Single-Photon Detection and Imaging by Using Superconducting Nanowires


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HOW TO DETECT A PHOTON WITH A SUPERCONDUCTOR?
Why are Superconductors Interesting?

- Zero resistance
- Exclusion of magnetic field
- Strong nonlinearity
Why are Superconductors Interesting?

- Zero resistance
- Exclusion of magnetic field
- Strong nonlinearity
Comparison-Based Device

![Graph showing critical current and superconducting behavior]

- Critical current, $I_c$
- Superconducting
- Resistive
Comparison-Based Device

Critical current, $I_c$

Bias point

Superconducting

Resistive
Comparison-Based Device

Critical current, $I_c$

Bias point

Superconducting

Resistive

$I$

$V$
Superconductive Nanowire Single-Photon Detector

Yang et al., IEEE TAS (2005)
Gol’tsman et al., APL (2001)
DEVICE OPERATION
Detection Mechanism

Critical Temperature $\sim 11$ K

The superconductor is biased near its transition.

Diagram:
- Critical Temperature $\sim 11$ K
- 4 nm thickness
- < 100 nm
- niobium nitride
- Detector
- $I_{bias}$
- $L$
- $R_{load}$
Detection Mechanism

Critical Temperature ~ 11 K

Photon-induced hotspot forces bias current above critical density

4 nm

Niobium nitride

< 100 nm

Detector

Detection Mechanism

Critical Temperature $\sim 11$ K

resistive barrier spans nanowire

4 nm $\rightarrow$ niobium nitride

$< 100$ nm

$\frac{I_{\text{bias}}}{\frac{R_{\text{load}}}{L}}$
Detection Mechanism

Critical Temperature ~ 11 K

resistance grows from heating

4 nm

< 100 nm

niobium nitride

detector

$L$

$I_{\text{bias}}$

$R_{\text{load}}$
Detection Mechanism

Critical Temperature ~ 11 K

Current is diverted

4 nm niobium nitride < 100 nm

detector

$I_{bias}$ $R_{load}$
Critical Temperature ~ 11 K

superconductivity is restored
Critical Temperature $\sim 11$ K

bias current is restored

Characteristics of Photon Detectors

- Efficiency
- Reset time
- Jitter
- Dark count rate

**Efficiency**

- Voltage
- Incident photons
- Time

**Reset time**

- Incident photons blocked by earlier signal
- Time

**Jitter**

- Varying delay between photons and signals
- Time

**Dark count rate**

- Voltage pulses with no corresponding photon
- Time
“LLCD will be the first high-rate space laser communications system that can be operated over a range ten times larger than the near-Earth ranges that have been demonstrated to date.” from http://esc.gsfc.nasa.gov/267/271.html, enabled by nanowire detectors developed at MIT Lincoln Laboratory in collaboration with MIT campus.
Superconducting Nanowire Single-Photon Detector (SNSPD)

NbN
@2.5 K

to electrode

100 nm

3 µm

to ground

Yang et al., IEEE TAS (2005)
Geometric Jitter

Detector area:

\[ d = 10 \, \mu m \]

\[ \text{Signal Speed } \equiv c' \sim \frac{c}{3} = 100 \, \mu m \, ps^{-1} \]

\[ \Rightarrow \text{geometric jitter } \sim 50 \, fs \]
Kinetic Inductance: Superconductivity’s Ugly Little Secret

Specific Inductance \( \equiv L_S \)
\[
= \mu_0 \frac{\lambda^2}{\text{Area}} \\
\approx 400 \text{ pH} \text{ \( \mu \text{m} \)}^{-1}
\]

Specific Capacitance \( \equiv C_S \)
\[
\approx 3.3 \epsilon_0 \\
\approx 30 \text{ aF} \text{ \( \mu \text{m} \)}^{-1}
\]

Signal Speed \( = c_{\text{eff}} \)
\[
= \frac{1}{\sqrt{C_S L_S}} \sim \frac{c}{30} \\
= 3\% \ c
\]
Kinetic Inductance: Superconductivity’s Ugly Little Secret

\[ \Lambda / d = 50 \text{ pH/square} \]
Geometric Jitter

Detector area:

\[ \vec{r}_0, t_0 \]

\[ \vec{r}_1, t_1 \]

\[ d = 10 \, \mu m \]

\[ c_{\text{eff}} \sim \frac{c}{25} = 100 \, \mu m \, \text{ps}^{-1} \]

\[ \Rightarrow \text{geometric jitter} \sim 20 \, \text{ps} \]
Ultra-High-Time-Resolution SNSPDs

- Single photon detection with 3.7 ps FWHM time resolution at 1550 nm
- 20 µm x 80 nm x 5 nm NbN nanowire, low-noise cryogenic amplifier
- Low jitter with larger active area may be practical using differential readout

JPL: Boris Korzh, Simone Frasca, Matthew Shaw
MIT: Qing-Yuan Zhao, KKB
NIST: Thomas Gerrits, Marty Stevens, Richard Mirin, Sae Woo Nam

Supported by: DARPA & NSF
Existing SNSPD arrays

Time-domain multiplexing (2 pix)

Frequency-domain multiplexing (2 pix)

SFQ readout (4 pix)

SFQ readout (4 pix)
Existing SNSPD arrays

Modulate SNSPD’s output

Inductive current splitting (4 pix)

Row-column addressing (64 pix)

MIT

NIST, JPL
Spatial and temporal detection in a wire

Photon arrives at $x$, $t_p$

left pulse arrival time:
$t_L = t_p + (L/2 + x)/c'$

differential time

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

sum time

right pulse arrival time:
$t_R = t_p + (L/2 - x)/c'$

Time: $t_p = (t_L + t_R - L/c')/2$

Photon position and arrival time can be detected **simultaneously**!
Similar readout architectures in other detector arrays

- micro-channel plate (MCP) using delay lines for imaging
- Neutron imager using delay lines


http://www.roentdek.com/
width = 300 nm, gap = 100 nm, total length = 19.7 mm, area = 286 μm × 193 μm
Two connectors for one imager (>500 pixels)

No cryogenic circuit is required
Output pulses from the SNSPI

Photon lands near the middle

$d_R = 8278 \, \mu m$

$d_L = 9357 \, \mu m$
Output pulses from the SNSPI

Photon lands near the right end

\( d_R = 1668 \, \mu m \)

\( d_L = 15967 \, \mu m \)
Mapping each photon position to form an image
- Imaging an MIT logo array
  - ~590 effective pixels (with 2 lines)
  - Spatial resolution (H: 5.6 μm, V: 13.0 μm)
  - 50 ps photon detection jitter
  - Maximum counting rate (2M counts/sec)
  - Efficiency is not optimized

Can We Observe Two-Photon Coincidences?

• Assume a pulsed source of photons (not continuous wave sources)

• Assume light will be coupled in via waveguides (not free space)
Delay-line Multiplexing

Nanowire microstrip transmission line
Delay line multiplexing

- Taper
- 16 detectors
- 100 μm
- 17 μm
- 80 nm
- Potential waveguide integration
- Detector
- Delay line multiplexing
\[ \tau = 435 \text{ ps} \]

4-element array
Only the first rising edge at each side is time-tagged.

4-element array
Only the first rising edge at each side is time-tagged

4-element array

\[ t_1 \rightarrow D1 \rightarrow D2 \rightarrow D3 \rightarrow D4 \rightarrow Ch2 \]

\[ t_2 \]

\[ t_{\text{sum}} = 2\tau \]

\[ t_{\text{diff}} \]

\[ t_{\text{diff}} = \pm 3\tau \]
mean photon number per pulse
\[ \tilde{\mu} = 1.14 \]
16-Element-detector chain

D Zhu, et. al, CLEO 2017: Applications and Technology, JTh5B. 4
Can we resolve more than two photons?
SPICE simulation for the pulse shapes

(SPICE modeling w/o amplifier gain and readout bandwidth)
Ambiguous two-photon events

Same time tagging
Two pulse shapes

Ch1

D1(D2)D3

Voltage (mV)

0 1000 2000 3000 4000 5000

Ch2

Voltage (mV)

0 1000 2000 3000 4000 5000
Ambiguous two-photon events

Same time tagging
Two pulse shapes

Ch1
voltage (mV)
0 100 200 300 400
0 1000 2000 3000 4000 5000
d_{1}(d_{2})d_{3}

Ch2
voltage (mV)
0 -100 -200 -300 -400
0 1000 2000 3000 4000 5000
d_{1}d_{2}d_{3} (rarer)
d_{1}d_{3}
Photon number resolving

Fraction of events where $k$ detectors fire
Applications

**Boson sampling**


**Quantum walk/simulation**


**Single-photon spectrometer**


What Have We Learned?
1. SNSPDs should be treated as distributed elements
2. Speed of light is extremely slow in these materials

Where Are We Going?
1. Photon-number resolution
2. Large imaging arrays
3. Even-shorter jitter
4. Apply slow-light effect to other kinds of devices and applications
Superconductivity Team in QNN Group

Qing-Yuan Zhao (Now Prof., Nanjing U.)
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Niccolo Calandri
Yachin Ivry
Adam McCaughan
Faraz Najafi
Kristen Sunter
Hao-Zhu Wang
Thank you!
Backup slides!
VLSI Circuit Evaluation

- VLSI circuit imaging and debugging
- SNSPD enables performance advances

Image courtesy of DCG Systems

Collaboration between BU, DCG Systems, IBM, Photonspot, funded by IARPA
"High-order temporal coherences of chaotic and laser light", Stevens, Baek, Dauler, Kerman, Molnar, Hamilton, Berggren, Mirin, and Nam, Optics Express, 18, 1430 (2010)
Ambiguous two-photon events

Ch1

Ch2

D_1D_2D_3

D_2D_3D_4

D_1D_2D_3D_4

D_1D_2

D_3

D_4
Large-Area 64-pixel SNSPD Arrays

- 64 pixel WSi SNSPD array, 97% yield
- 320 µm diameter, free space coupling
- 74% System Detection Efficiency
- 1.1 Gcps maximum count rate
- < 150 ps FWHM timing jitter
- Background limited dark counts
- Interdigitated pixels offer pseudo-PNR

Work supported by NASA Deep Space Optical Communication Project

Jason Allmaras, Andrew Beyer, Ryan Briggs, Francesco Marsili, Bill Farr, and Matthew Shaw
Dark count map
SNSPI: superconducting nanowire single-photon Imager

Detection performance

SNSPD-like DE

50 ps detection jitter

1 cps dark count

1 MHz maximum counting rate

Fewer constrictions contributing for DCR
SPICE circuit simulation including simplified electrothermal model

The device is treated as a lumped device. It gives NO information of the photon hit location.
Low velocity and high impedance superconducting nanowire transmission/delay line

$L, Z_n, V_n$

Lumped model of transmission lines

\[ v = \sqrt{\frac{1}{LC}} \quad Z = \sqrt{\frac{L}{C}} \]

\[ L = L_K + L_G \approx L_K \]

velocity = 2.5\%c = 7.5 \mu m/ps
impedance = 4 k\Omega

NbN nanowire: 100 nm wide, 50 p\Omega/square
Microwave transmission line

Lumped model of transmission lines

\[ v = \sqrt{\frac{1}{LC}} \quad Z = \sqrt{\frac{L}{C}} \]

\[ L = L_K + L_G \cong L_K \]

First London equation

\[ J_S = E_z \frac{1}{jw\mu_0\lambda_L^2} = E_z \frac{1}{jwL_{ks}d} \]
Questions?
Transmission line effects, evidence 1

T.L. Impedance

\[ \frac{\lambda}{2} \text{ Resonance indicates } V_o = 4.2\% \]

Transmission line effects, evidence 1

Geometry jitter / propagation jitter in SNSPD

Spatial distribution of incident photons contributes to propagation jitter

Light illuminates evenly

Histogram

Convolve with other jitter

Span of propagation time

Each detected pulse

$t_R$, $t_B$, $t_G$ - time
Measured propagation time independently to photon detection time

Independent of $t_{ph}$

$t_{ch2} - t_{ch1}$: differential propagation time
Timing differential cryogenic amplifier

Set discrimination level lower to have less effects from reflections

N. Calandri, et. al., arxiv:1607.06713, 0–8 (2016).
Propagation time in SNSPDs of different area

Standard SNSPD of different area

\[ t_{\text{ch2}} \]

\[ t_{\text{ch1}} \]

Jitter of \((t_{\text{ch2}} - t_{\text{ch1}})\) increases as the area goes up

<table>
<thead>
<tr>
<th>Devices dimension</th>
<th>Devices dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 \mu m x 3 \mu m</td>
<td>3 \mu m x 3 \mu m</td>
</tr>
<tr>
<td>10 \mu m x 10 \mu m</td>
<td>10 \mu m x 10 \mu m</td>
</tr>
<tr>
<td>15 \mu m x 15 \mu m</td>
<td>15 \mu m x 15 \mu m</td>
</tr>
<tr>
<td>20 \mu m x 20 \mu m</td>
<td>20 \mu m x 20 \mu m</td>
</tr>
</tbody>
</table>

Single constriction SNSPDs

Standard SNSPD of different area

Only a short wire at the center can respond to photons

No variation in propagation time. The jitter measured is mostly from electrical noise.

Estimate jitter attributed to signal propagation time

- Larger area detectors will have jitter attributed to propagation time variation
- If location is well known, the overall jitter can be reduced by removing the propagation time

\[ \text{Interarrival jitter, FWHM (ps)} = \sqrt{(j_{\text{norm}}^2 - j_{\text{cons}}^2)^{1/2}} \]
Simulation of a transmission line in a normal SNSPD

SPICE simulation of an ideal nanowire transmission line at different firing location $x$
Reflections inside an meander wire

\[ v = \sqrt{\frac{1}{LC}} = 7.9 \ \mu m/ps \]

\[ Z = \sqrt{\frac{L}{C}} = 4 \ k\Omega \]
Crosstalk (coupling) between adjacent wires

Capacitive coupling in a meandered SNSPD

RF simulation of the transmission at 5 GHz

Transmission (dB/100 um)

Gap distance (um)

4% signal is lost due to coupling
What we have learned?

1. SNSPDs do have T.L. effects

2. The T.L. effects are not well exhibited in normal SNSPDs,
   due to:
   - The wire is not long enough
   - The impedance too high
   - Not designed for a good microwave transmission line
Application of a distributed SNSPD: Single-photon Imager
Microwave taper for transforming impedance

100 μm/50 Ω → NbN taper → 5 μm/300 Ω

Length = 17.3 mm

Delayed by 666 ps
Velocity = 8.7%c

S21 (dB)

Frequency (GHz)

0 1 2 3 4

0 10 20 30 40

-15 -10 -5

Input pulse

Voltage (V)

PCB TL

Taper

0 2 4 6 8 10

0 0.1 0.2

0 0.1 0.2
From a lumped inductor to a transmission line

Meandered SNSPD

Typical values:
- \( L = 500 \, \mu\text{m} \), \( w = 100 \, \text{nm} \), \( d = 5 \, \text{nm} \)
- \( L_{ks} = 50 \, \text{pH/square} \), \( R_s = 400 \, \Omega/\text{square} \)
- \( I_C = 20 \, \mu\text{A} \)

\( S_{ph} \): ideal switch triggered by photon detection

\[
L_K = \mu_0 \lambda_{eff}^2 \times \frac{L}{wd} \\
R_n(t) = R_s \times \frac{l_{hp}(t)}{wd} \\
L_K = 250 \, \text{nH} \\
\text{Max} \ (R_n(t)) \cong 1 \, \text{k\Omega} 
\]

Histogram of pulse arrivals
Detector metrics are compared at 1550 nm based on Hadfield, Nat. Photon. (2009).

SNSPD – Superconducting nanowire single-photon detector
TES – Transition edge sensor
SAPD – Single-photon avalanche photodiodes
PMT – Photomultiplier tube

Detection efficiency
- 57% DDE (MIT 2006)
- 93% SDE (NIST 2012)
- Near-unity ODE (UBC 2015)

Count rate [MHz]
- 500 MHz (MIT LL 2012, 4-pixel array)

1/jitter [ps⁻¹]
- 1/(18 ps) (Yale 2012)
- 1/(24 ps) (MIT 2015)

1/dark count [seconds/count]
- 1 count/10³ seconds (Kitami, Japan 2015)
From a lumped inductor to a transmission line

Meandered SNSPD

Lumped model

Distributed model

\[ D_e/2 \]

\[ D_e/2 \]

\[ D_e/2 \]

\[ D_e/2 \]

\[ L_m \]: inductance per unit length
\[ C_m \]: capacitance per unit length

\[ S_{ph} \]

\[ S_{ph} \]

\[ L_K \]

\[ R_n \]

\[ R_n \]
Multiple detection events

Details of the pulse shape could give a full information of photon numbers, arrival times and locations
Detecting two-photon-firing events

16 two-photon firing events among 50,000 photon detection events (flood illumination over the entire area)
SN: a slow-wave and high Z transmission line

First London equation

\[ J_S = E_z \frac{1}{jw\mu_0\lambda_L^2} = E_z \frac{1}{jwL_{ks}d} \]

\[ v = \sqrt{\frac{1}{LC}} \quad Z = \sqrt{\frac{L}{C}} \]

\[ L = L_K + L_G \approx L_K \]

velocity = 2.5\%c = 7.5 \mu m/ps
impedance = 4 \k\Omega

Lumped model of transmission lines

NbN SNSPD 100 nm wide, 50 pH/square
Microstrip-based SNSPI

High efficiency, improved readout and avoid propagation jitter

There will be a trade-off between fill factor (light absorption) and EM mode coupling.
Detection timing jitter is not affected

Location:

\[ x = \frac{(t_L - t_R) \times v}{2} \]

Time:

\[ t_p = \frac{t_L + t_R - L/v}{2} \]

Position and time are simultaneously detected!
Superconducting nanowire: a plasmonic waveguide

First London equation asks for a longitudinal $E$ to drive the kinetic inductance

$$J_S = E_z \frac{1}{j\omega \mu_0 \lambda_L^2} = E_z \frac{1}{j\omega L_{ks} d}$$

Complex permittivity:

$$\varepsilon = \varepsilon_0 - \frac{1}{w^2 \mu_0 \lambda_L^2}$$

Kinetic energy:

$$E_K = \frac{1}{2} L_k I^2$$

Analogous to plasmonic waveguides:

- Large negative dielectric constant
- Dominant kinetic resistance
Tested wire: Fabricated by Heidelberg (Laser direct writing).

Port 4-8: 10 um wide, 3um gap CPW, $R_n = 0.43$ Mohm ($I_c = 400$ uA)
The wire coming out is narrower than 10 um, probably about 6 um, with gap increasing to 5 um.

**Update:**
1. Diced the chip and tested in a transmission line holder.
2. Removed the ripples in frequency domain that were caused by a bad SMA connector
3. Time domain measurement and find the velocity to be $17.3\text{mm}/(755\text{ps}-96\text{ps}) = 8.8\%c$.
4. The experimental velocity from S parameter is about $8.3\%c$
5. The Sonnet simulated velocity is $13.7\%$ at $L_k = 50 \text{ pH/sq}$
First Clue: Self-Resonance

\[ Z_c \approx 50\Omega \]

Estimate frequency of self-resonance:
\[ \lambda \approx 34\,\mu m \]
\[ \Rightarrow f_{res} \approx \frac{c/3}{\lambda} \approx 3\,\text{THz} \]

Daniel F. Santavicca; Jesse K. Adams; Lierd E. Grant; Adam N. McCaughan; Karl K. Berggren;
A "Slight" Discrepancy

Predicted self-resonance: 3 Thz

Self-resonant frequency is off by a factor of \(240 \times\)
Almost There...

Use device length of 462 µm instead

⇒ λ ≈ 924 µm

⇒ f_{self-res} ≈ 109 GHz

Now only off by factor of 8.7

If c' ~ c/26 problem would be resolved...
Timing jitter FWHM vs. area