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This invited oral presentation Th-I-QTE-03 was given at ISEC 2017.

Superconducting Thin Film Nanostructures as THz and Infrared Heterodyne and Direct Detectors

Gregory Goltsman

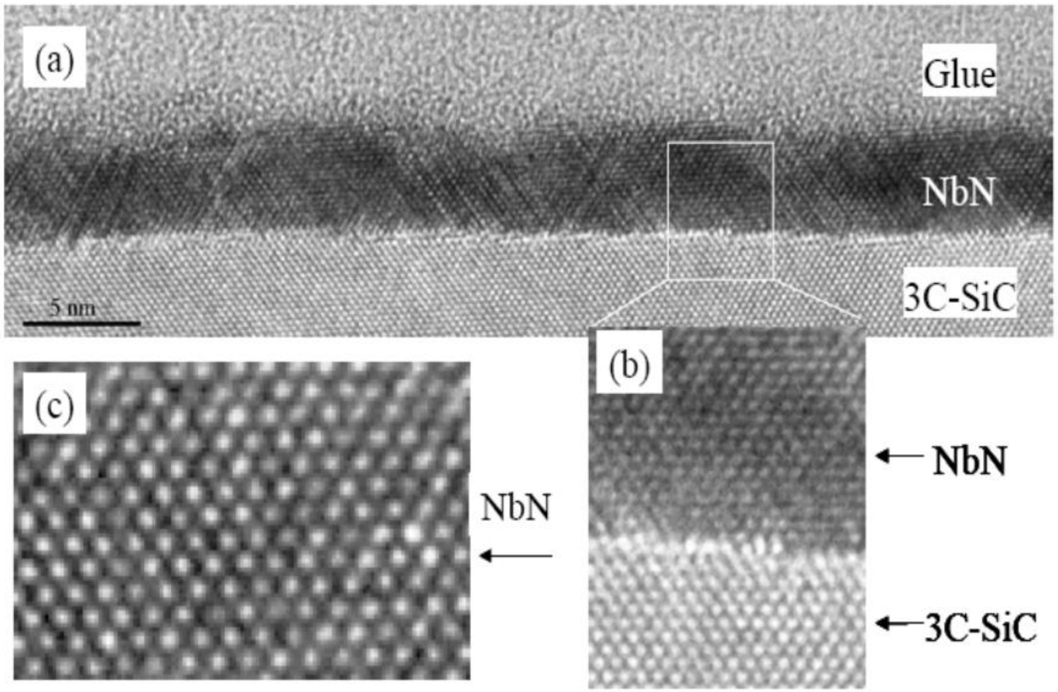
Moscow State Pedagogical University

Outline

- Ultrathin superconducting NbN film as a unique material for fast and sensitive THz and IR detectors
- Superconducting hot-electron-bolometer (HEB) mixer and applications to THz radio astronomy
- HEB as an ultrafast direct detector with an atto-joule energy resolution
- Superconducting single-photon detector (SSPD) – from the idea to commercially available devices and systems
- Travelling-wave single-photon detector with nearly 100% quantum efficiency – superconducting strip on an optical waveguide
- Single-photon platform for the realization of an integrated SSPD array. The technology is scalable on Si chips and includes grating couplers, beam splitters, MZ interferometers, etc.
- Fully integrated quantum-photonic circuit with an electrically driven light sources – waveguide-coupled semiconducting single-wall carbon nanotubes
- Heterodyne receiver prototype with an SSPD quantum efficiency of 90% operating very close to the quantum limit
- Conclusions

Ultrathin superconducting NbN film structure

NbN on 3C-SiC buffer layer on Si substrate (HREM)



NbN is monocrystalline
a_0 (3C-SiC) =4.36Å
a_0 (NbN) =4.39Å
Thickness is 3.5 – 4.1 nm
Not really flat surface

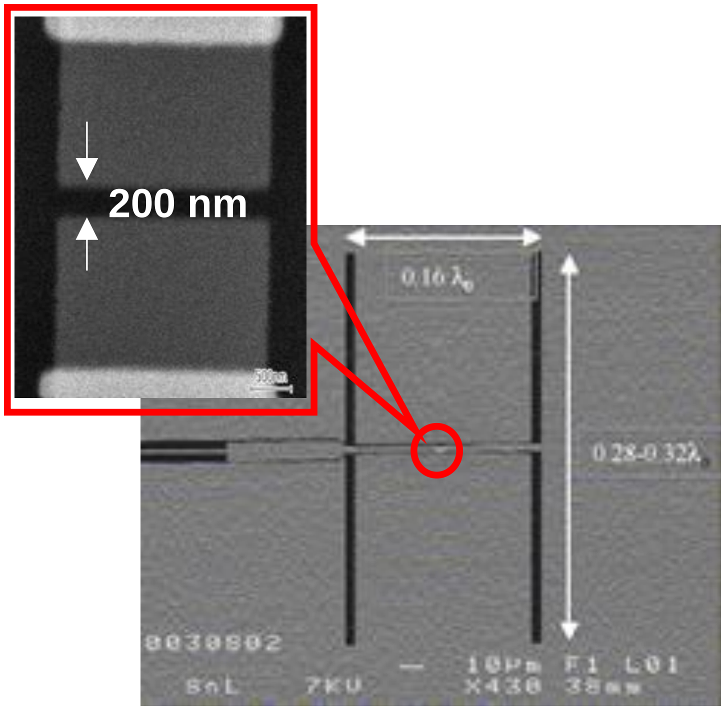
$Tc \geq 10$ K
$Jc \approx 10^7$ A/cm^2

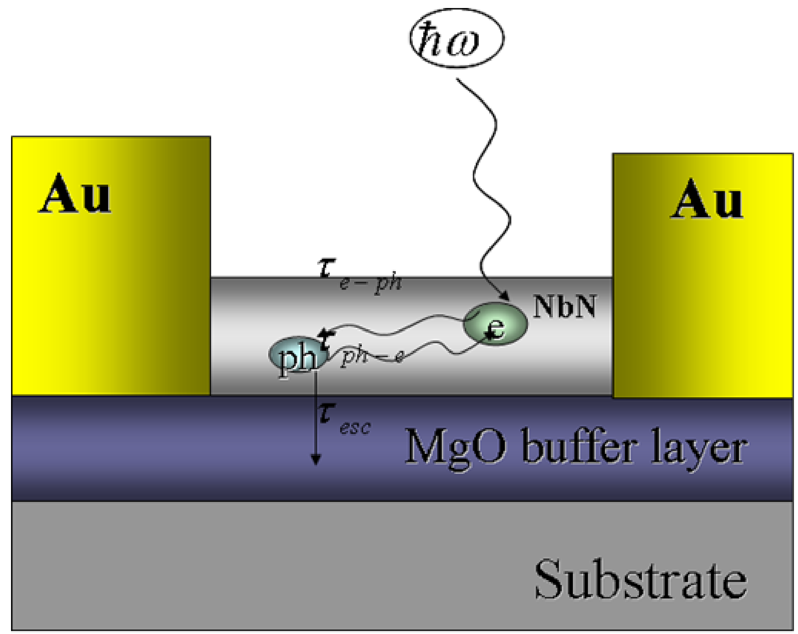
Gao, J.R. et al, APL, 91 (6), 2007.

Our NbN films are space-qualified

MSPU

Hot-Electron Bolometer (HEB) mixer





E.M.Gershenzon, G.N.Gol'tsman et al. Sov. Phys. Superconductivity 3,1582,1990

Herschel Space Observatory launched, May 2009

HEB mixers in Bands 6 and 7 of the HIFI instrument: 1.41 THz – 1.91 THz

Our NbN films are space-qualified

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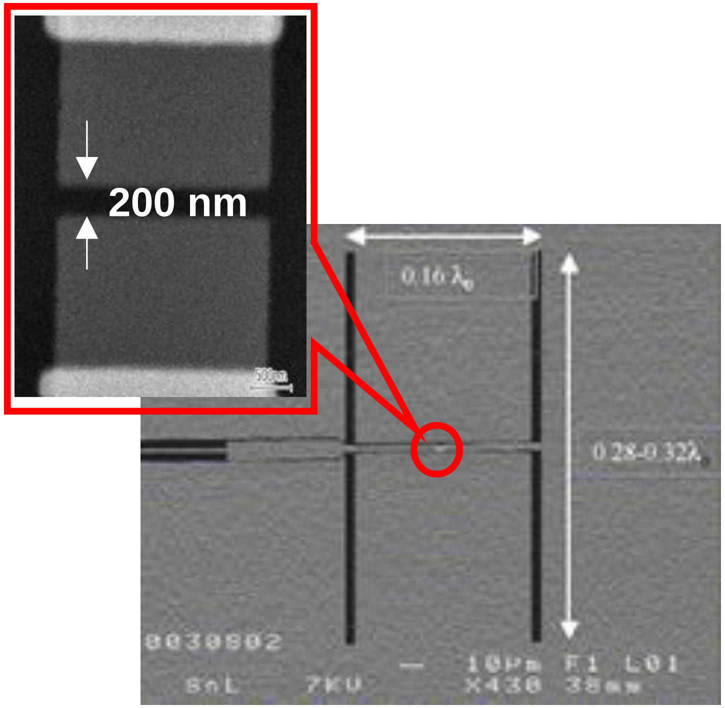
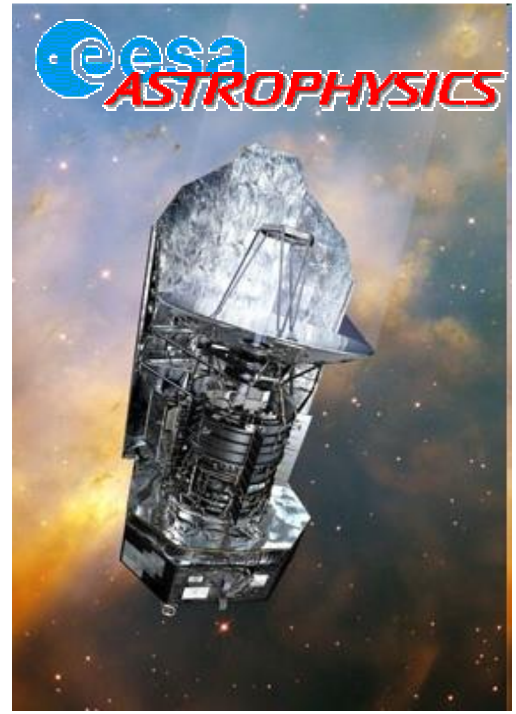
CHALMERS

Hot-Electron Bolometer (HEB) mixer





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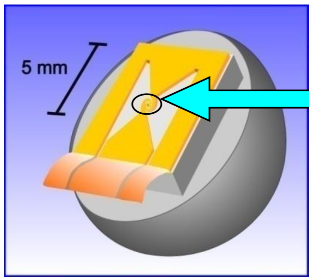
Herschel Space Observatory launched, May 2009

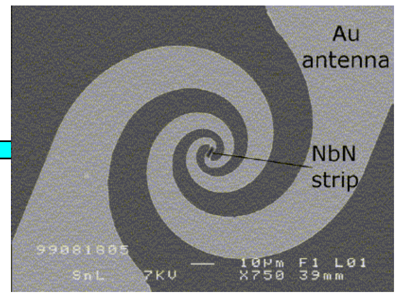
HEB mixers in Bands 6 and 7 of the HIFI instrument: 1.41 THz – 1.91 THz

Hot electron bolometers as direct detectors

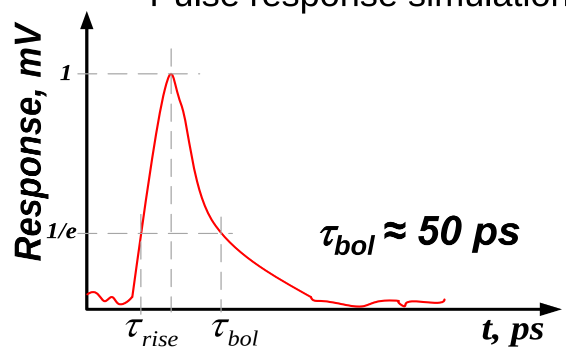
are capable to detect *aJ* pulse energy at GHz rate

Spiral antenna coupled bolometer





Pulse response simulation

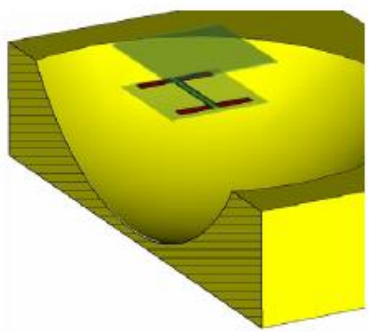


NEP ≈ 3×10 $^{-13}$ ***W/√Hz***

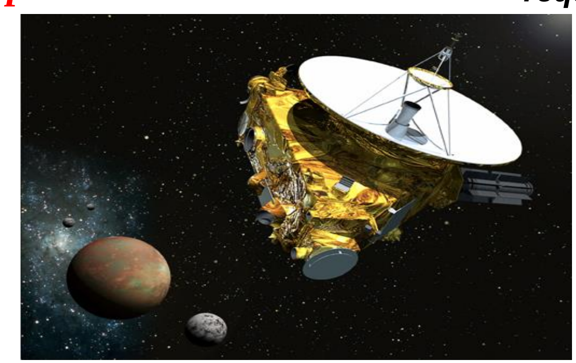
$W_{pulse} = SNR \times NEP \times \sqrt{\tau_{bol}} \approx 10$ aJ $<$ $SNR^2 \times h\nu \approx 25$ aJ

No photon shot noise in THz!

Signal to noise ratio (SNR) ≈ 5 is required for stable link



Double dipole antenna coupled bolometer



New Horizons:

approaching Pluto

(artist's view, to happen in summer 2015)

2.1 m diameter dish antenna to communicate with Earth from 7.5 billion kilometers away

Credit: Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute (JHUAPL/SwRI)

NbN HEB has a record energy resolution in the THz range for fast detectors. Nowadays it reaches 1 aJ (Seliverstov, S.; et al. IEEE Trans. Appl. Supercond. 2015, 25, 3–6.)

First observation of SSPD response and first idea of device physics

APPLIED PHYSICS LETTERS VOLUME 79, NUMBER 6 6 AUGUST 2001

Picosecond superconducting single-photon optical detector

G. N. Gol'tsman,[a] O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, and A. Dzardanov
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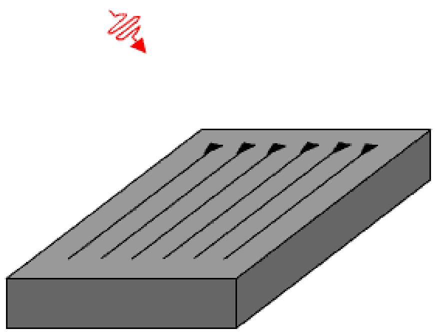

FIG. 1. Schematics of the supercurrent-assisted hotspot formation mechanism in an ultrathin and narrow superconducting strip, kept at temperature far below T_C are shown. The arrows indicate direction of the supercurrent flow.

Physica C 351 (2001) 349–356

Quantum detection by current carrying superconducting film

ex D. Semenov *,1, Gregory N. Gol'tsman, Alexander A. Korneev
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Received 18 July 2000; received in revised form 9 October 2000; accepted 11 October 2000
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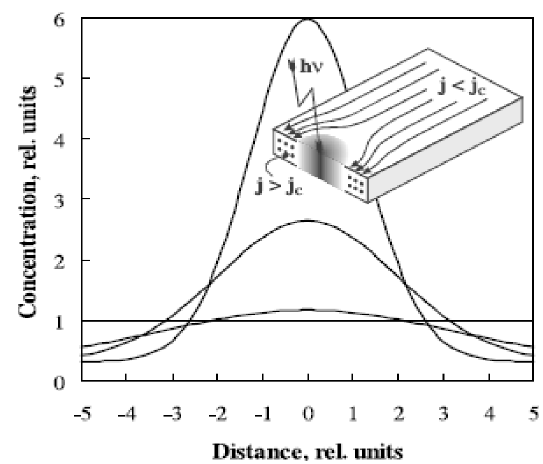
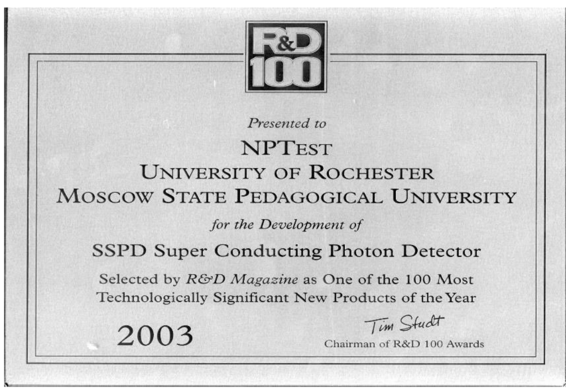


Fig. 1. Concentration of nonequilibrium quasiparticles across the width of the film at different moments after the photon has been absorbed. Time delays are 0.8, 2.0 and 5.0 measured in units of the thermalization time. Distance from the absorption site is shown in units of the thermalization length. Inset illustrates redistribution of supercurrent in the superconducting film with the normal spot – the basis of quantum detection. It shows the cross-section of the film drawn through the point where photon has been absorbed.

The first two papers publishing a theoretical analysis (on the right) and the first experimental results of single-photon detection of a current-carrying superconducting nanowire.

First Implementation of NbN SSPD: Silicon CMOS IC Device Debug OptiCA® System with NbN SSPD commercialized by NPTest, Inc.



R&D 100

Presented to

NPTEST
UNIVERSITY OF ROCHESTER
MOSCOW STATE PEDAGOGICAL UNIVERSITY

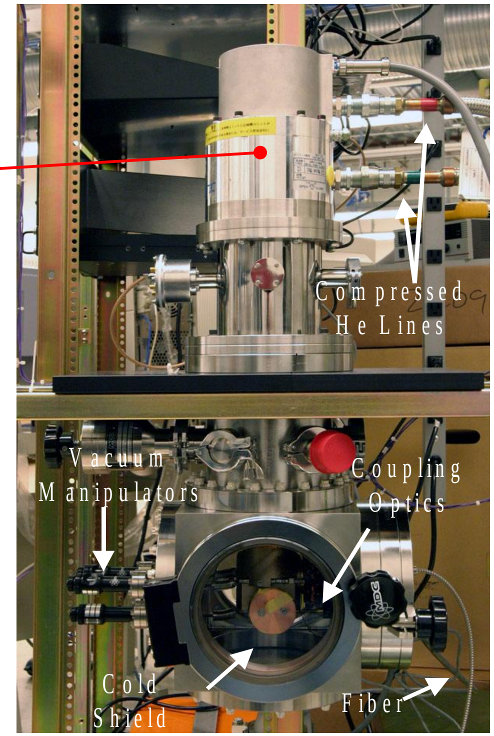
for the Development of

SSPD Super Conducting Photon Detector

Selected by *R&D Magazine* as One of the 100 Most Technologically Significant New Products of the Year

2003

Tim Studt
Chairman of R&D 100 Awards



Normally operating nMOS transistor emits near IR photons (0.9-1.4um) when current passes through the channel. Time-correlated photon emission detection measures transistor switching time.

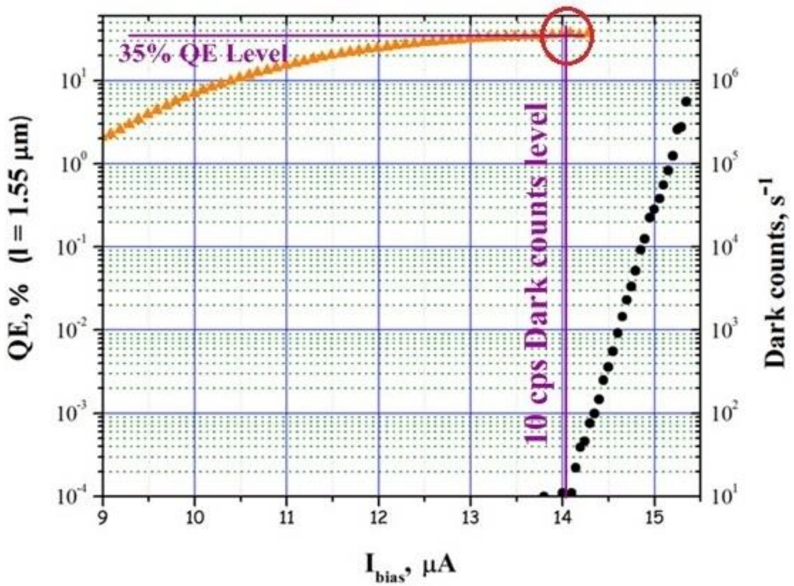
For more information: http://www.nptest.com/products/probe/idsOptica.htm

MSPU

Practical single-photon receiver based on SSPD

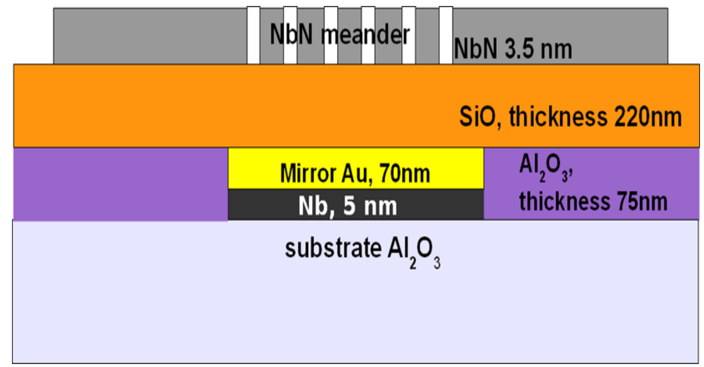
Now: Quantum efficiency 80% at 1550nm, jitter 20ps, max. counting rate 100 MHz and dark count rate $10 s^{-1}$

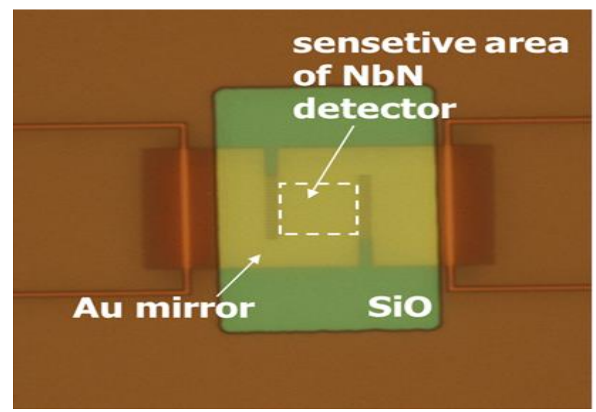
WWW.SCONTEL.RU SCONTEL SUPERCONDUCTING NANOTECHNOLOGY



Spectral range	Quantum efficiency (referred to optical input)
0.7 – 1.3 µm	85 %
1.3 – 1.6 µm	80 %
1.6 – 2.3 µm	50 %

Cavity-integrated SSPD

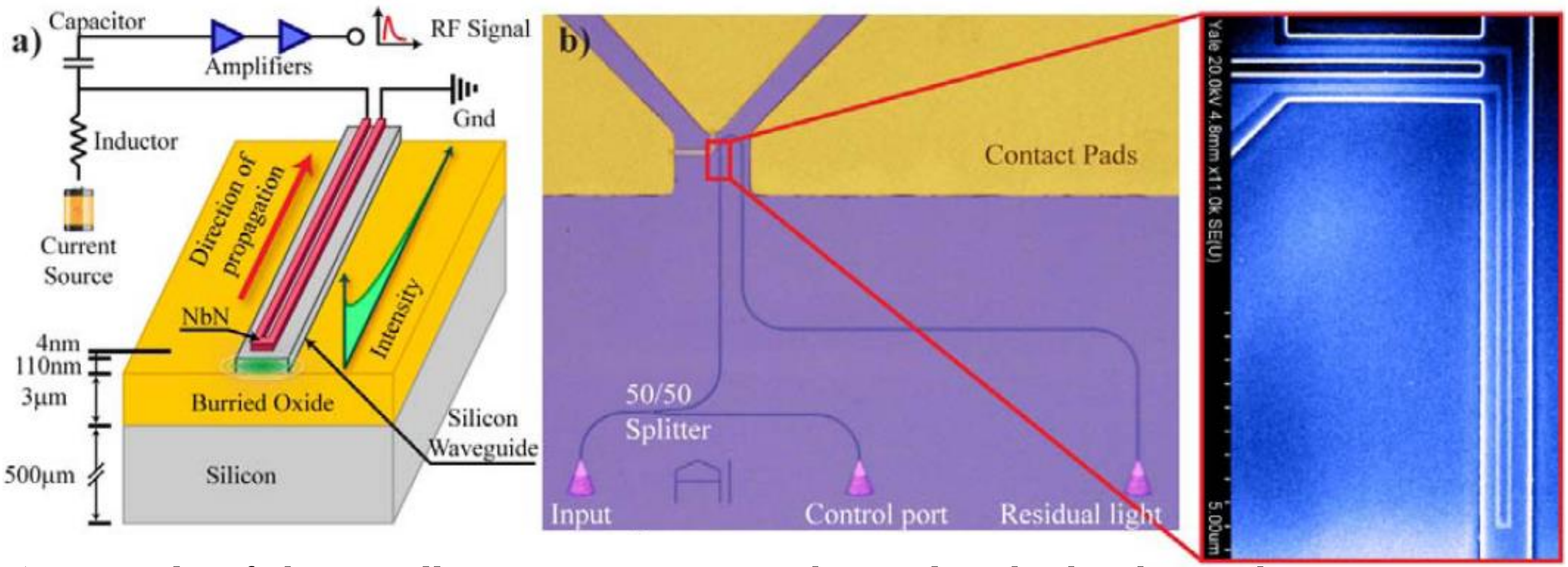




The spin-off of MSPU "Superconducting Nanotechnology LLC" (SCONTEL) has turned 13. The company has successfully commercialized NbN HEB mixers, direct detectors and single-photon detectors (SSPDs).

High Speed Travelling Wave Single-Photon Detectors With Near-Unity Quantum Efficiency

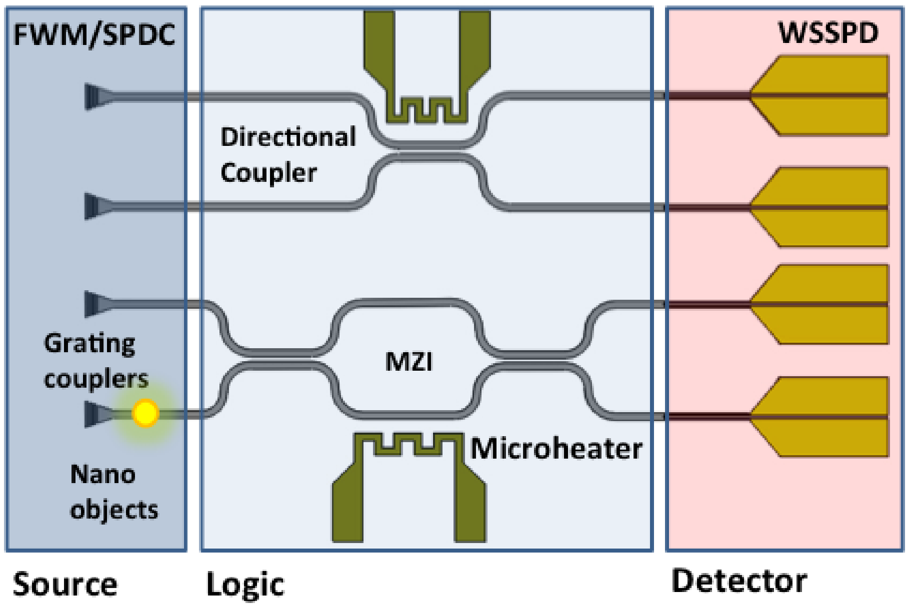
Pernice, W. H. P. et al. Nat. Commun. 2012, 3, 1325.



a) Principle of the travelling-wave SSPD: a sub-wavelength absorbing NbN nanowire is patterned on top of a silicon waveguide to detect single photons; Max. QE= 91%
b) Optical micrograph of a fabricated device showing the optical input circuitry, RF contact pads and the SSPD; Inset: zoom into the detector region with an SEM image showing the detector regime. The control and residual ports are used for calibration purposes.

Light propagates along the waveguide and 99% of the photons are absorbed by the 20 µm strip.

Single-photon platform for the realization of integrated SSPD array



Why on-chip photonics?

- ✓The ability to integrate a huge number of optical components in a small area,
- ✓Superposition of quantum states can be easily represented, encrypted, transmitted and detected
- ✓Easy to manipulate (Linear Optics Quantum computation(LOQC), using only linear optical elements: beam splitters, phase shifters and mirrors)
- ✓Low power consumption

Why silicon nitride?

- ✓Wide band gap → small absorption in visible and in IR range
- ✓High refractive index
- ✓Good mechanical properties
- ✓Possibility to create SPS due to nonlinearity
- ✓Compatibility with NbN thin film deposition process

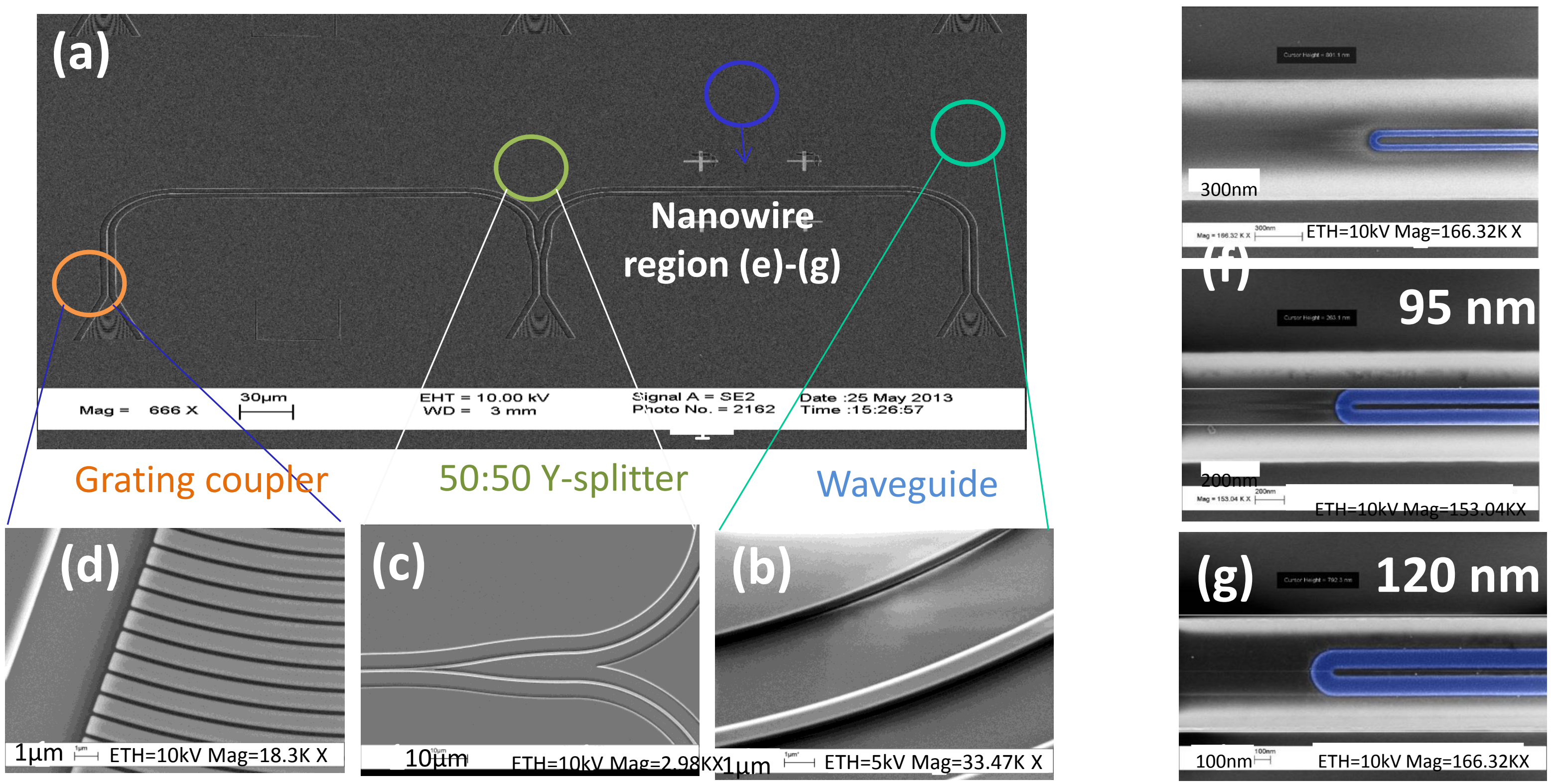
Why WSSPD?

- ✓Compact design
- ✓High detection efficiency
- ✓Low timing jitter
- ✓Low dead time
- ✓No gating needed
- ✓No afterpulsing

Examples of waveguide devices: SEM images of waveguide circuits

SEM image of a fabricated nanophotonic circuit for balance measurements of an absorption coefficient

False colors of nanowire atop of waveguide with different width

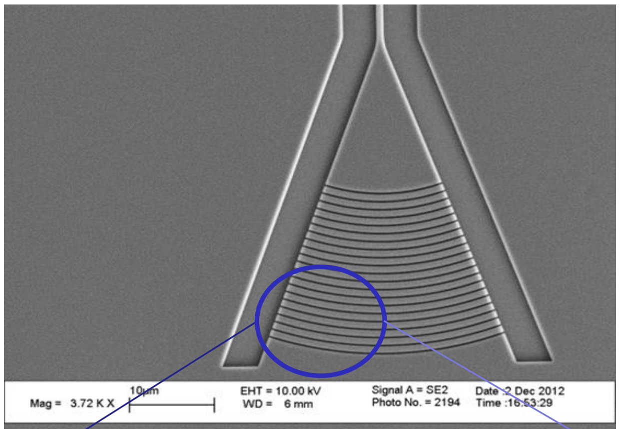


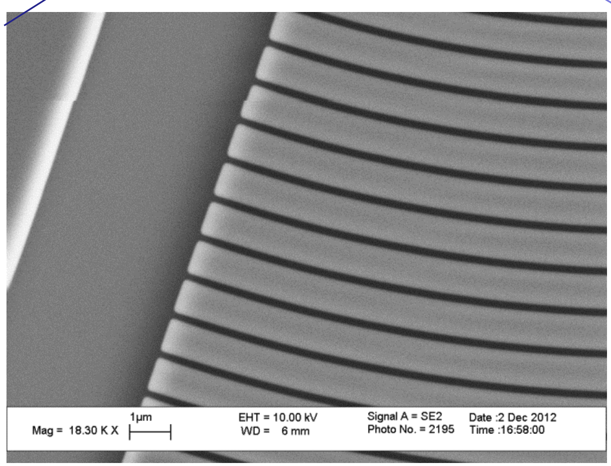
V. Kovalyuk, W. Hartmann, O. Kahl, N. Kaurova, A. Korneev, G. Goltsman, and W. H. P. Pernice, "Absorption engineering of NbN nanowires deposited on silicon nitride nanophotonic circuits," *Opt. Express*, vol. 21, no. 19, pp. 22683–92, 2013.

Focusing grating coupler optimization

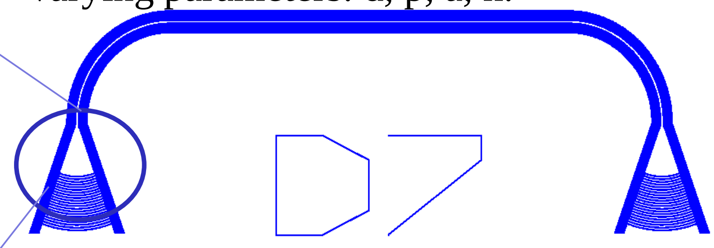
Lee Carroll et al, Appl. Sci. 2016, 6(12)

SEM image of (FGC)





Hundreds of devices on a single chip are manufactured with varying parameters: d, p, a, h.

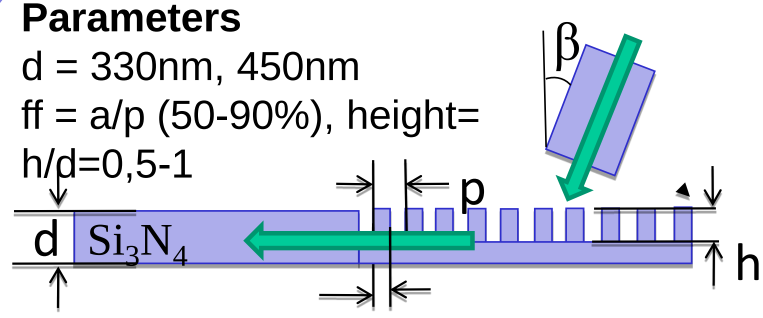


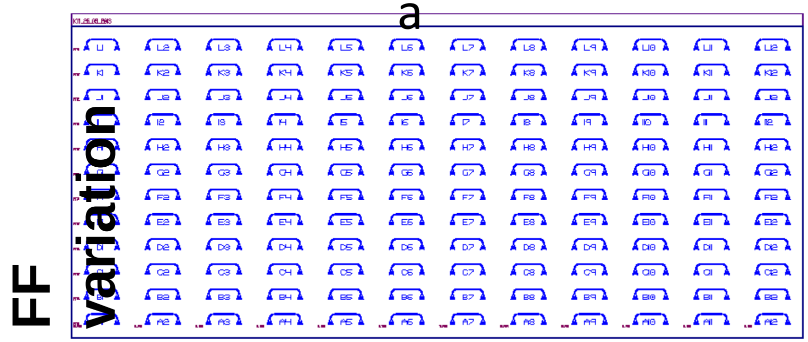
Parameters

d = 330nm, 450nm

ff = a/p (50-90%), height=

h/d=0,5-1

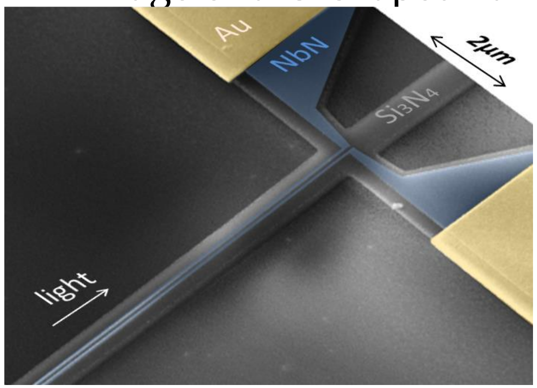




Variation of period FGC

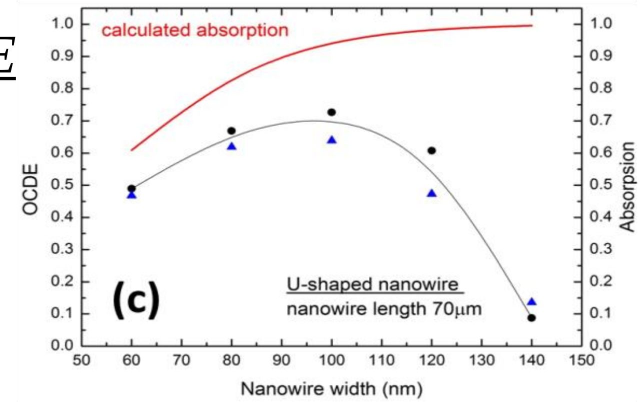
On-chip detection efficiency (OCDE) vs nanowire width

SEM Image of a U-shaped nanowire

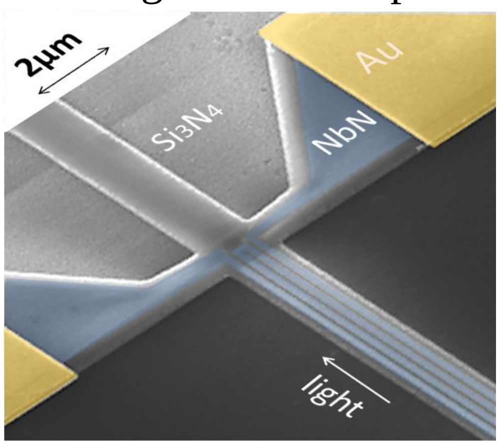


*OCDE=A*IQE*

OCDE vs NbN nanowire width (U-shaped)

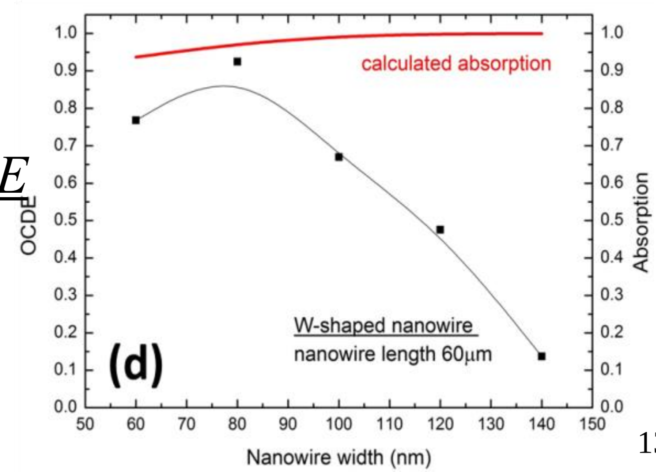


SEM Image of a W-shaped nanowire



OCDE≈IQE

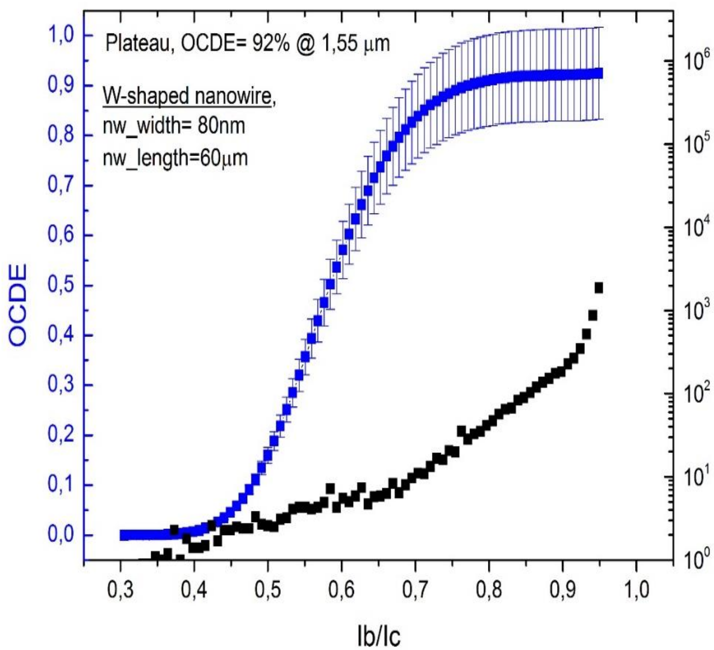
OCDE vs NbN nanowire width (W-shaped)



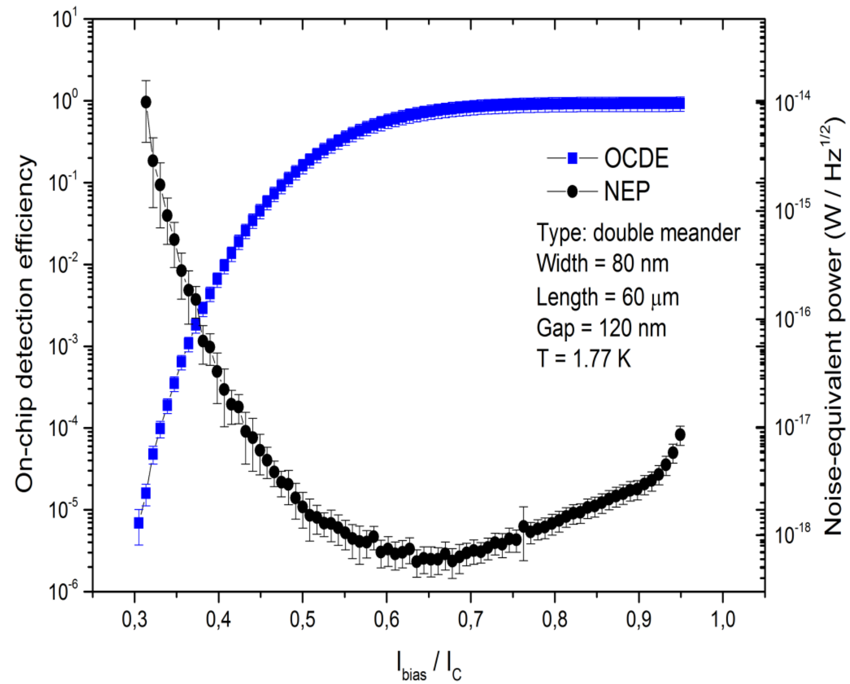
Kahl O. et al, Scientific Reports 5, 10941, 2015

Waveguide-based SSPD characterization: on chip detection efficiency (OCDE), dark count rate and NEP vs bias

OCDE vs normalized bias current



OCDE and NEP vs normalized bias current

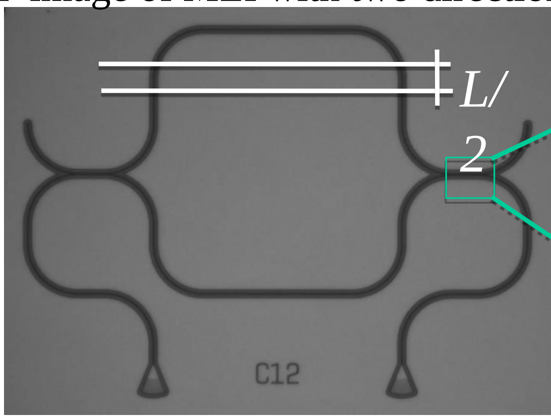


The error is important in measurements where the detection efficiency exceeds 90%. Interferogram on MZI on the chip is high quality.

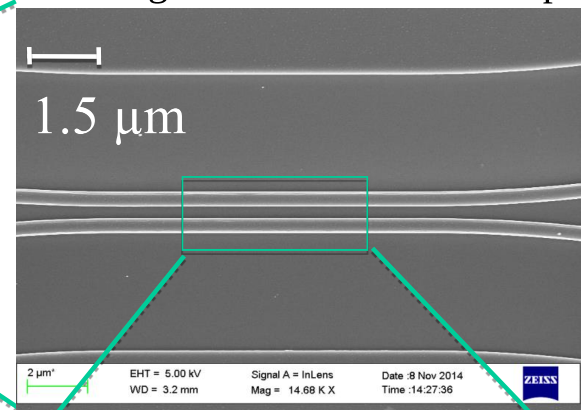
 Ferrari, S et al. Appl. Phys. Lett. 2015, 106.

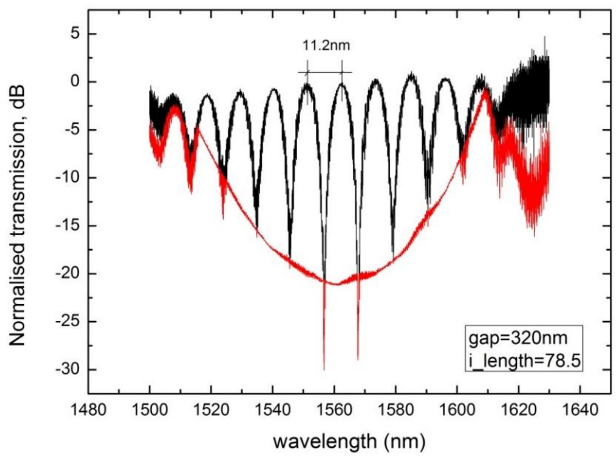
MZI with two directional couplers

Optical image of MZI with two directional couplers

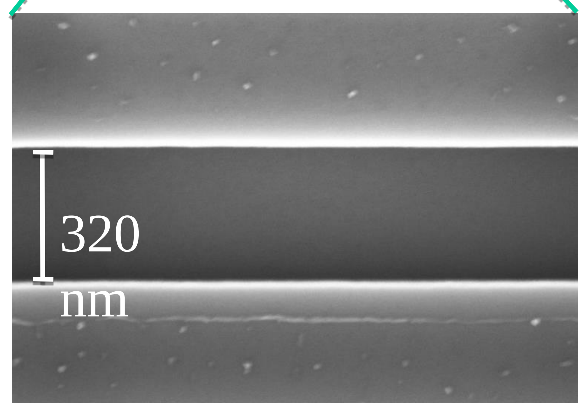


SEM image of the directional coupler





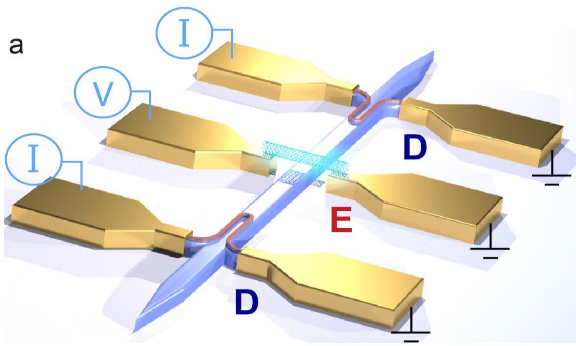
Normalized transmission MZI vs wavelength

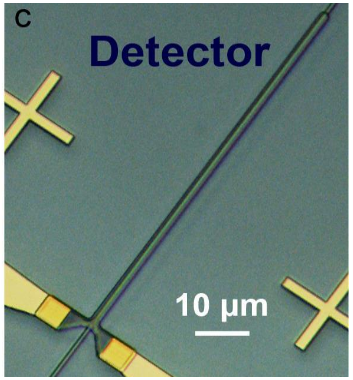


SEM image of the directional coupler (central part)

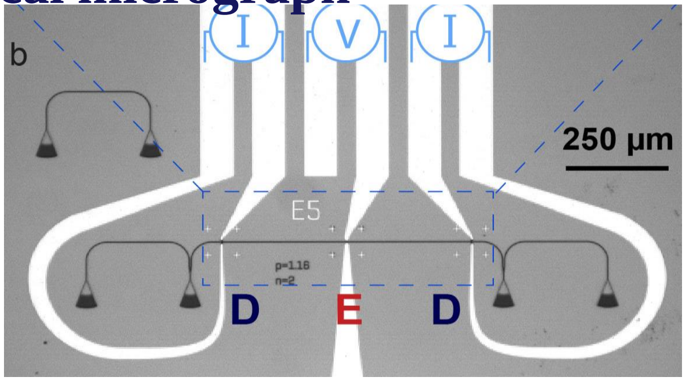
Fully integrated quantum-photonic circuit with an electrically driven light source - waveguide-coupled semiconducting single-wall carbon nanotubes

Sc-SWCNT and two SNSPDs, all biased electrically

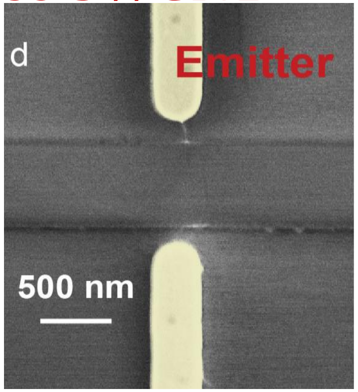




Optical micrograph

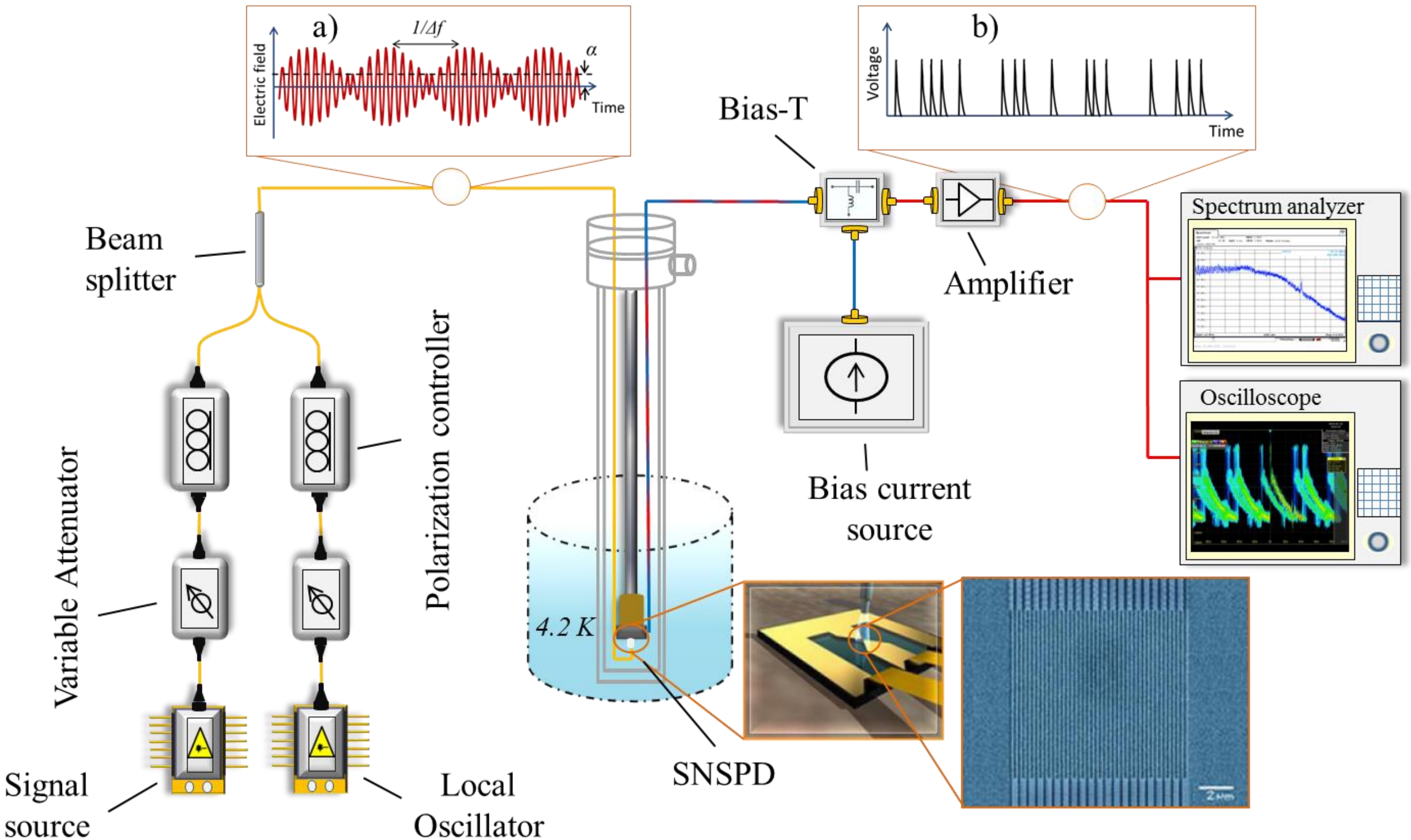


sc-SWCNT



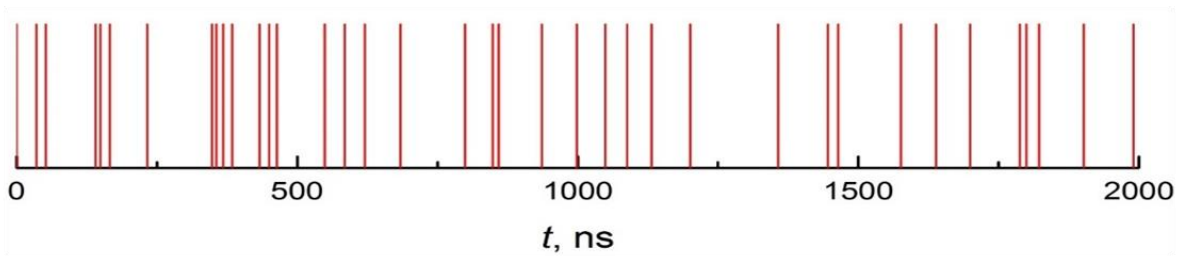
S. Khasminskaya, *Nat. Photonics*, 10, 727–732, 2016

SSPD as a photon-counting mixer: measurement setup

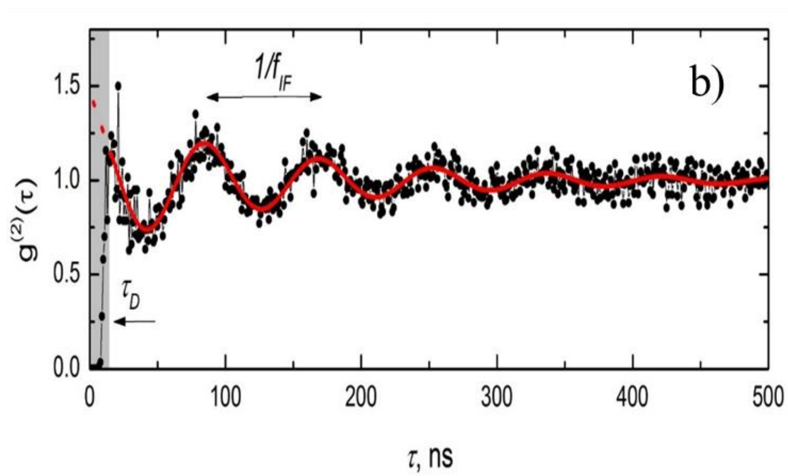


Time-domain technique based on recording time moments of counts and digital post-processing

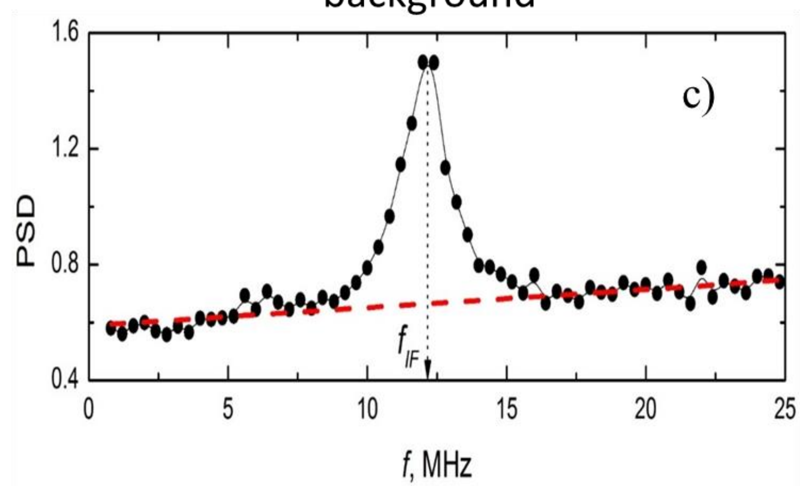
Short fragment of sequence of recorded counts a)



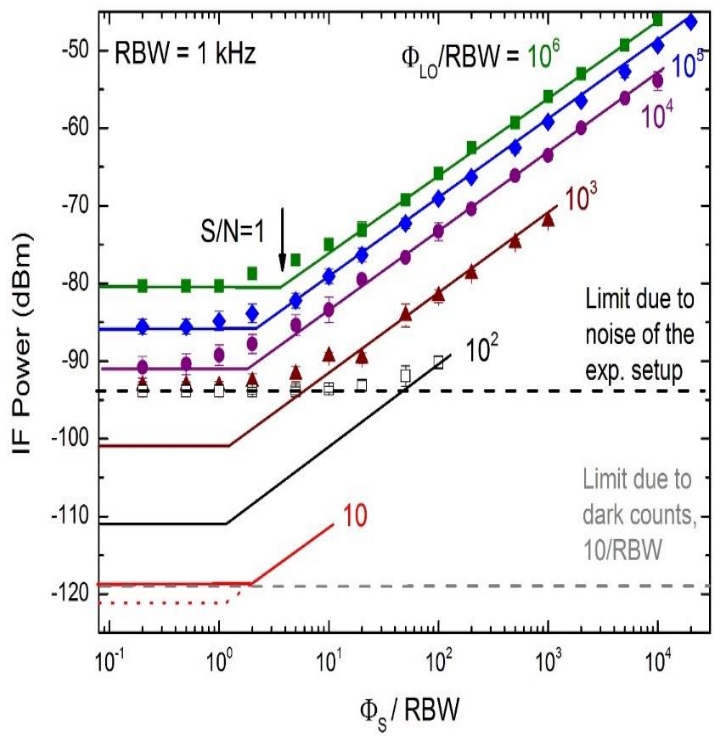
Second-order correlation function, the solid curve is a fit by dumped oscillations

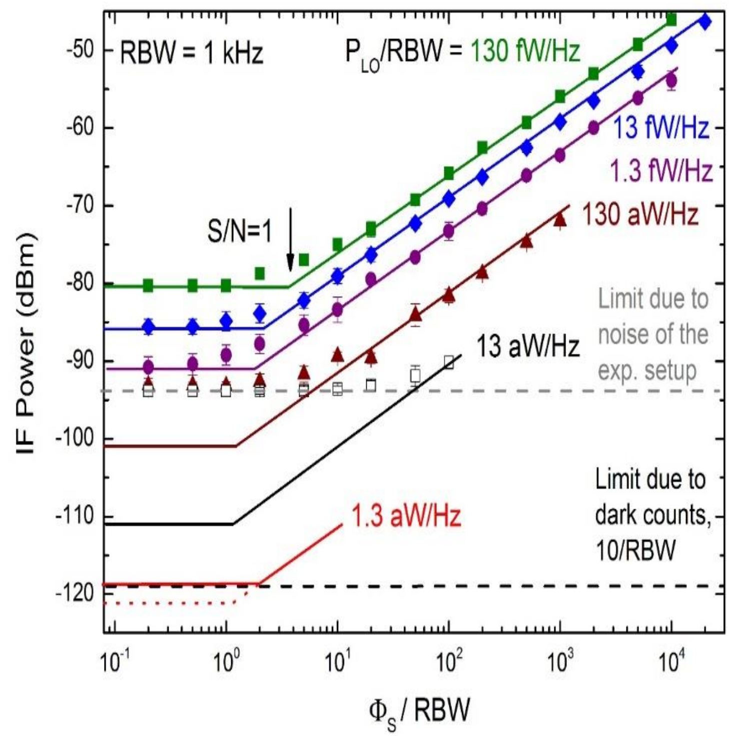


Fourier-spectrum; the dashed line is a linear fit for statistical noise background



With statistical analysis of the time domain data we see that we are still far from limitation by dark count background and that the LO power can be decreased by many orders of magnitude, down to the atto-watt range





Thank you for your attention!