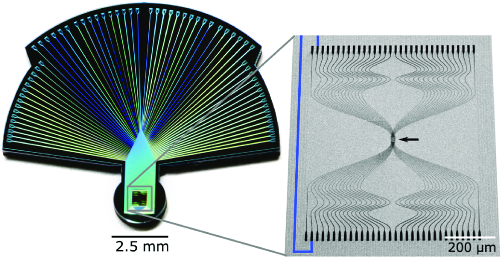
Superconducting Nanowire Single-Photon Detectors

Antonín Černoch and Jan Soubusta

Joint laboratory of optics of Palacky University and
Institute of Physics of the Czech Academy of Sciences



Obsah

Historical development

- 1911 superconductivity of metals discovered by Dutch physicist Heike Kamerlingh Onnes
- 1971 rate of change in resistance of a Pb superconductor when illuminated by a laser pulse
- 1977 constructed TES (Transition-edge sensor) working at the edge of superconductivity
- 1996 a superconducting sensor can work much faster than a thermal bolometer
- 2001 the first functional prototype of a detector based on a superconducting nanowire

SNSPD – *Superconducting Nanowire Single-Photon Detectors*

Characteristics of single-photon detectors

Spectral properties

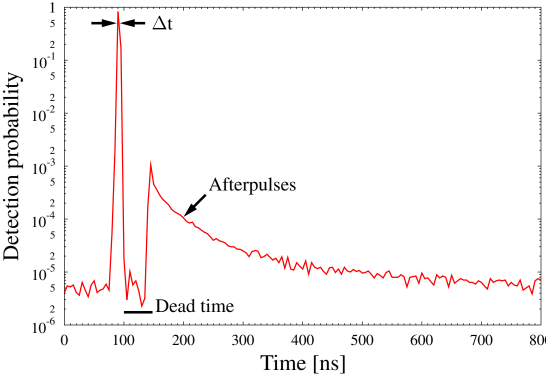
- dependence of quantum efficiency η on wavelength

Time characteristics

- dead time
- jitter (Δt)

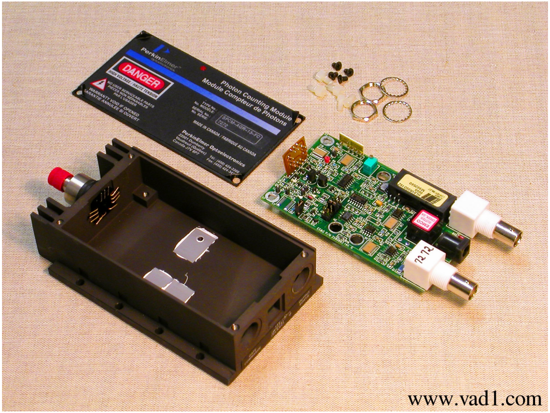
Noise properties

- Dark counts rate D
- Afterpuls probability



SPCM – Single photon counting module

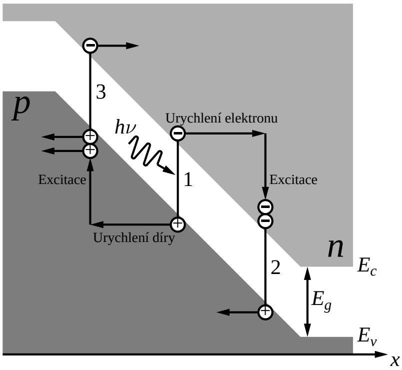
Perkin-Elmer EG&G SPCM-AQR-14(-FC) $\rightarrow$ TODAY Excelitas



- $\eta_{max} \sim 73\ \%$ 700 nm
- maximum repetition rate 16 MHz

- $D < 100/\mathrm{s}$
- Cooling to $-20\,^{\circ}\mathrm{C}$

Avalanche photodiode in geiger mode



- **p-n** or **p-i-n** junction
- applied voltage $V > V_{break}$
- avalanche multiplication
- active and passive avalanche suppression
- influence on dead time

Typical materials

VIS Si, 400 – 1 000 nm, $\eta_{max} = 75$ %, $D < 100$/s

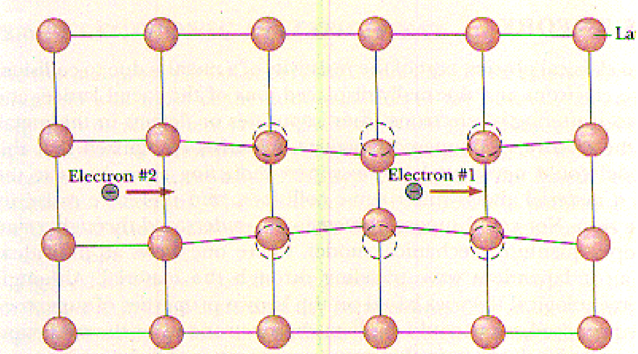
NIR Ge, InGaAs/InP, $\eta_{max} \sim 20$ %, $D \sim 5000/$s, slower

Cooper pairs

- Why does superconductivity work?
- Cooper pair binding energy is in units of meV
- Impact of a photon with an energy of units of eV will break hundreds of these pairs
- In the impact area, superconductivity is disrupted and a *hotspot* is formed

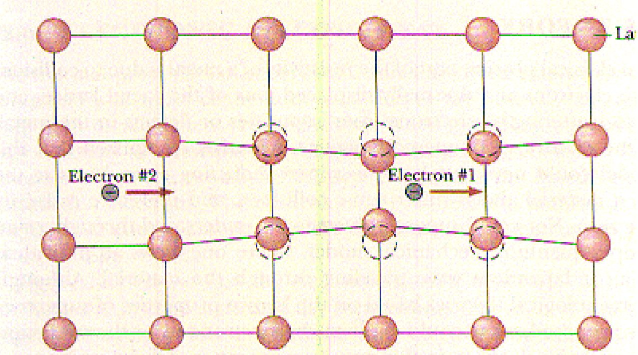
Cooper pairs

- Why does superconductivity work?
- Cooper pair binding energy is in units of meV
- Impact of a photon with an energy of units of eV will break hundreds of these pairs
- In the impact area, superconductivity is disrupted and a *hotspot* is formed



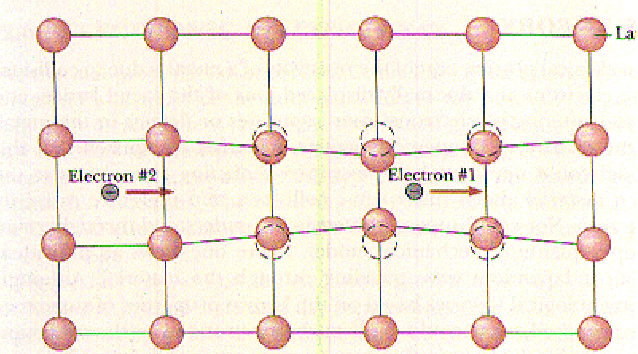
Cooper pairs

- Why does superconductivity work?
- Cooper pair binding energy is in units of meV
- Impact of a photon with an energy of units of eV will break hundreds of these pairs
- In the impact area, superconductivity is disrupted and a *hotspot* is formed



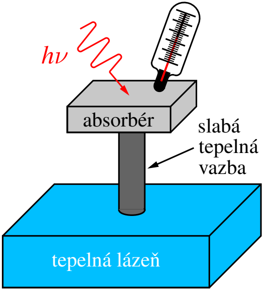
Cooper pairs

- Why does superconductivity work?
- Cooper pair binding energy is in units of meV
- Impact of a photon with an energy of units of eV will break hundreds of these pairs
- In the impact area, superconductivity is disrupted and a *hotspot* is formed



Obsah

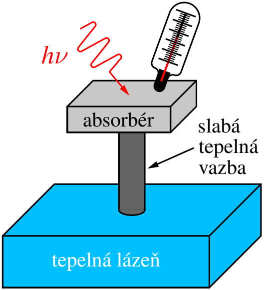
TES – *Transition Edge Sensor*



Microcalorimeter at the superconductivity edge

- increase of temperature → resistivity change
- superconductivity temperature $T_c \sim 100\,\text{mK}$
- narrow wolfram film $25 \times 25 \times 0.035\,\mu\text{m}^3$ on Si substrate with Al contacts
- wide-spectrum, calibration required according to photon energy ($E = hc/\lambda$)

TES – *Transition Edge Sensor*



Microcalorimeter at the superconductivity edge

- increase of temperature → resistivity change
- superconductivity temperature $T_c \sim 100\,\mathrm{mK}$
- narrow wolfram film $25 \times 25 \times 0.035\,\mu\mathrm{m}^3$ on Si substrate with Al contacts
- wide-spectrum, calibration required according to photon energy ($E = hc/\lambda$)

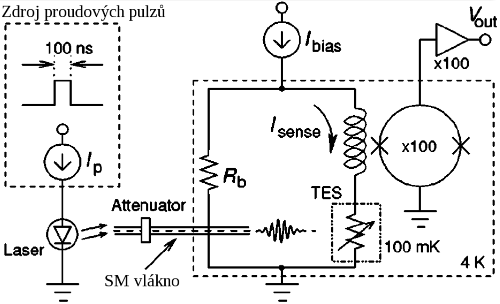
Quantum efficiency

- theoretically 80 %, in practise 20 % (for 1550 and 1310 nm)
- optical trap or rezonator → 95 %
- small absorption, great reflectance

TES – Functional diagram

Current pulse processing

- The current pulse in the detector circuit is proportional to the temperature change
- 100× SQUID (Superconducting Quantum Interference Device)
- SQUIDs @4 K, other electronics are at room temperature



Miller *et al.*, App. Phys. Lett. **83**, 791 (2003)

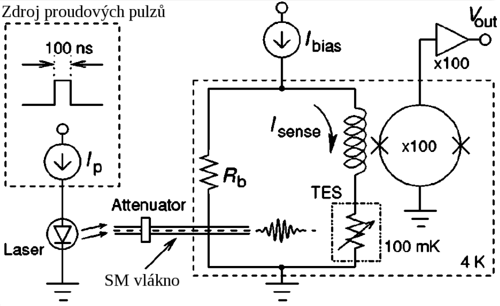
TES – Functional diagram

Current pulse processing

- The current pulse in the detector circuit is proportional to the temperature change
- 100× SQUID (Superconducting Quantum Interference Device)
- SQUIDs @4 K, other electronics are at room temperature

Properties of TES

- slow (heat conduction) – $\Delta t \approx 100\,\text{ns}$, $\tau_D \approx 2\,\mu\text{s}$
- negligible $D \approx 3\,\text{Hz}$
- resolution of up to 8 photons in the range from 200 to 1800 nm



Miller *et al.*, App. Phys. Lett. **83**, 791 (2003)

Obsah

Quid pro quo

What do we want?

- increase efficiency
- speed up the detection process
- reduce timing jitter
- keep D small

Quid pro quo

What do we want?

- increase efficiency
- speed up the detection process
- reduce timing jitter
- keep D small

What are we willing to sacrifice?

- NOTHING
- ...
- If there has to be something, then e.g. the resolution of the number of photons.

Quid pro quo

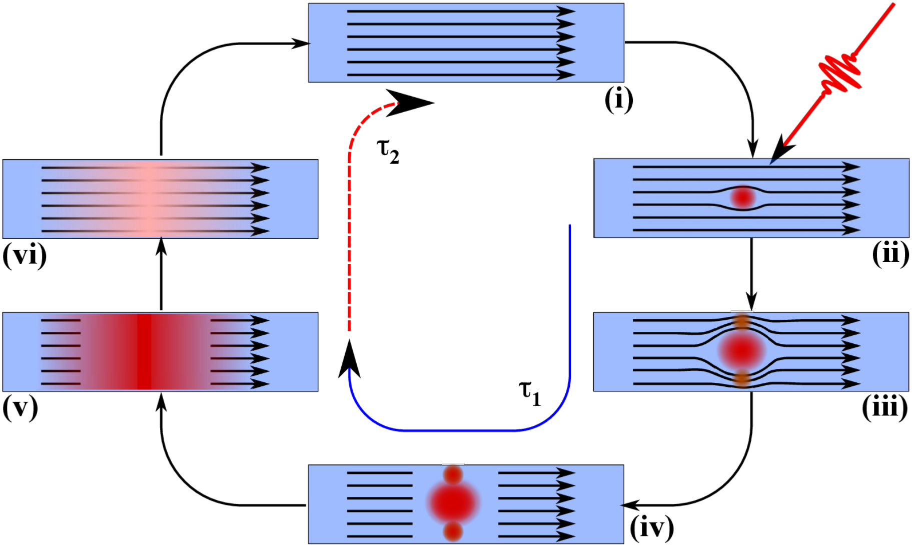
What do we want?

- increase efficiency
- speed up the detection process
- reduce timing jitter
- keep D small

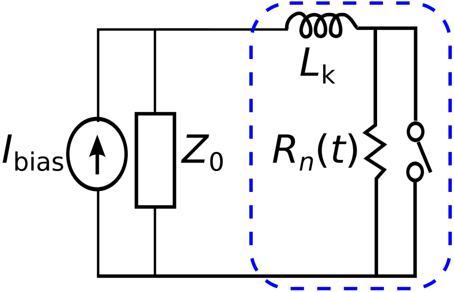
What are we willing to sacrifice?

- NOTHING
- ...
- If there has to be something, then e.g. the resolution of the number of photons.

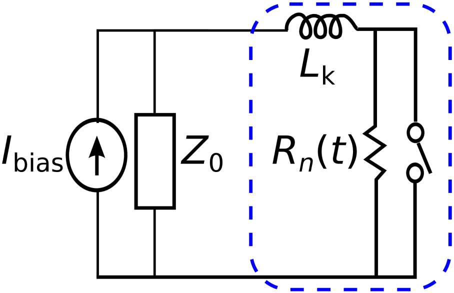
Principle of detection in a nanowire



Replacement electrical diagram



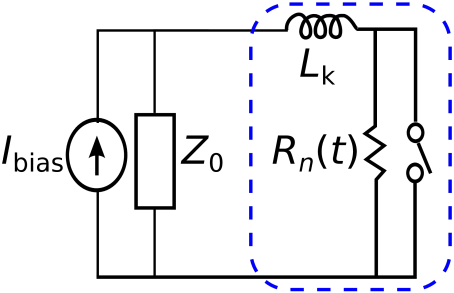
Replacement electrical diagram



kinetic inductance L_k

inductance – the magnetic field causes inertia of the current direction
kinetic inductance even without a coil – in superconductors with very high current density and at very high frequencies

Replacement electrical diagram



- detection voltage pulse very weak (µV)
- cryogenic amplifiers 30 dB (1-2 GHz bandwidth)
- another broadband amplifier at room temperature 20 dB (9 GHz)
- output detection pulse 300 – 400 mV, SNR 100:1

kinetic inductance L_k

inductance – the magnetic field causes inertia of the current direction
kinetic inductance even without a coil – in superconductors with very high current density and at very high frequencies

Quantum efficiency

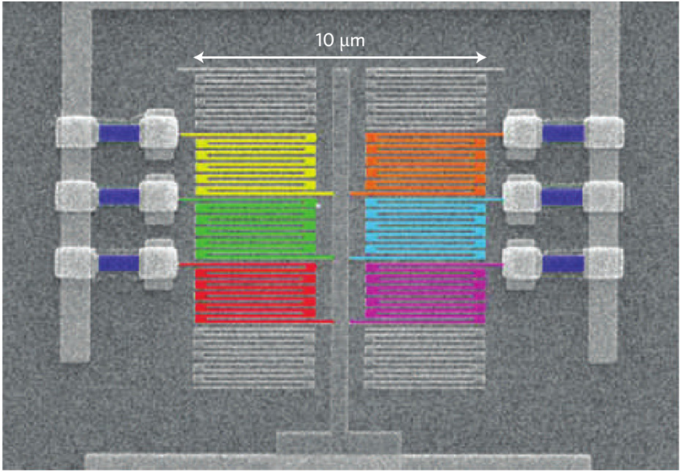
limited nanowire width → small area ⇒ meanders

Efficiency

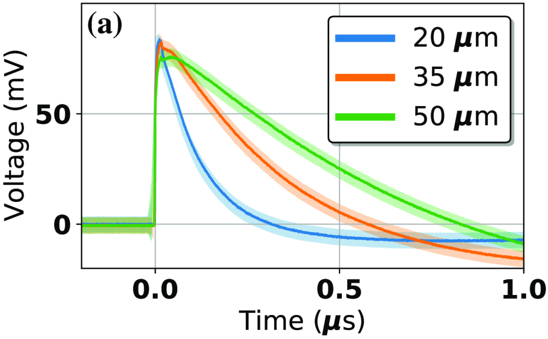
- coupling
- absorption
- recognizing

DDE or SDE

Optimization for various applications see design



Time properties



leading edge τ_1

$\approx$ 1 ns

trailing edge τ_2

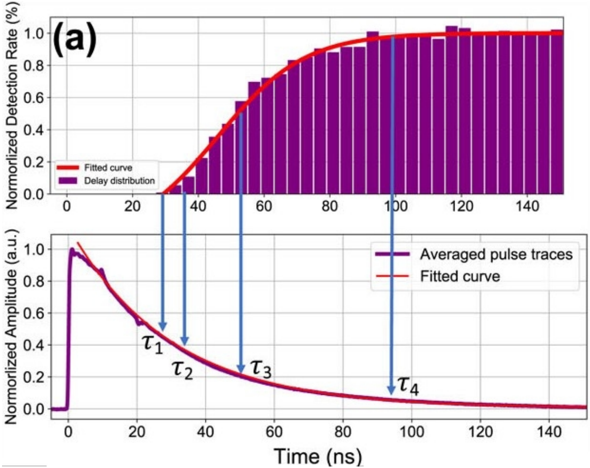
from units to hundreds of nanosecond depending on the active area of the meander (length of the nanowire)

timing jitter Δt

- multiple sources: detector, amplification electronics, photon source or detection oscilloscope
- greatest influence nanowire length

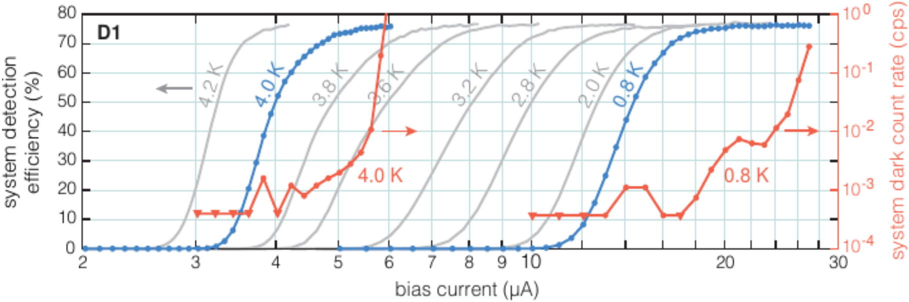
detection efficiency × dead time τ_d

- the hit section of the nanowire is not in a superconducting state
- substrate temperature (reservoir) significantly below T_c, as it goes



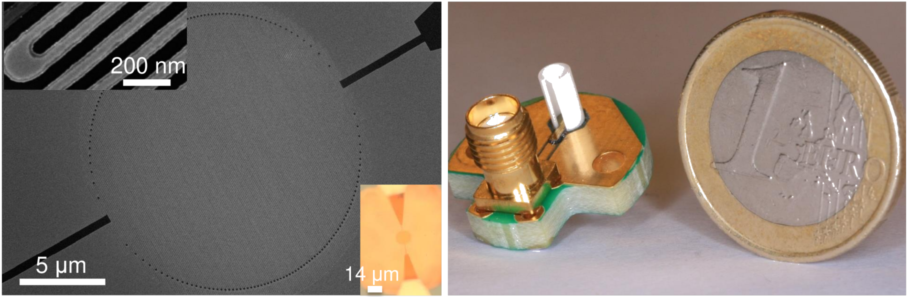
Dark counts D

- outer – small excitation energy of Cooper pairs ⇒ cooled filters
- inner – current fluctuations, grow exponentially with I_{sw}, for 0.9 I_{sw} they are negligible
- lower temperatures → better SNR



Obsah

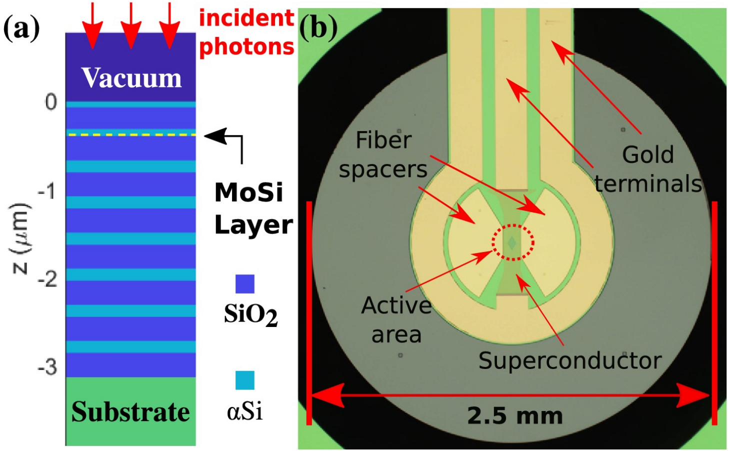
Perpendicular to the optical fiber tip



- diffraction limit or beam path from an optical fiber $10 \times 10\,\mu m^2$ pro 1550 nm
- centering of the optical fiber relative to the sensor when the temperature changes
- narrower nanowire $\rightarrow$ greater probability of recording, but smaller area $\rightarrow$ longer meander $\rightarrow$ larger Δt
- optimization of meanders for given applications and wavelengths

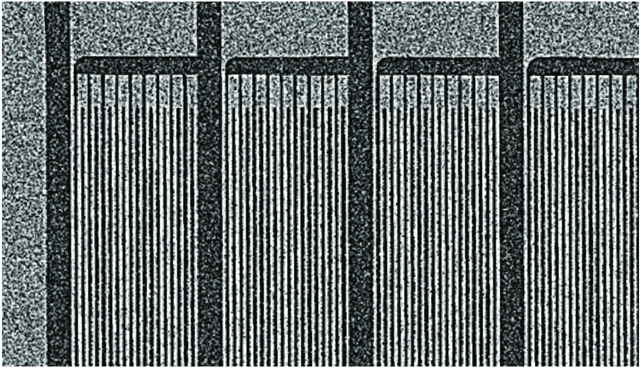
Nanowire in a resonator

- the nanowire itself has an absorption efficiency of only 30 %
- mirrors below (and above) from Au, Ag or dielectric Bragg mirror



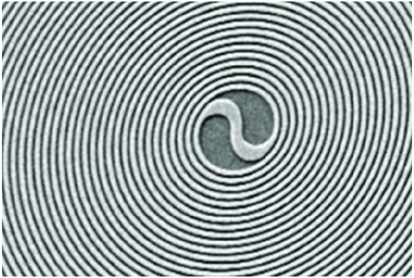
Segmentation

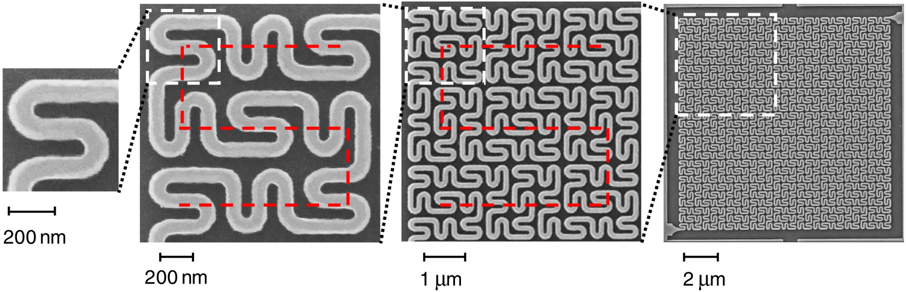
- division of the meander into several segments with separate reading
- increase in counting frequency or resolution in the number of photons
- possibility of crosstalk if nanowires are close to each other



Polarization dependence

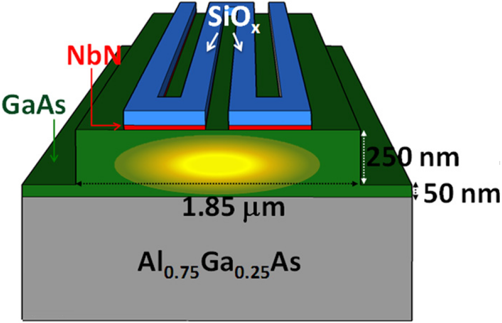
- pronounced anisotropy of meanders
- polarization in the direction of the nanowire has less absorption than perpendicular one
- new shapes - spirals, fractals





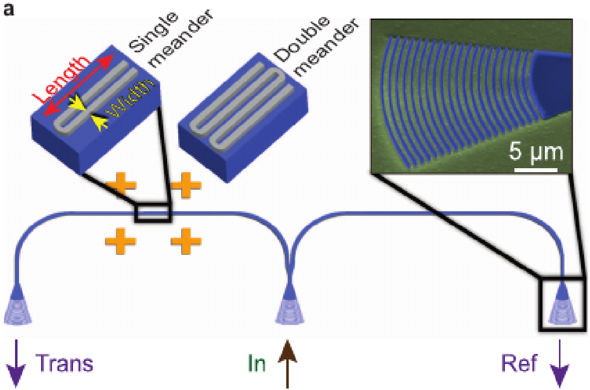
Nanowire on top of waveguide

- integrated optics – generation, processing and detection of light in a waveguide
- eliminates the problem of inefficient coupling into or decoupling from a material with a high refractive index
- energy transfer through an evanescent wave

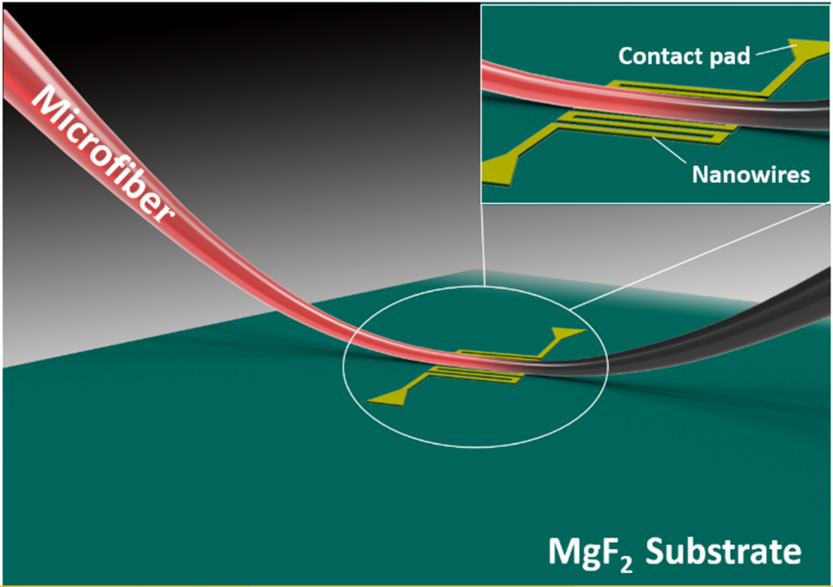


Results are improving very quickly

- shape and length of meander optimized with respect to wavelength and guided mode profile
- short meander $\rightarrow$ faster response (hundreds of MHz)
- maximum DDE 66 % (for 0.96 $I_{\mathrm{sw}} \rightarrow D = 1.8\,\mathrm{kHz}$)

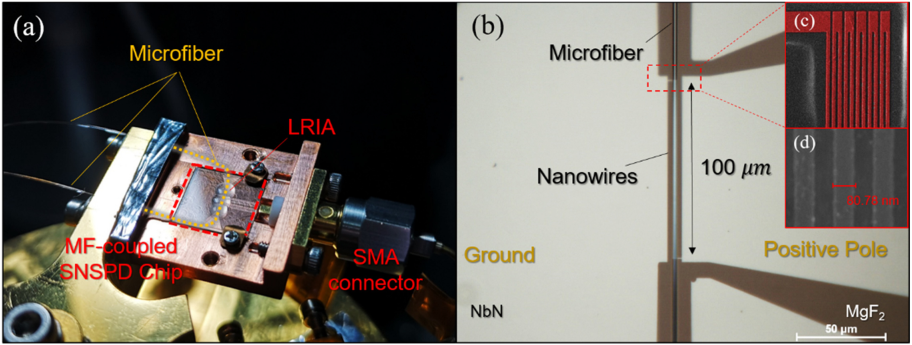


Microfiber for focusing



Results are improving very quickly

- typical fiber core diameter for 1550 nm $\sim$ 6 µm
- microfiber without cladding tapered down to 1.3 µm $\rightarrow$ significant losses, more pronounced for longer wavelengths
- experimental SDE 45 % and $D = 50$ Hz for 1550 nm



Obsah

Maximal secret bit rate

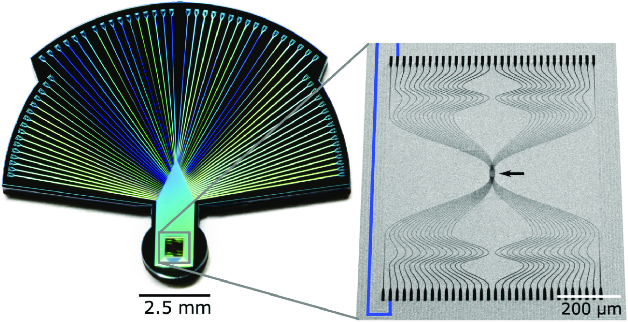
- counting frequency 10 GHz
- $\Delta t < 10$ ps (3 ps)
- best SDE 100 % (98 %)
- noise-free (6×10^{-6} Hz)

Record holders in individual categories?

who will win the modern pentathlon?

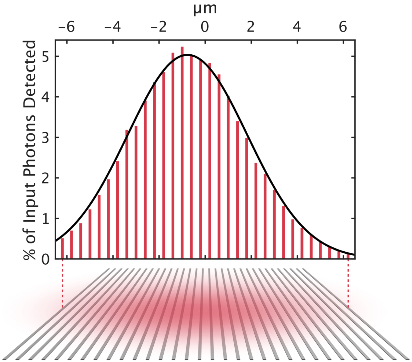
PEACOQ *Optica* **10**, 183 (2023)

Performance-Enhanced Array for Counting Optical Quanta



- 32 individually read nanowires 13 µm long
- all electrical contacts have the same length

Performance



- probability of crosstalk 0.5 %
- efficiency of one segment multiplied by 25 → SDE (78 ± 4) %
- dead time 5 ns + 2 ns for SDE at least 25 % → 143 MHz
- polarization independent
- technically possible to realize photon counting

All together: for 1 GHz has SDE 50 % and a timing jitter 46 ps

QKD at a distance of 100 km (source 10 GHz, $\langle n \rangle = 0.025$ per pulse, 0.2 dB km^{-1}) will reach 70 Mbit/s secret key rate.

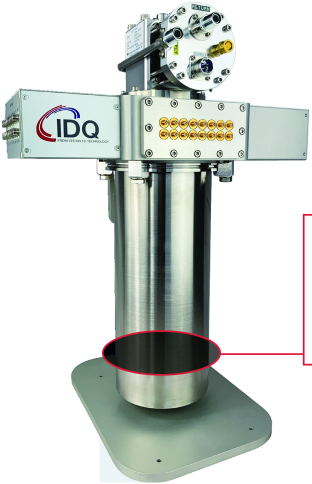
Obsah

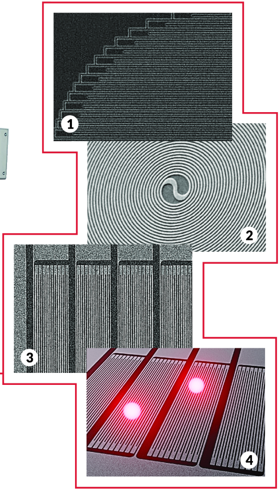
Manufacturers and suppliers

ID Quantique

- spin-off
  prof. N. Gisin (Genf)
- support for their QKD
- up to 16 different sensors in one cryostat

www.idquantique.com

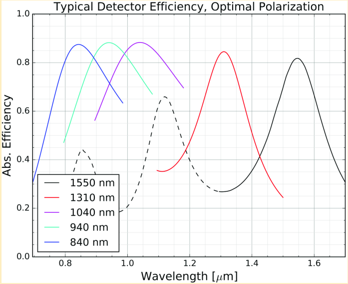




Photon Spot (USA) www.photonspot.com

- spin-off dr. Anant
- custom-made
- NIST certificate: 1550 nm SDE 95.5 % for 100 kHz

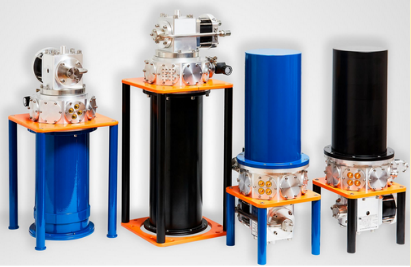
Quantum Opus (USA) www.quantumopus.com



- spin-off dr. A. J. Miller
- model Opus One, up to 16 sensors, rack mountable
- cheapest configuration for $105 000

Scontel (Russia) www.scontel.ru

- founded in 2004 by Prof. G. Gol'tsman and his students
- 5 types of models optimized for efficiency, low noise, wide-spectrum response



Single Quantum (Netherlands) www.singlequantum.com

- on the market since 2012, involved in the EuroQCI project
- sensors optimized for 800, 900, 1064, 1310 and 1550 nm

Comparison 1550 nm

	ID Quantique		Photon	Quantum	Scontel	Single
	ID230	ID287*	Spot*	Opus		Quantum
SDE [%]	25	95	85	80	90	85
D [Hz]	50	0.01	100	100	100	10
Δt [ps]	150	24	30	100	50	20
CR [MHz]	0.5	100	20	20	67	50

What to say in conclusion?

Recommended literature

- G. N. Gol'tsman *et al.*, "Picosecond superconducting single-photon optical detector", *Appl. Phys. Lett.* **79**, 705 (2001).
- Ch. M. Natarajan, M. G. Tanner and R. H. Hadfield, "Superconducting nanowire single-photon detectors: physics, and applications", *Supercond. Sci. Technol.* **25**, 063001 (2012); ArXiv quant-ph 1204.5560.
- Lixing You, "Superconducting Nanowire Single-Photon Detectors for Quantum Information", arXiv quant-ph 2006.00411 (2000).
- I. Craiciu *et al.*, "High-speed detection of 1550 nm single photons with superconducting nanowire detectors", *Optica* **10**, 183 (2023).

AI was used to create several images in this presentation.

What to say in conclusion?

Thank you for your attention !

Recommended literature

- G. N. Gol'tsman *et al.*, ”Picosecond superconducting single-photon optical detector”, *Appl. Phys. Lett.* **79**, 705 (2001).
- Ch. M. Natarajan, M. G. Tanner and R. H. Hadfield, ”Superconducting nanowire single-photon detectors: physics, and applications”, *Supercond. Sci. Technol.* **25**, 063001 (2012); ArXiv quant-ph 1204.5560.
- Lixing You, ”Superconducting Nanowire Single-Photon Detectors for Quantum Information”, arXiv quant-ph 2006.00411 (2000).
- I. Craiciu *et al.*, ”High-speed detection of 1550 nm single photons with superconducting nanowire detectors”, *Optica* **10**, 183 (2023).

AI was used to create several images in this presentation.