A distributed superconducting nanowire single photon detector for imaging

Qing-Yuan Zhao, D. Zhu, N. Calandri, F. Bellei, A. McCaughan, A. Dane, H. Wang, K. Berggren

Massachusetts Institute of Technology

D. Santavicca

University of North Florida

Acknowledgement:
Superconducting Nanowire Single-Photon Detector (SNSPD)

NbN @ 2.5 K

Yang et al., IEEE TAS (2005)
Detection mechanism

Trigger

Thermal & resistance expansion assisted by Joule heating

Electro-thermal feedback
Nanowire resets to superconducting

Reset
Detector performance

Single SNSPD performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection efficiency</td>
<td>$N_{ph}/N_{in}$</td>
<td>93% (WSi) [NIST 2012]</td>
</tr>
<tr>
<td>Timing jitter</td>
<td>FWHM of hist($\Delta t$)</td>
<td>24 ps [MIT 2015]</td>
</tr>
<tr>
<td>Counting rate</td>
<td>$N_{dt}$ per sec</td>
<td>~100 Mcps [MIT LL 2012]</td>
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<tr>
<td>Dark counts</td>
<td>$N_{dcr}$ per sec</td>
<td>1 count / $10^3$ sec [Kitami]</td>
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</table>
Constrains of an SNSPD

1. It has wide response spectrum, but cannot resolve photon energy

2. It is difficult to have a large SNSPD array ✓
Move to detector arrays

1. Encode detector position on the amplitude of output pulses

Move to detector arrays

2. Detector array + RSFQ readout circuits


NICT (4-pixel)

UCB & KIT (4-pixel)
3. Frequency multiplexing

Move to detector arrays

4. Time multiplexing

KIT (2-pixel)

Easy!
Possible!
Very challenging!
Photon position → Hotspot boundary
Q: what is the equivalent circuit model of an SNSPD?

Inductor $L_K$

Lumped device SNSPD

Transmission line $L, Z_n, V_n$

Distributed device Imager
Design a superconducting nanowire into a CPW

Simulation a superconducting nanowire transmission line

Lk = 50 pH/square

width = 100 nm

width (μm)

velocity (%c)

Z_{nw}

Z_{nw}

width = 100 nm

Lk = 50 pH/square
Spatial and temporal detection in a wire

Photon arrives at $t_p$

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

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

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

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

Photon position and arrival time can be detected **simultaneously**!
Read out the propagation delay without reflections
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 μm)

(d_L = 15967 μm)
Output pulses from the SNSPI

Photon lands near the left end

\(d_R = 13317 \, \mu m\)

\(d_L = 4318 \, \mu m\)
Mapping each photon position to form an image
~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

Similar readout architectures in other detector arrays

Micro-channel plate (MCP) using delay lines for imaging

http://www.roentdek.com/


Neutron imager using delay lines

Delay line multiplexing of waveguide SNSPDs

D Zhu, et. al, CLEO 2017: Applications and Technology, JTh5B. 4
Time delay: $\Delta t = 435 \text{ ps}$

4-element array

$t_1$ - $t_2$
Time delay: $\Delta t = 435$ ps

*Only the first pulse will be detected*
mean photon number per pulse
\( \tilde{\mu} = 1.14 \)
Multi-photon detection

single photon (1), two photon (6),
three photon (4), four count (1)

Photon number resolving!
Q: what is the equivalent circuit model of an SNSPD?

- Inductor $L_K$
- Lumped device
- Nanowire’s kinetic $L$
- Microwave design
- Impedance match
- Differential readout
- ...
- Transmission line $L, Z_n, V_n$
- Distributed device