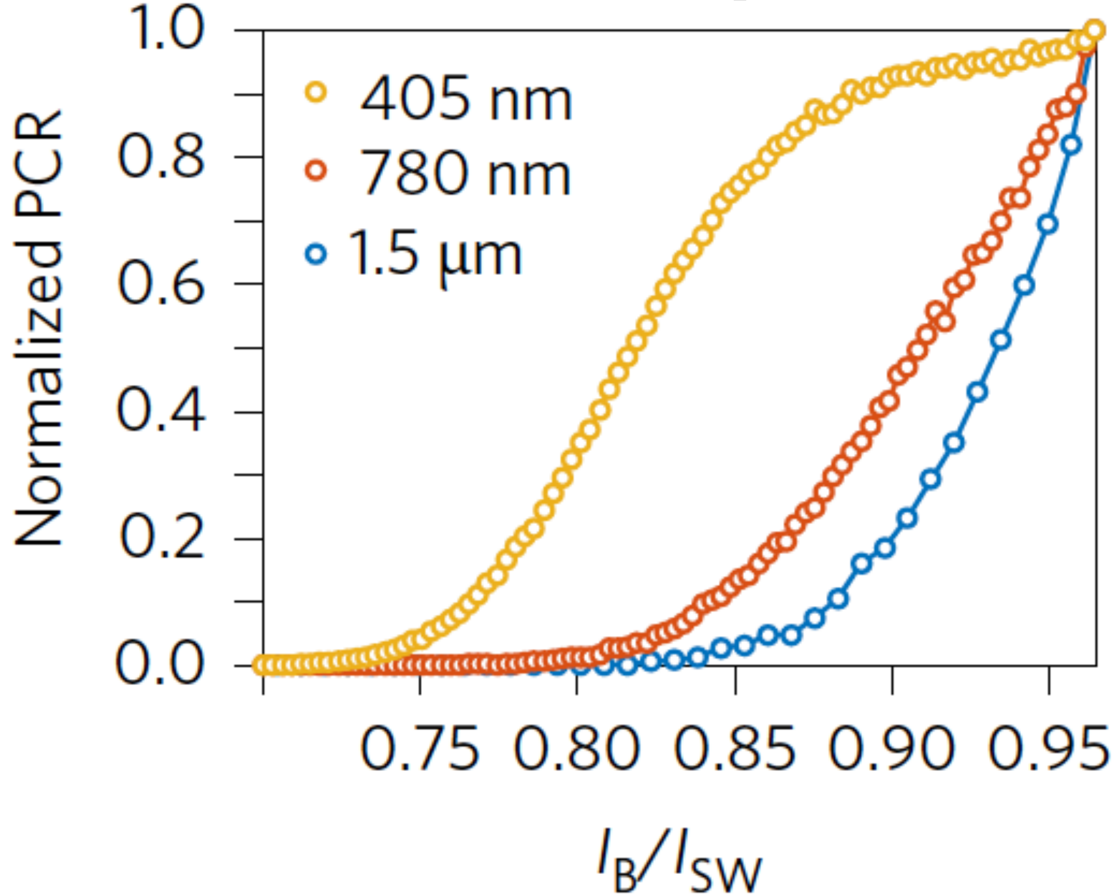
Timing jitter (j_d) = 50ps



$$t_p = \frac{\left((\tau_2 + \tau_1) - \frac{L}{v}\right)}{2}$$

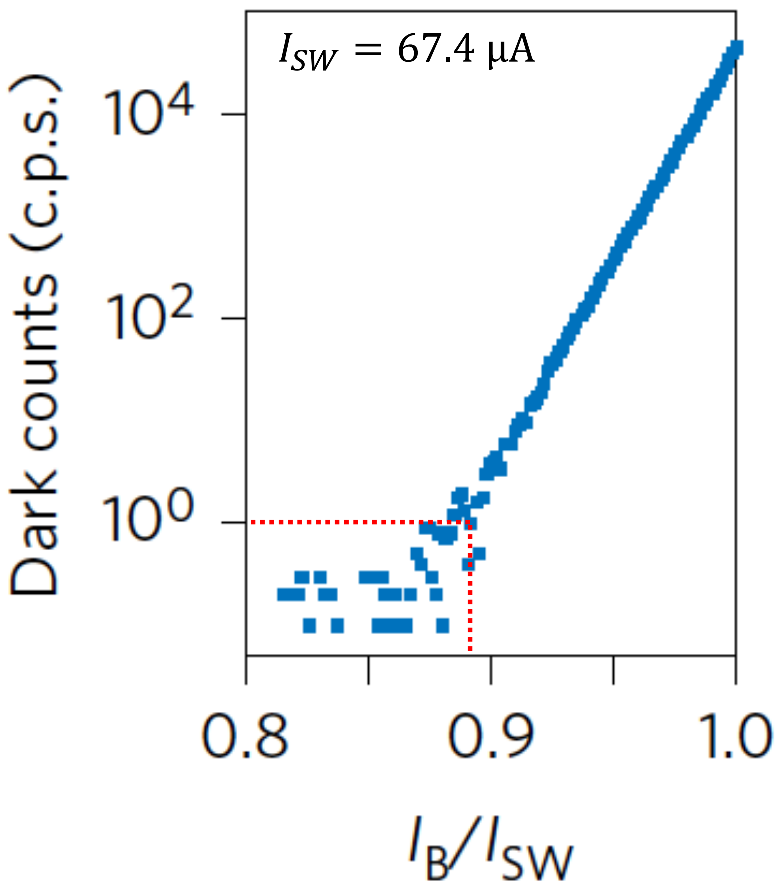
Detection performance

Wide optical bandwidth



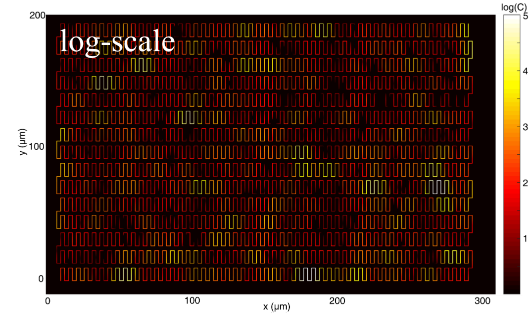
$I_{SW} = 67.4\ \mu A$

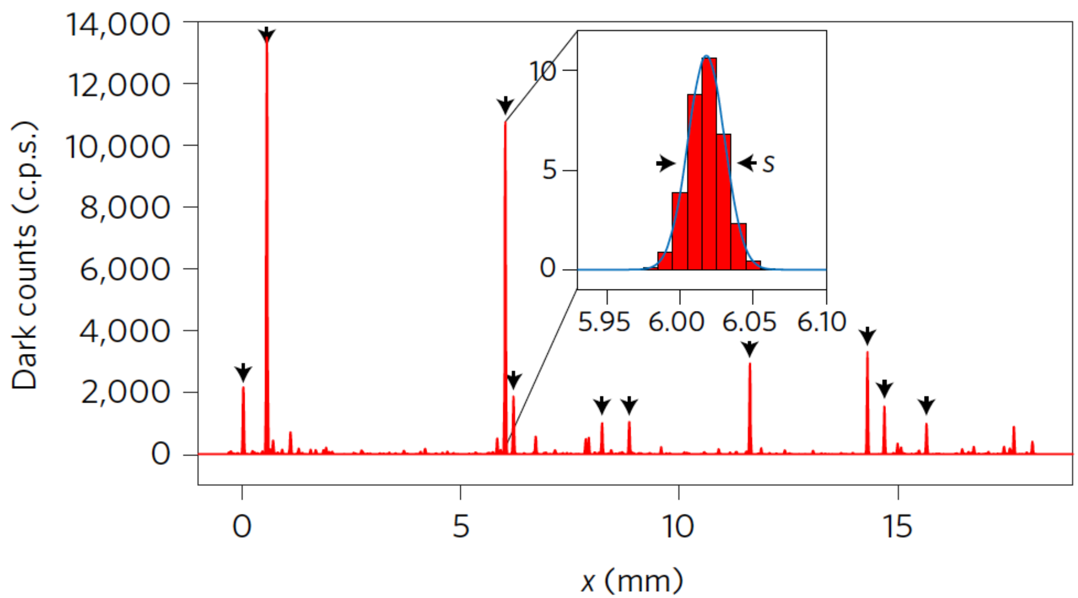
Detection performance



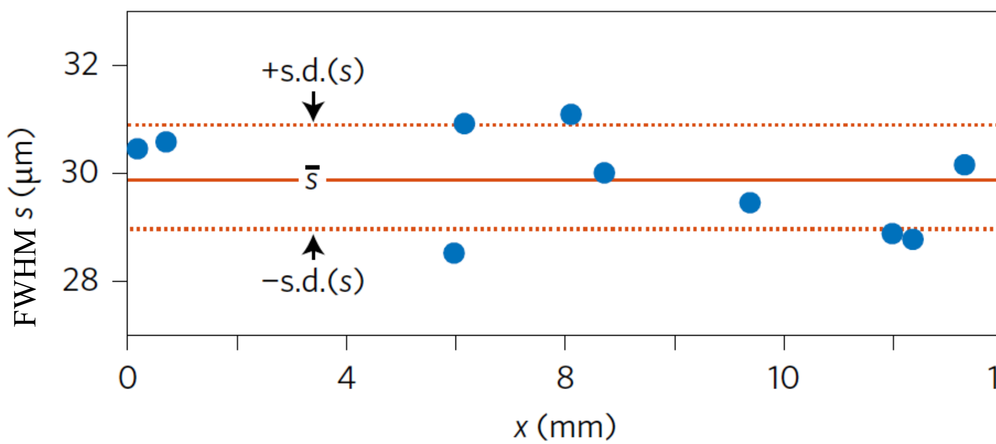
Exponential dependence
(similar to SNSPDs)

Detection performance





$f_w = 28.4\ \mu\text{m}$



$\bar{s} = 29.9\ \mu\text{m}$
$s.d. = 0.9\ \mu\text{m}$

number of pixels

$$\boxed{N_P = L_e/\bar{s} \cong 590}$$

$L_e = 17.635\ \text{mm}$

$\sim 10^6\ \text{pixels/cm}^2$

Summary

- A scalable architecture for single-photon imagers with precise temporal resolution
- ~590 effective pixels, sub 20 um spatial resolution and 50 ps FWHM temporal resolution
- Further scaled up by integrating multiple SNSPIs

More…

Superconducting nanowire single photon detector (SNSPD)

Applied physics letters **98**, 251105 (2011)

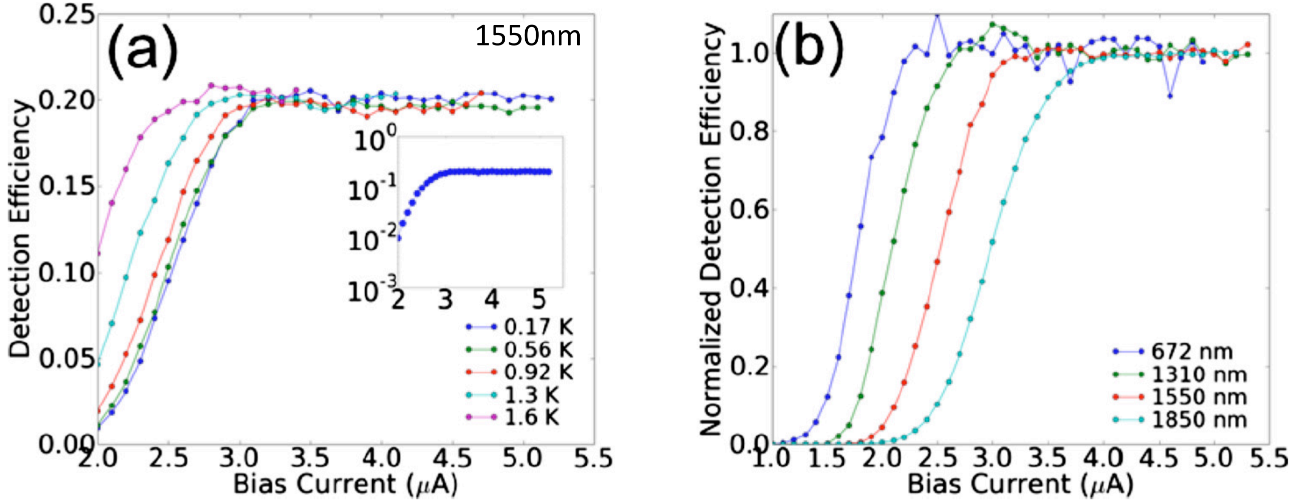
Superconducting a-W_xSi_{1-x} nanowire single-photon detector with saturated internal quantum efficiency from visible to 1850 nm

Burm Baek,[a)] Adriana E. Lita, Varun Verma, and Sae Woo Nam
National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA

(Received 6 May 2011; accepted 27 May 2011; published online 21 June 2011)

NbN/NbTiN ➔ a-W_xSi_{1-x} (amorphous tungsten-silicon alloy)

Tunable transition temperature T_c up to 5 K
Larger hotspots (smaller superconducting gap energy)
Lower electron density → low critical current density



Detection efficiency of 19%-40% over a wavelength range of 1280-1650nm

Superconducting nanowire single photon detector (SNSPD)

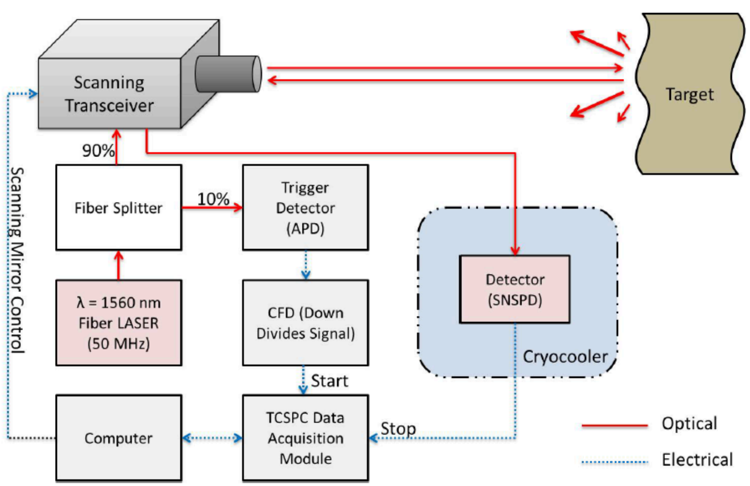
Optics express 8904 (2013)

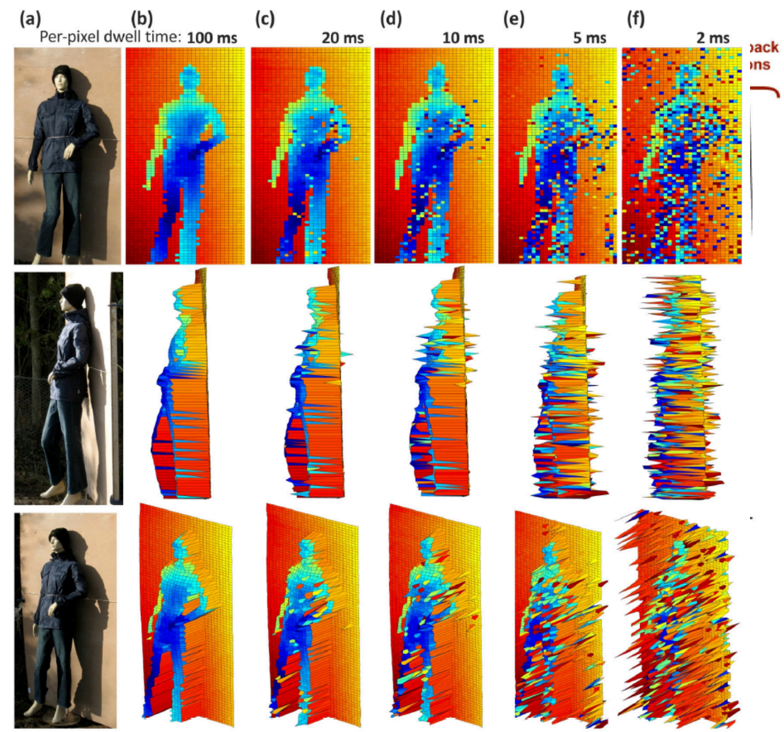
Kilometer-range, high resolution depth imaging via 1560 nm wavelength single-photon detection

Aongus McCarthy,[1,*] Nils J. Krichel,[1,2] Nathan R. Gemmell,[1] Ximing Ren,[1] Michael G. Tanner,[1,3] Sander N. Dorenbos,[4] Val Zwiller,[4] Robert H. Hadfield,[1,3] and Gerald S. Buller[1]

[1]Institute of Photonics and Quantum Sciences, and Scottish Universities Physics Alliance (SUPA), School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, UK
[2]Current address: Helia Photonics Ltd, Rosebank Park, Livingston EH54 7EJ, UK
[3]Current address: School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK
[4]Kalvi Institute of Nanoscience, Delft University of Technology, 2628 CJ Delft, The Netherlands
[*]A.McCarthy@hw.ac.uk

Time-of-flight technique





At 1560nm
Detection efficiency of 18% 1 kHz d.c. rate
with system jitter of ~100ps

1 km away

Superconducting nanowire single photon detector (SNSPD)

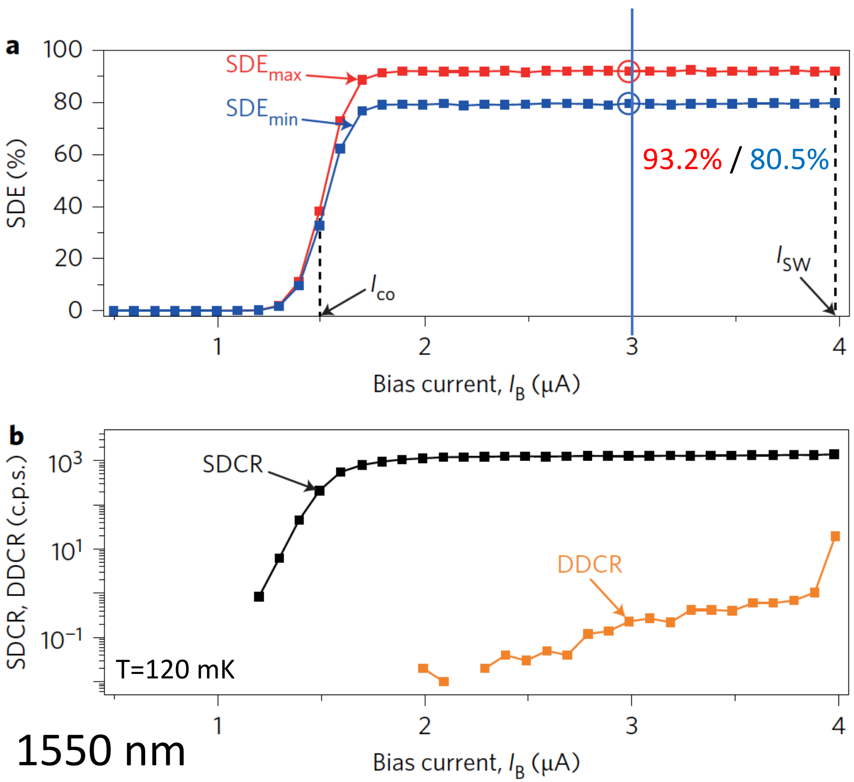
Nature Photonics **7**, 210–214 (2013)

LETTERS
PUBLISHED ONLINE: 24 FEBRUARY 2013 | DOI: 10.1038/NPHOTON.2013.13
nature photonics

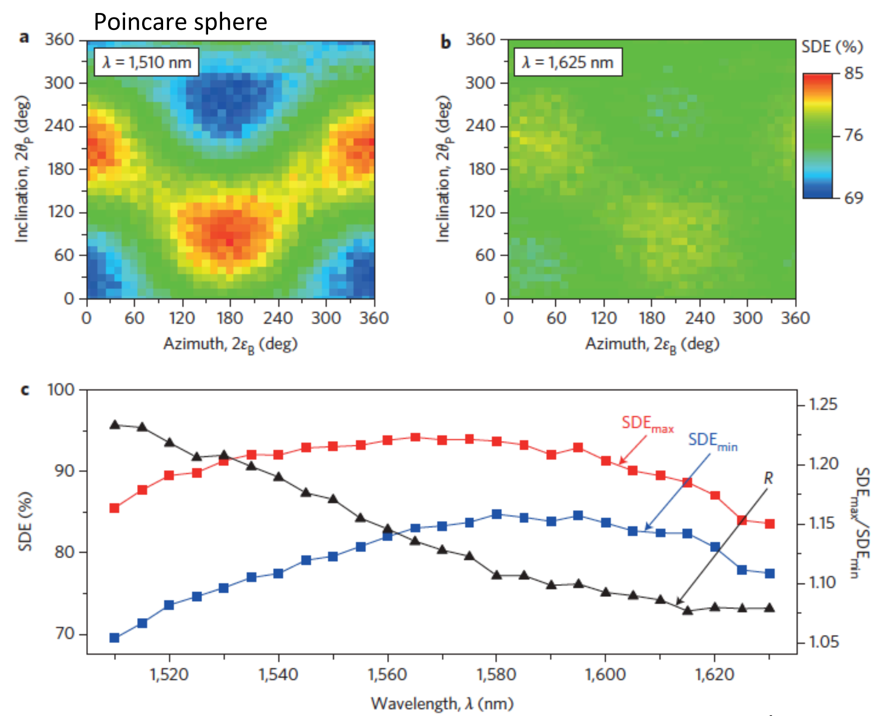
WSi SNSPD

Detecting single infrared photons with 93% system efficiency

F. Marsili[1]*, V. B. Verma[1], J. A. Stern[2], S. Harrington[1], A. E. Lita[1], T. Gerrits[1], I. Vayshenker[1], B. Baek[1], M. D. Shaw[2], R. P. Mirin[1] and S. W. Nam[1]*



1550 nm

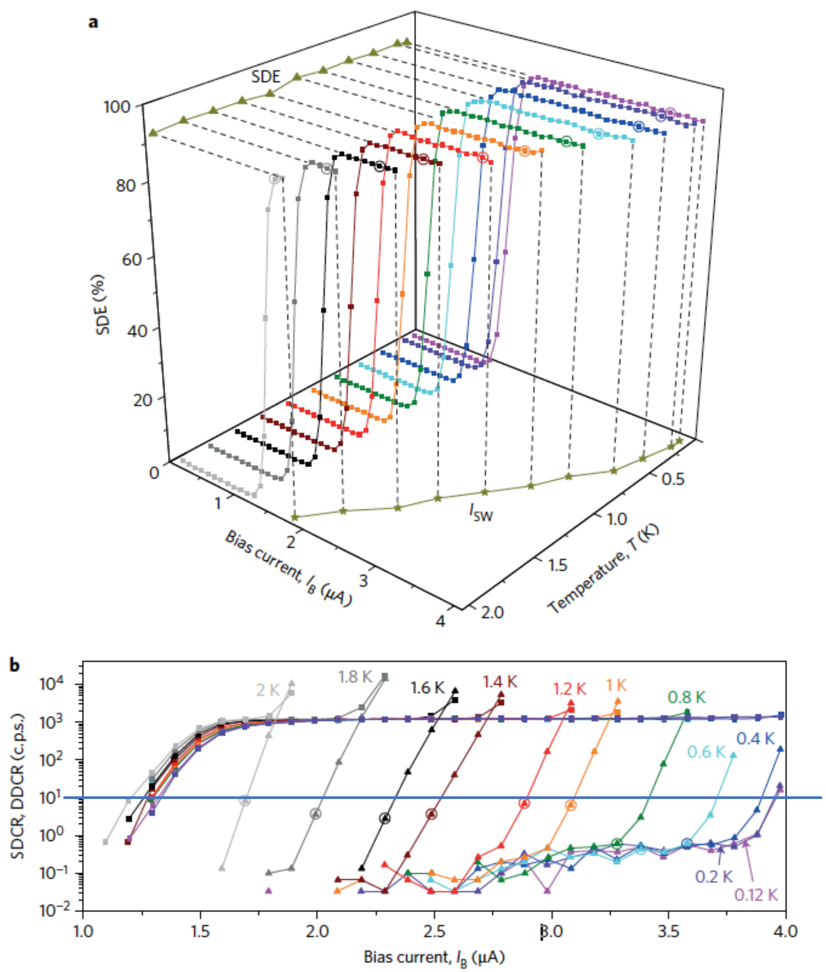


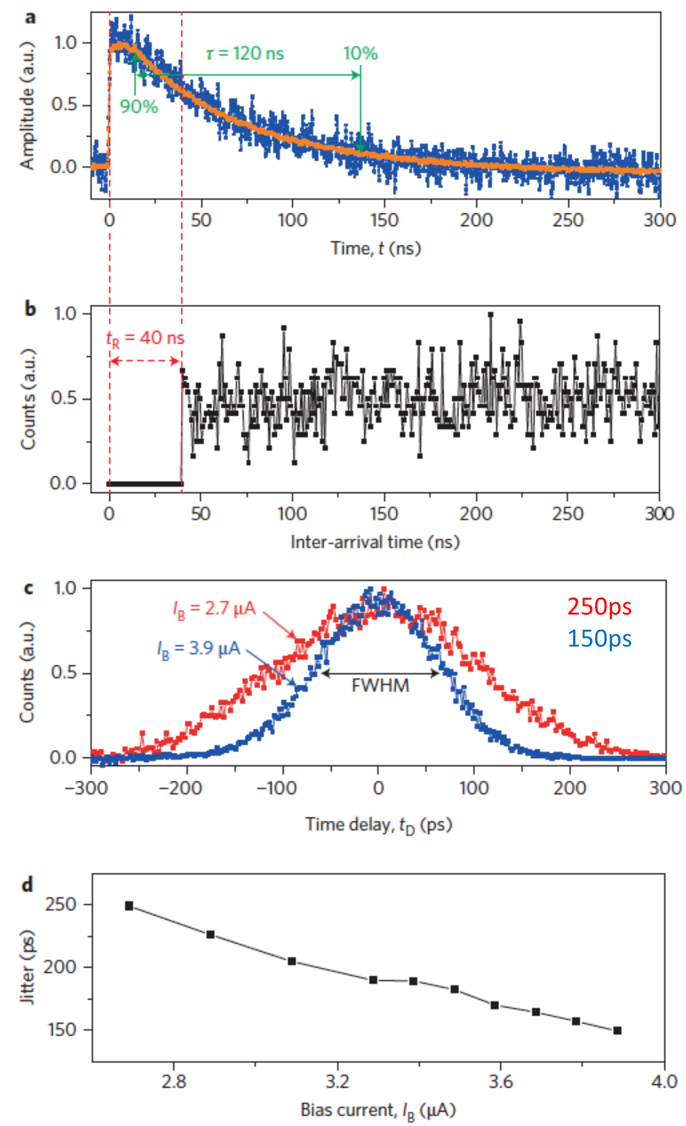
$R = SDE_{max}/SDE_{min}$

Superconducting nanowire single photon detector (SNSPD)

Nature Photonics **7**, 210–214 (2013)

1550 nm





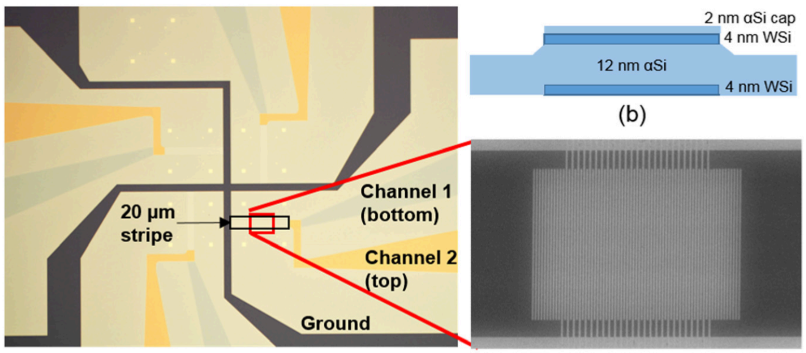
Superconducting nanowire single photon detector (SNSPD)

Applied physics letters **108**, 131108 (2016)

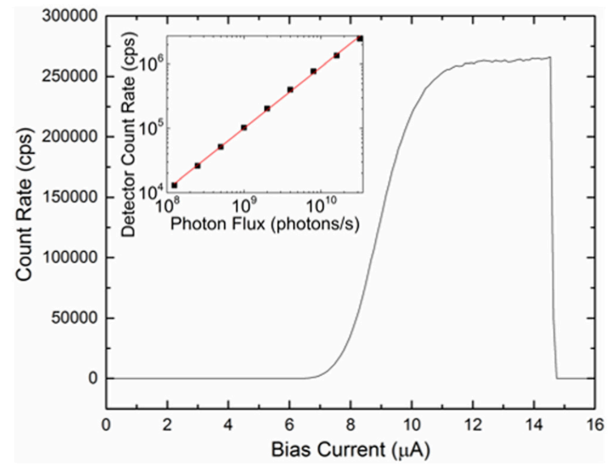
Athermal avalanche in bilayer superconducting nanowire single-photon detectors

V. B. Verma,[a)] A. E. Lita, M. J. Stevens, R. P. Mirin, and S. W. Nam
National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA

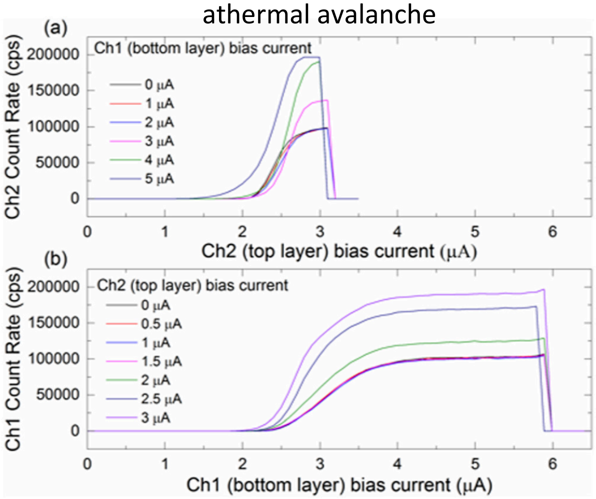
(Received 13 January 2016; accepted 24 March 2016; published online 31 March 2016)



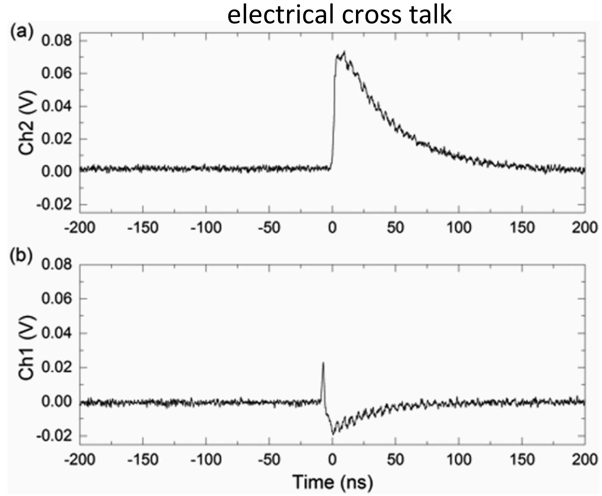
(a) (c)

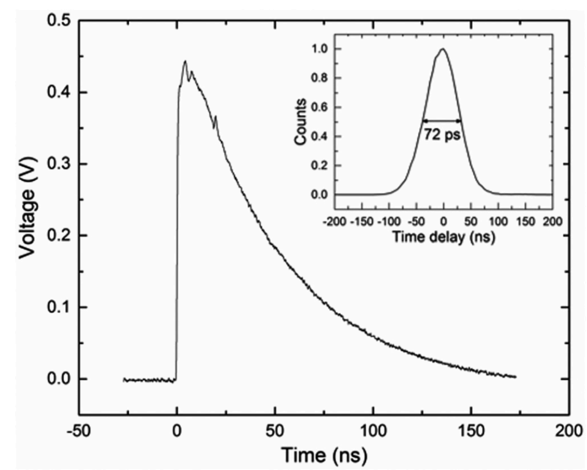


athermal avalanche



electrical cross talk





Superconducting nanowire single photon detector (SNSPD)

Optics express 8705 (2017)

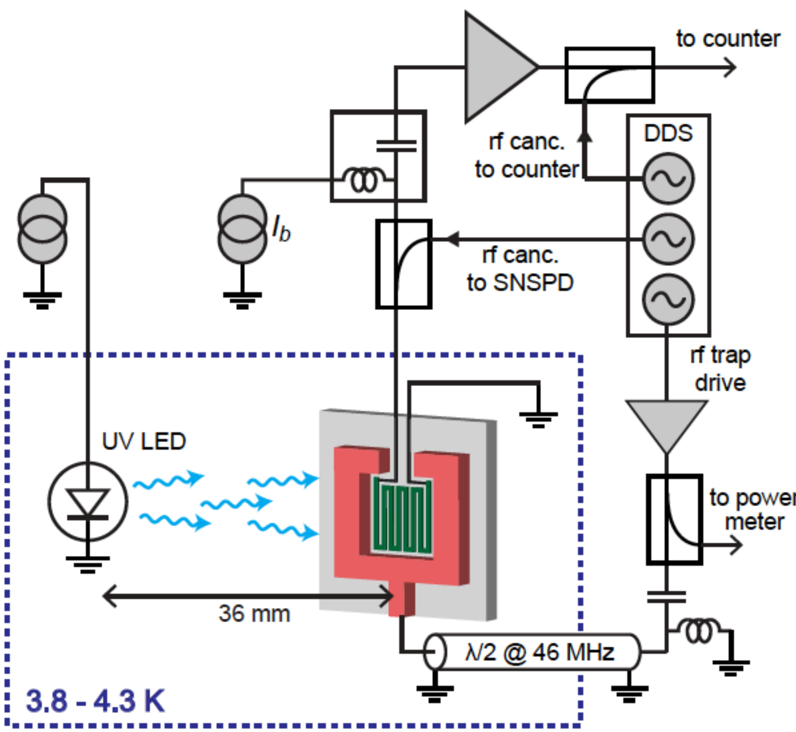
Optics EXPRESS

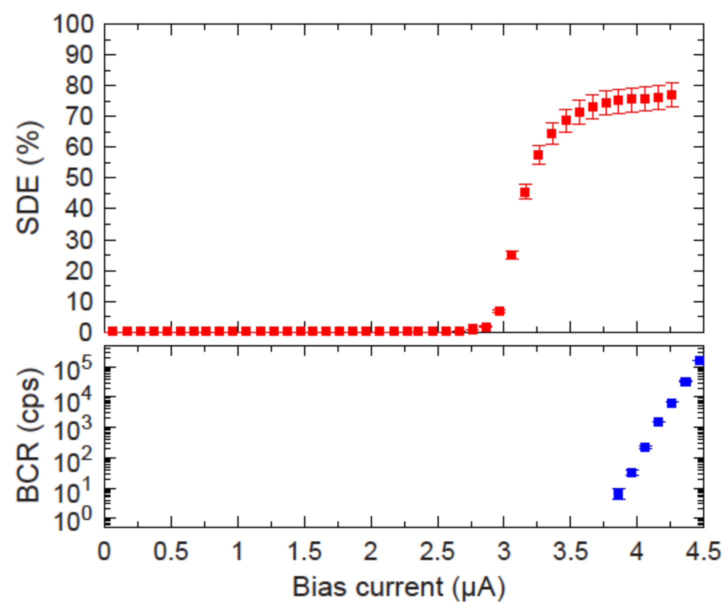
MoSi SNSPD

UV-sensitive superconducting nanowire single photon detectors for integration in an ion trap

D. H. SLICHTER,[1,*] V. B. VERMA,[2] D. LEIBFRIED,[1] R. P. MIRIN,[2] S. W. NAM,[2] AND D. J. WINELAND[1]

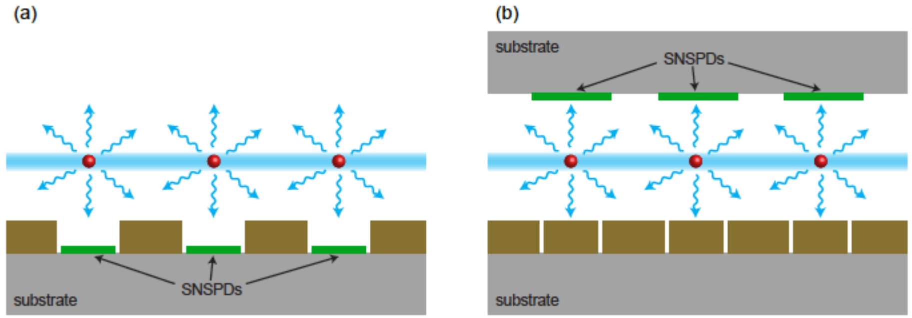
SDE = 76 $\pm$ 4% (3.2 K) at 315nm for $^{9}Be^{+}$

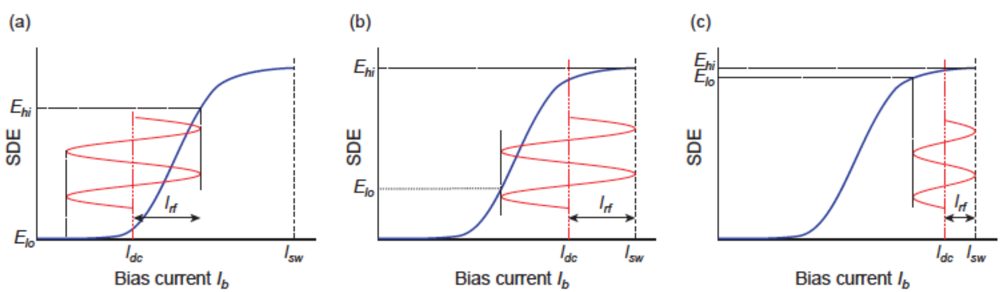




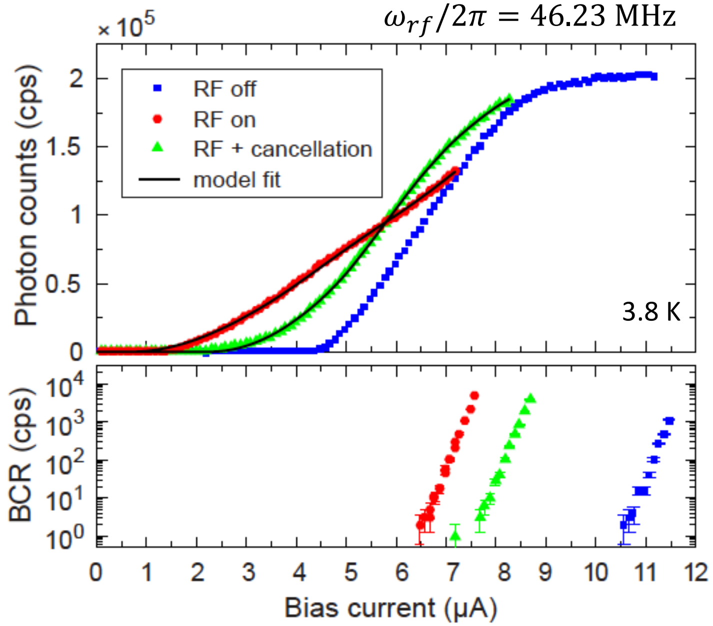
Superconducting nanowire single photon detector (SNSPD)

Optics express 8705 (2017)





$\omega_{rf}/2\pi = 46.23$ MHz



Superconducting nanowire single photon detector (SNSPD)

Optics express 10322 (2017)

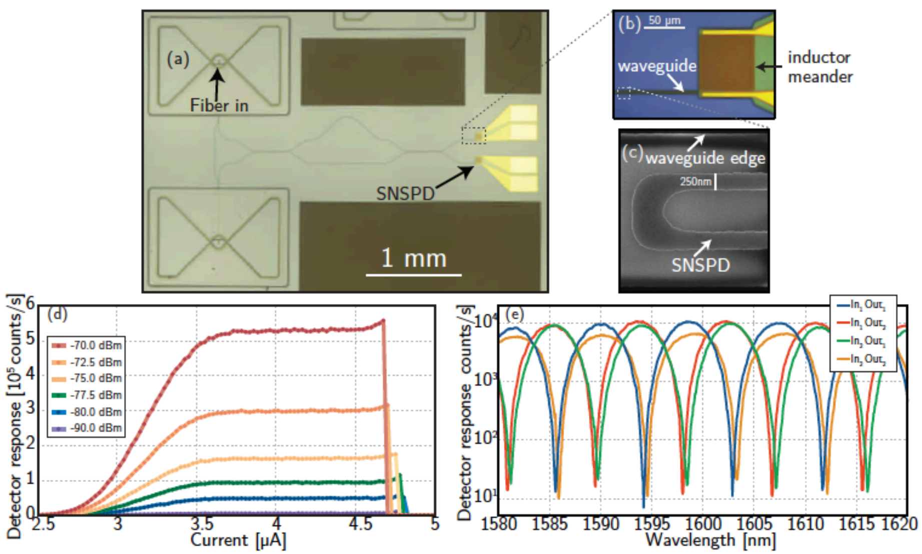
Optics EXPRESS

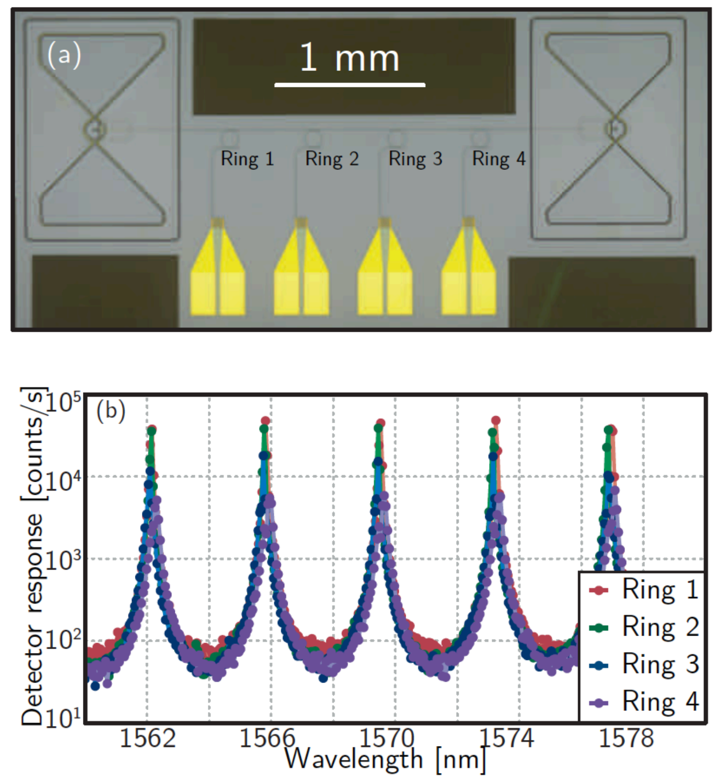
Room-temperature-deposited dielectrics and superconductors for integrated photonics

Jeffrey M. Shainline,[1,*] Sonia M. Buckley,[1] Nima Nader,[1] Cale M. Gentry,[2] Kevin C. Cossel,[1] Justin W. Cleary,[3] Miloš Popović,[2] Nathan R. Newbury,[1] Sae Woo Nam,[1] and Richard P. Mirin[1]

Ring filter

MZI



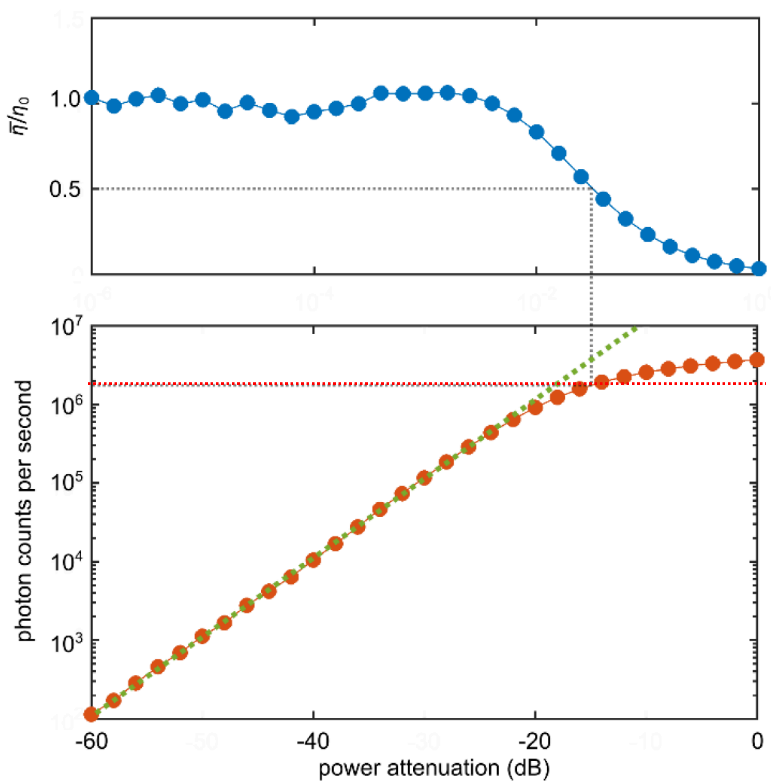


$ 4M

Supplementary

SNSPI speed

- Using a 200MHz counter (w/o timing info.)
- Removed the charging effects from the amp.



(Maximum counting rate)

$= CR_{max}$

→ 2×10^6 cps

η_0 : detection efficiency when the device is fully reset to its initial bias current

$*$ the linear part (gives η_0)
→ inter arrival time of individual photons is longer than the current recovery time

Detection performance