ПРИЕМНИКИ ИНФРАКРАСНОГО И ТЕРАГЕРЦОВОГО ИЗЛУЧЕНИЯ НА ОСНОВЕ ТОНКОПЛЕНОЧНЫХ СВЕРХПРОВОДНИКОВЫХ НАНОСТРУКТУР

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План

•Ультратонкая сверхпроводниковая NbN пленка как уникальный материал для сверхчувствительных терагерцовых и инфракрасных детекторов.

•Сверхпроводниковый болометр на горячих электронах (HEB) и его применения в терагерцовой радиоастрономии.

•Сверхпроводниковый болометр на горячих электронах (HEB) как прямой детектор;

•Сверхпроводниковый однофотонный детектор (SSPD) в инфракрасном и терагерцовом диапазонах.

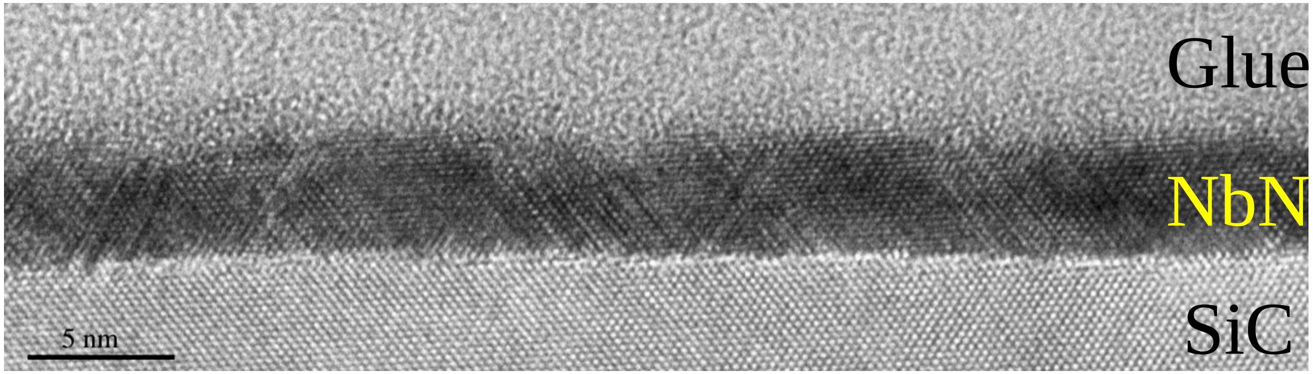
• Однофотонный нановолноводный детектор для интегральной оптики.

• SSPD как однофотонный смеситель для гетеродинной спектроскопии.

•Заключение

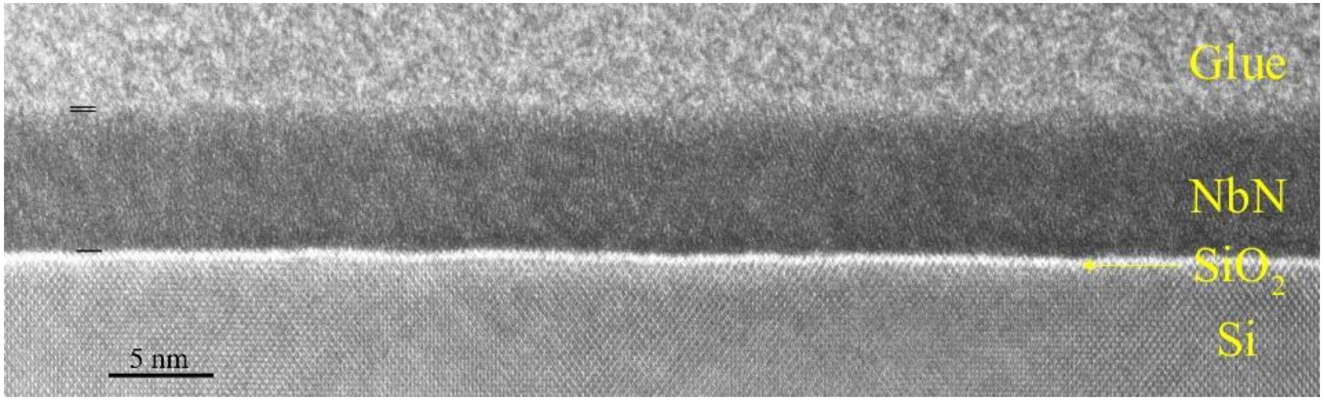
Ultrathin superconducting NbN film structure

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

NbN on Si substrate



The NbN on Si is polycrystalline.

J.-R. Gao, G. Gol'tsman, B.Voronov, *et al*, *APL (2007)*

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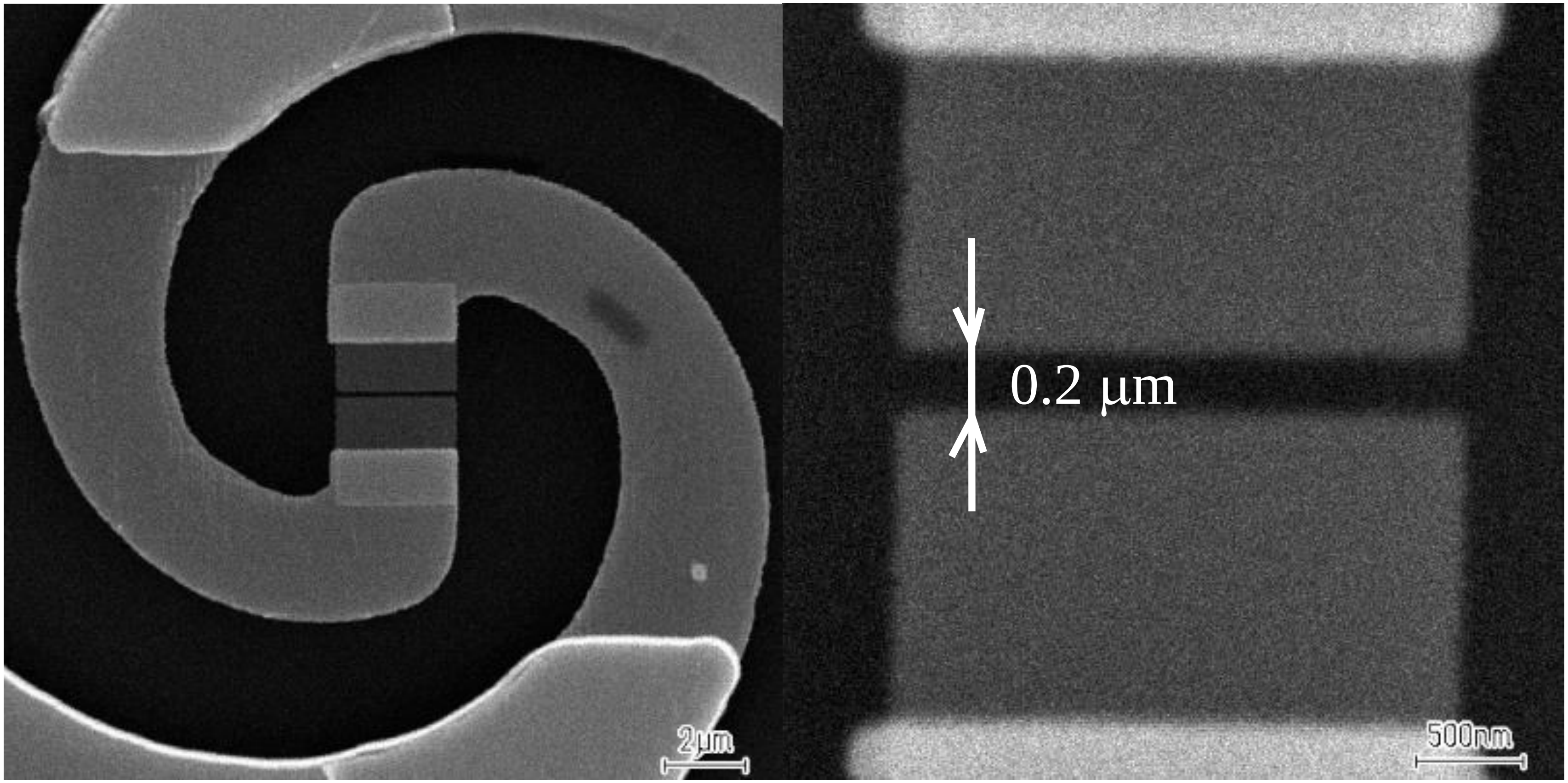
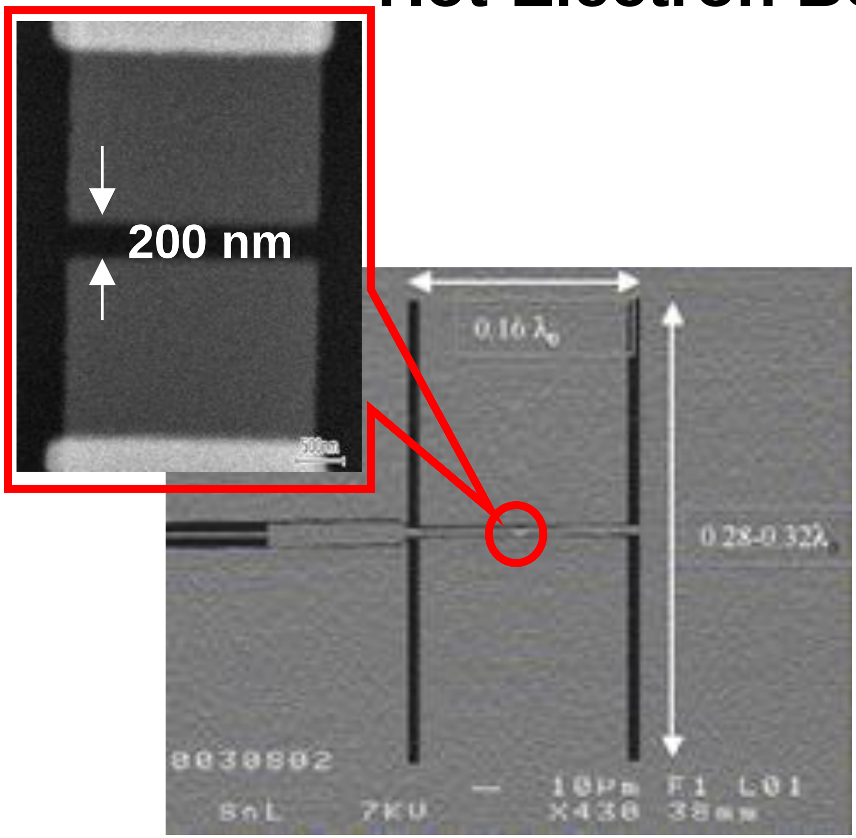
SEM micrographs of the central area of HEB mixer chip



Our NbN films are space-qualified

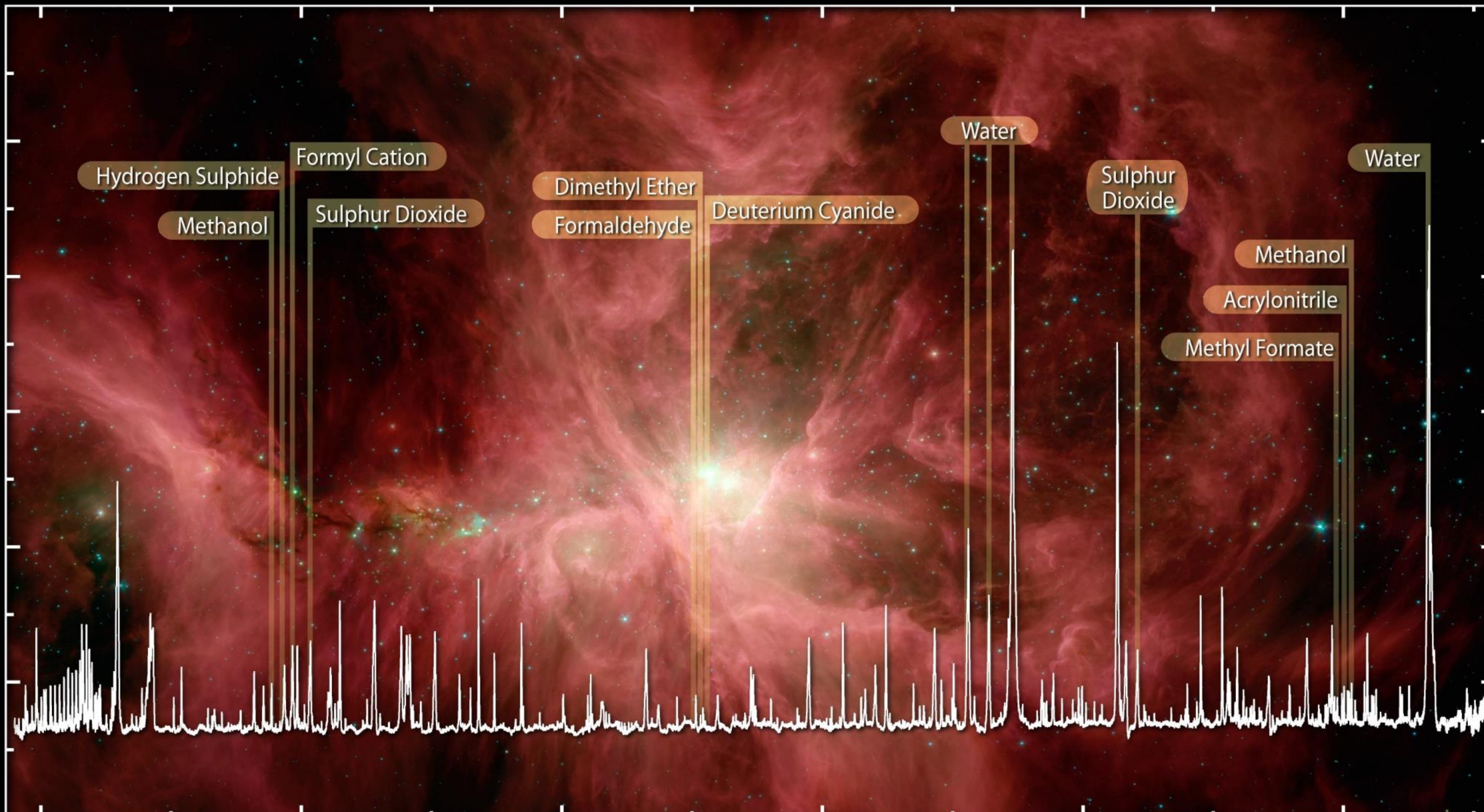
MSPU

Hot-Electron Bolometer (HEB) mixer



CHALMERS

Herschel Space Observatory launched, May 2009
HEB mixers in Bands 6 and 7 of the HIFI instrument: 1.41 THz – 1.91 THz



HIFI Spectrum of Water and Organics in the Orion Nebula

HEB mixers in radio astronomy: now and future

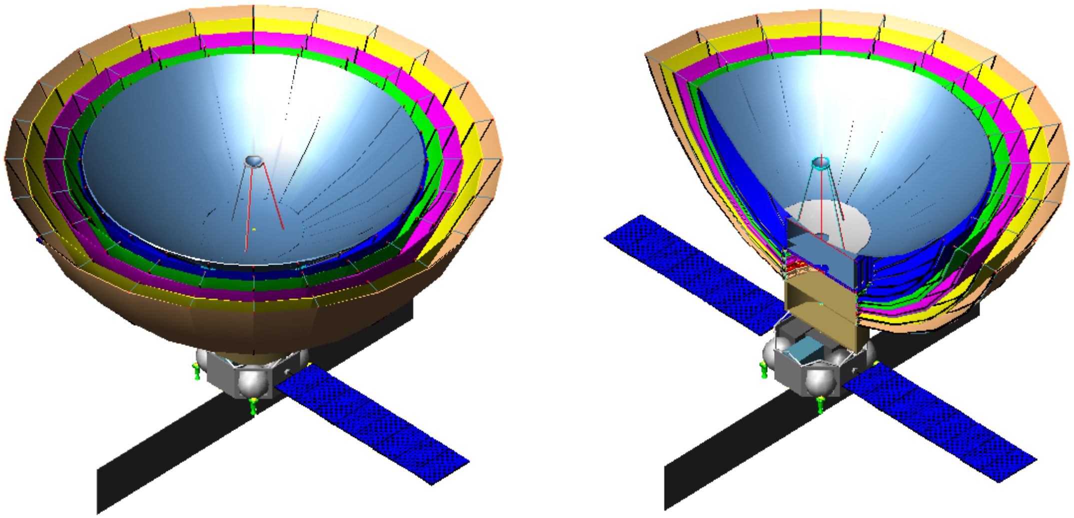
HERSCHEL

- Launched in 2009
- 3.5-m diameter space telescope
- HEB for 1.41–1.91 THz

Millimetron

10-m diameter space telescope

HEB for 1-6THz heterodyne receiver



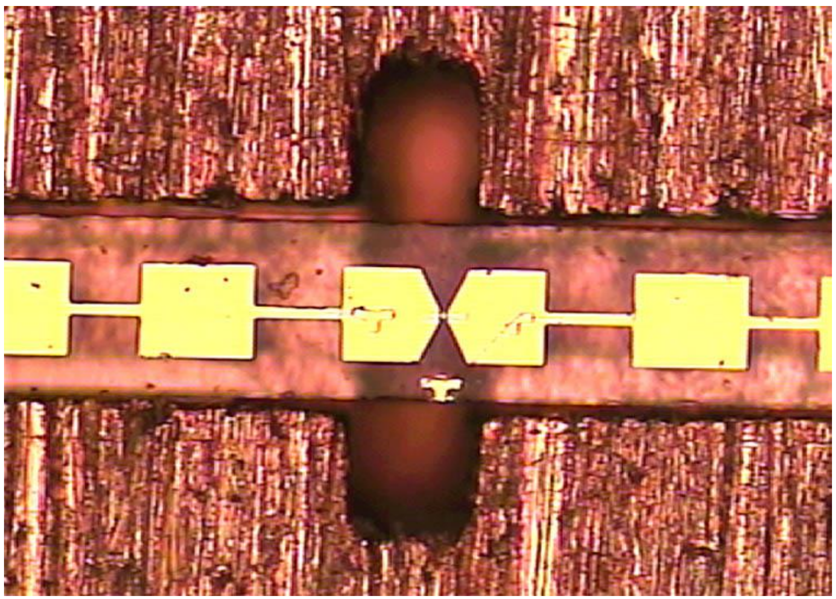
The GBW of the HEB-based HIFI receiver does not exceed 4 GHz.

Need more for future heterodyne missions – 8 GHz and more.

MSPU

From waveguide mixer chip to practical receiver up to 1.5 THz and astronomical observations in Chile from an altitude of 5525 meters

Superconducting waveguide hot-electron bolometer (HEB) mixer at 1.5 THz frequency



The 1.5 THz chip's sizes are 72 um wide, 1100 um long and 18 um thick

The Receiver Lab Telescope of the **Harvard-Smithsonian Center for Astrophysics** is the first ground-based radio telescope designed for operation at frequencies above 1 THz.

Observations since 2002 from an altitude of 5525 meters in Chile at 0.8-1.5 THz

HEB Mixers on SOI wafers for Greenland Telescope

- *The Greenland Telescope* is based on the ALMA North America prototype antenna built by Vertex AG, which will be refitted for operation in the colder and somewhat lower altitude conditions.
- It is a 12-m diameter Cassegrain system with a primary F/d ratio of 0.4 and maximum field of view of approximately 15 arc-min.

The Greenland Telescope antenna in its current location at the VLA site in Socorro, NM

Location of Summit/Apex Stations in Greenland

- The Greenland Telescope will be deployed at Apex Station, a new NSF operated Arctic research station to be constructed 5 miles north of the existing Summit Station at 72°35'N 38°25'W and 3,210 m (10,530 ft) above mean sea level.
- The site is near the peak of the Greenland ice sheet, near the center of Greenland.

http://www.cfa.harvard.edu/greenland12m/

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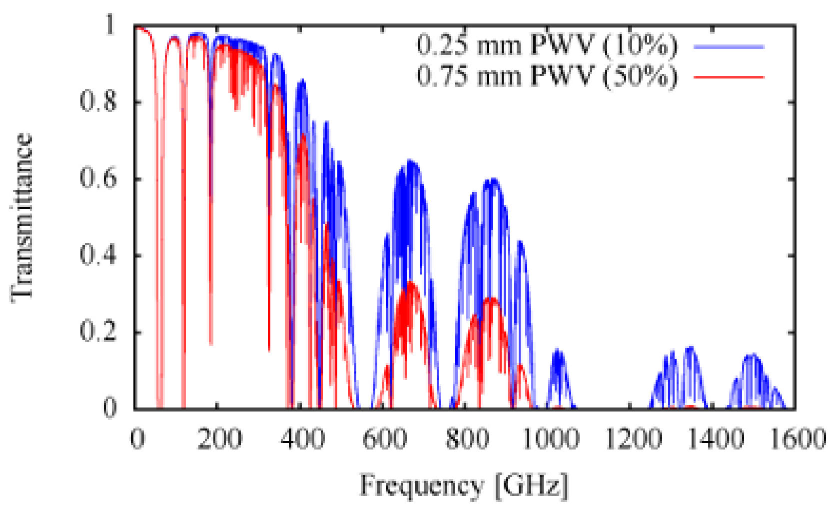
HEB Mixers on SOI wafers for Greenland Telescope

Frequency (GHz)	Wavelength (mm)	Receiver Noise (K)	Transmission	System Noise (K)	Continuum NEFD (mJy/beam 1s)	Spectral NEFD (mJy/beam 1s, 1km/s)	Spectral NEFD (K/beam 1s, 1km/s)
1050	0.286	525	0.16	**7798**	3748.2	179199.0	4.17
1300	0.231	650	0.16	**10659**	5942.8	255344.1	5.12
1500	0.200	750	0.15	**14711**	9448.9	377955.2	6.58



Calculated atmospheric transmission at Apex Station for median (red) and 10% (blue) winter (Oct-May) conditions

http://www.cfa.harvard.edu/greenland12m/

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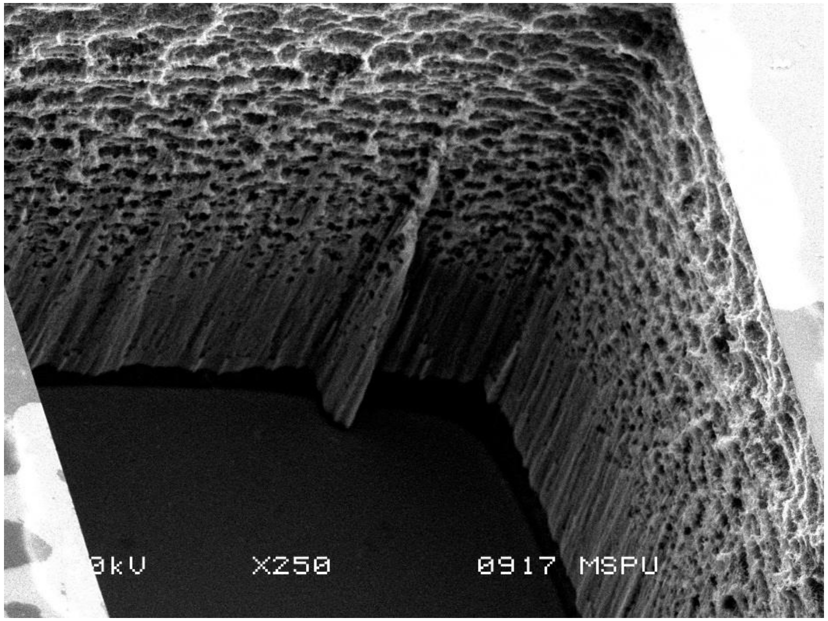
HEB Mixers for Greenland Telescope: test deep etching of Si



SEM photograph of the Si etched surface

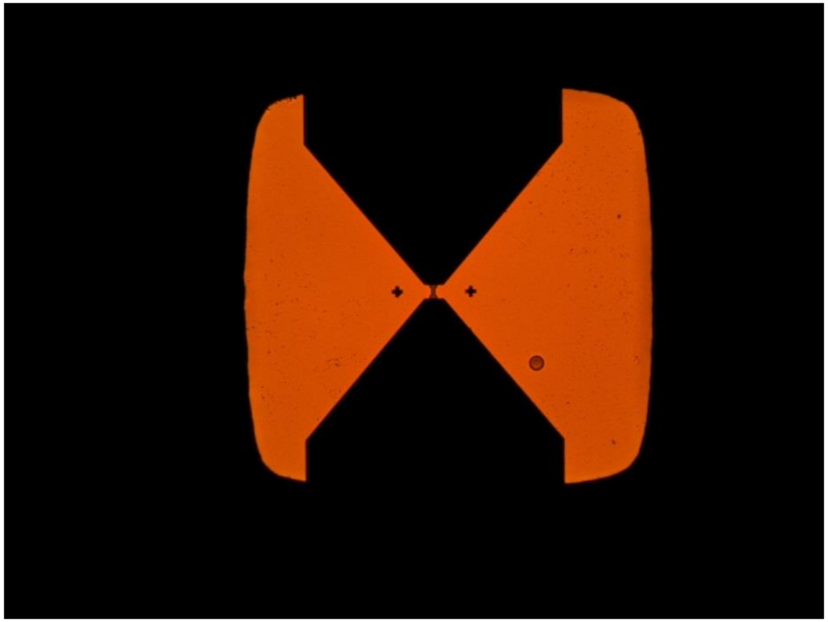


Image of the membrane with an optical microscope.
(The membrane is transparent to light)

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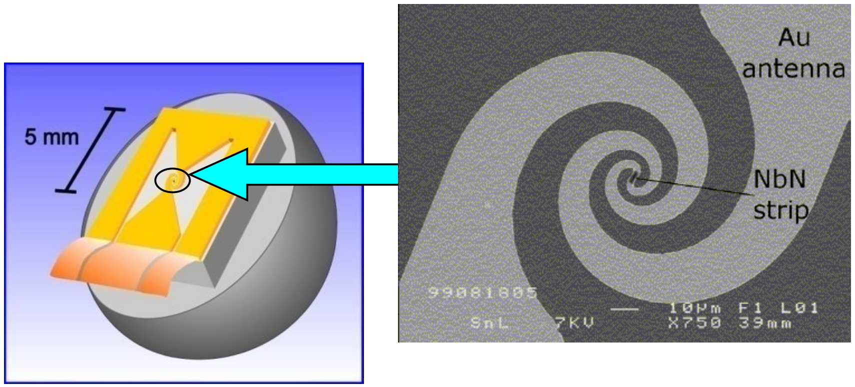
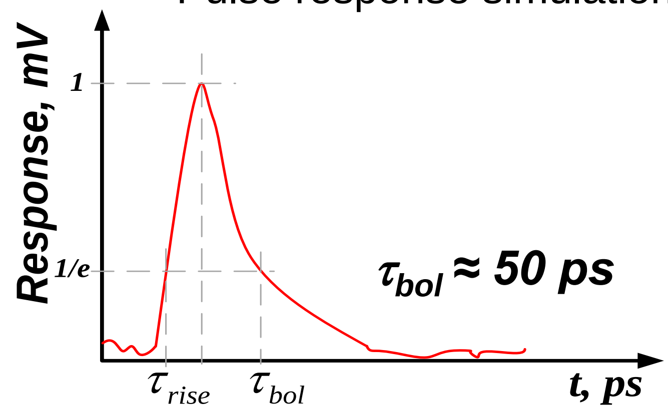
Hot electron bolometers as direct detectors

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

Spiral antenna coupled bolometer



Pulse response simulation

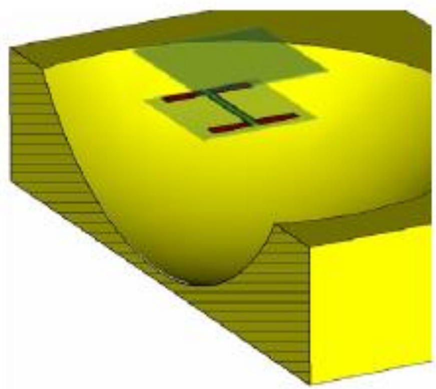


NEP $\approx 3\times10^{-13}$ ***W/√Hz***

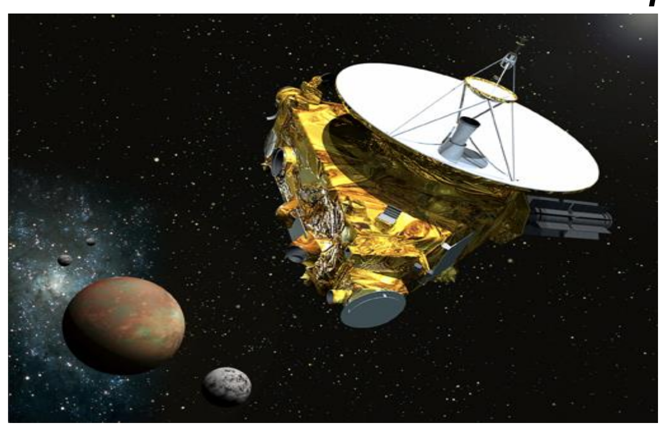
$W_{pulse} = SNR \times NEP \times \sqrt{\tau_{bol}} \approx 10\ aJ \ < \ SNR^2 \times h\nu \approx 25\ aJ$

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)

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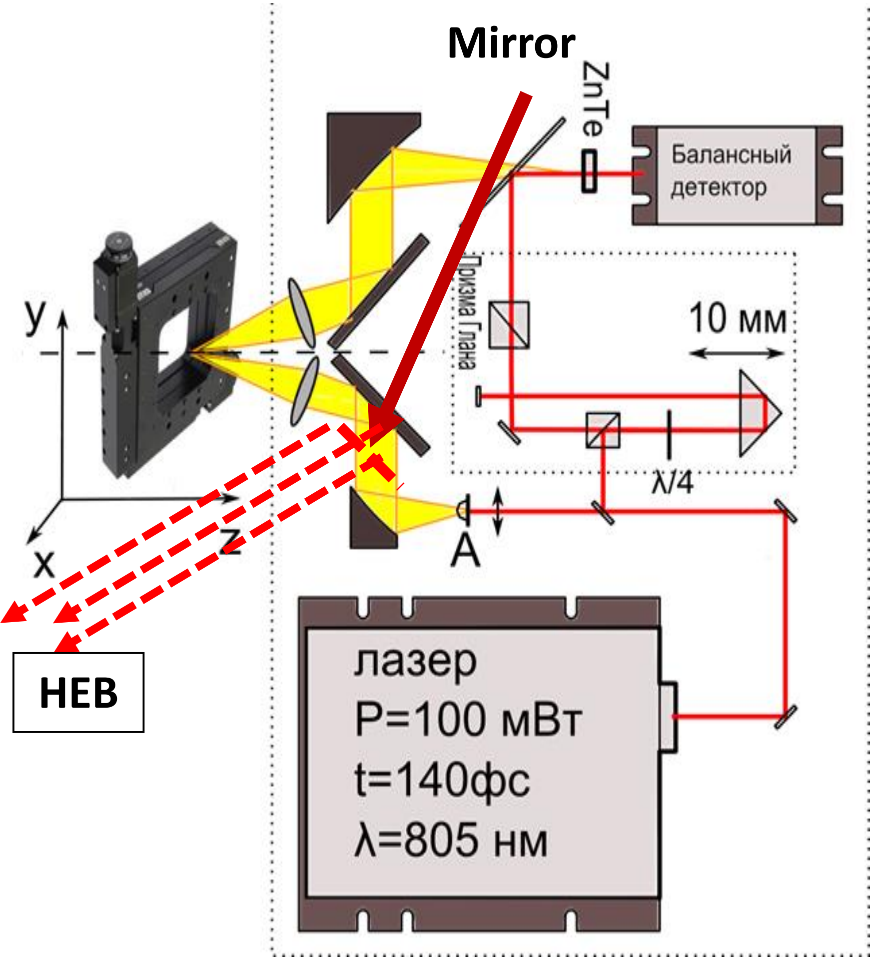
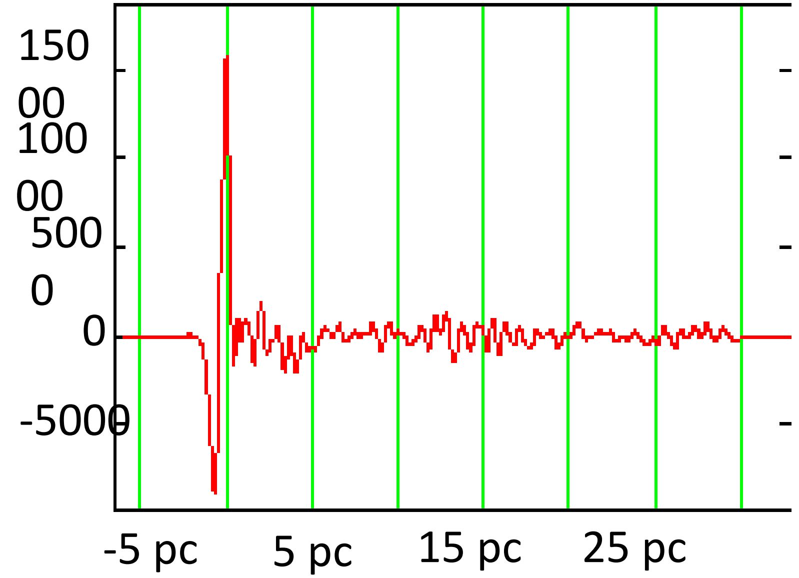
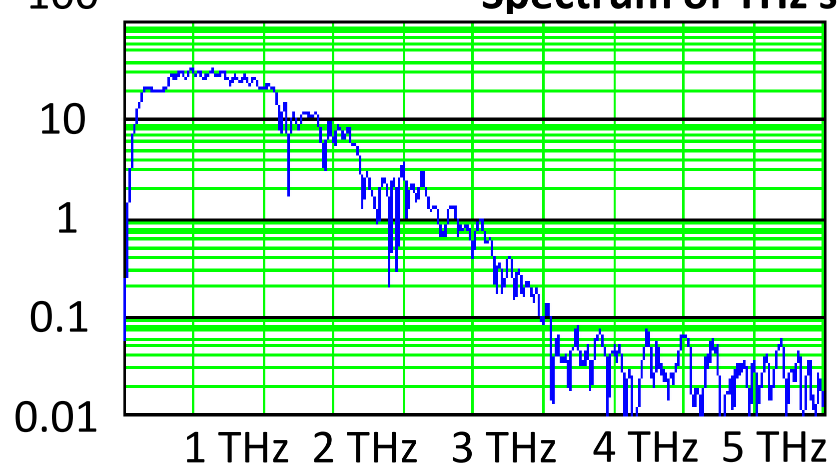
Experimental set-up: short THz pulses and HEB detector with record energy resolution



Sensitivity 2 mV **Transient THz pulse**



Spectrum of THz signal



First observation of SSPD response and first idea of device physics

Picosecond superconducting single-photon optical detector

APPLIED PHYSICS LETTERS VOLUME 79, NUMBER 6 6 AUGUST 2001

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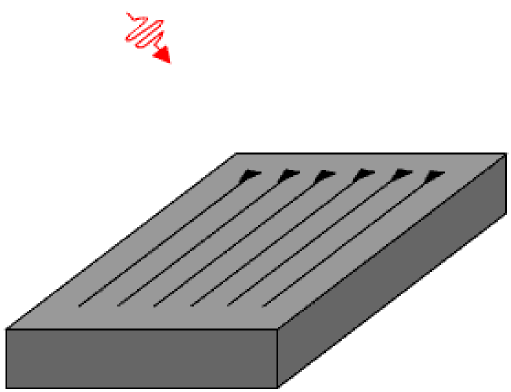

FIG. 1. Schematics of the supercurrent-assisted hotspot formation mechanism in an ultrathin and narrow superconducting strip, kept at temperature far below T_C are shown. The arrows indicate direction of the supercurrent flow.

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Quantum detection by current carrying superconducting film

Physica C 351 (2001) 349–356

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www.elsevier.nl/locate/physc

Received 18 July 2000; received in revised form 9 October 2000; accepted 11 October 2000

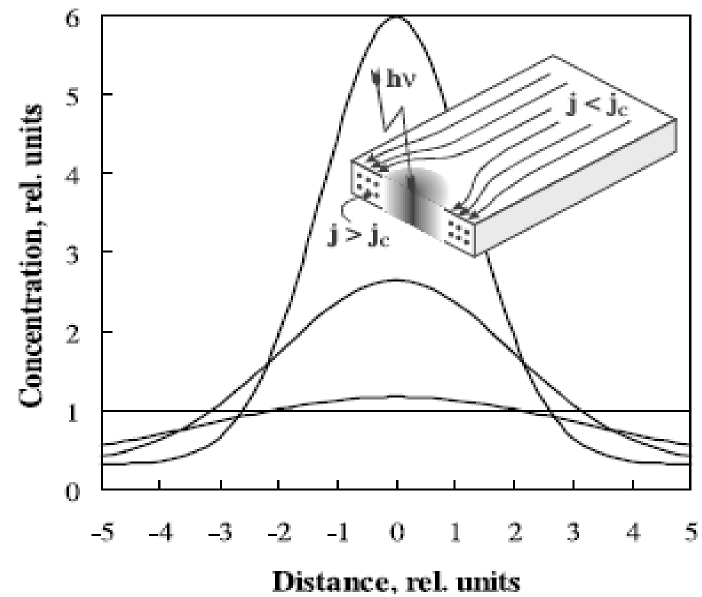
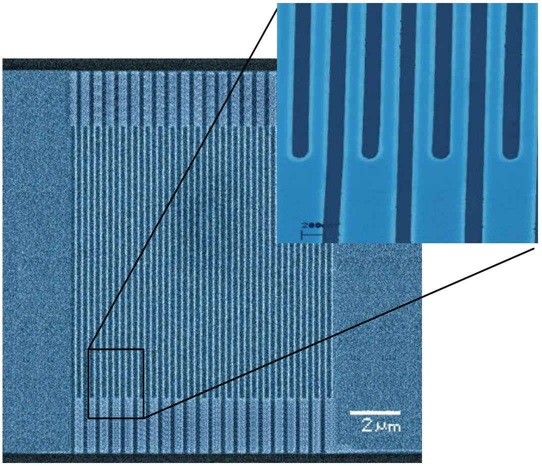


Fig. 1. Concentration of nonequilibrium quasiparticles across the width of the film at different moments after the photon has been absorbed. Time delays are 0.8, 2.0 and 5.0 measured in units of the thermalization time. Distance from the absorption site is shown in units of the thermalization length. 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.

Meander-type SSPD Fabrication



Fabrication:

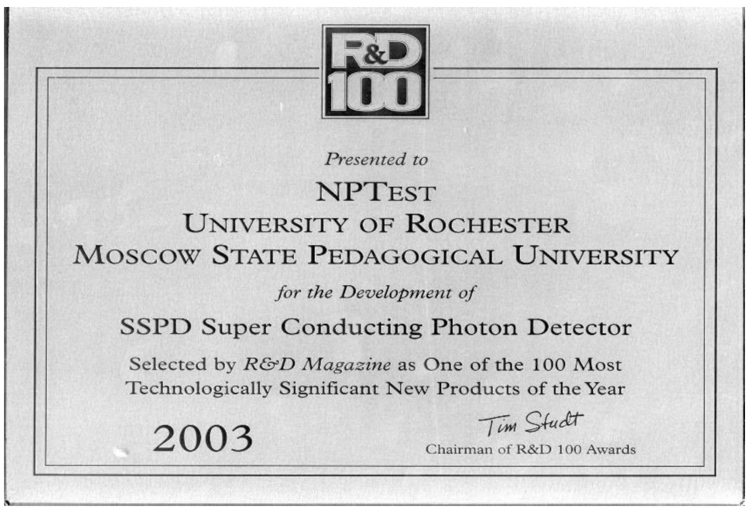
- DC magnetron sputtering of NbN film on sapphire (Al_2O_3) substrate
- E-beam lithography with reactive ion etching

Present day challenges:

- increase filling factor (presently about 60%)
- to reduce strip width from 100 nm to 50 nm or even less

Korneev A. *et al*, *Appl. Phys. Lett.* 84 (2004) 5338

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

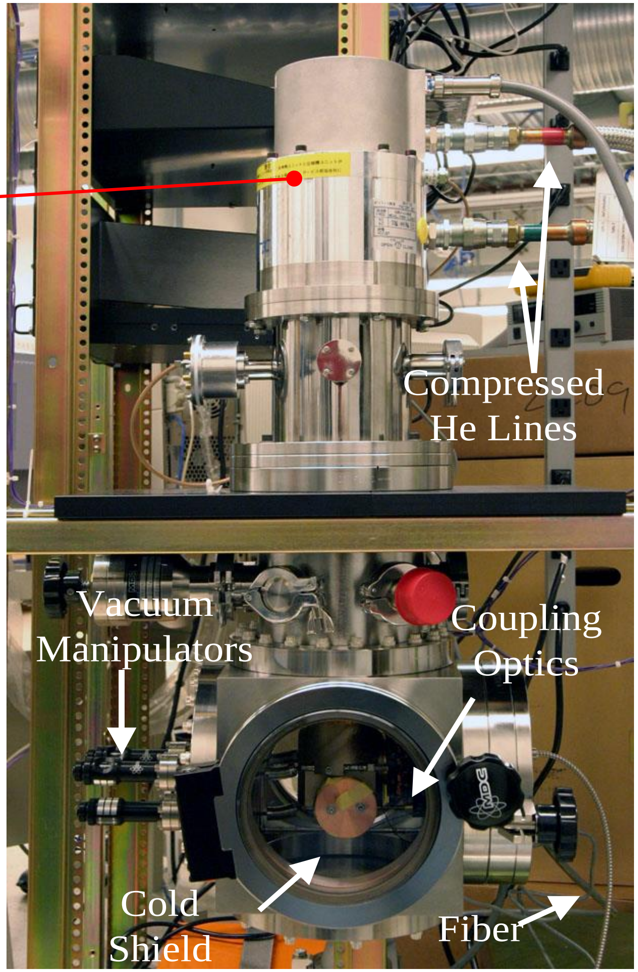
for the Development of

SSPD Super Conducting Photon Detector

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

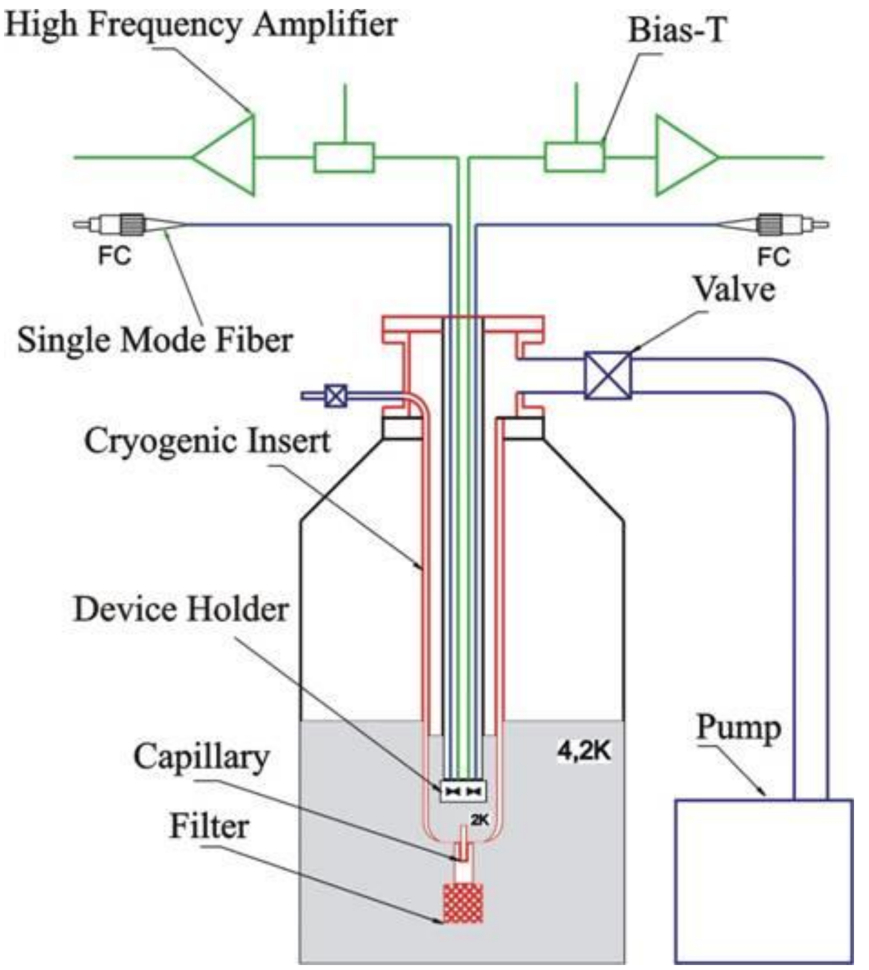
2003

Tim Studt
Chairman of R&D 100 Awards



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

Practical detectors and systems



Two-channel single-photon receiver

Cryocooler-based solution

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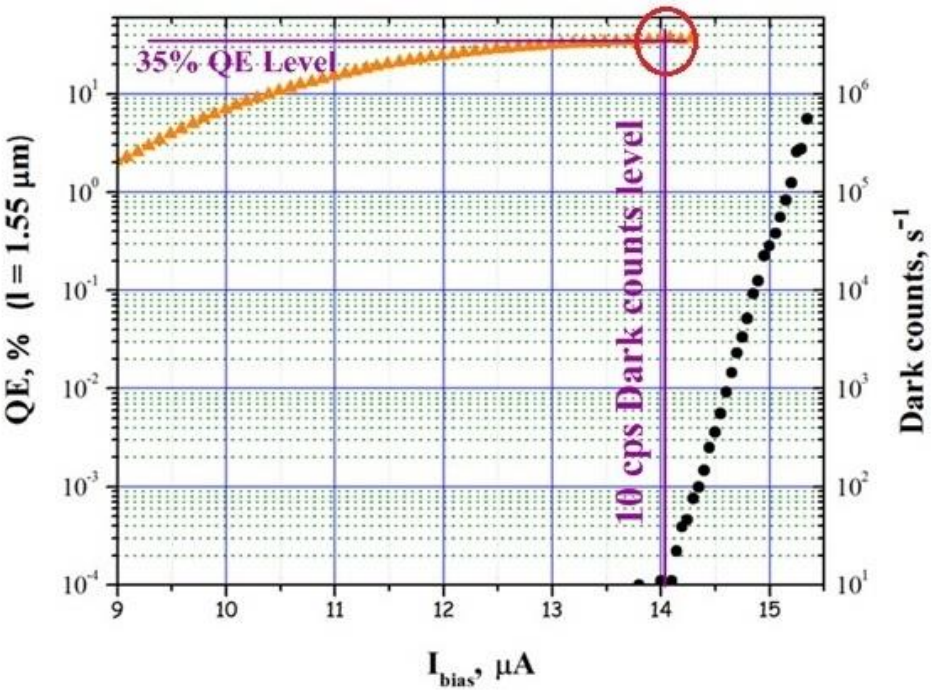
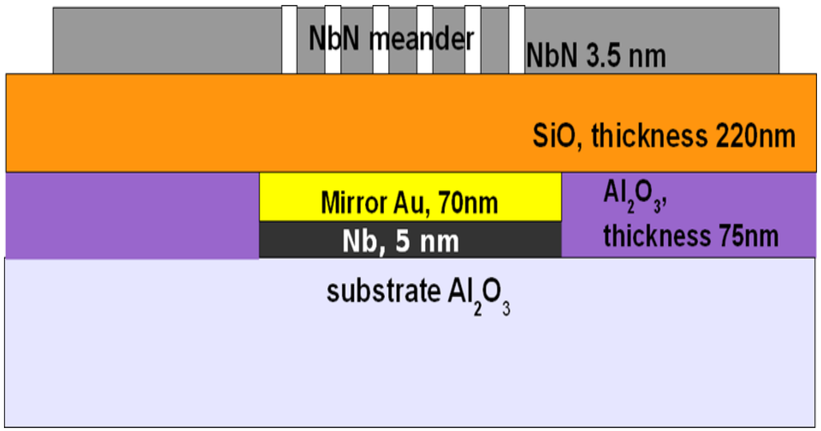
Practical single-photon receiver based on SSPD

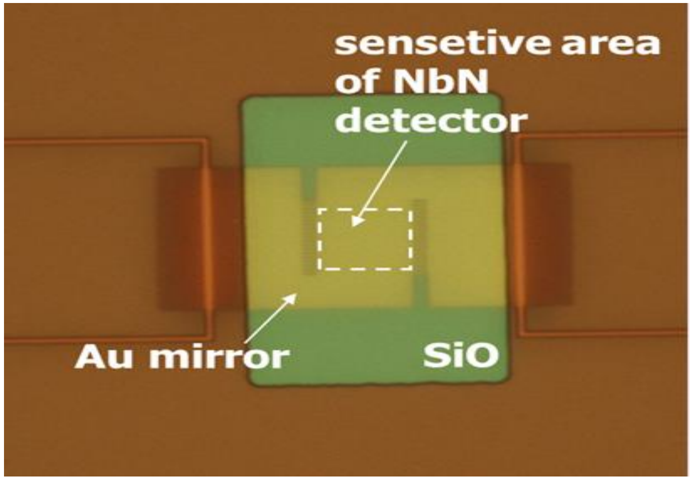
Now: Quantum efficiency 80% at 1550nm, jitter 20ps, max. counting rate 100 MHz and dark count rate $10 s^{-1}$



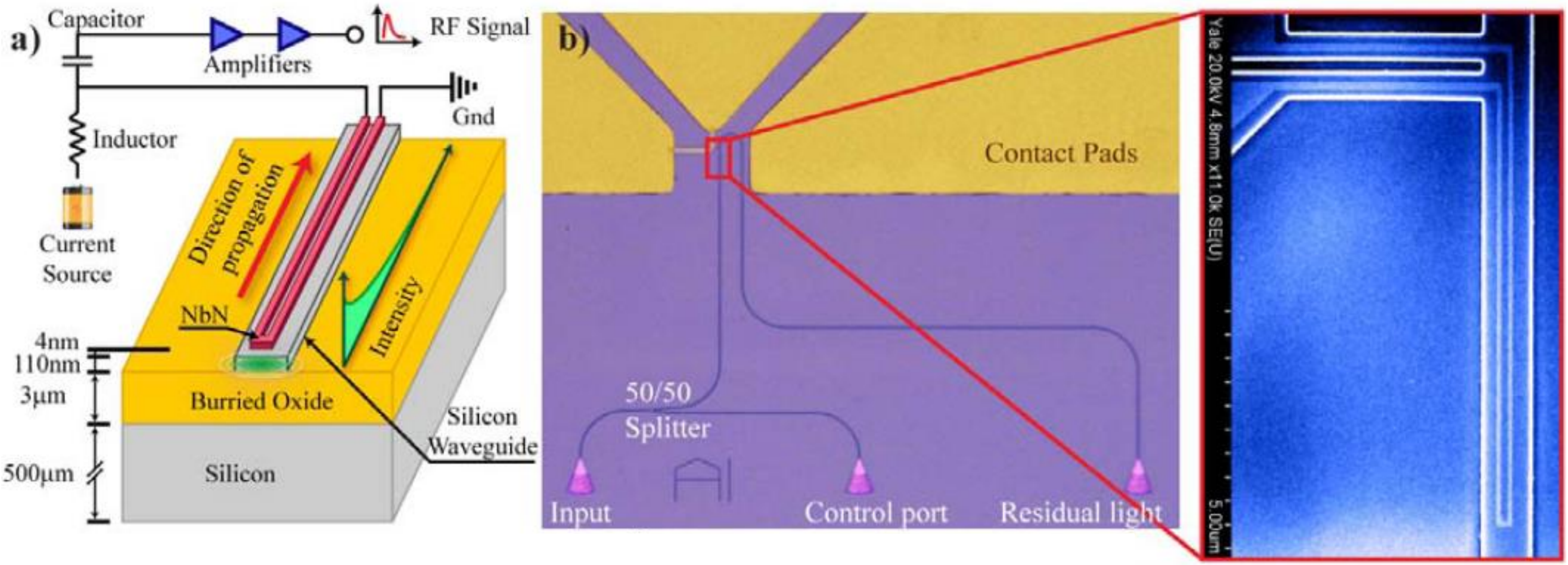
Cavity-integrated SSPD



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 %



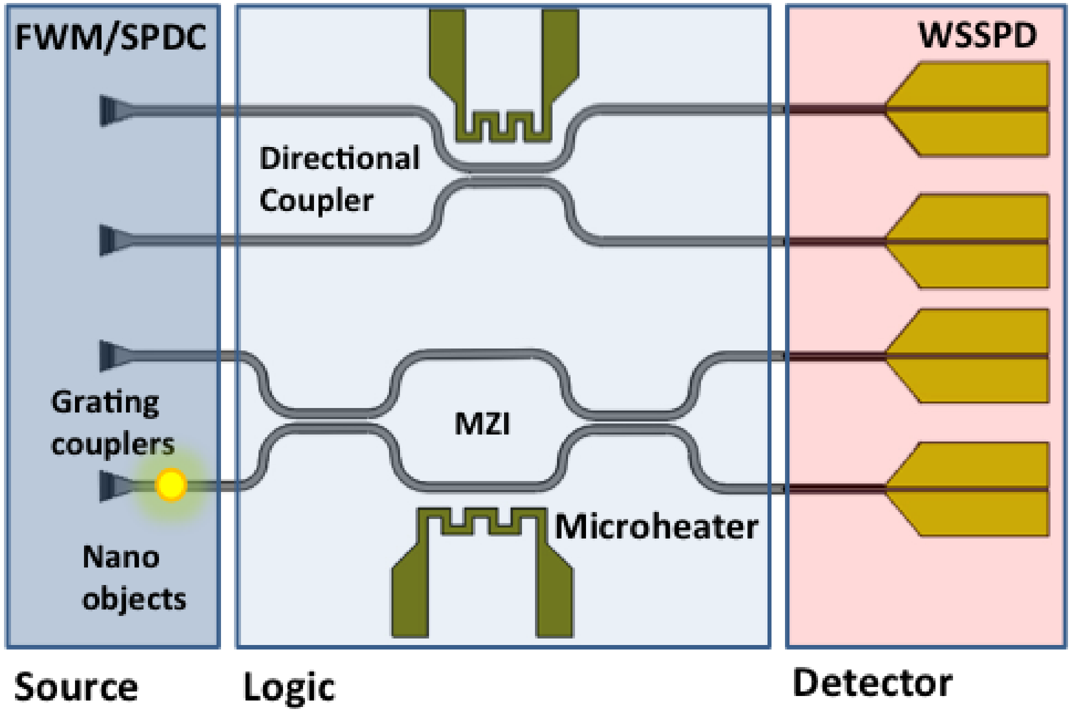
High Speed Travelling Wave Single-Photon Detectors With Near-Unity Quantum Efficiency W. Pernice, C. Schuck, O. Minaeva, M. Li, G. Goltsman, A. Sergienko, H. Tang, “High speed travelling wave single-photon detectors with near-unity quantum efficiency”, Nature Communications, 3, 1325 (2012)



a) Principle of the travelling wave SSPD: a sub-wavelength absorbing NbN nanowire is patterned atop 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.

Single-photon platform for the realization of integrated quantum optics.



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

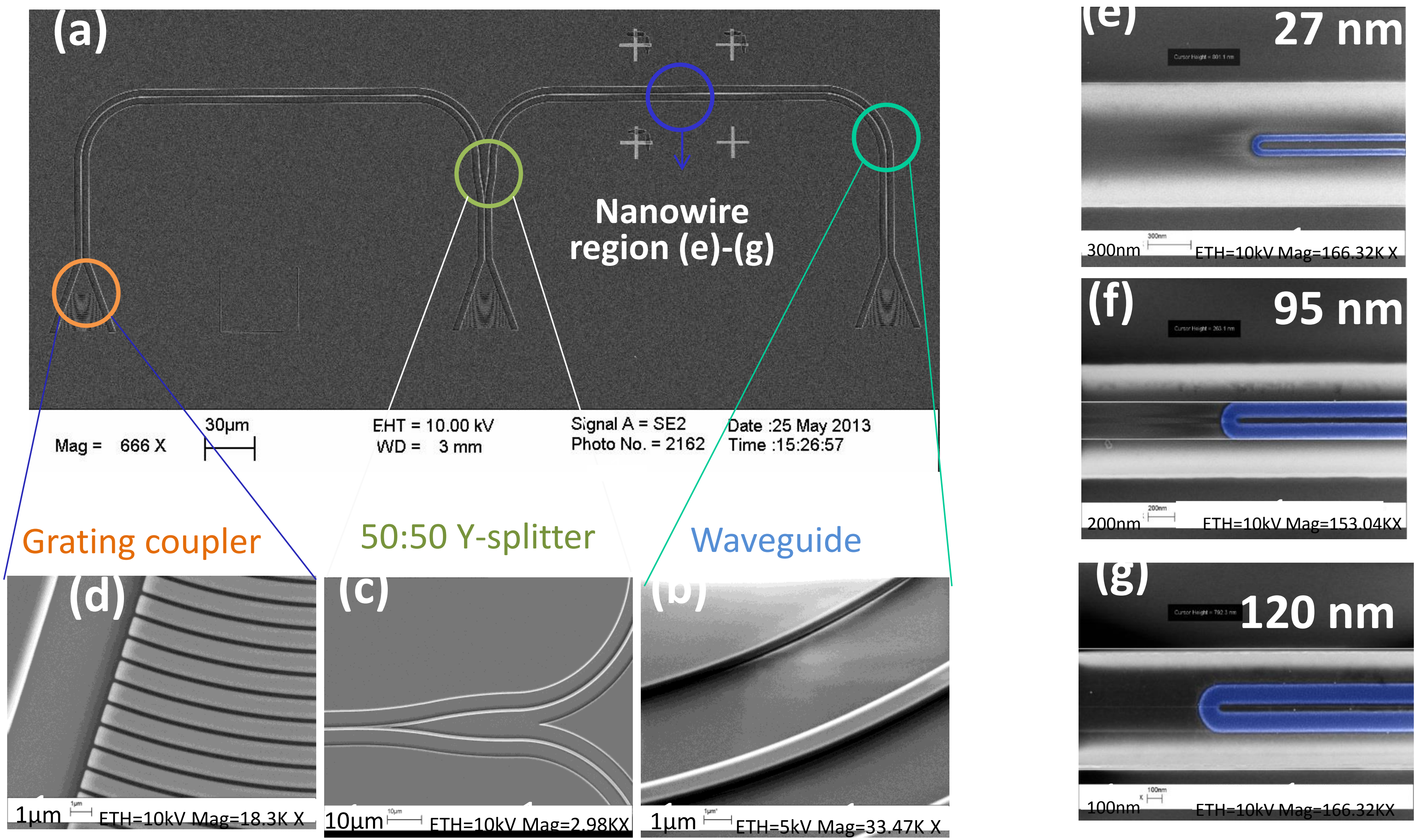
Why WSSPD?

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

SEM image of a fabricated nanophotonic circuits

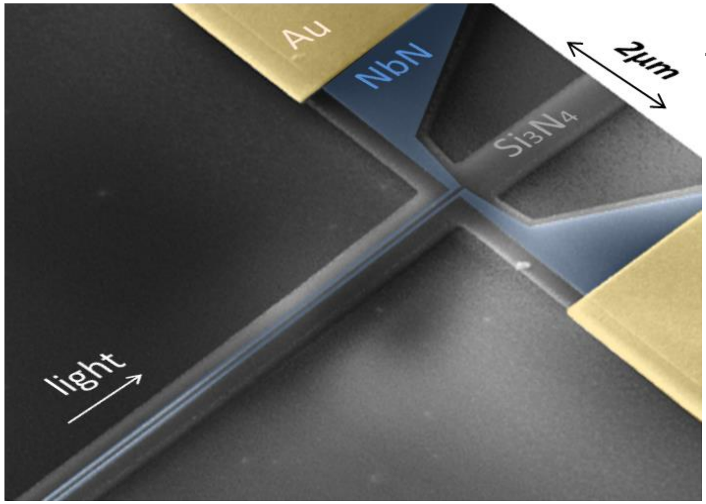
SEM image of a fabricated nanophotonic circuit for balance measurements of an absorption coefficient

False colors of nanowire atop of waveguide with different width



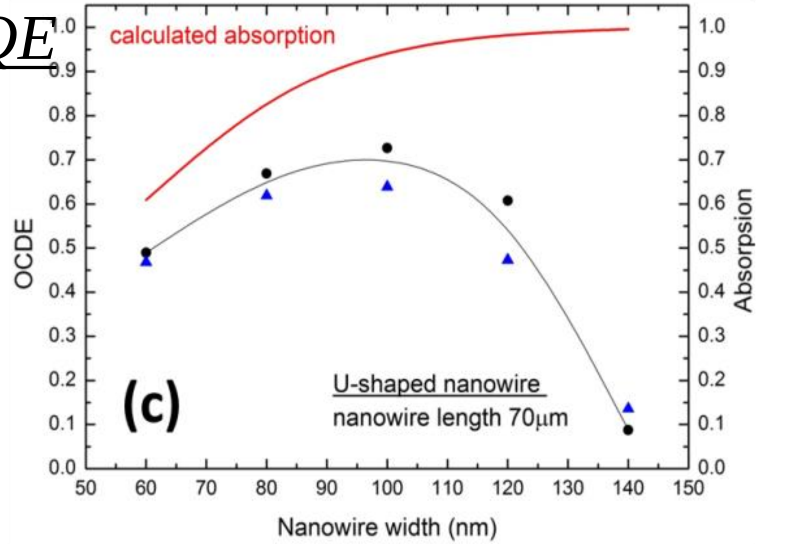
On-chip detection efficiency (OCDE)

SEM Image of a U-shaped nanowire

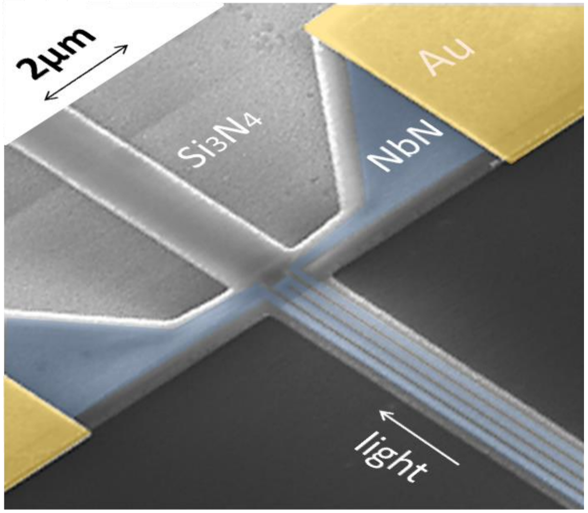


$OCDE = A * IQE$

OCDE vs NbN nanowire width (U-shaped

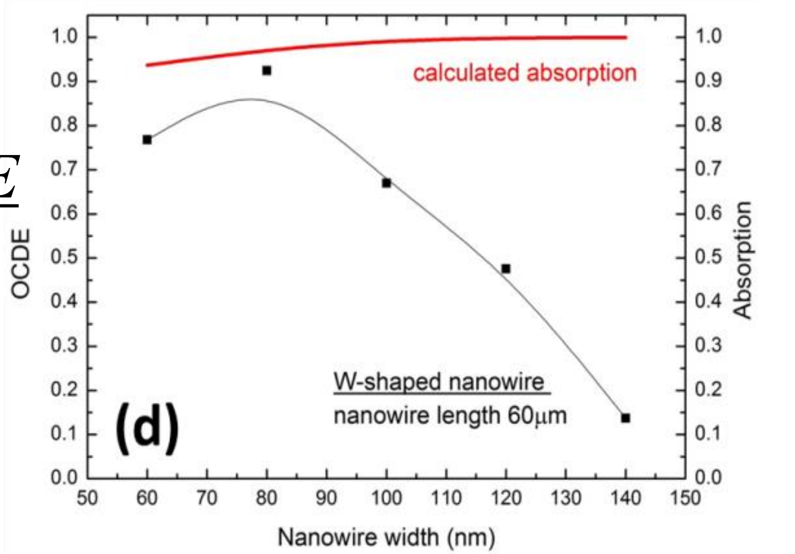


SEM Image of a W-shaped nanowire



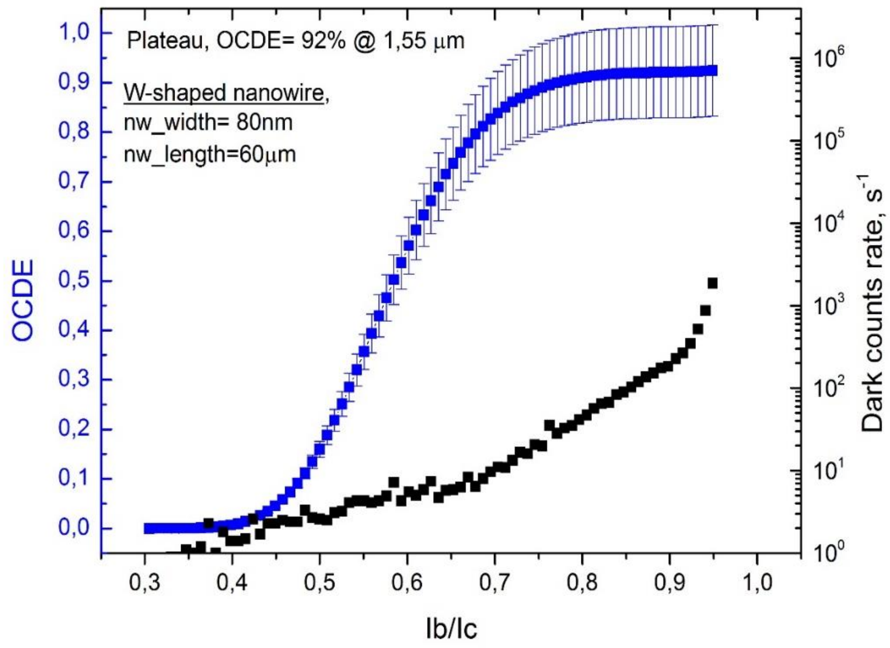
$OCDE \approx IQE$

OCDE vs NbN nanowire width (W-shaped)

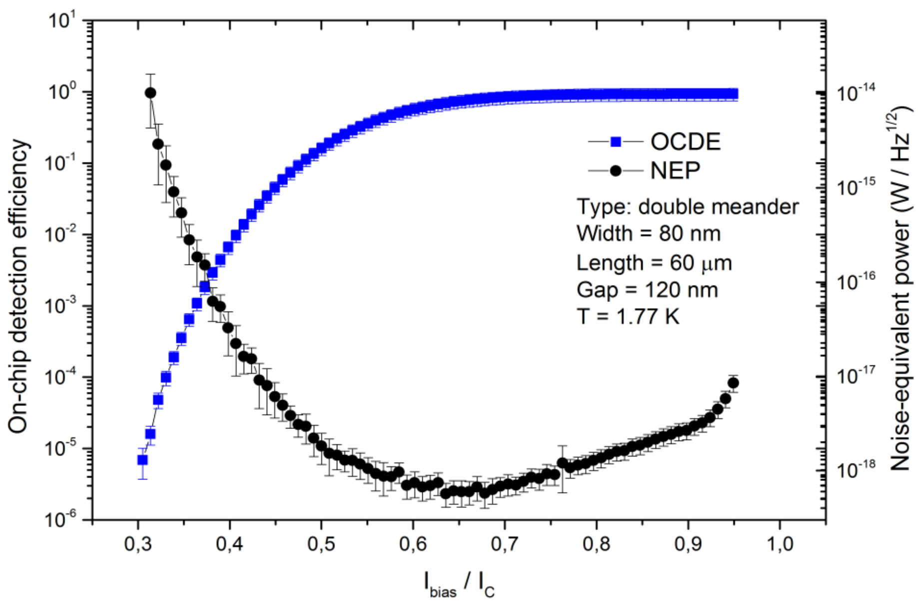


The best W-shaped nanowire

OCDE vs normalized bias current



OCDE and NEP vs normalized bias current



$$NEP = h\nu\sqrt{2DCR}/\mathrm{OCDE}$$

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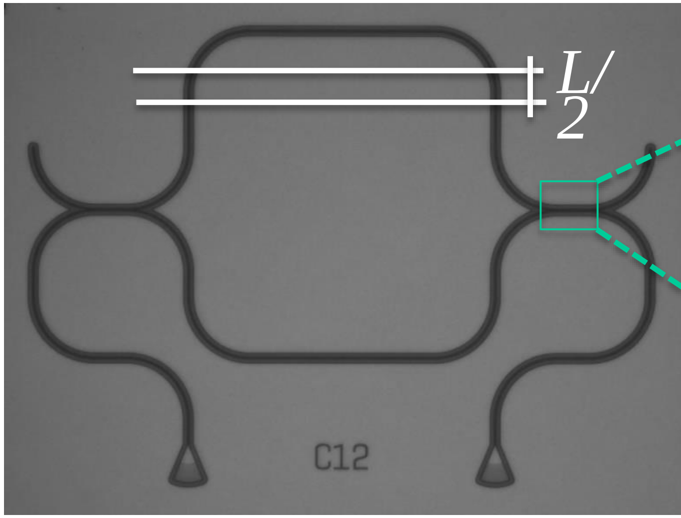
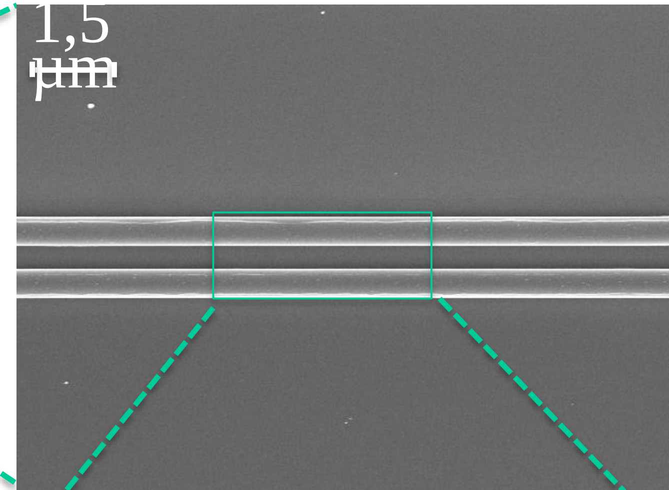
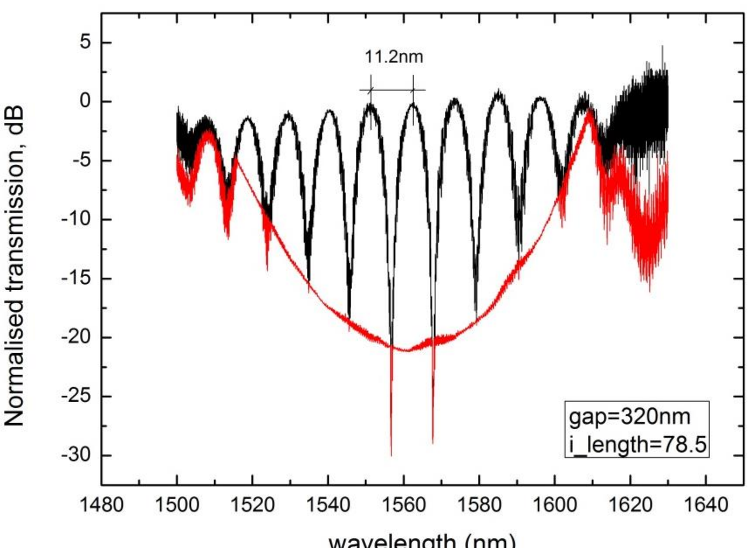
MZI with two directional couplers

Optical image of MZI with two directional couplers

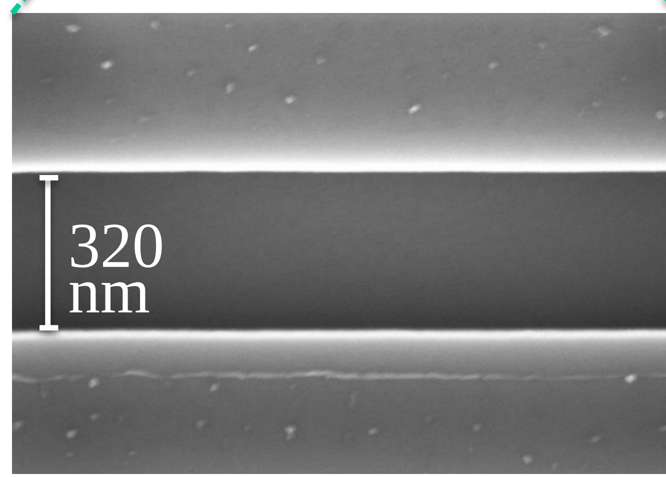


SEM image of the directional coupler





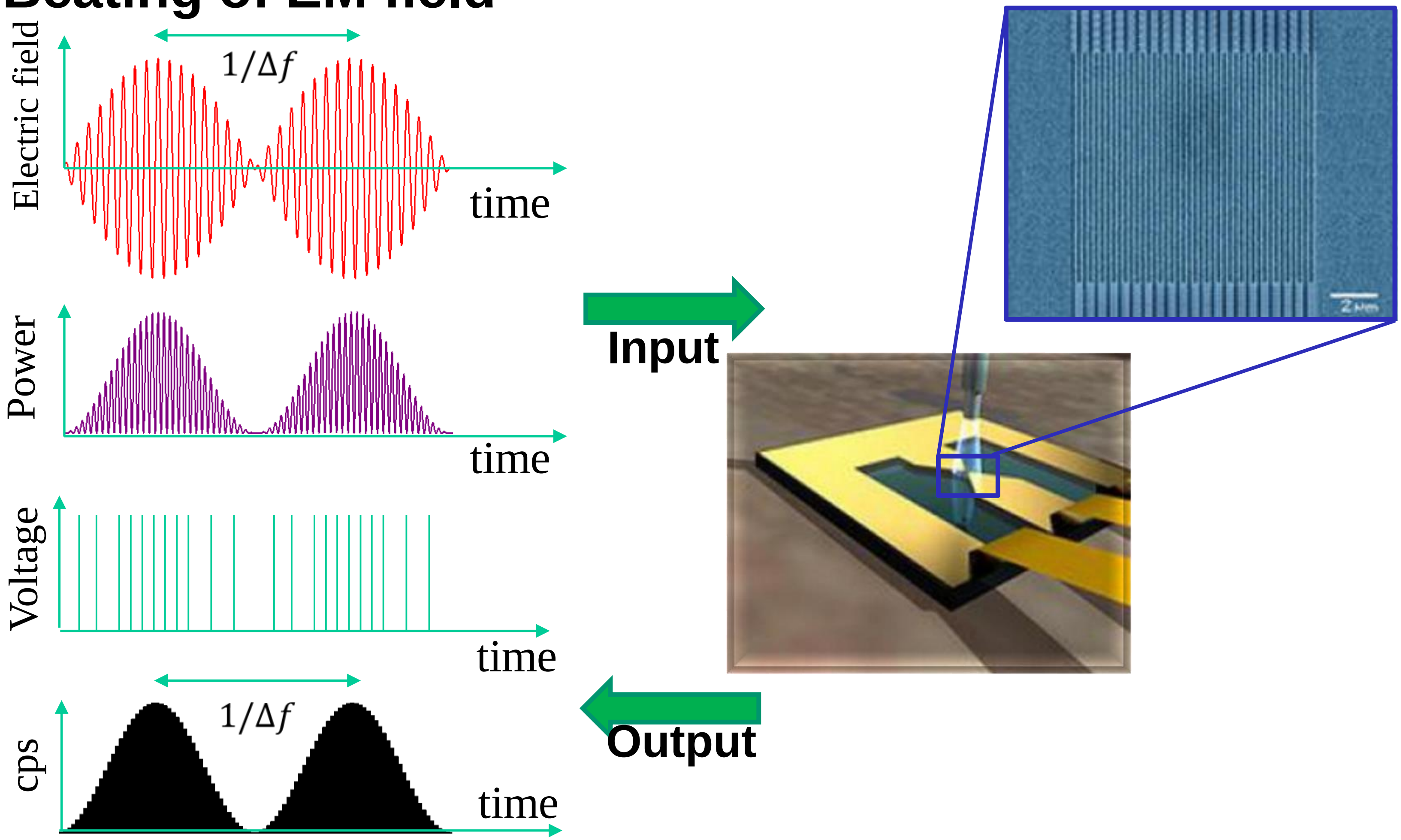
Normalized transmission MZI vs wavelength



SEM image of the directional coupler (central part)

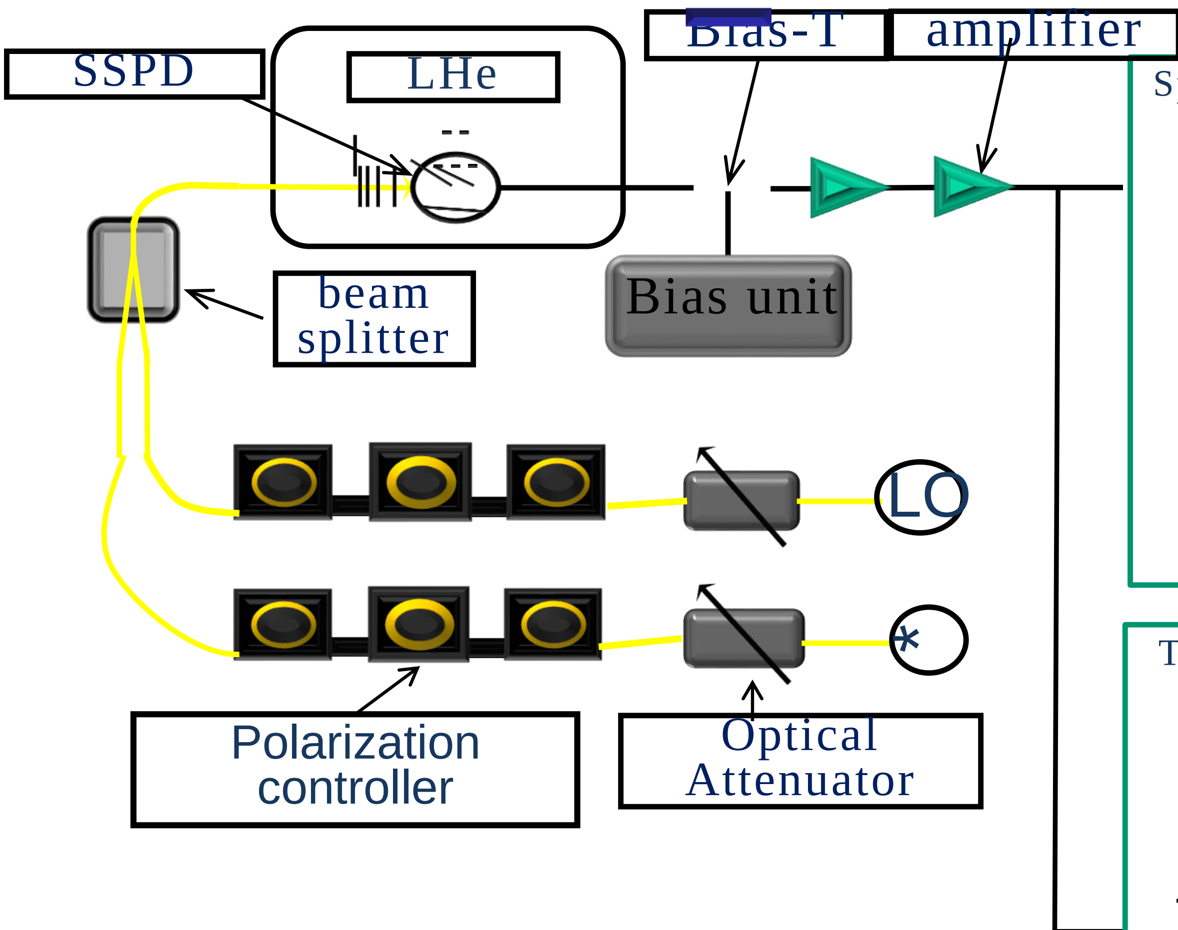
SSPD as a photon counting mixer for heterodyne spectroscopy: Operation principle:

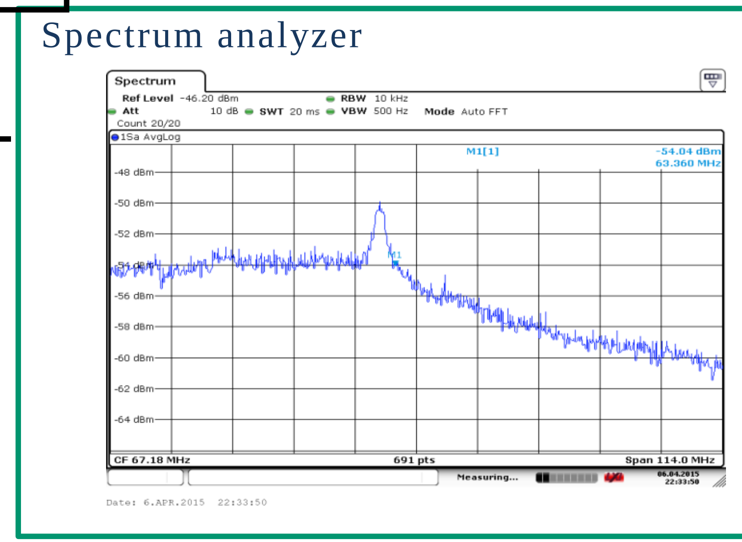
Beating of EM field

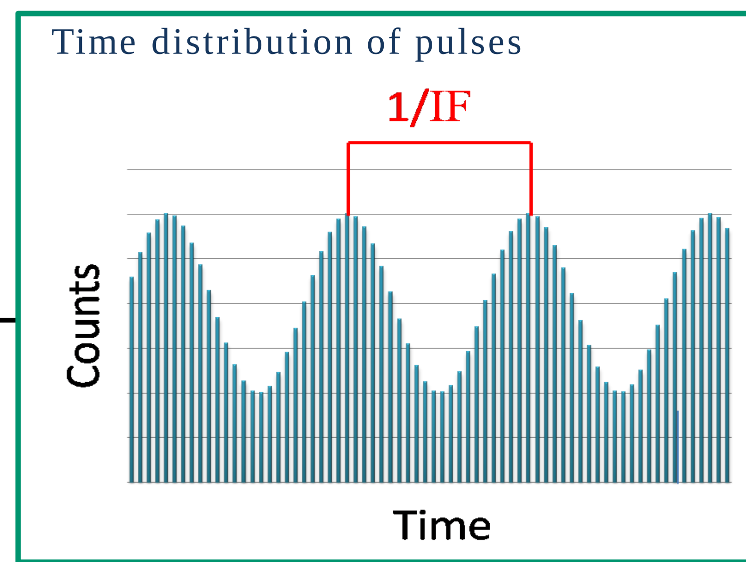


Counts per second oscillation versus time

SSPD as a photon counting mixer for heterodyne spectroscopy: Measurement setup:



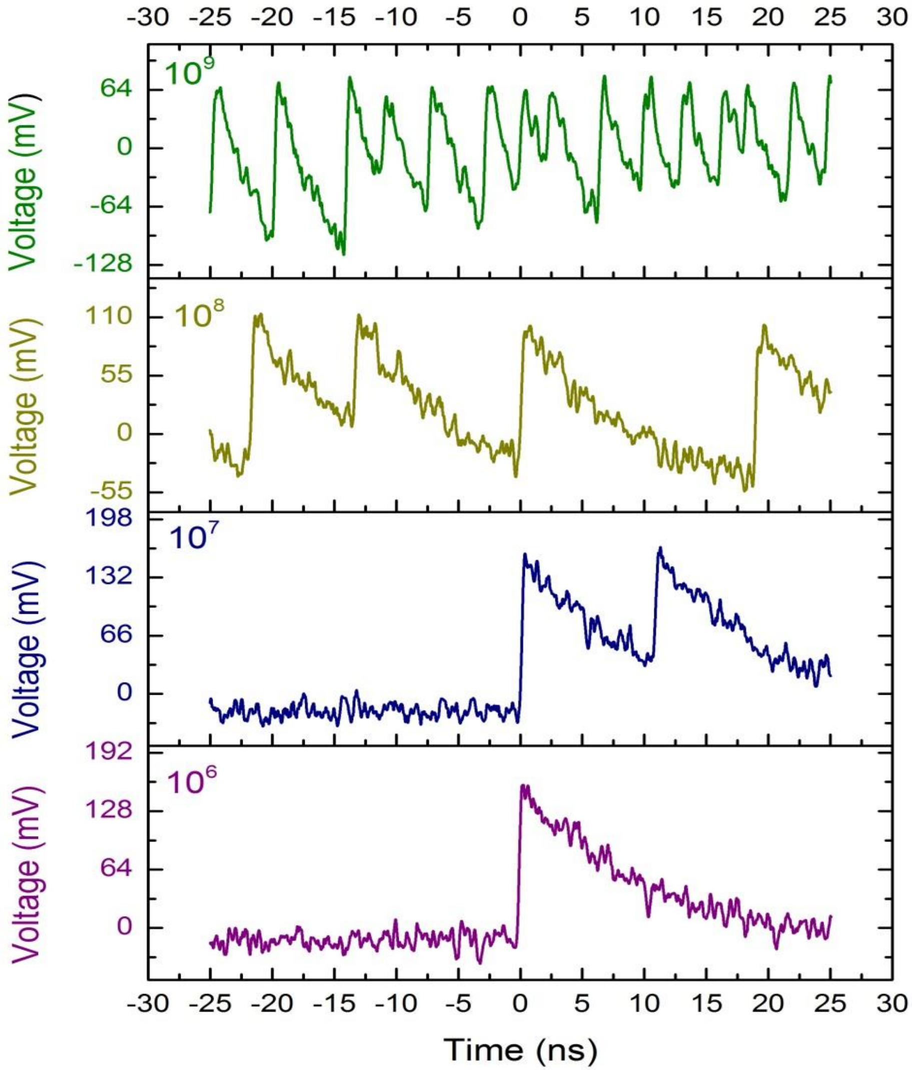




Laser wavelength: 1.55 µm,

Laser linewidth: 5 MHz.

Amplified pulses from SSPD



$\Phi_{LO}= 10^9 (ph/s)$

$\Phi_{LO}= 10^8 (ph/s)$

$\Phi_{LO}= 10^7 (ph/s)$

$\Phi_{LO}= 10^6 (ph/s)$

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Professor Gregory Goltsman received the IEEE Award for Continuing and Significant Contributions to Applied Superconductivity at the International Superconductive Electronics Conference in Sorrento, Italy, 13 June 2017.

http://ieeecsc.org/news/professor-gregory-goltsman-received-ieee-award-continuing-and-significant-contributions-applied

Thank you for your attention!

Laboratory prototype of .hertz imager

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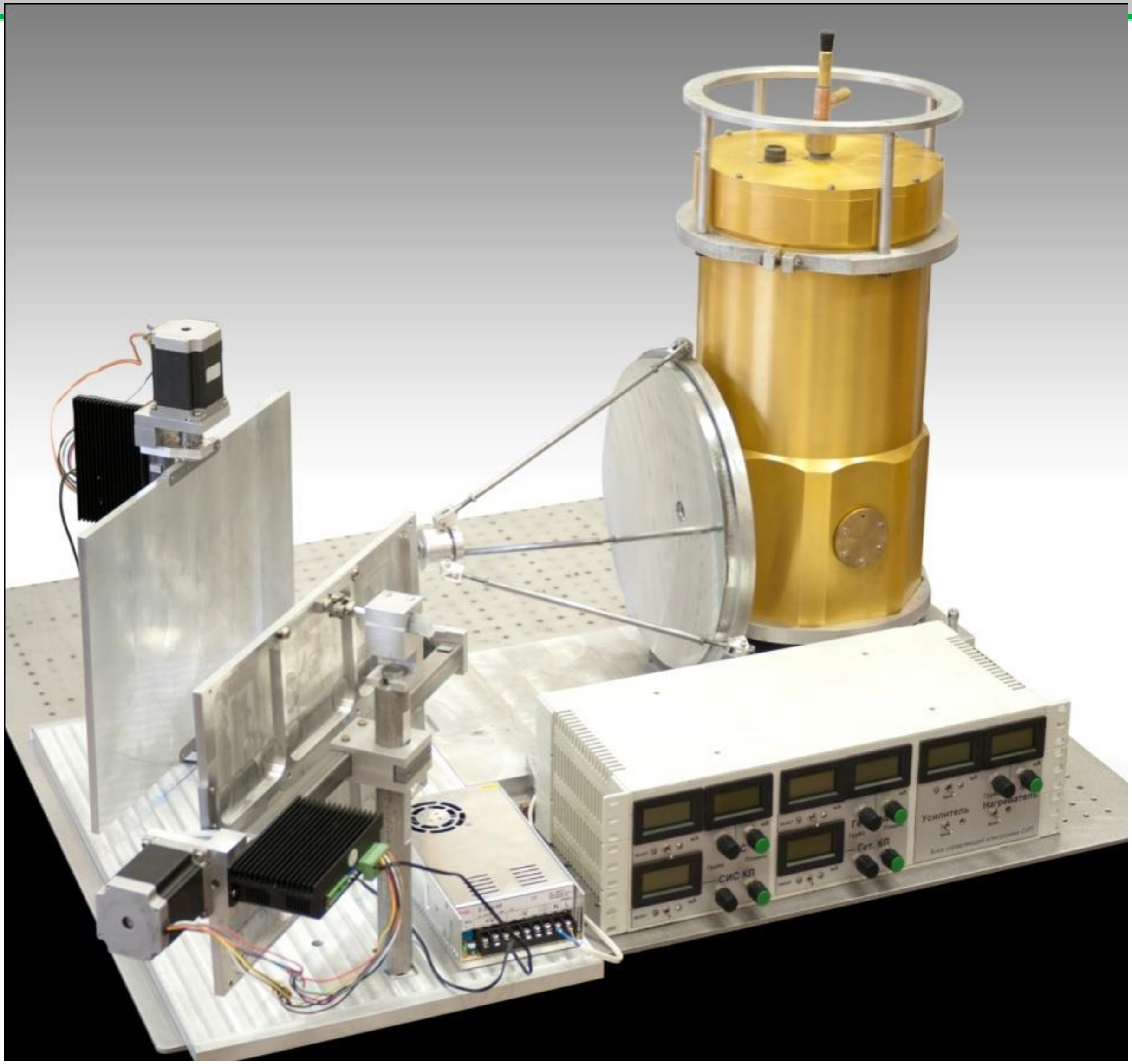
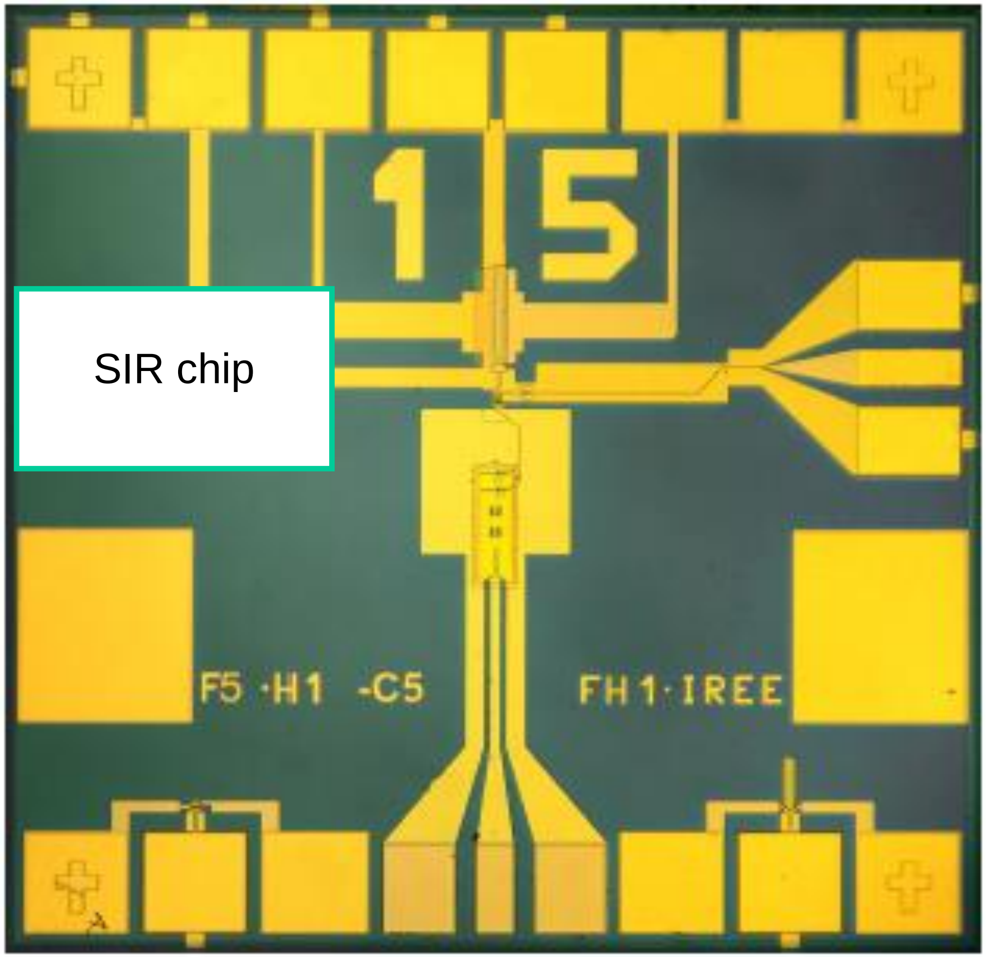
SCONTEL
SUPERCONDUCTING NANOTECHNOLOGY

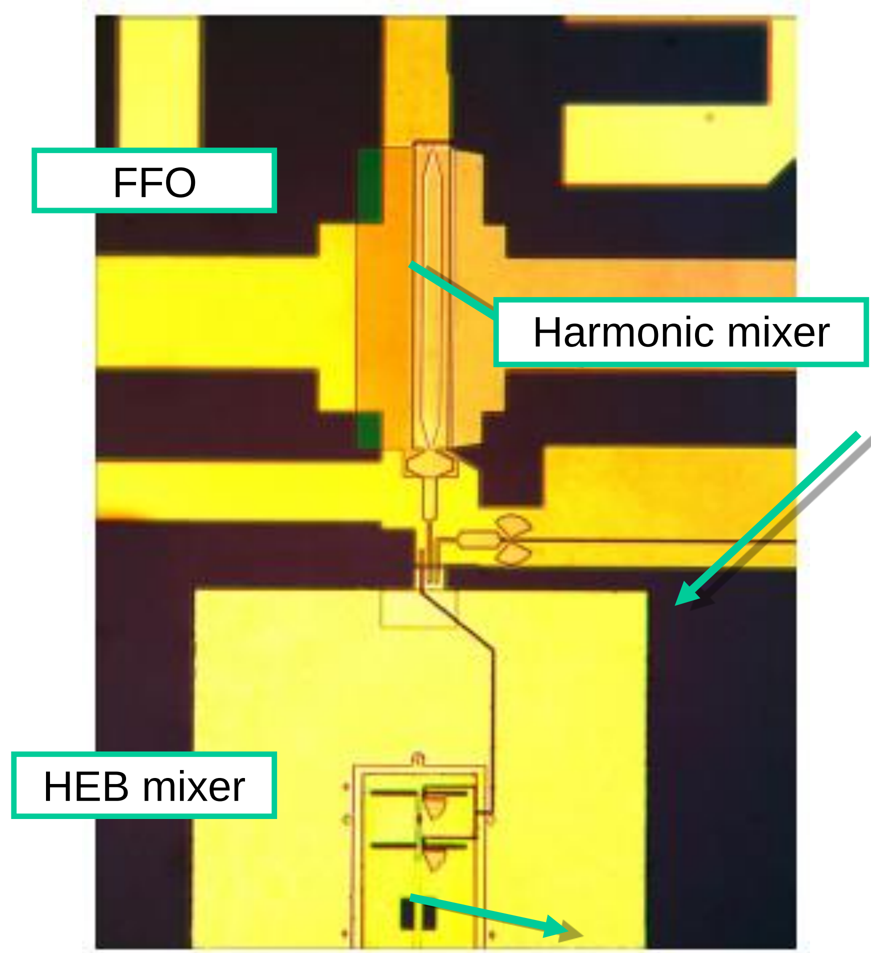


LO frequency: 470 - 660 GHz
Spatial resolution at 3m distance : <1 cm
Noise Equivalent Temperature Difference: 13 mK
Temperature resolution: ~1 K for picture quality 50x50 px
Distance to the object: 3 m
Primary mirror diameter: 30 cm
Picture acquisition time: ~10 sec

HEB mixer integrated with FFO local oscillator

MSPU





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Scanned images