Superconducting single-photon detectors as photon-energy and polarization resolving devices

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Single Photon Counting Detectors
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Nanostructured superconducting single-photon detectors: OUR TEAM

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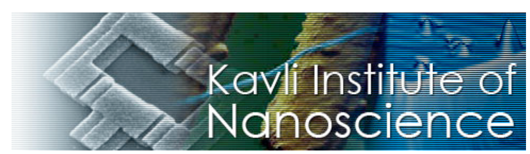

Outline

Superconducting Single-Photon Detectors (SSPDs):
introduction and motivation.

Energy-resolving capability of SSPDs:
statistical approach based on the quantum efficiency dependence on the absorbed photon energy.

Energy- and photon-number resolving capabilities:
high-input impedance cryogenic HEMT read-out circuit.

Polarization sensitivity of SSPDs.

Conclusions and outlook

Single-photon detectors: desired properties

- High quantum efficiency (QE reaching 100%)
- Broadband operation (200 nm to >3000 nm)
- Low dark count rates
  - no false/unwanted counts
  - no afterpulsing
- Very high speed
  - fast, picosecond signal rise and recovery
  - no "dead" time between counts
- Photon energy resolving
- Photon number resolving
- Photon polarization resolving

NbN SSPDs are 2-dimensional -wire, inter-digitated, nanostructures

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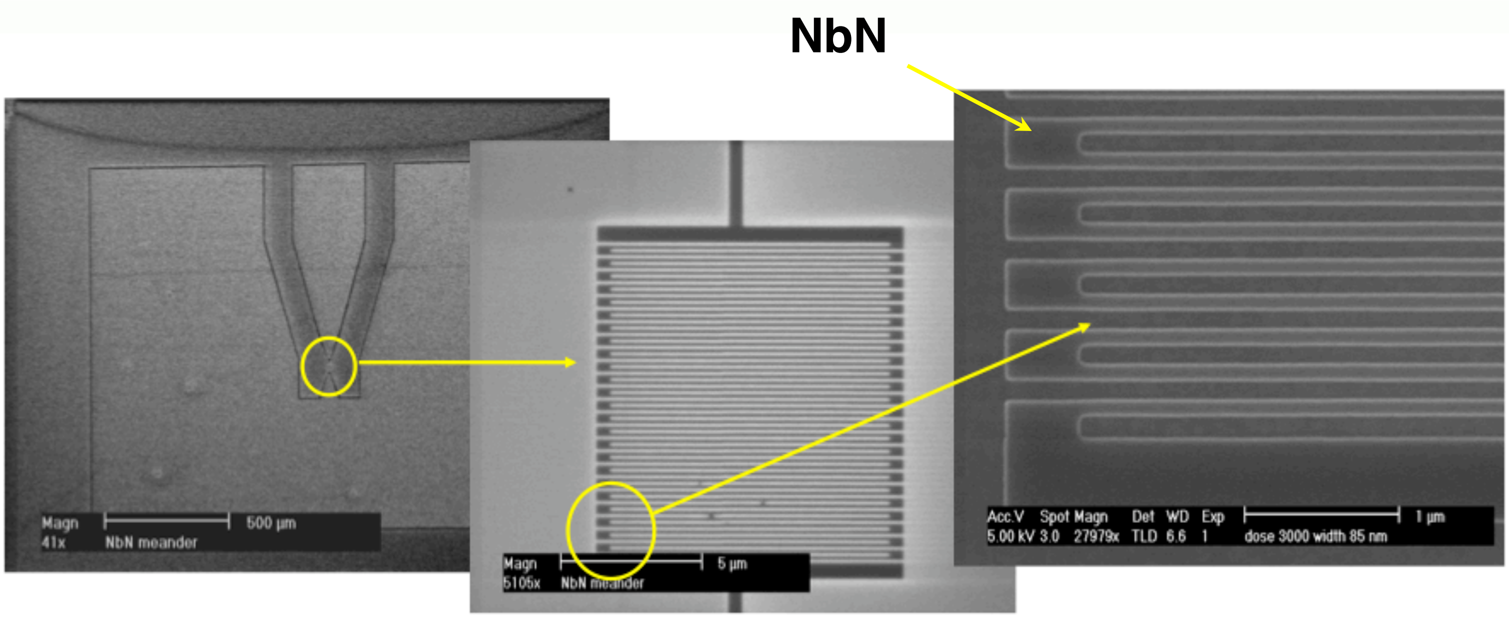
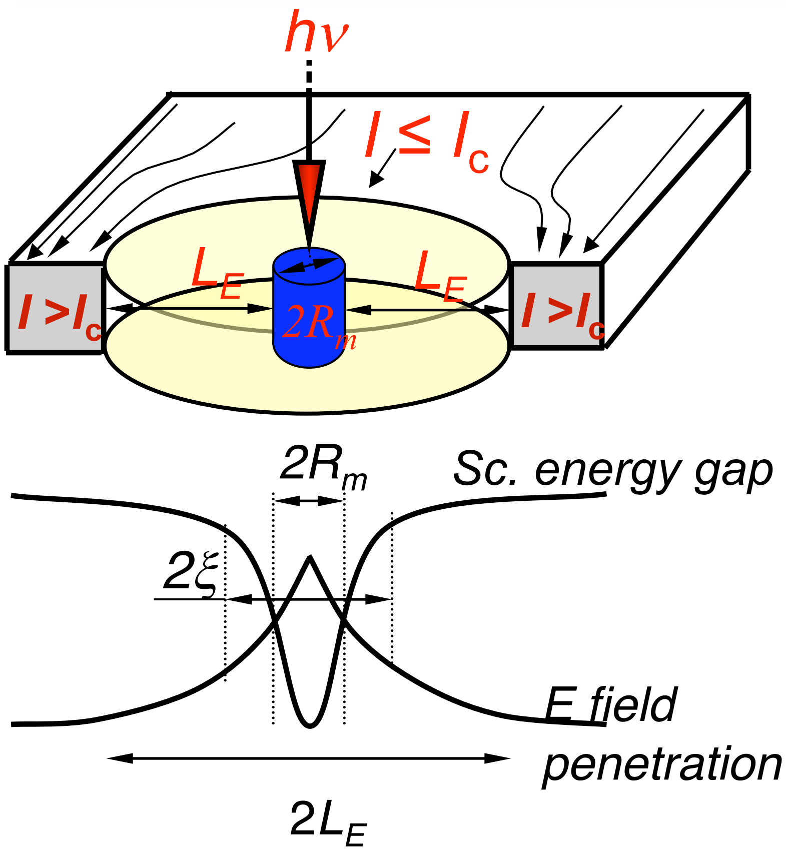
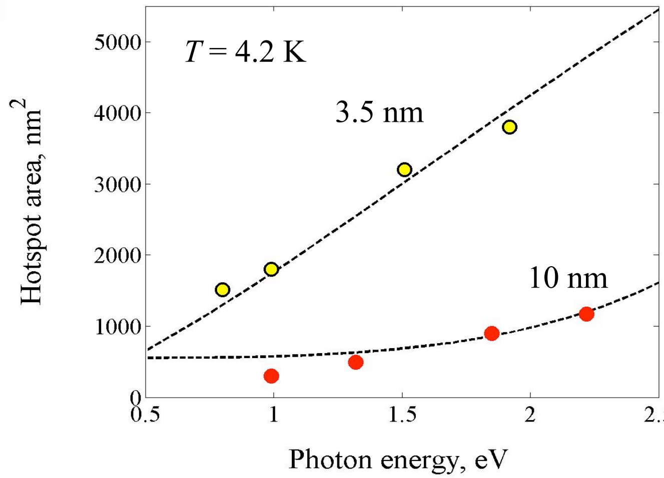


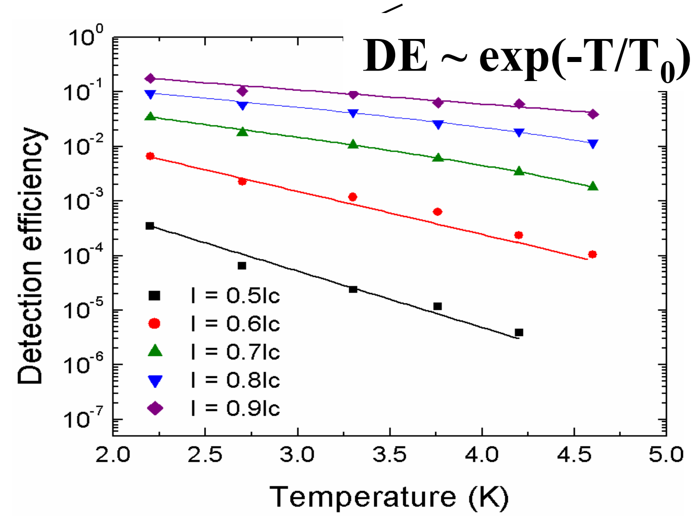
Stripe thickness: 4 nm, width: 120 nm, length: ~0.5 mm.
Active device area: 10 x 10 μm^2

The NbN and NbTiN devices were fabricated at the Delft Technical University.

Photon counts result from transient resistive hotspot formation in 2-D stripe



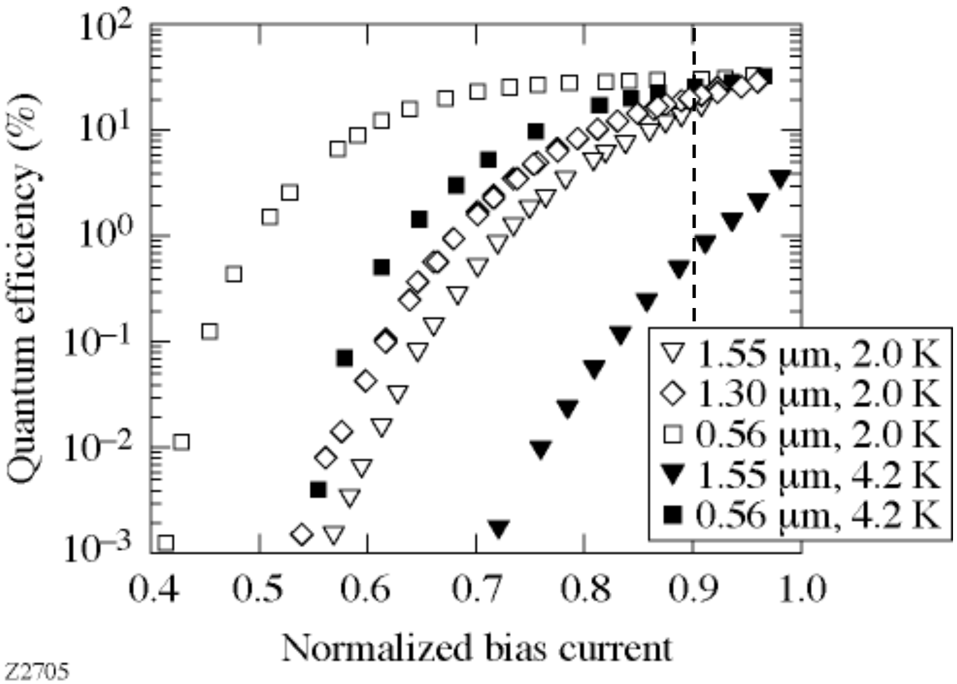




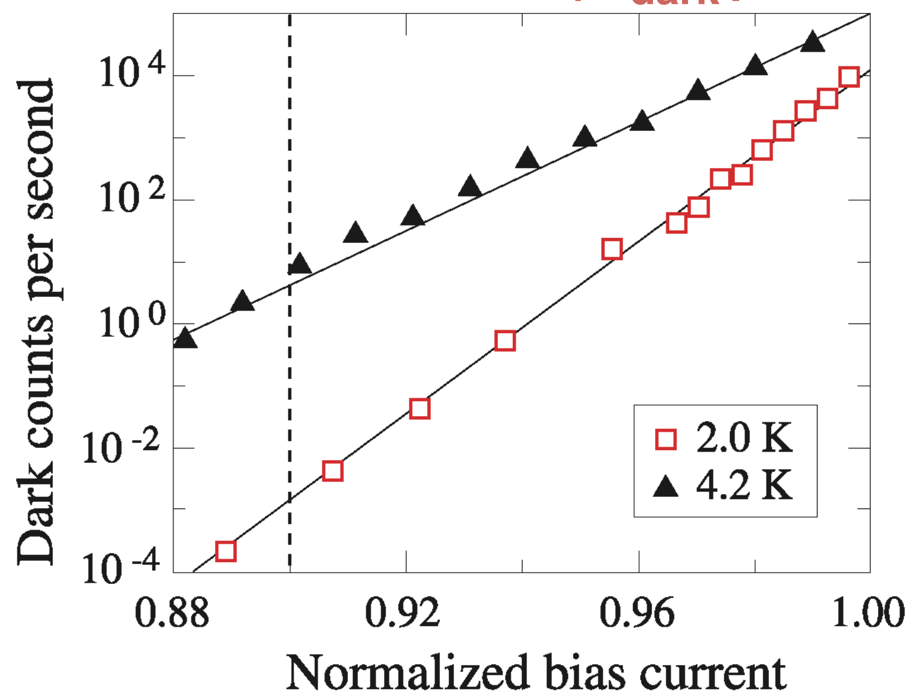
Single-photon response is based on the quantum hotspot formation, followed by resistive heating.
One optical photon can create a hotspot of up to ~1500 quasiparticles.

SSPD performance parameters

Quantum efficiency (QE)



Dark counts (R_{dark})



Noise equivalent power:

$$NEP = \frac{h\nu}{QE}\sqrt{2R_{dark}}$$

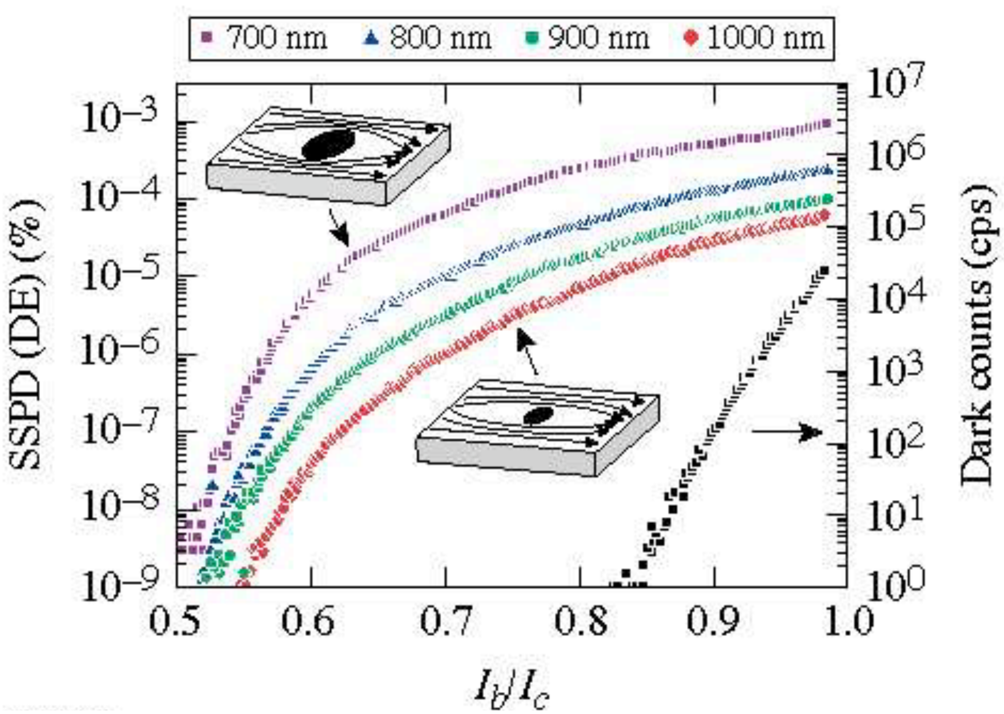
Trade-off between QE and R_{dark}

$T = 4.2$ (2.0) K, $I_b/I_c = 0.9$
QE ~25-20 (~30)% for visible light
QE ~8-4 (~20)% for 1.3 - 1.55 μm
R_{dark} <10 (<10^{-3}) Hz
NEP ~5×10^{-17} (~3×10^{-20}) W/Hz$^{1/2}$

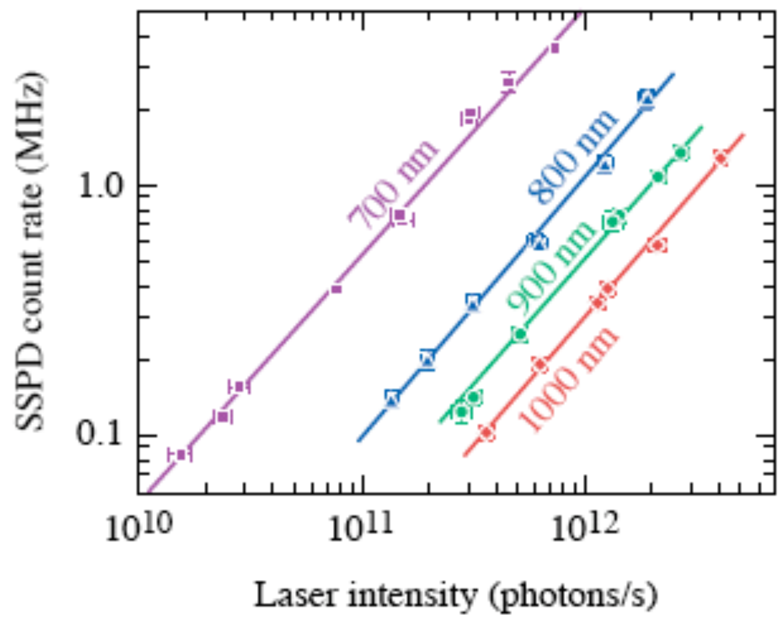
A. Korneev *et al.,* IEEE Trans. Appl. Supercon., (2005).

Photon energy resolving capability of SSPDs

Detection efficiency vs. the bias and photon energy



Photon counts at different wavelengths

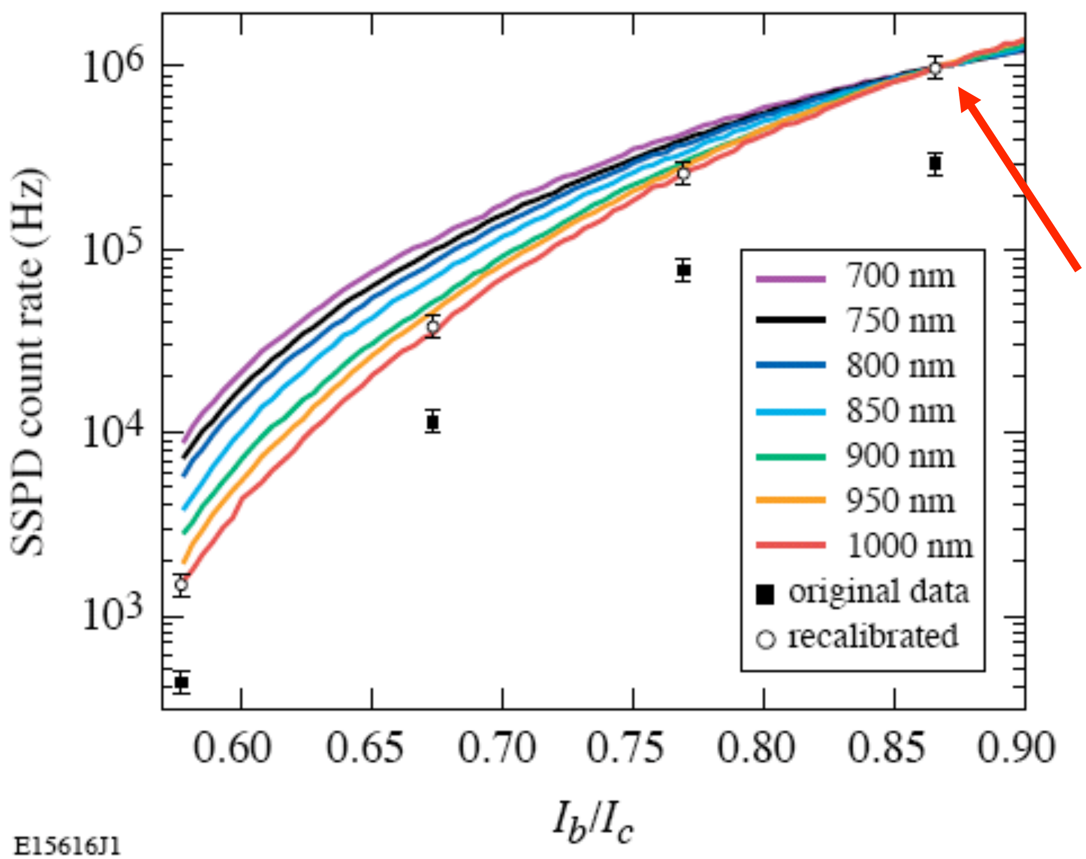


The spectroscopy is achieved by scanning an unknown photon source versus the detector current bias and comparing the result with the set of "calibration" curves.

Reiger *et al.,* J. Sec. Topics QE, (2007)

Photon energy resolving capability of SSPDs (II)

Calibration curves



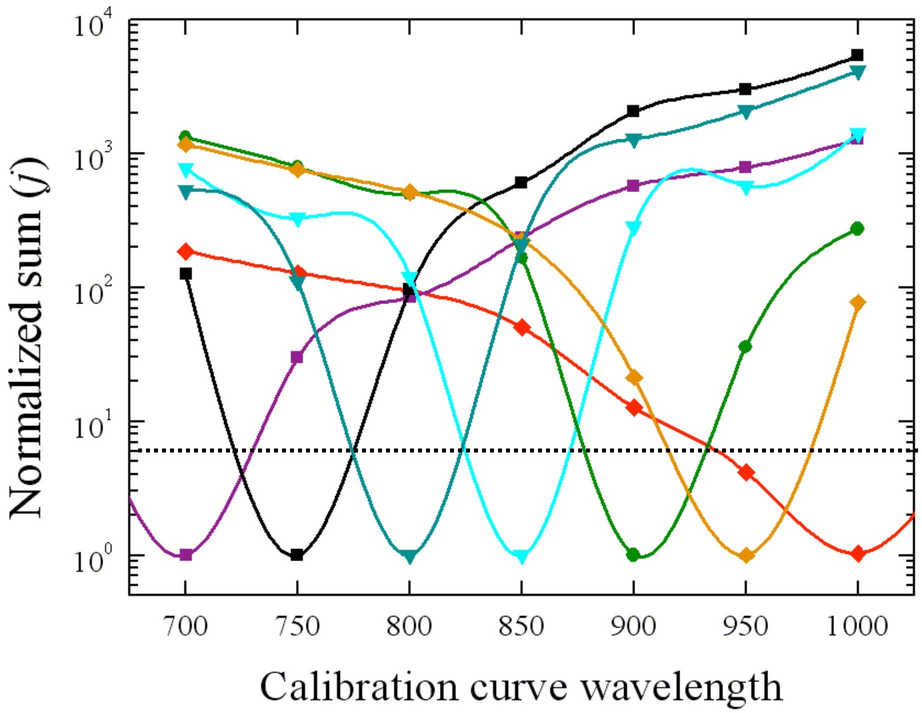
Laser intensity of each curve was chosen such that at this point, the obtained photon-count rate was approx. 1 MHz. Then, each curve was normalized to exactly 10^6 cps.

To demonstrate the energy-resolving property, we took test curves (black squares) measured for arbitrary intensities of incident photons, and normalized them at same point as the calibration curves.

Correct wavelength can be assigned!

Reiger *et al.,* J. Sec. Topics QE, (2007)

Photon energy resolving capability of SSPDs



For each test curve, the minimum of the sum of squares corresponds to the wavelength assignment.

One problem–any external disturbances within our measurement time window (1-2 min) are critical.

Wavelength (energy) resolution: 50 nm.

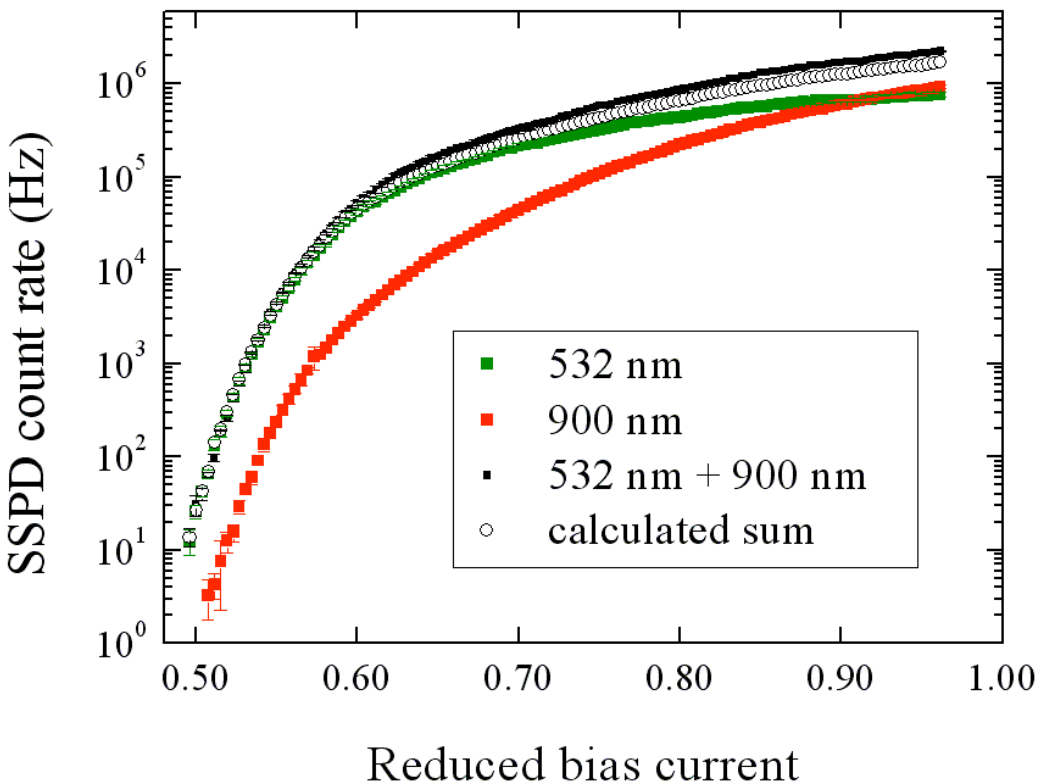
$$sum(j) = \sum \left(x_i - cal_i(j)\right)^2 / cal_i(j)$$

Test curves	Symbol	700 nm	750 nm	800 nm	850 nm	900 nm	950 nm	1000 nm
# 1	—■—	**163**	7811	22812	64473	158987	219322	357780
# 3	—■—	5303	**34**	3755	24369	82857	122838	217515
# 5	—▲—	17352	3545	**24**	7032	42720	69536	137118
# 7	—▲—	38175	16227	5868	**34**	14270	28732	70996
# 9	—●—	83177	50765	32191	11316	**59**	1612	15006
# 11	—◆—	96165	61828	41631	17736	1347	**63**	7358
# 13	—◆—	126994	88303	64930	35211	9277	3240	**440**

Reiger *et al.*, J. Sec. Topics QE, (2007)

Two-color, photon-energy resolving capability

Can two wavelengths simultaneously detected be resolved?



At low bias currents, both the summed curve and the black curve follow the green line.

At higher bias currents, the slopes of the black and the summed curves start to deviate from the green curve.

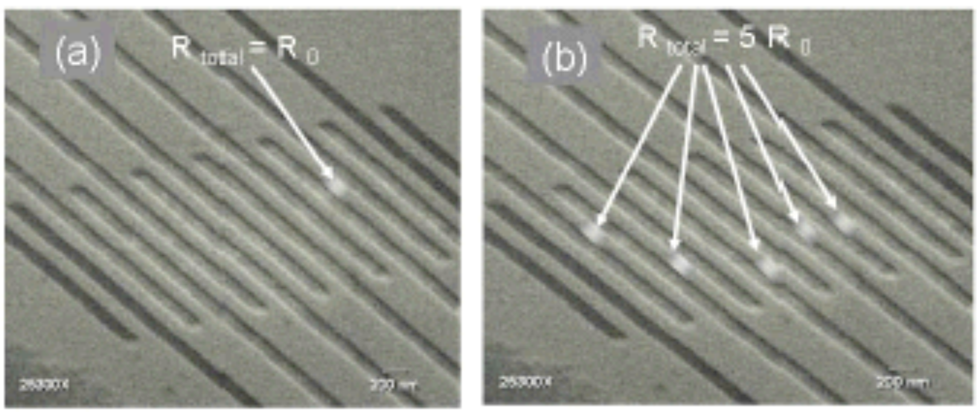
With proper calibration and careful analysis, it is possible to distinguish the contribution from the two different wavelengths.

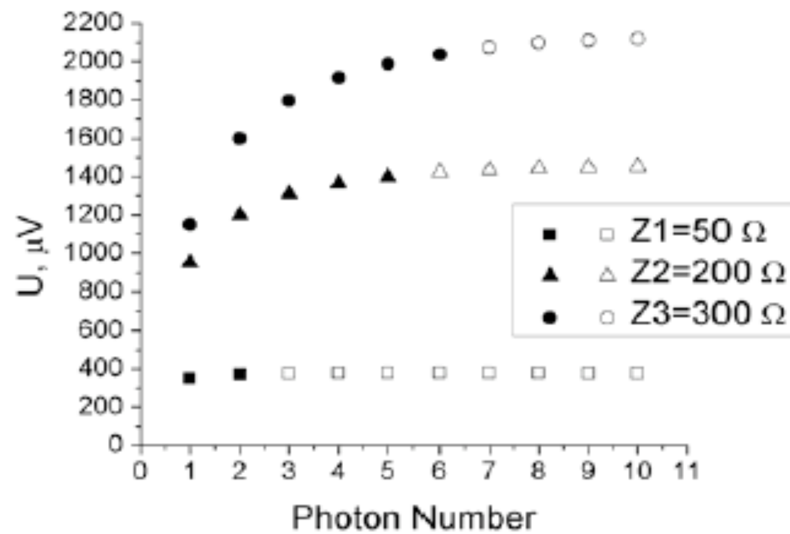
Reiger *et al.*, J. Sec. Topics QE, (2007)

Photon-number-resolved detection is highly desired in quantum optics

Solution suggested by Bell et al. [IEEE Trans. Appl. Supercon. (2007)]:

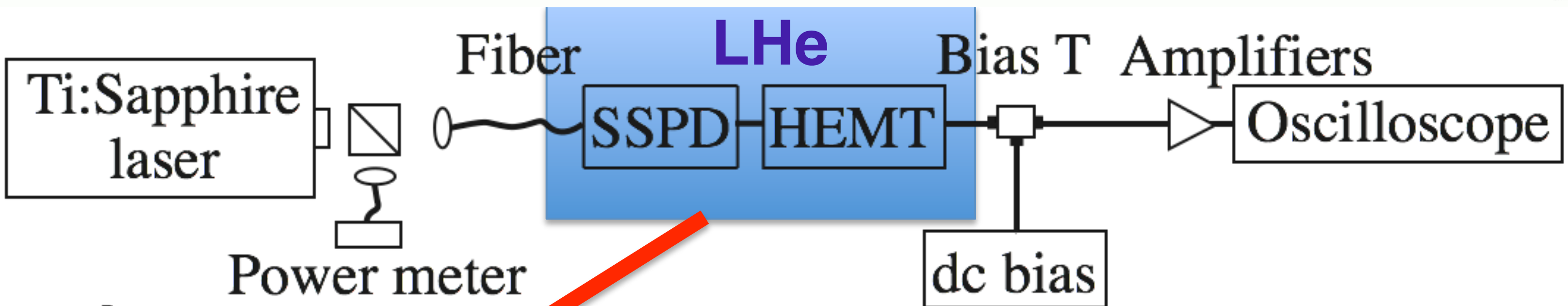
put an amplifier with high impedance next to SSPD.

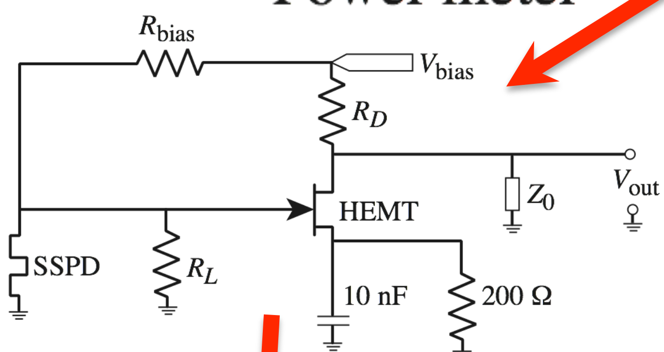




Thus, we will read out the true voltage across the SSPD, which depends on the number of photons, i.e., number of hotspots simultaneously generated.

Cryogenic HEMT read-out for SSPDs





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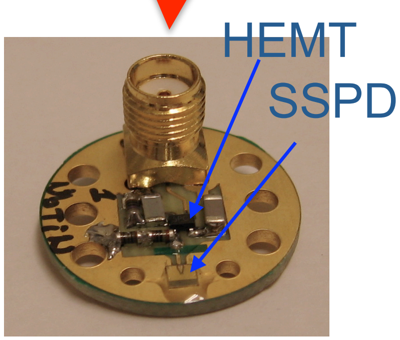
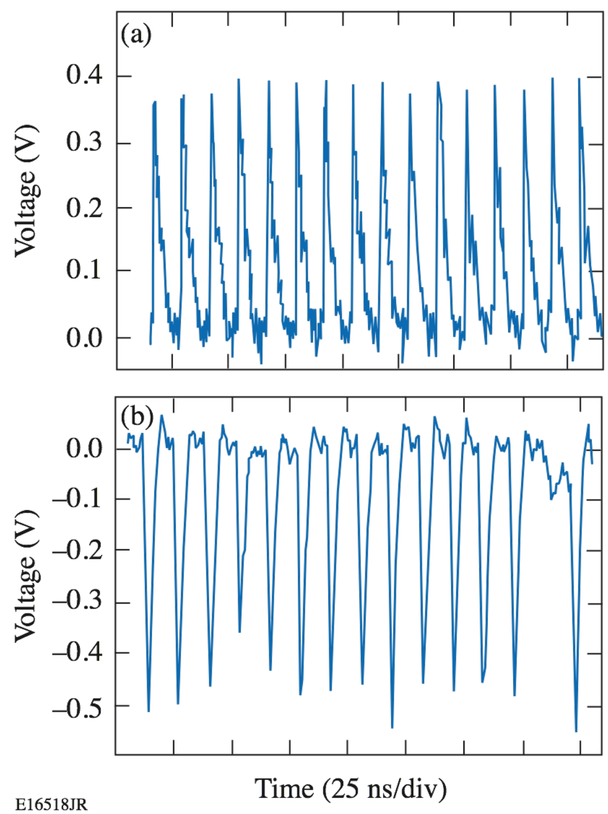


High-impedance HEMT is integrated with SSPD (in LHe).



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Real-time SSPD pulse record using the standard 50-Ω read-out.

Real-time SSPD pulse record (inverted) using the HEMT read-out.

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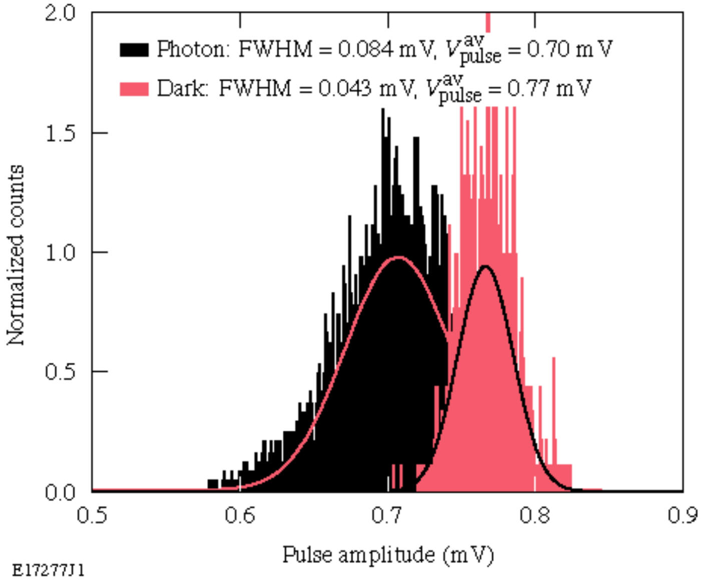
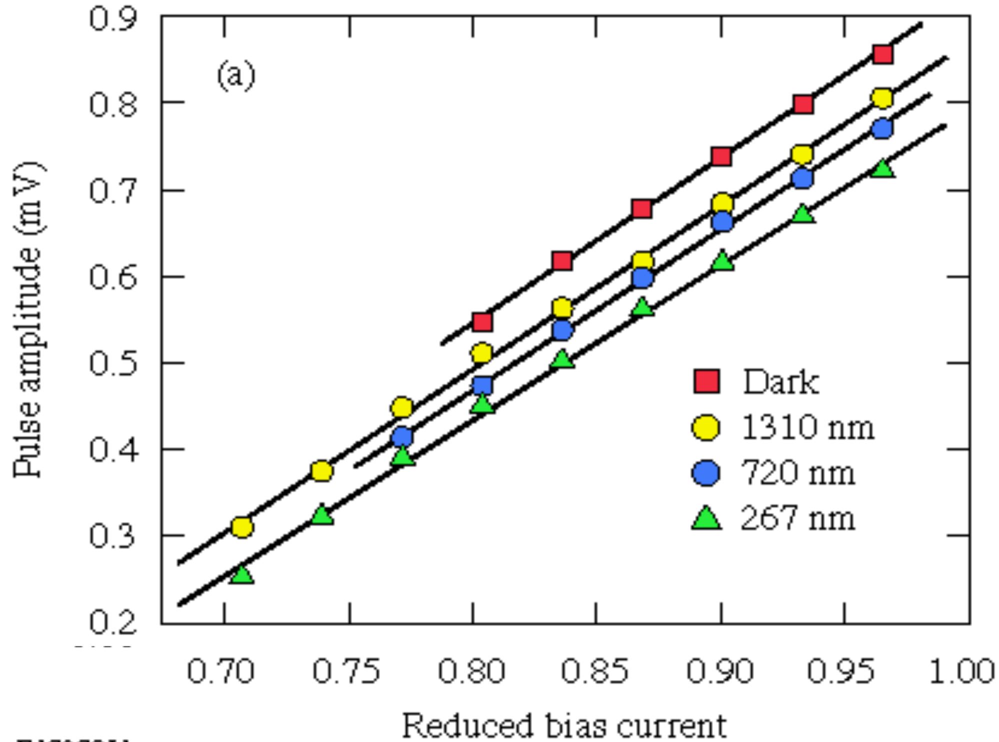
Cryogenic HEMT read-out enables photon-energy resolution



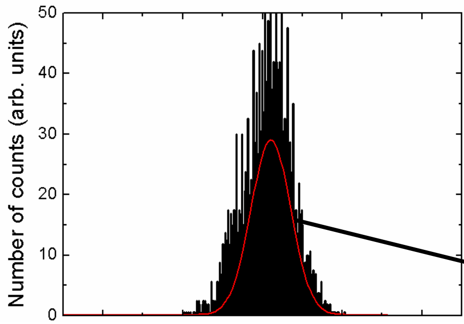
We observed statistically significant difference between the dark-count and photon-count (720 nm) histograms, when we used the HEMT read-out.



Mean-pulse amplitudes versus normalized bias current

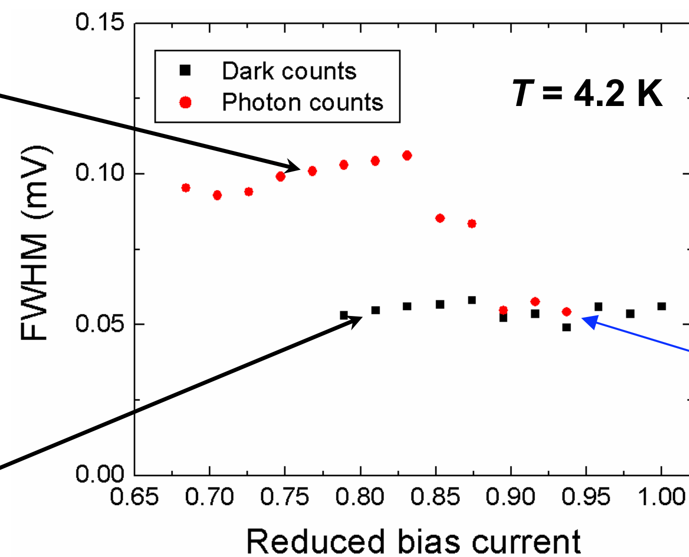
HEMT read-out allows to unanbigously distinguish between photon and dark counts

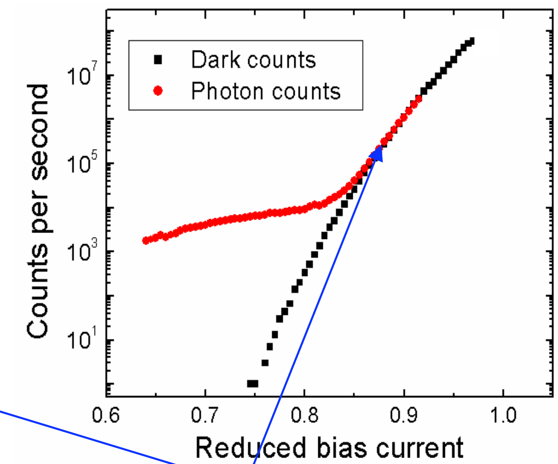
Excitation ~1 photon/pulse



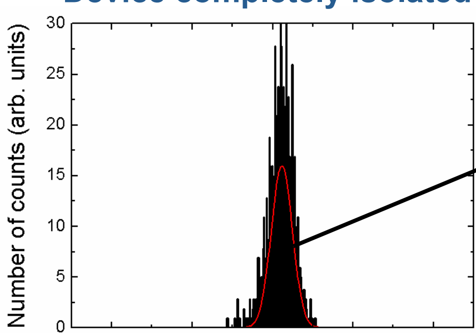
Amplitude distribution function of photon counts

Photon counts result from transient resistive hotspot formation and exhibit wide distribution in photoresponse amplitudes.





Device completely isolated



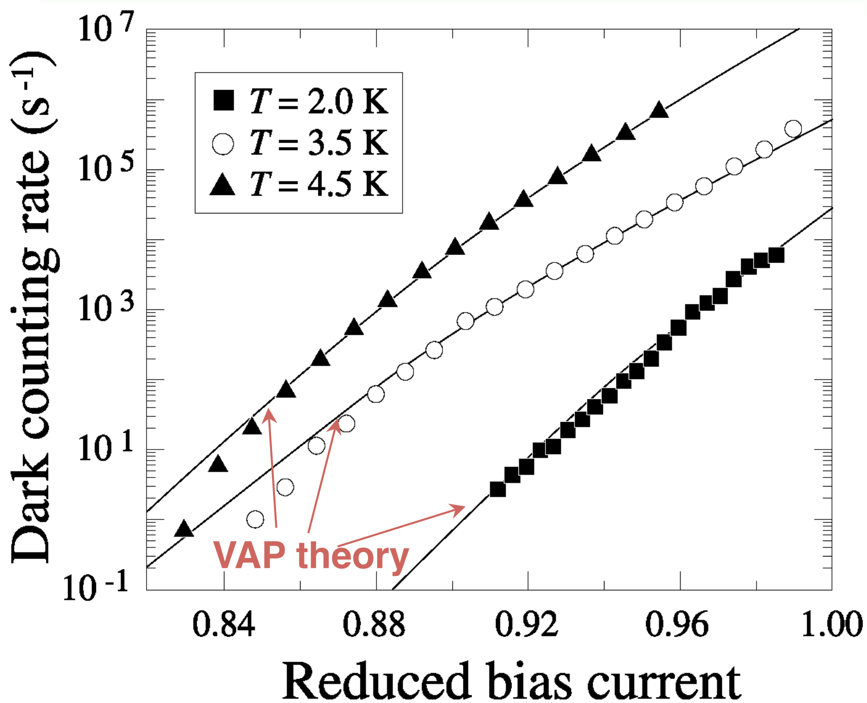
Amplitude distribution function of dark counts

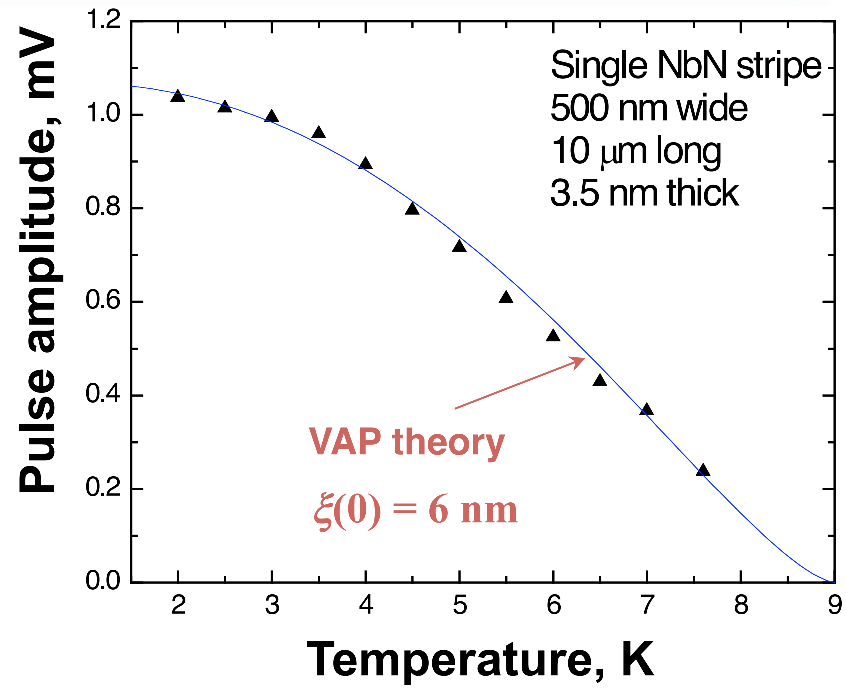
Dark counts are due to spontaneous vortex-antivortex, essentially identical, unbinding events (very narrow distribution).

As the bias approaches I_c, dark counts begin to dominate the SSPD photoresponse.

Kitaygorsky *et al.*, J. Mod. Opt. - in print

Dark-count events are due to vortex-antivortex unbinding in our 2-D superconducting stripes





Dark-count rate:

$$R_{dk} = \Omega_{VAP} \exp\left[\frac{A(T)}{\varepsilon(l_j)k_B T}\right] \times \left(\frac{J}{2.6 J_c}\right)^{\frac{A(T)}{\varepsilon(l_j)k_B T}}$$

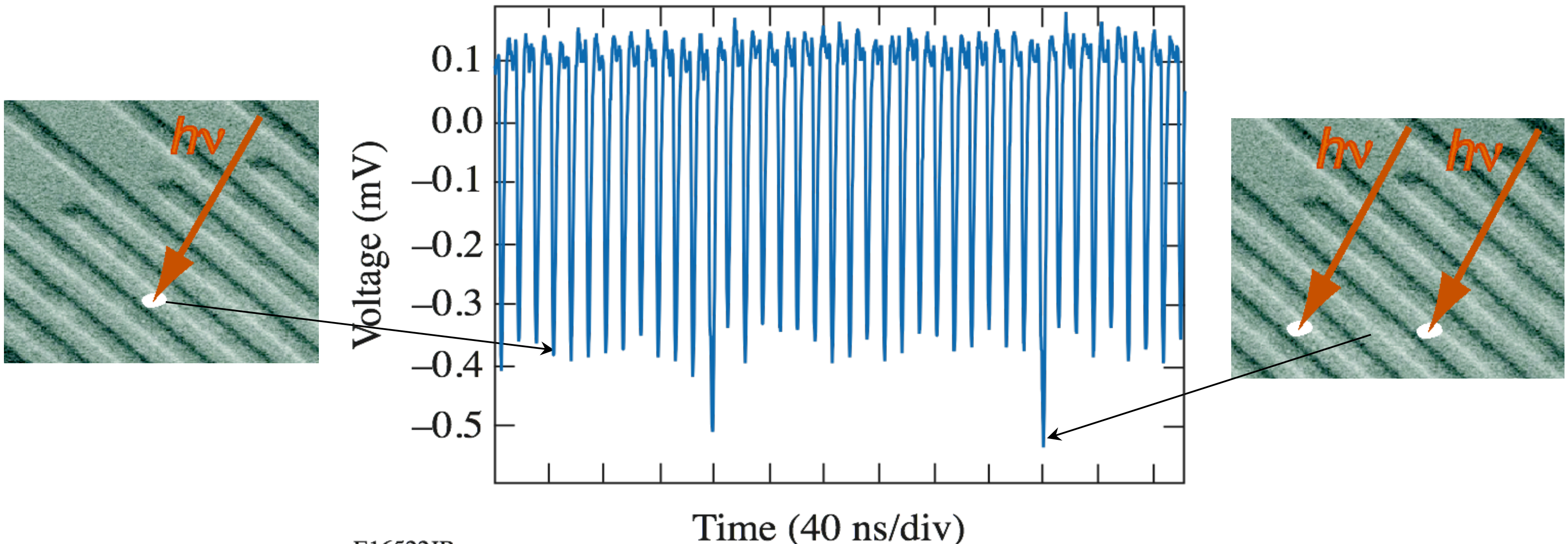
Depairing voltage of a vortex pair:

$$V(T,J) = \frac{\Phi_o d \xi J_c}{e} \ln(J / J_c)$$

J. Kitaygorsky *et al.*, IEEE TAS, 17, 275 (2007).

A. Engel *et al*, Phys. Stat. Sol. C, 2, 1668 (2005).

Photon-number-resolved detection: first, preliminary result



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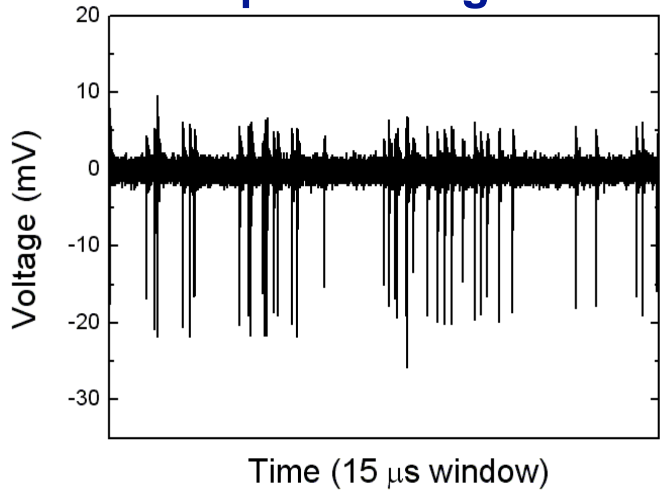
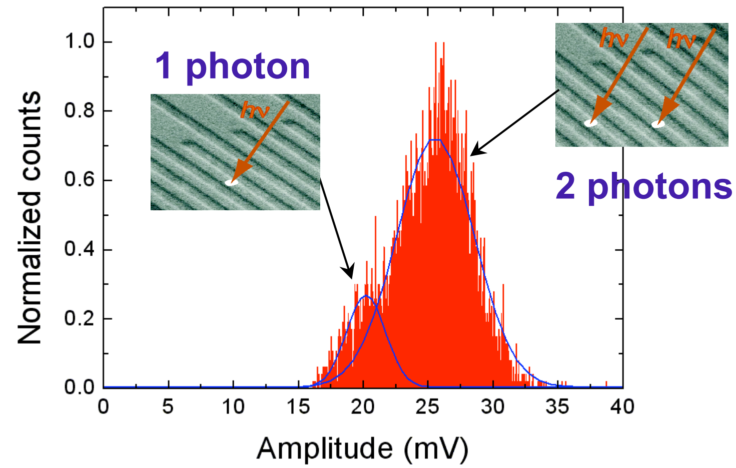
We adjusted the incident laser power, so on average the SSPD detected one photon per pulse, and, occasionally, we observed pulse vacancies (no photon detected) or significantly larger pulses, which are the "suspect," two-photon events.

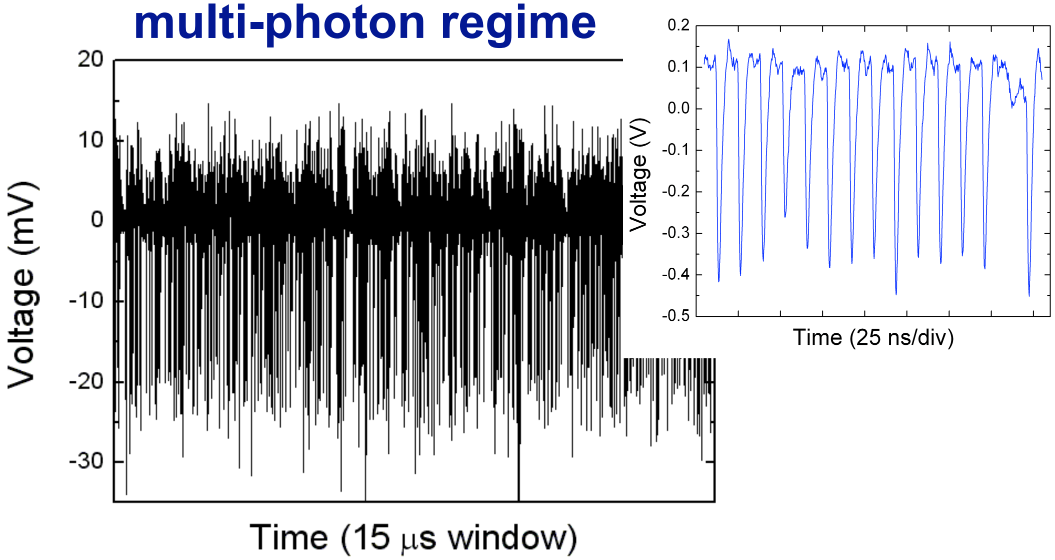
HEMT read-out for photon number resolution–statistical analysis

low-photon regime

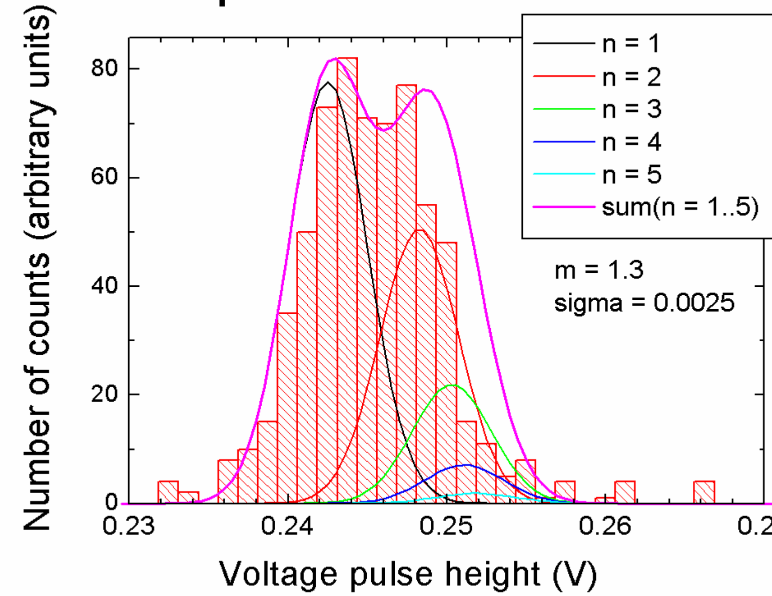




multi-photon regime



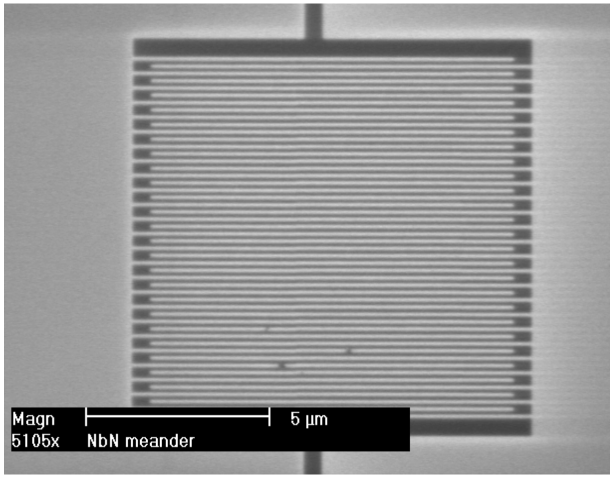
Statistical analysis based on pulse amplitude distribution function



Kitaygorsky *et al.*, J. Mod. Opt. - in print

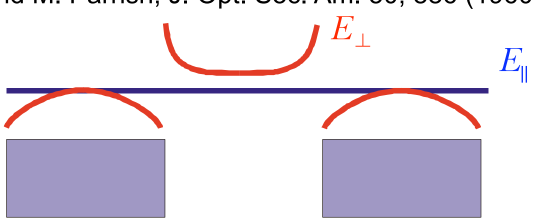
Polarization dependence in SSPDs

The geometry of SSPDs leads to a polarization dependence of the absorption of photons and thus the quantum efficiency.

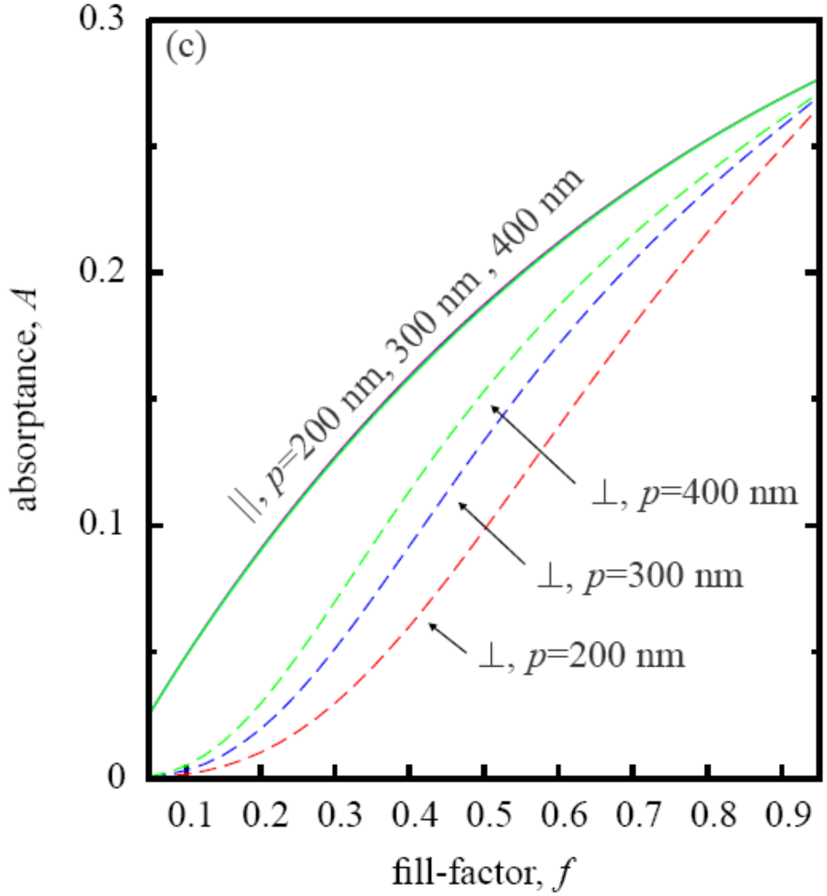


Infinite wire grid polarizer[1]:
-Electric field is deformed at the edges

[1] G. R. Bird and M. Parrish, J. Opt. Soc. Am. 50, 886 (1960)

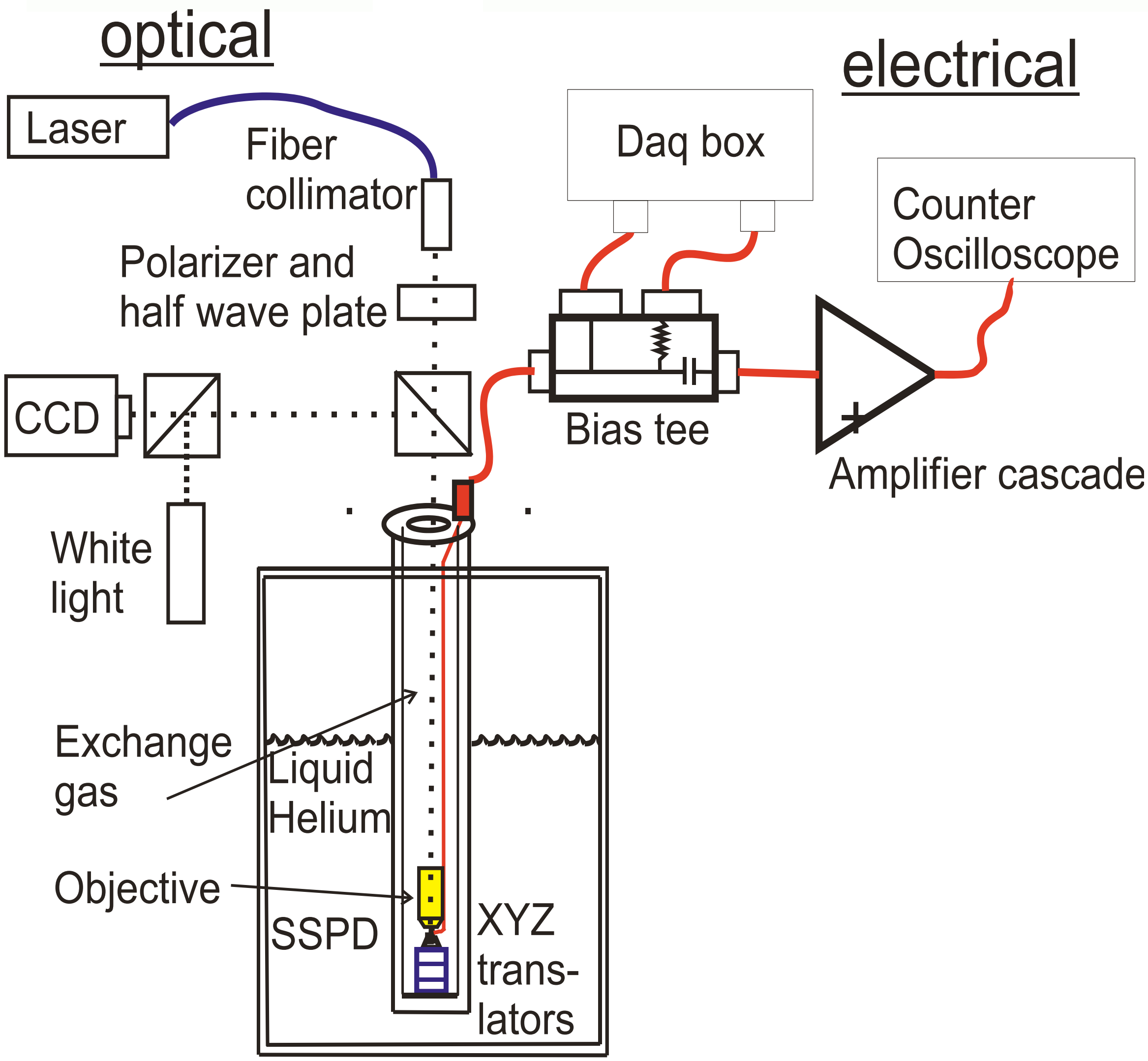


Absorption

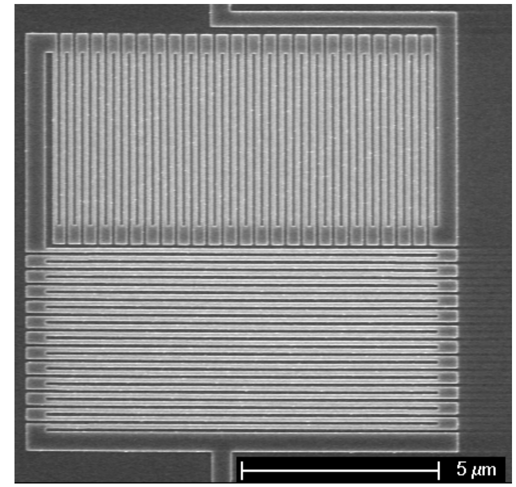


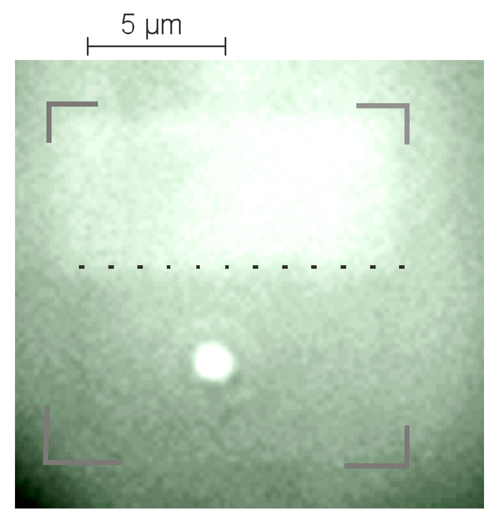
Anant et al, Optics Express 16,10750 (2009)

Polarization dependence: experimental setup



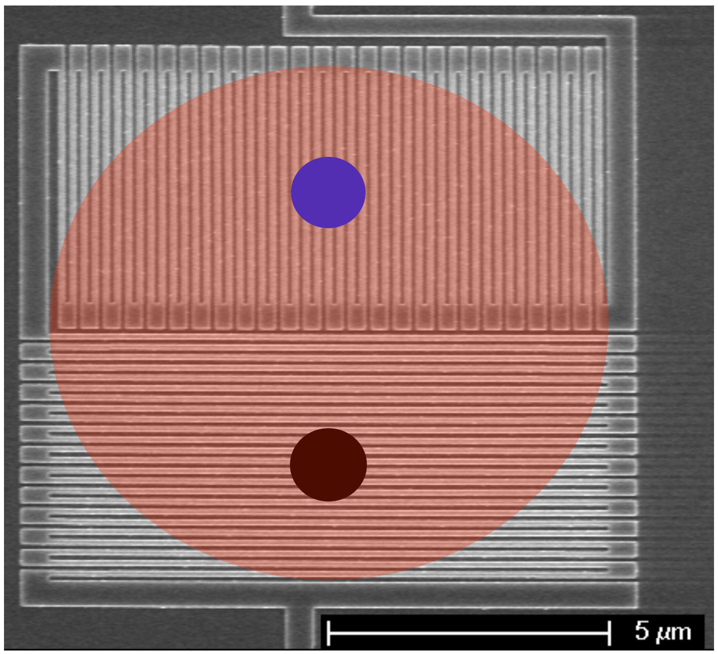
2-section SSPD

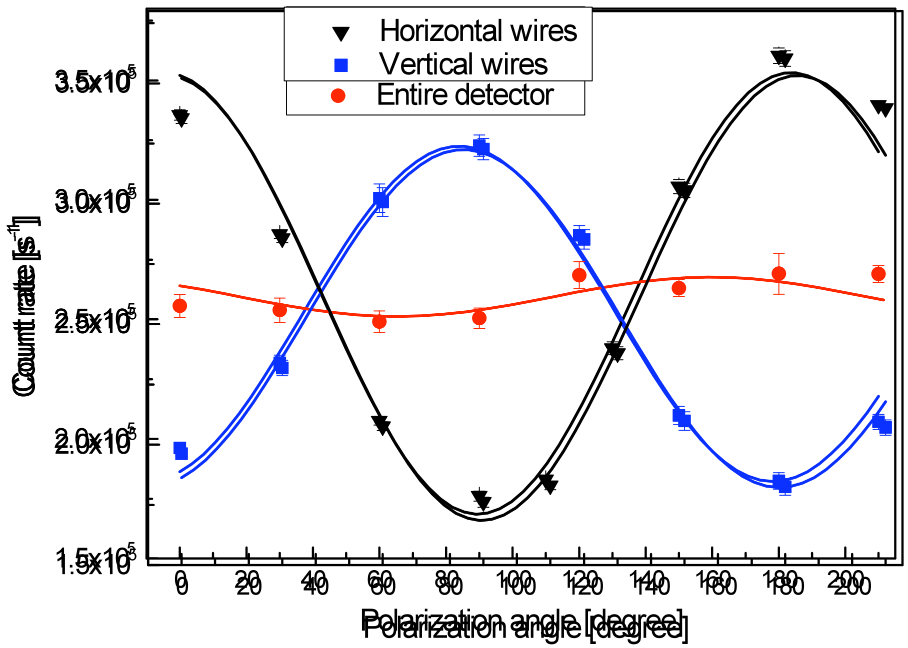




Anant et al, Optics Express 16,10750

Polarization dependence: measurements

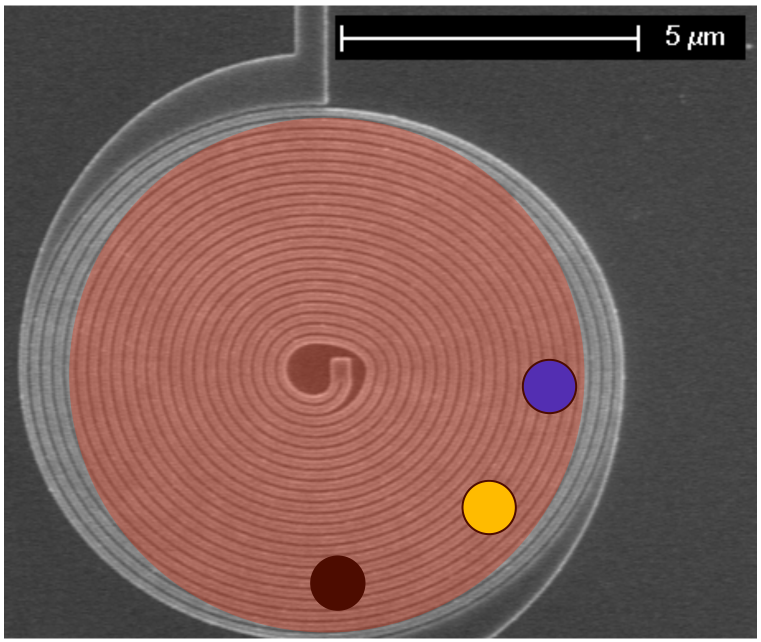


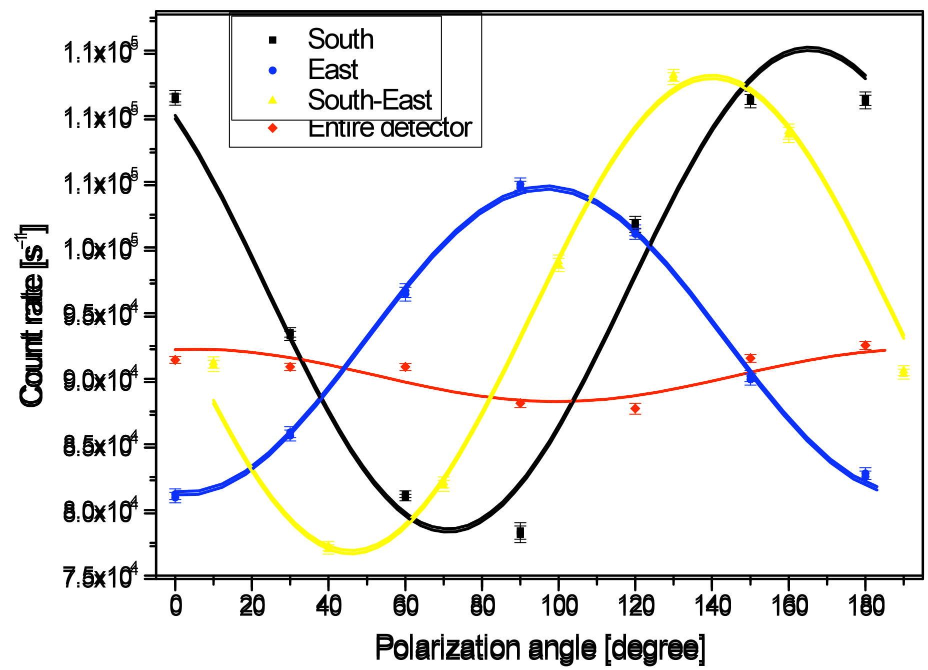


Degree of polarization: $C = \dfrac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}} \approx 0.02$

Polarization dependence: measurements

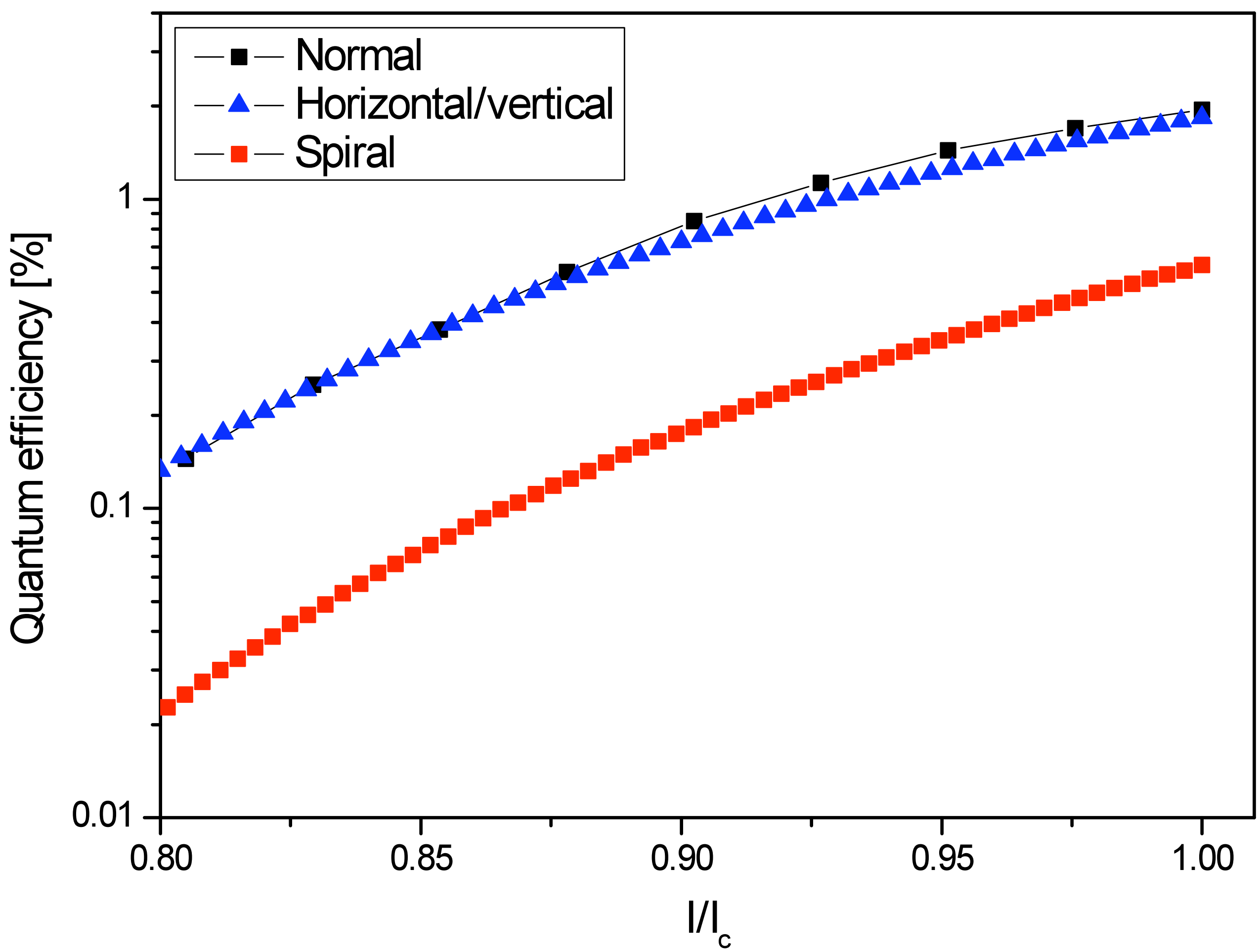
Spiral SSPD



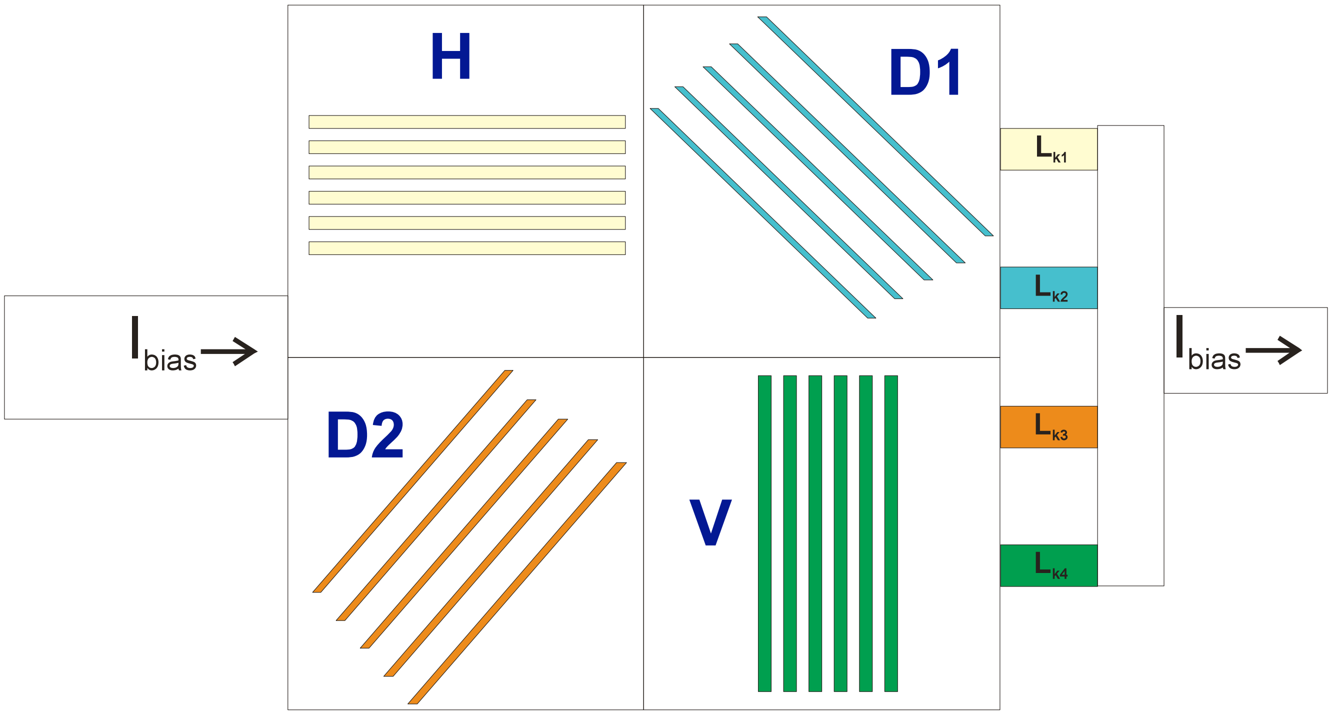


Degree of polarization: $C = \dfrac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}} \approx 0.02$

Polarization dependence: quantum efficiency



The imaging polarization detector concept



- **Photons with different polarizations are absorbed in different sections of the detector.**
- **The section in which a photon is absorbed is recognized by the pulse shape (e.g., different L_{kin} of each section).**

Conclusion and outlook

- SSPDs currently outperform competing optical single-photon counters in the counting rate and dark counts.

- SSPDs are NOT just “click-type” counters:
  - multi-sectional devices can be used for photon-number measurements;
  - rectangular-meander structures are polarization discriminators;
  - statistical analysis allows to extract information of the energy of counted photons.