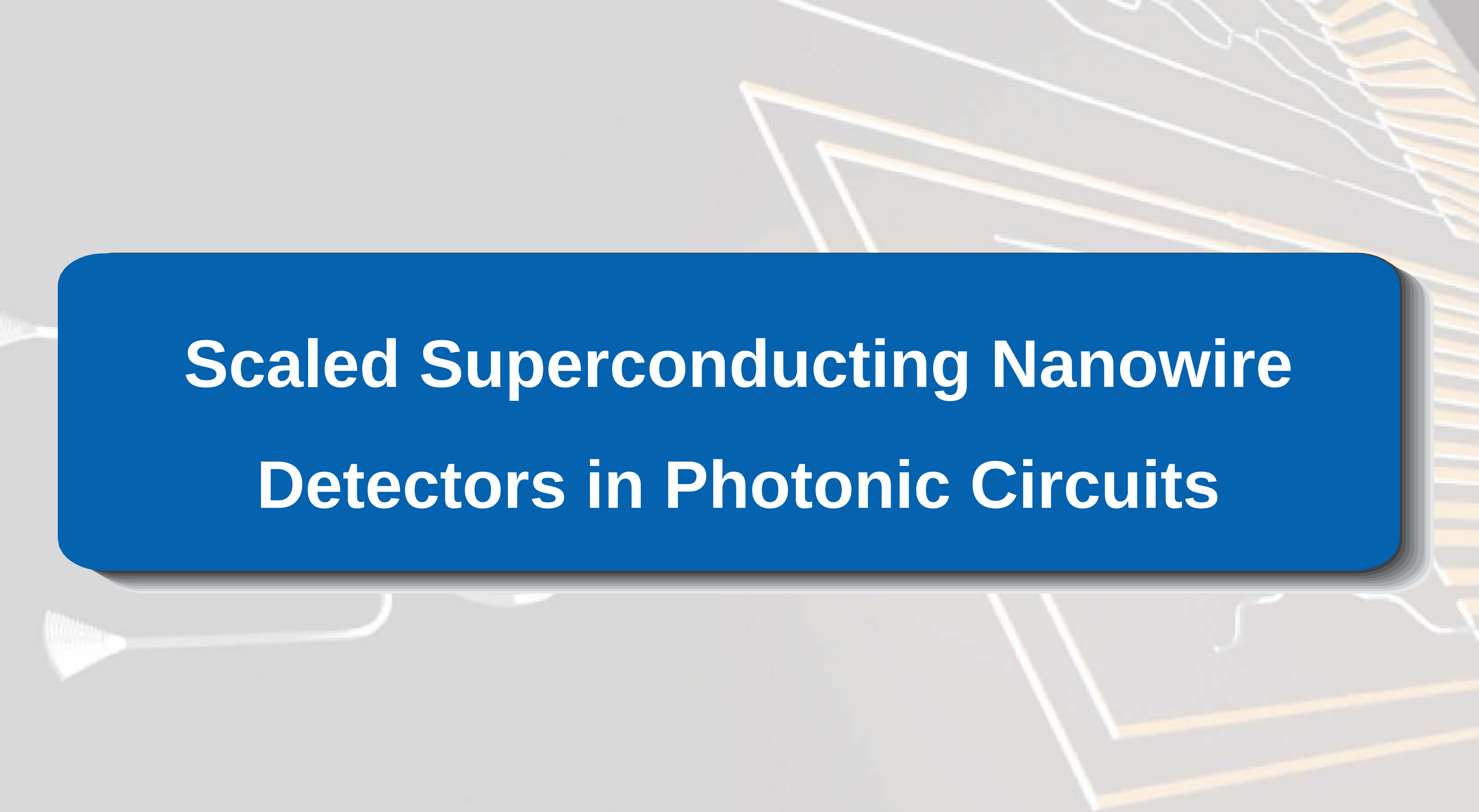


Scaled Superconducting Nanowire Detectors in Photonic Circuits

Hong Tang

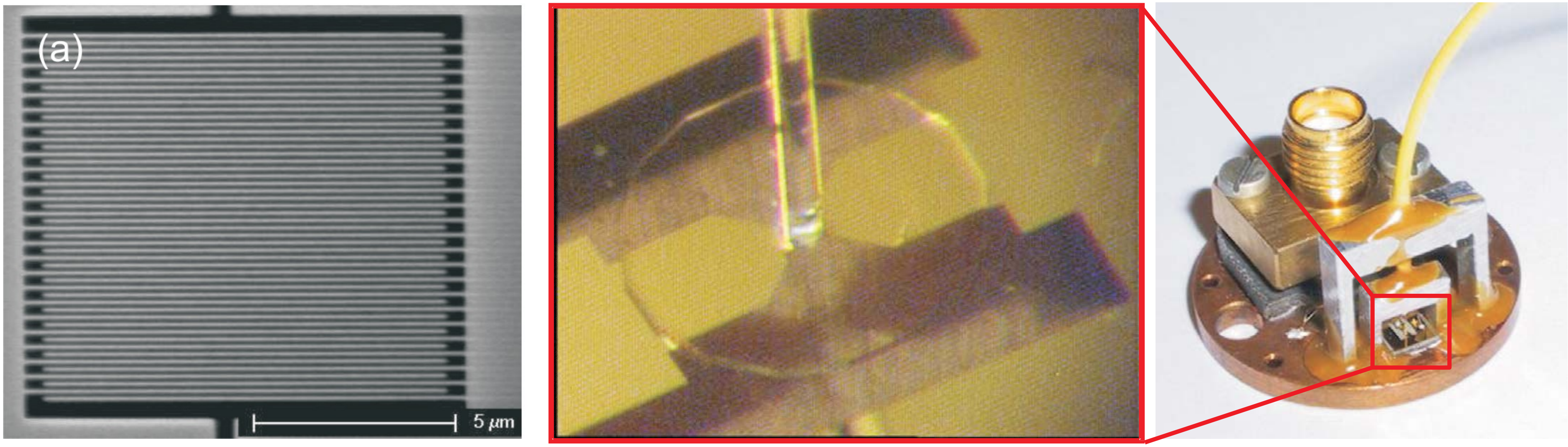
Yale University, Dept. of Electrical Engineering, New Haven, CT, USA

Single-photon detectors

Desired features of single-photon detectors:

- high detection efficiency
- low dark count rate
- high speed
- high timing accuracy
- sensitivity from VIS-MIR
- many of them!

Superconducting single-photon detectors

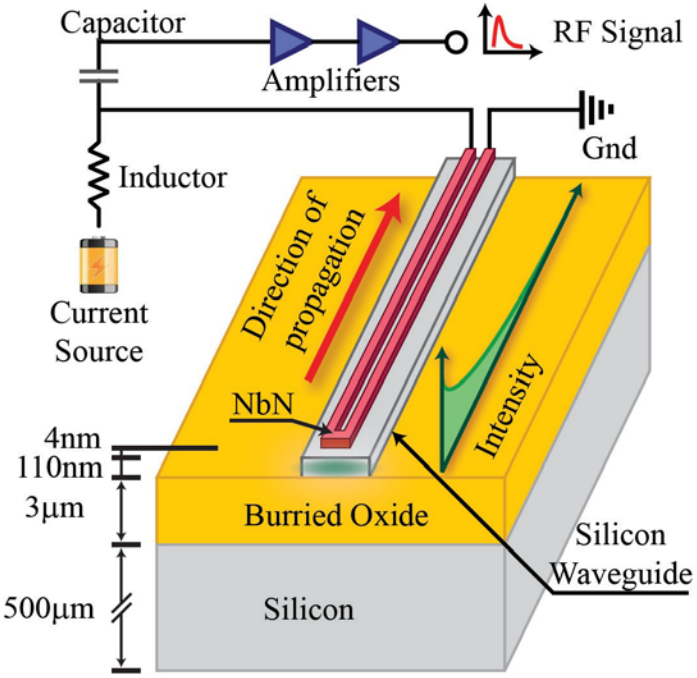


Dorenbos, TU-Delft (2011)

- meander of nanowires fabricated from 4nm NbN thin-film
- active area ~ 10x10 µm, nanowire widths ~100nm
- absorb photons under normal incidence from optical fiber
- cool below critical temperature (Tc = 11K)
- dc-bias close to critical current (Ic = 10-30µA)
- ~ 20% single pass absorption efficiency

Superconducting single-photon detectors

SSPD fully integrated with nanophotonic circuitry



<u>NbN on Si:</u>

W.H.P. Pernice et al.,
Nat. Comm. 3, 1325 (2012)

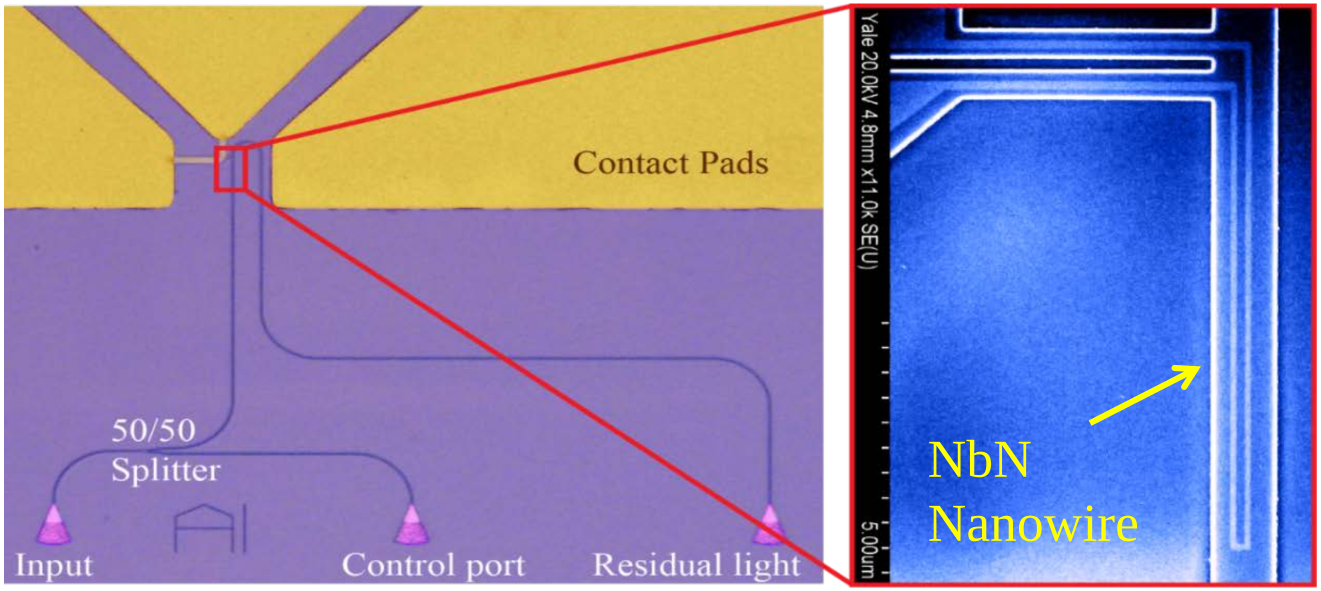
Schuck et al.,
IEEE Trans. ASC 23, 2201007 (2013)

<u>NbTiN on SiN:</u>

Schuck et al.,
APL 102, 051101 (2013)
Schuck et al.,

Sci. Rep. 3, 1893 (2013)
Schuck et al.,
APL 102, 191104 (2013)

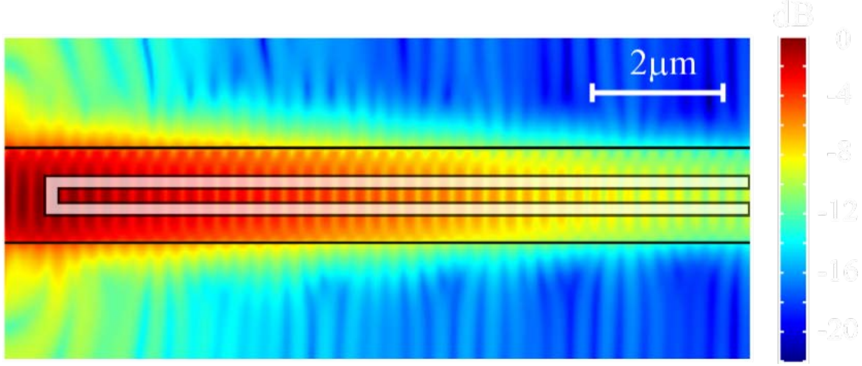
Waveguide micro-SSPD: NbN on Si waveguide



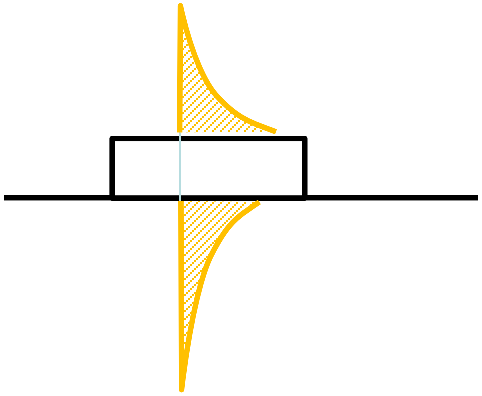
W. Pernice, C. Schuck, O. Minaeva, M. Li, G. N. Goltsman, A. V. Sergienko, H. X. Tang, Nature Communications, 2012

Travelling wave design

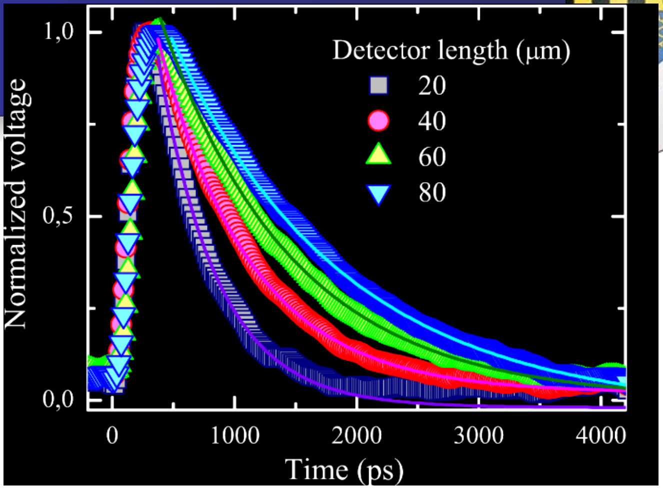
- Waveguide coupling allows for absorption engineering
- Plasmonic coupling of NbN wire to evanescent waveguide mode



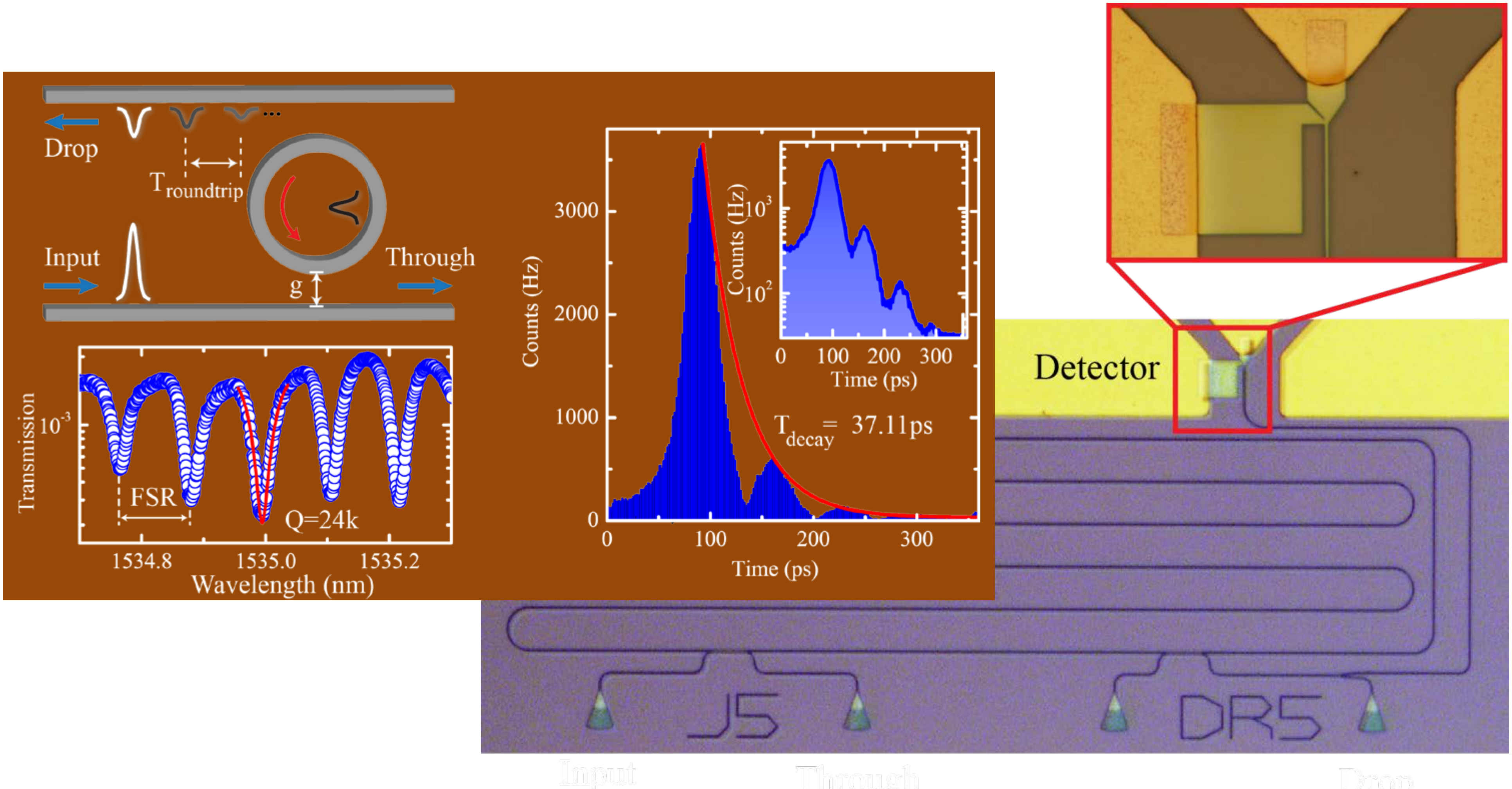
Absorption rate: 1dB/μm



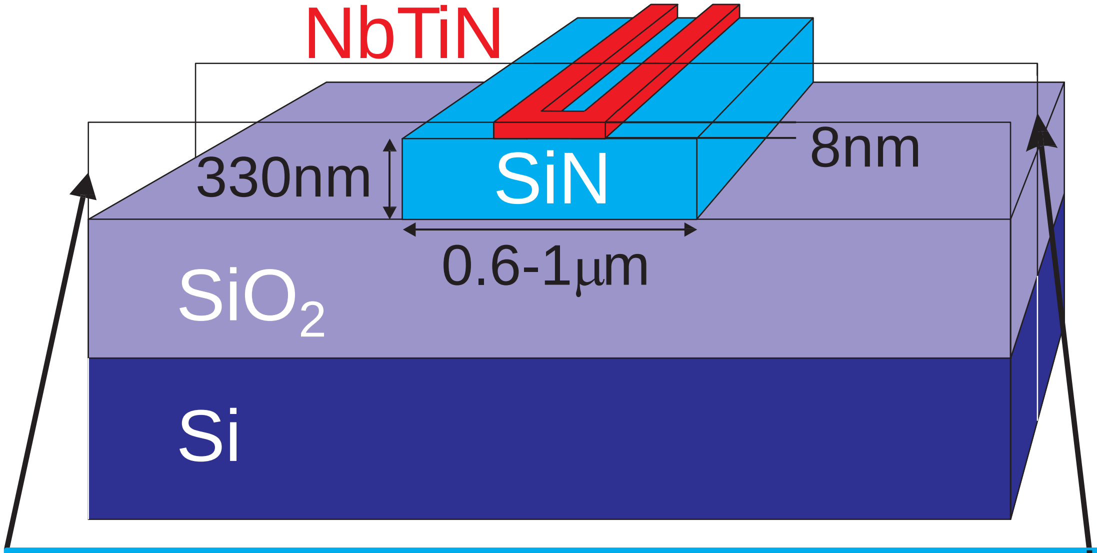
Jitter



- Jitter = 18.4ps
- 5.8mm Ring, Propagation loss of 4dB/cm
- Decay 37ps => round trips are observed



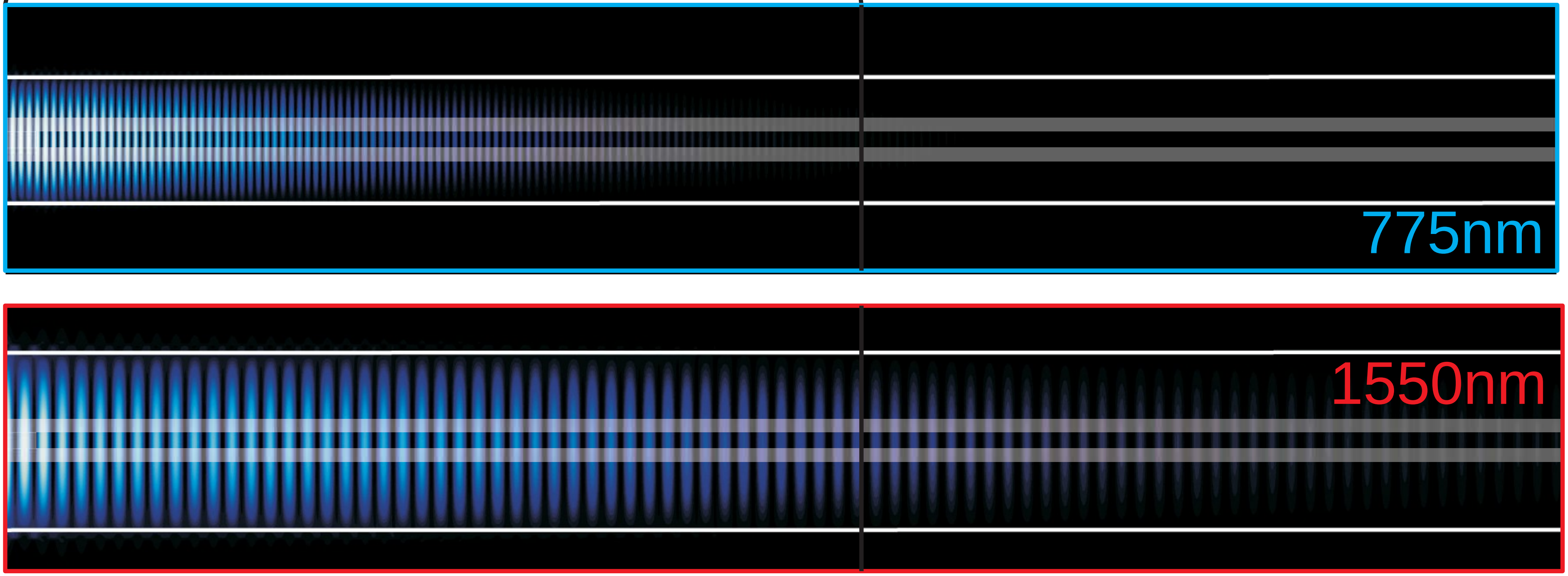
Efficient photon absorption on-chip



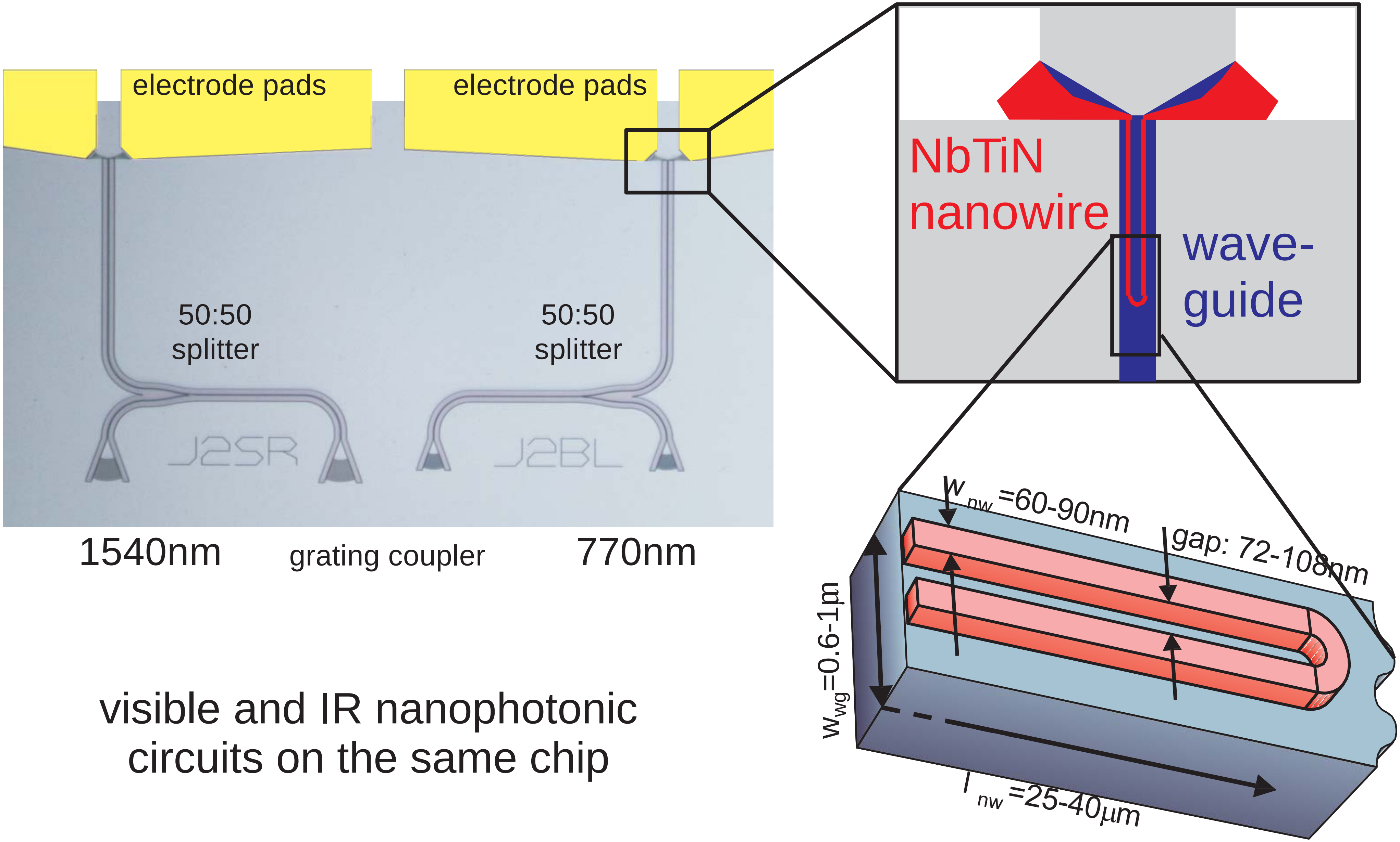
FDTD-simulations

775nm light: 0.71 dB/μm
→ 99.9% absorption for 40μm

1550nm light: 0.33 dB/μm
→ 95.2% absorption for 40μm

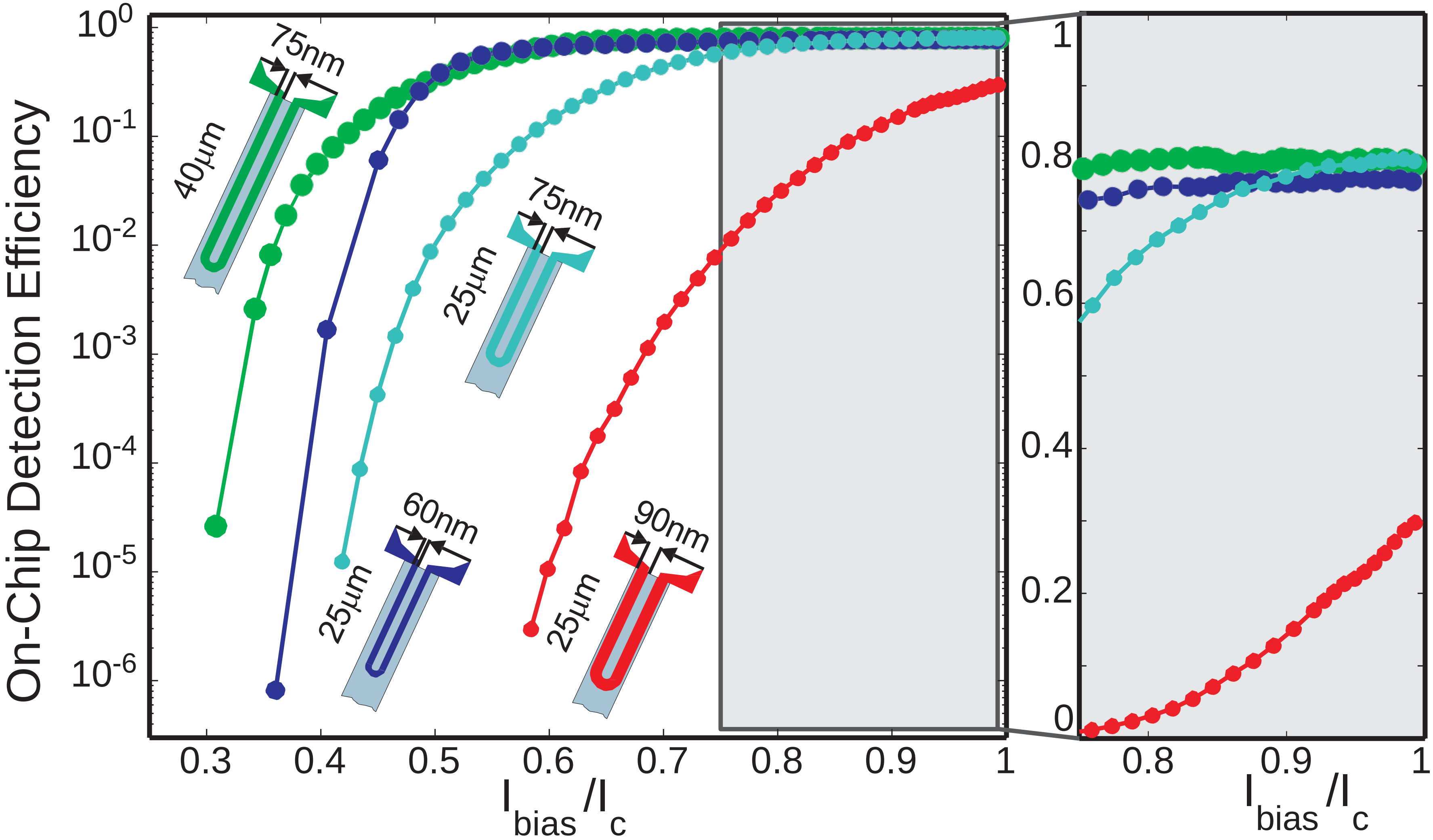


NbTiN-SSPDs on SiN waveguides



visible and IR nanophotonic
circuits on the same chip

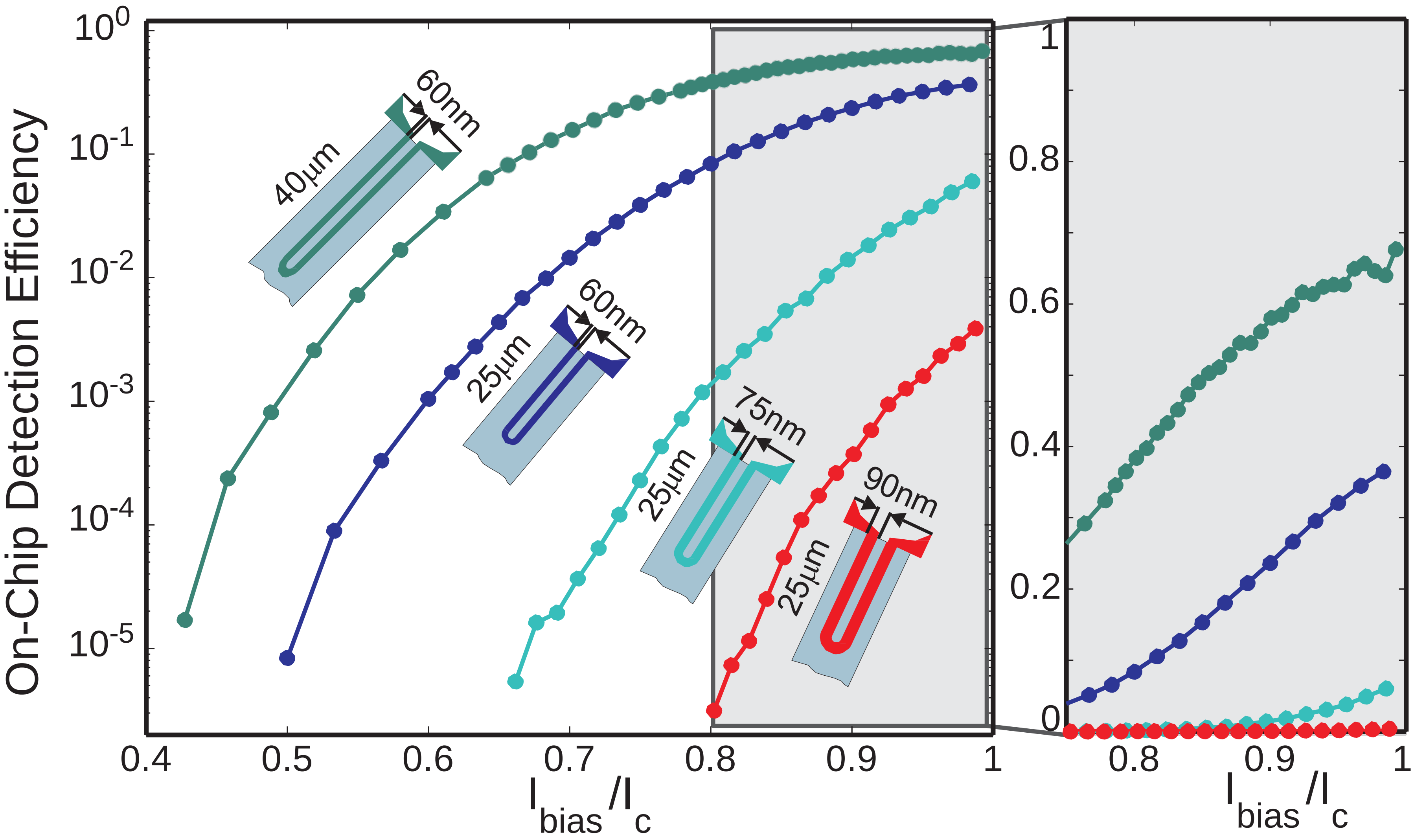
Detection efficiency: 768nm



Detection efficiency ∝ hotspot size (∝ photon energy):

saturation @ 80% when hotspot diameter ~ nanowire width

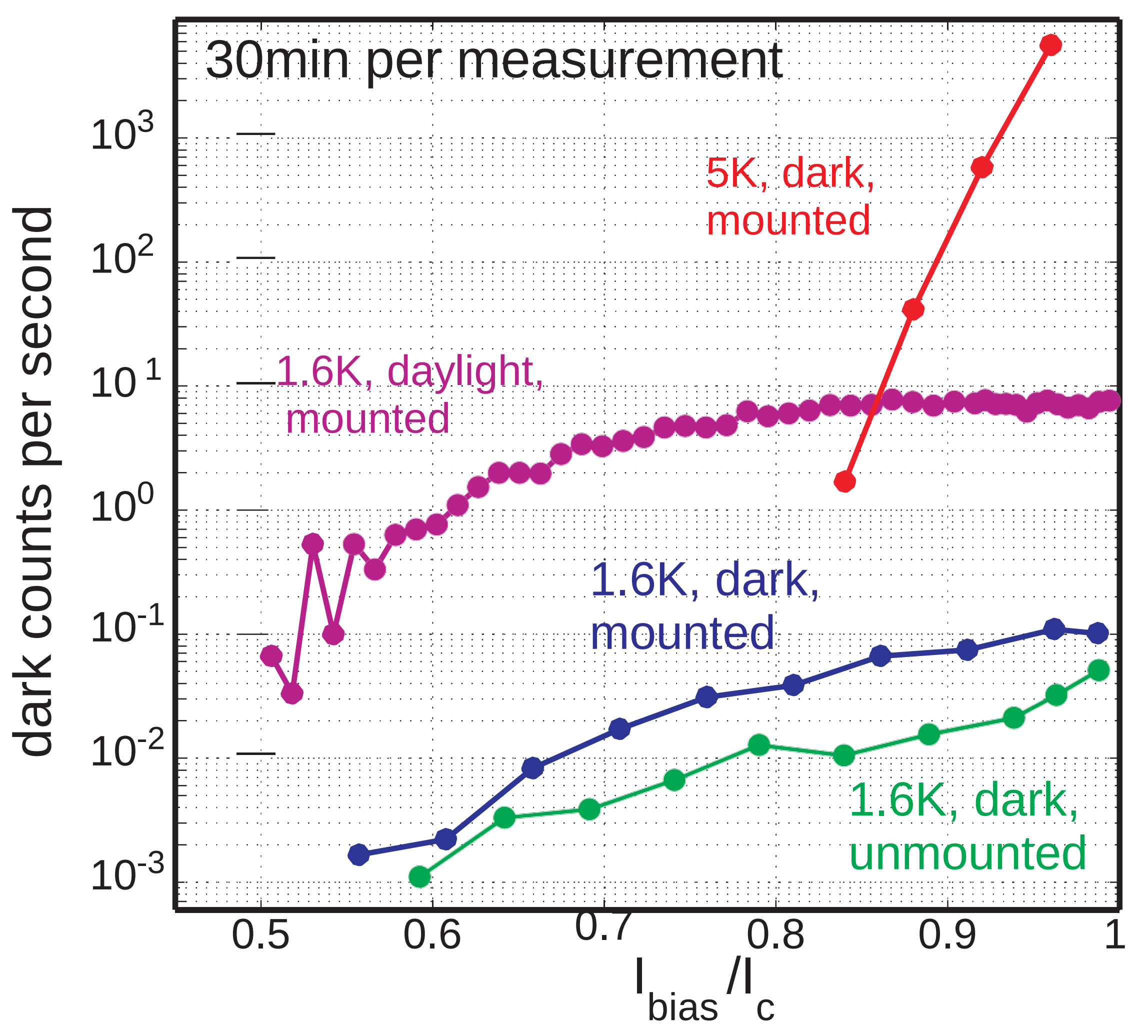
Detection efficiency: 1542nm

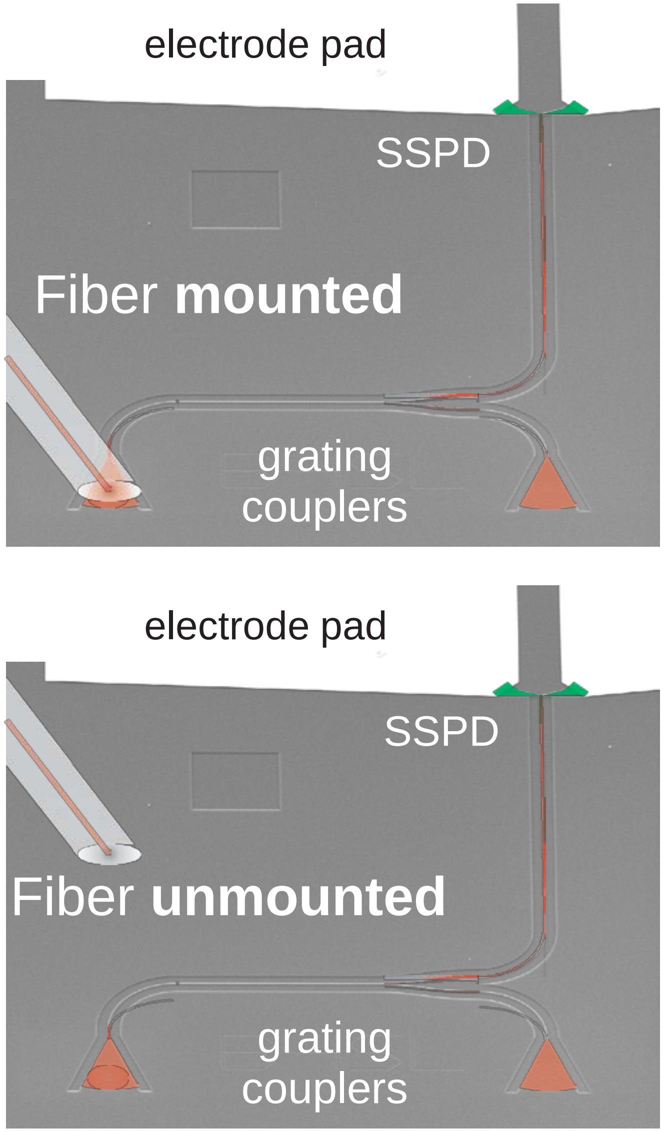


Optimize nanowire geometry for optimal performance:

decrease nanowire width & increase length: 68% OCDE @ 99% Ic

Low dark count rate

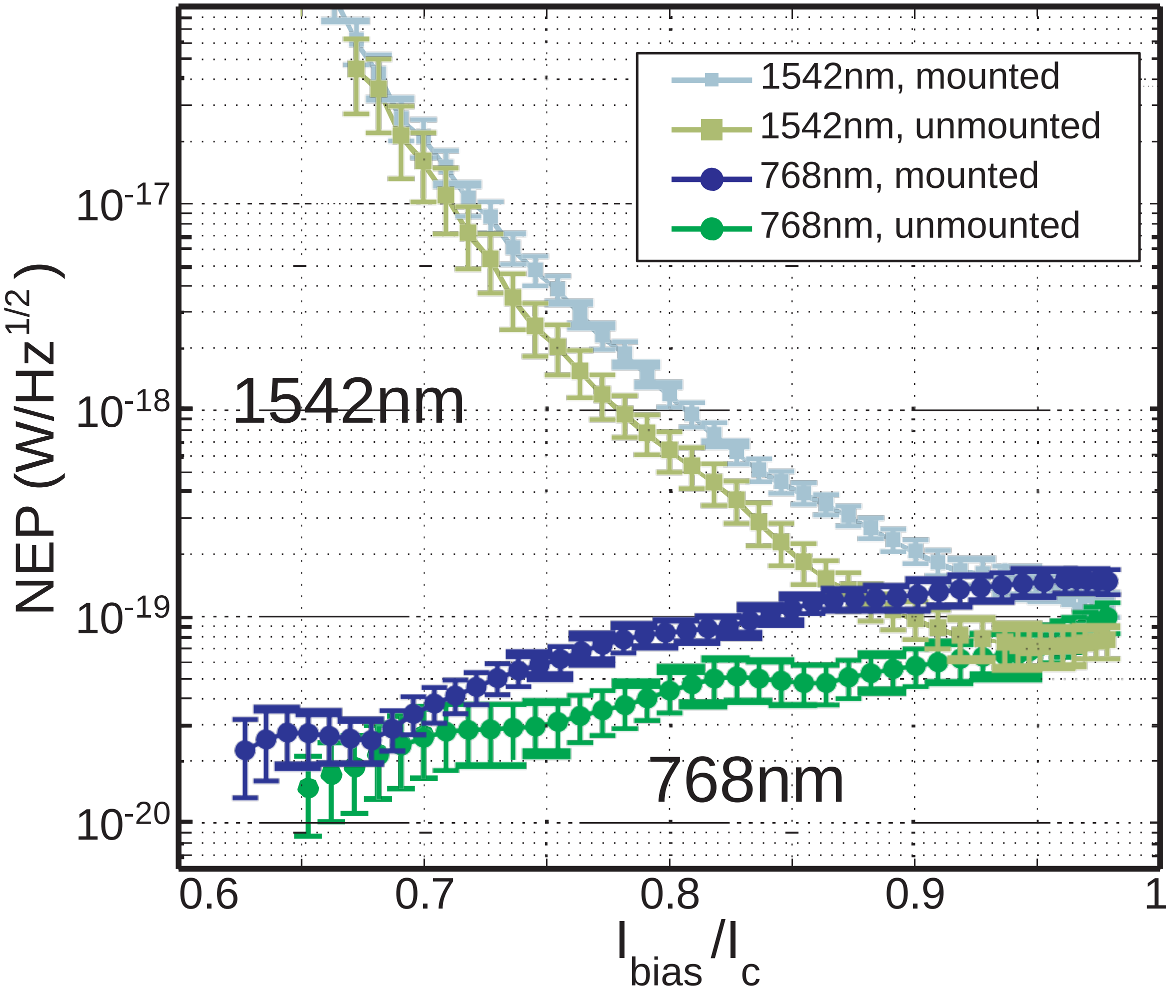




DCR: 1-100mHz (60%-99% Ic)

1.6K: decoherence mechanisms are suppressed below stray light-level!

Low noise equivalent power



$$NEP = \frac{h\nu\ (2\ DCR)^{1/2}}{DE_{on\text{-}chip}}$$

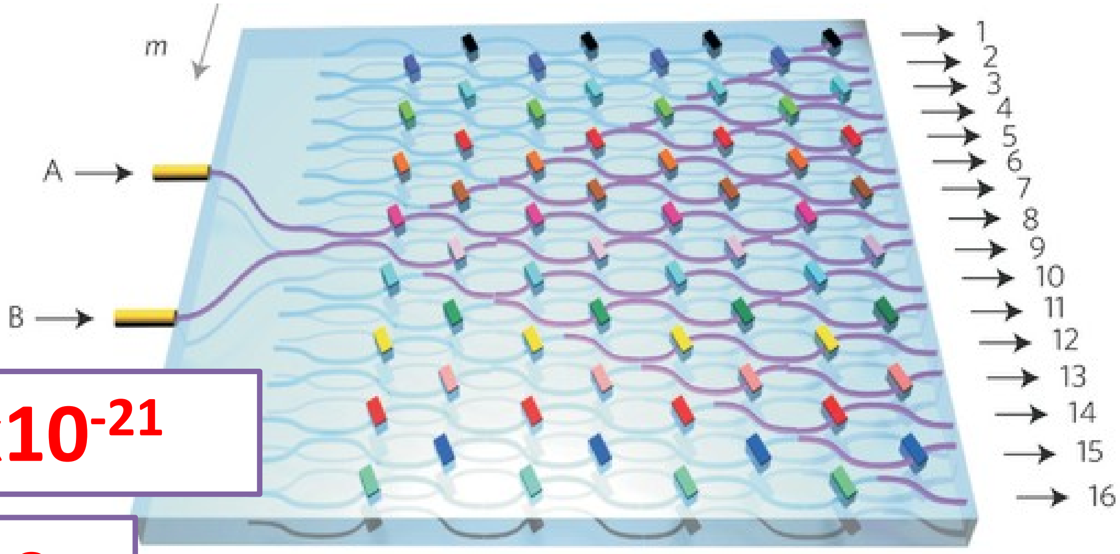
768nm (on-chip)	1542nm (on-chip)	1542nm (system)
2x 10^{-20} @ 65% Ic	7x 10^{-20} @ 94% Ic	8x 10^{-18} @ 95% Ic

Detectors for integrated photonics

Applications:

- **integrated quantum optics**
- quantum cryptography
- **sensing (optical time domain reflectometry)**
- spectroscopy & biomedical applications

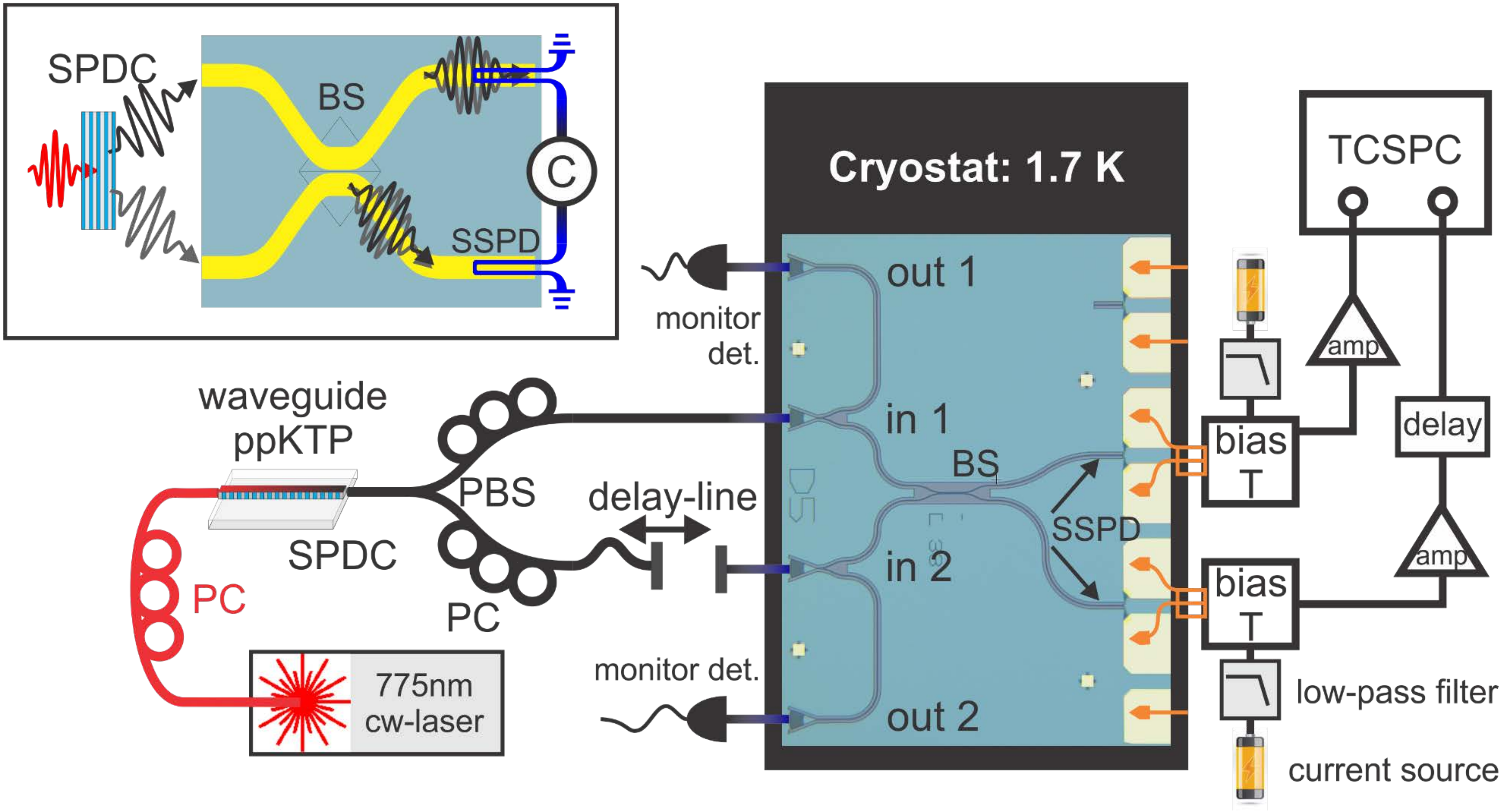
Scalable quantum information processing needs efficient interfaces between source circuit & detectors.



$(5\%)^{16} = 1.5\text{x}10^{-21}$

$(90\%)^{16} = 0.20$

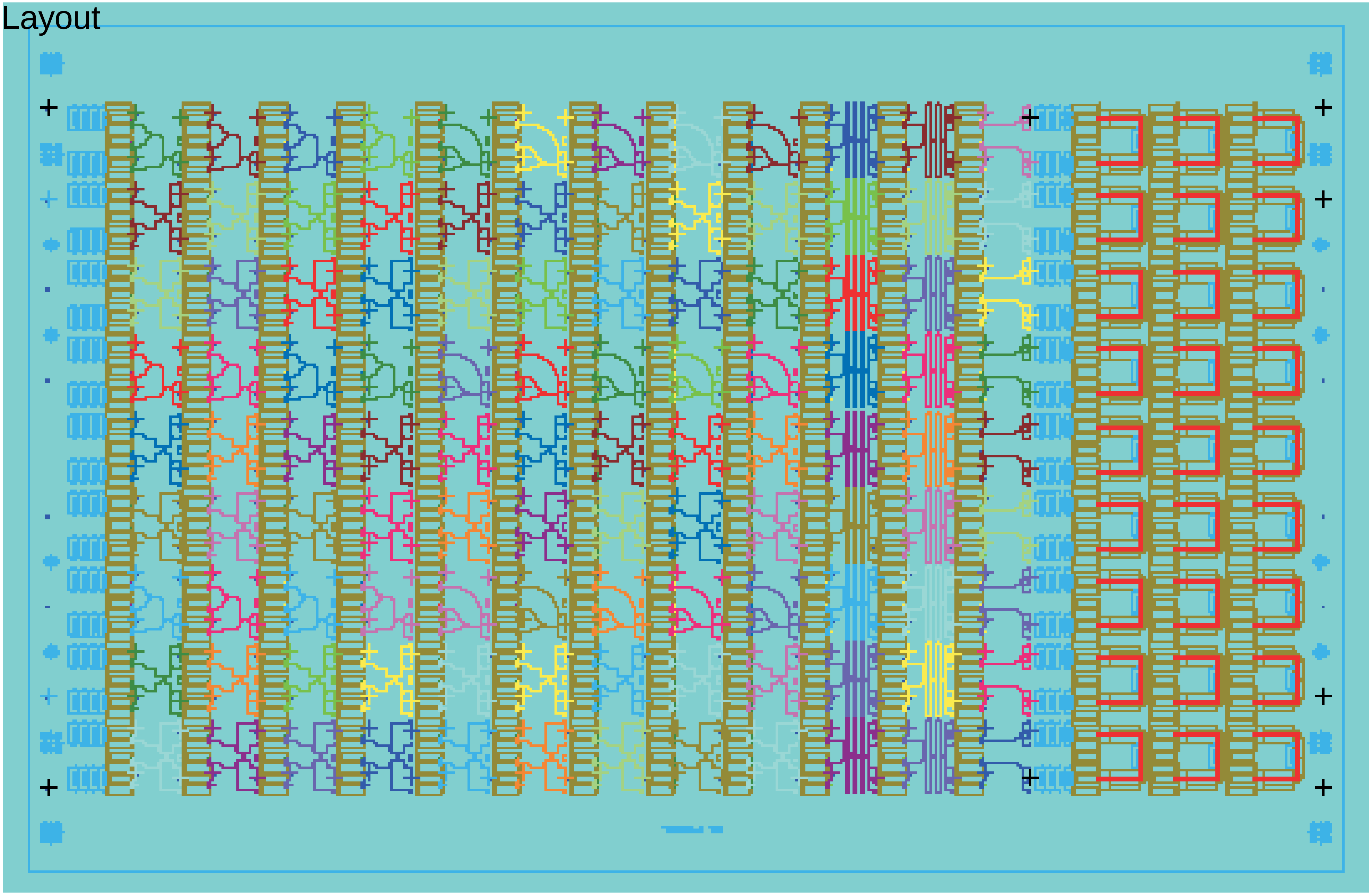
Building a HOM interferometer on a chip



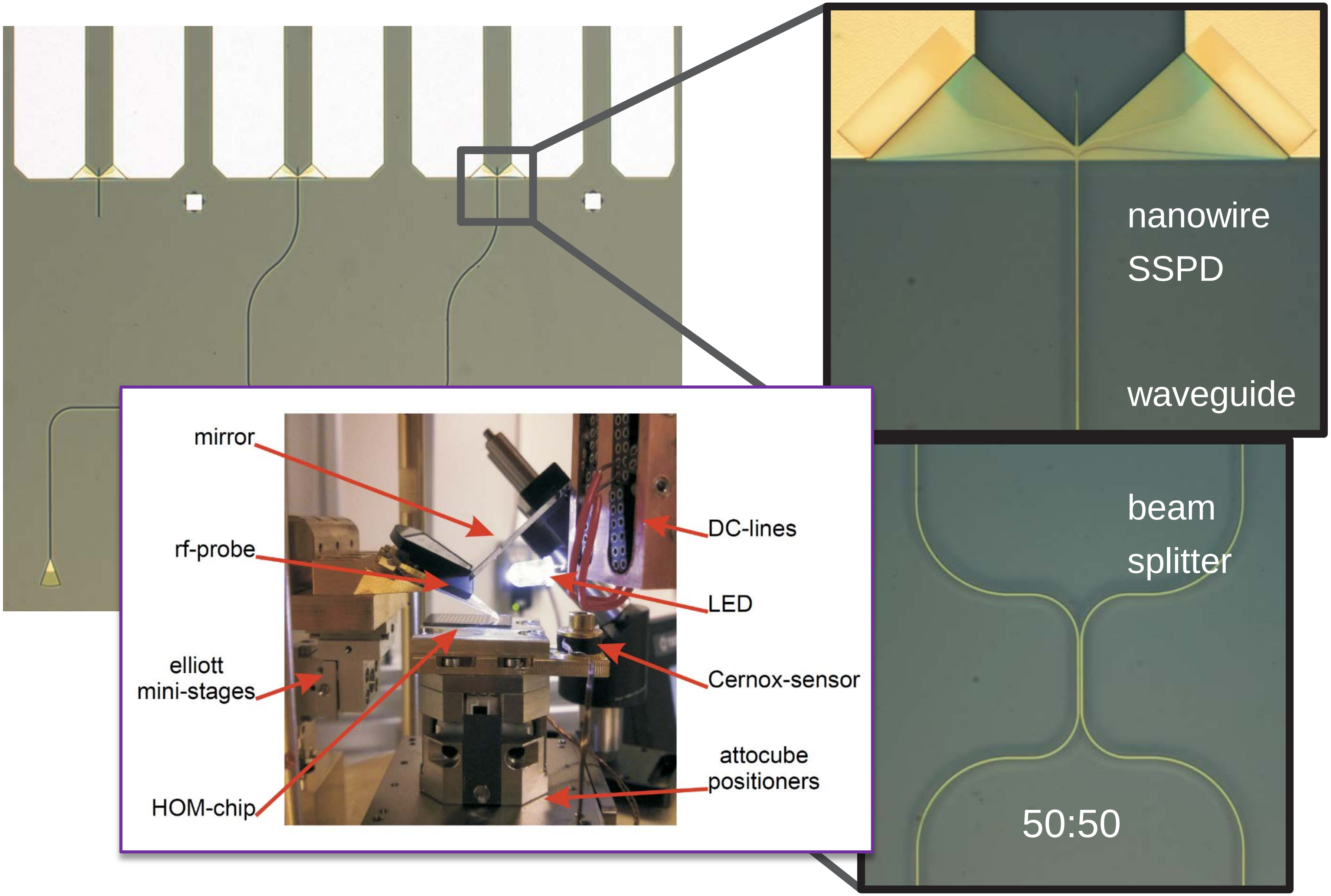
Two detectors + 1 Beam Splitter

On-chip HOM with integrated detector

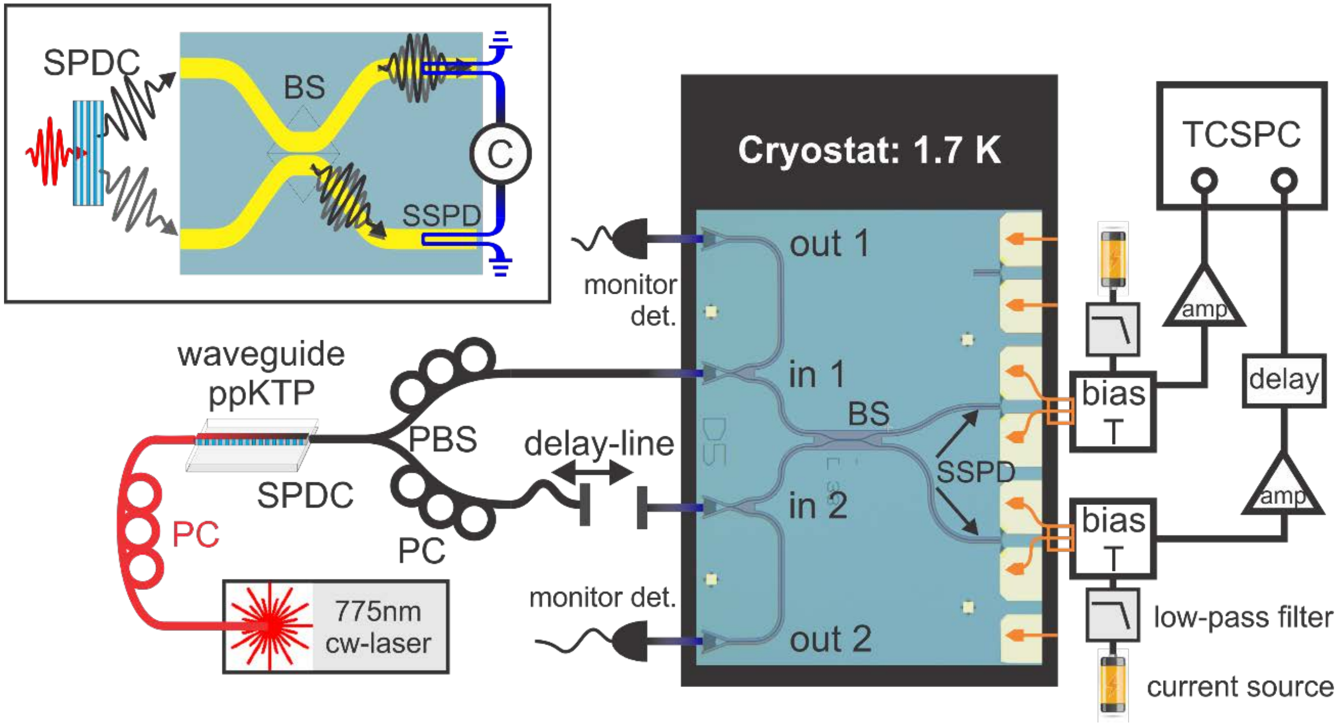
Layout

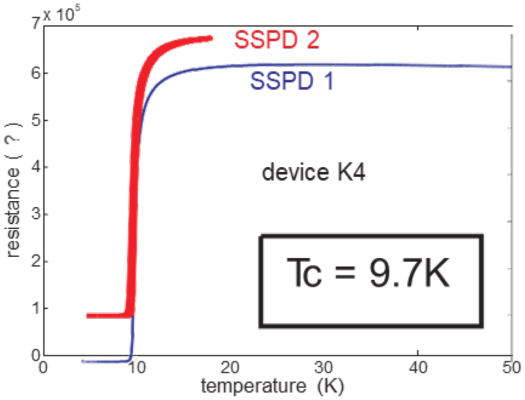


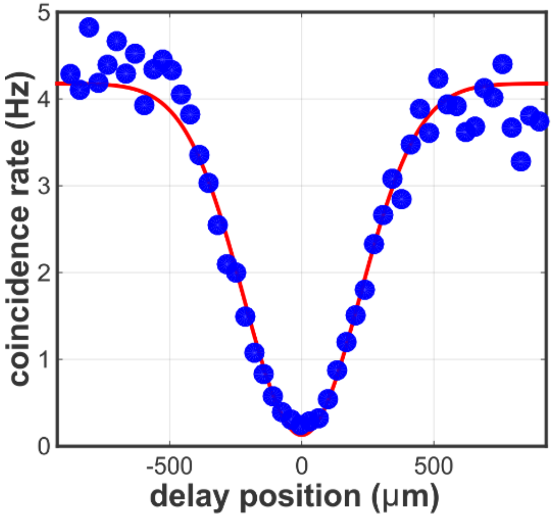
HOM + 2 SSPD device

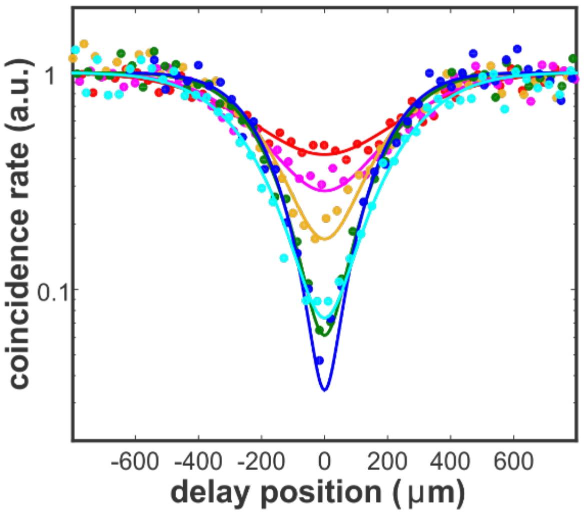


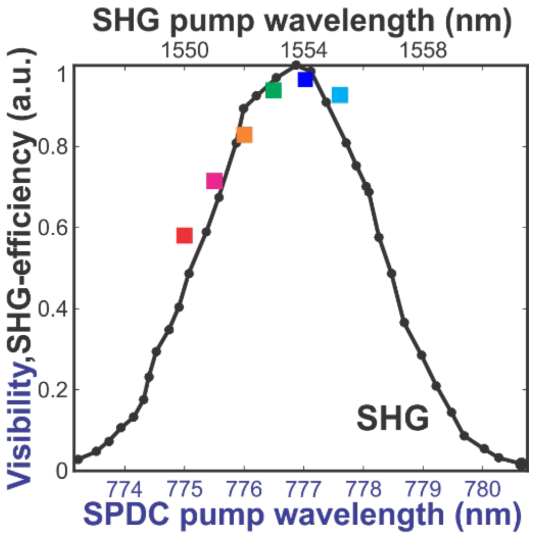
HOM + 2 SSPD device



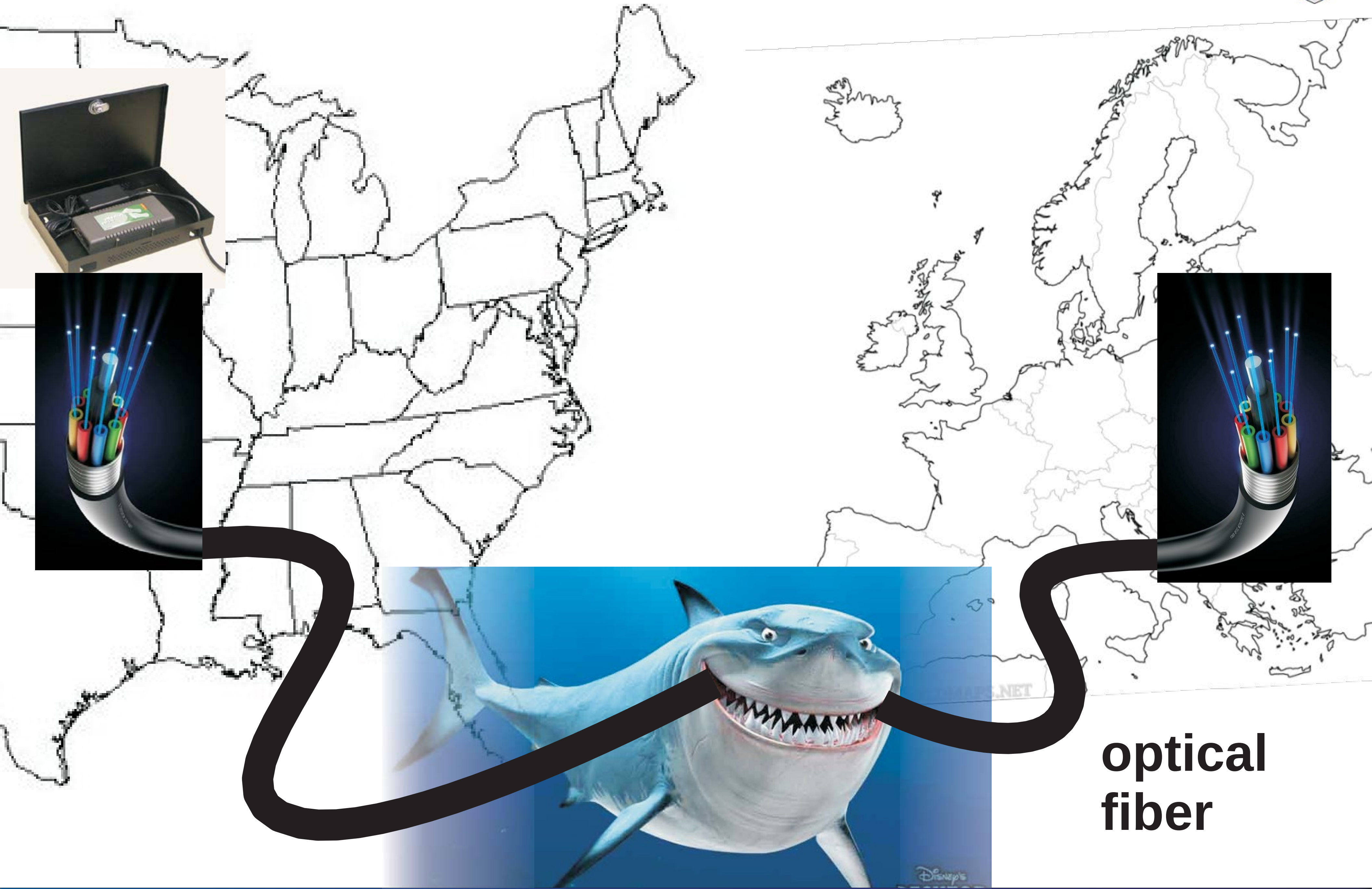






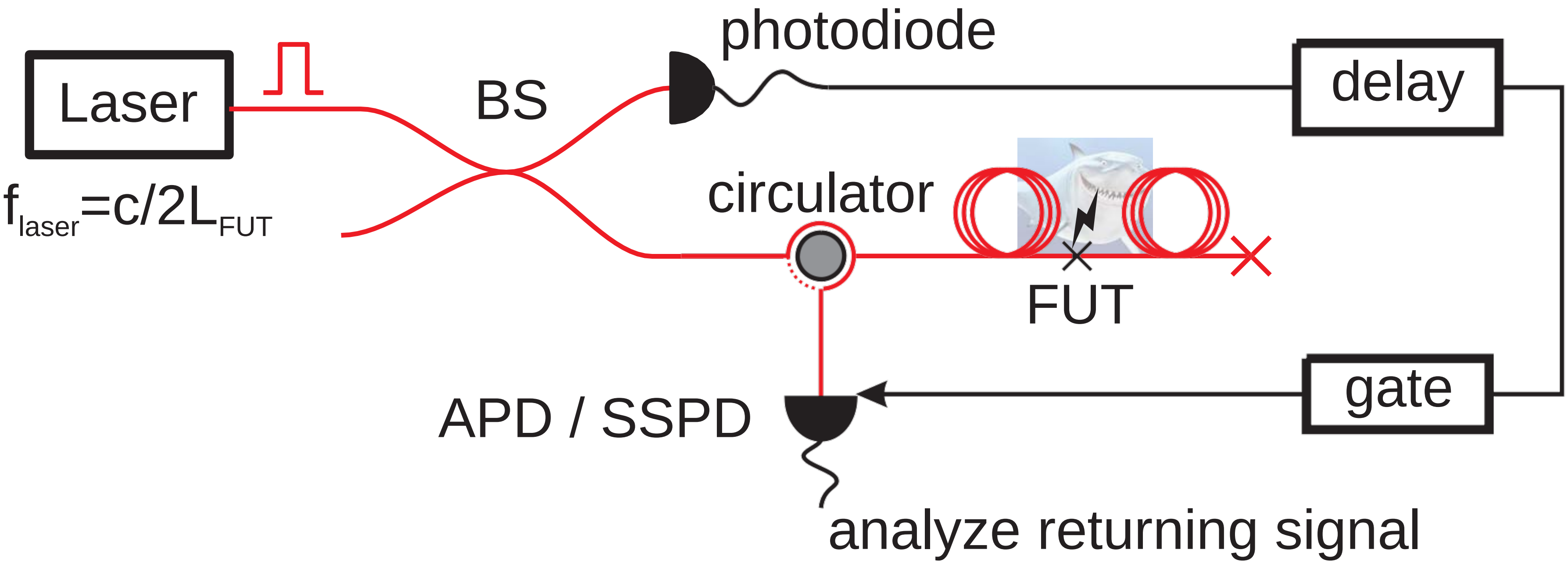


Optical Time Domain Reflectometry



optical fiber

Optical Time Domain Reflectometry


Laser

$f_{laser}=c/2L_{FUT}$

BS

photodiode

delay

circulator

FUT

APD / SSPD

gate

analyze returning signal

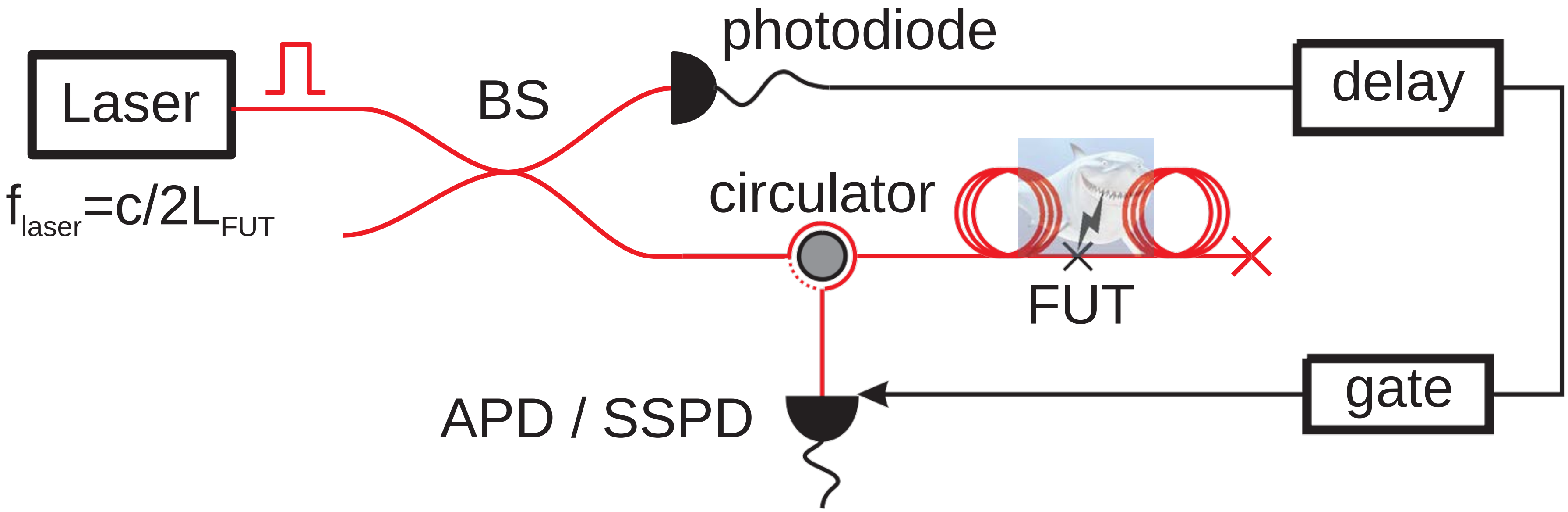
<u>OTDR: Diagnose physical condition of a (long) optical fiber *in situ*.</u>

→ localization of defects

→ fiber loss & attenuation properties

→ refractive index changes

Optical Time Domain Reflectometry



$f_{laser}=c/2L_{FUT}$

analyze returning signal

<u>Advantages SSPD vs. APD:</u>

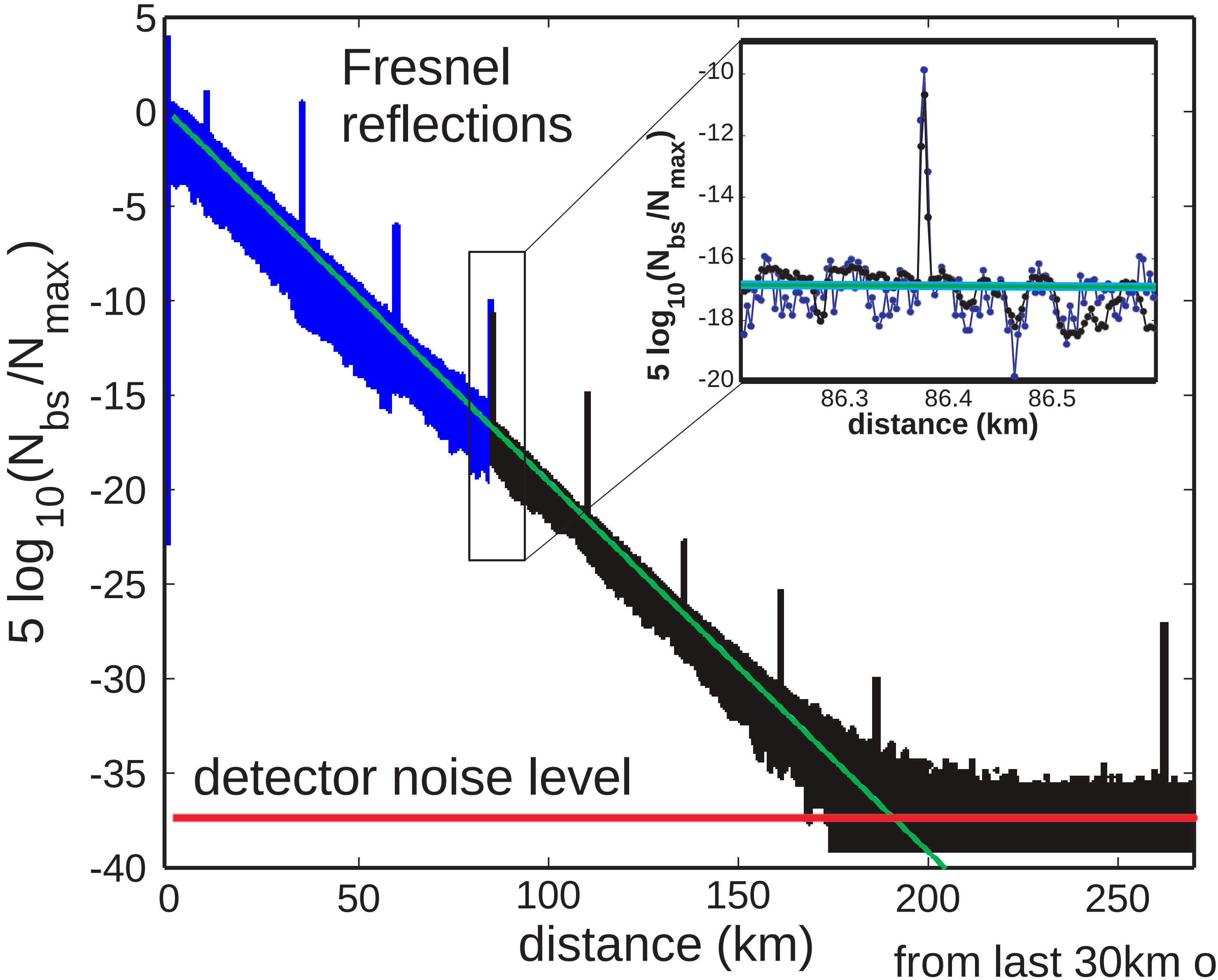
lower detector noise (NEP)

free-running (no gating)

larger dynamic range

no afterpulsing, charge persistence effects, deadzones

OTDR: dynamic range



50ns-pulses

10.5mW peak

1550nm

attenuation:

0.196 dB/km

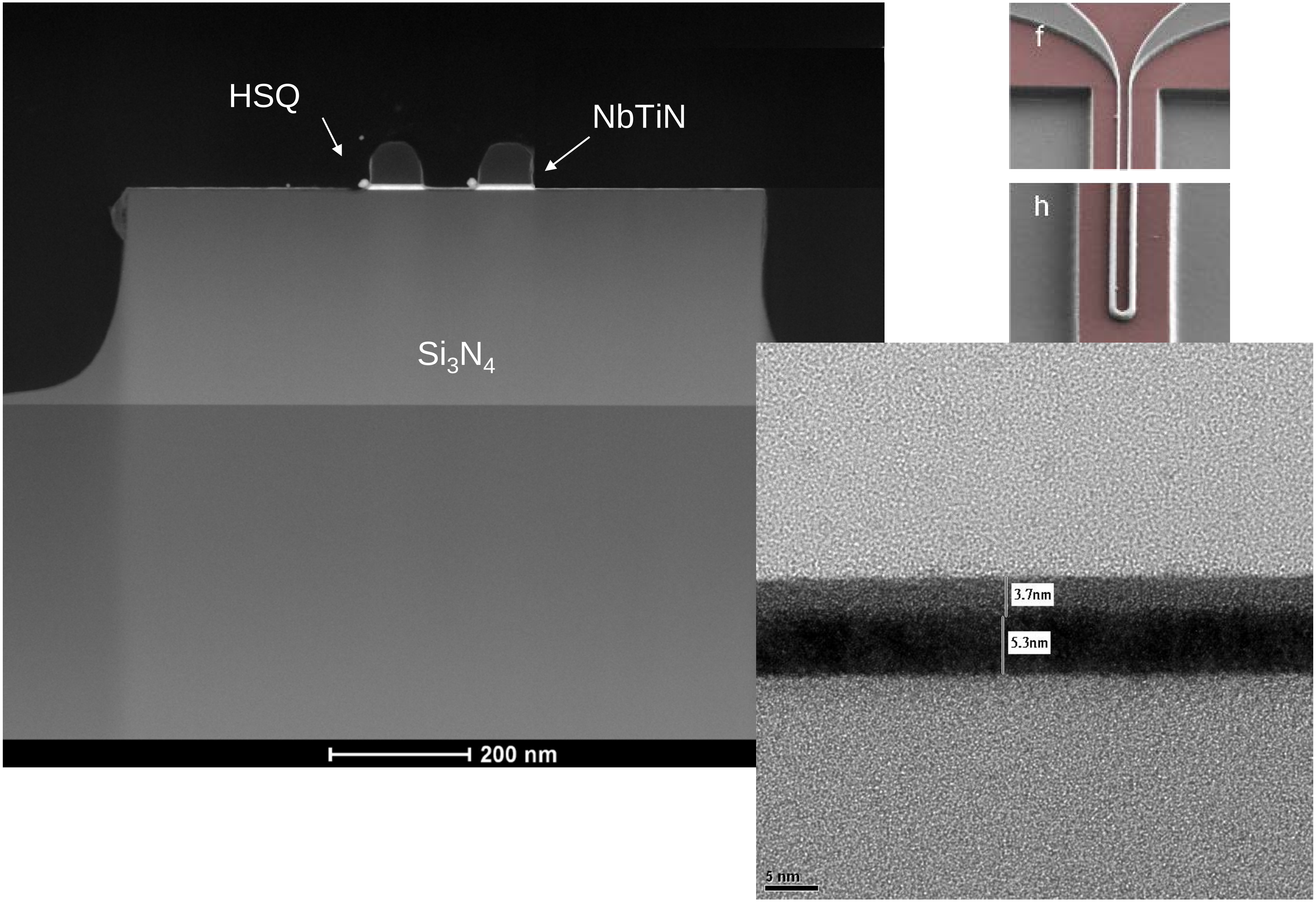
dynamic range:

37.4dB

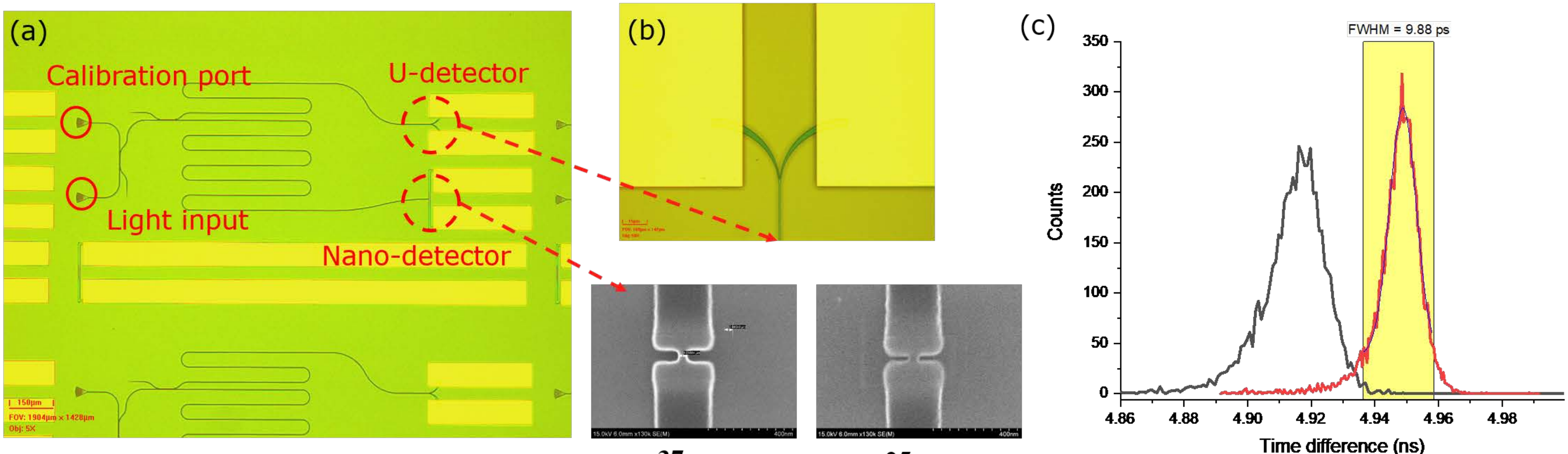
from last 30km of fiber

→ DCR: 3Hz (→ NEP=8×10^{-18} W/Hz$^{-1/2}$)

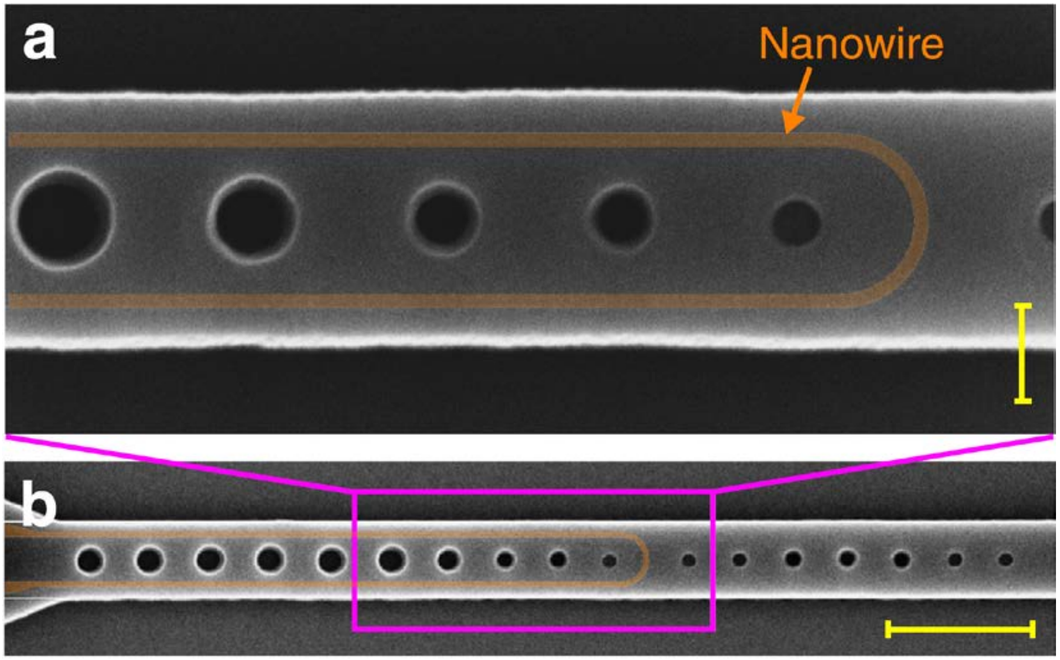
TEM analysis of NbTiN detectors



Nano-SSPD



37nm 25nm



M.K. Akhlaghi, E. Schelew, J. F. Young, Nat. Comm. 6, 8233 (2015)

- Loaded Q = 275, photon lifetime = 1.4 ps (measured jitter: 63ps)
- Wire length 8um

Detector scaling to nano-SSPD

Absorber design – Jitter consideration

100fs

= Light transits 30um in free space

= Electrical signal propagation time in 1um wire

➔ To achieve better than 100fs jitter, we need to absorb all the light in 1um travel distance

➔ Cavity lifetime < 100fs, or Q < 20

Absorber design – efficiency consideration

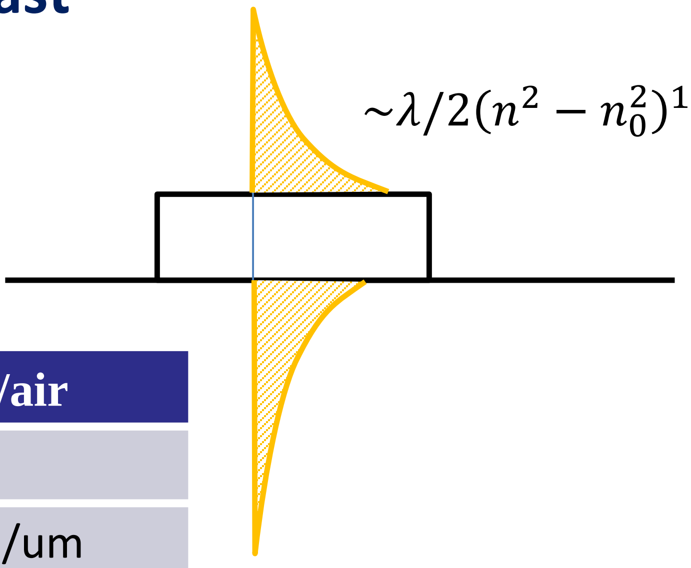
Quantum efficiency > 99% requires

- Need 20dB absorption within 1um length, or 20dB/um
- No design can achieve such fast absorption → cavity is required
- Absorption in a cavity: $\alpha LQ > 20dB$
- Considering $L < 1um$, Q < 20 ➔ $\alpha > 1dB/um$

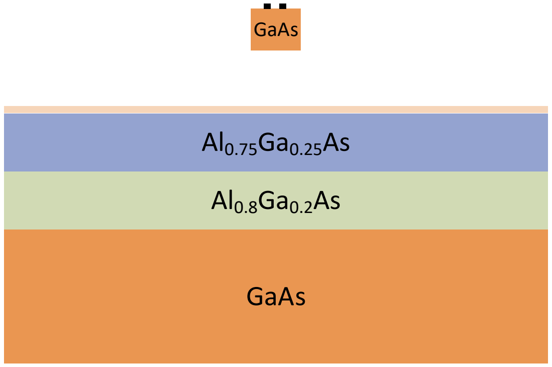
Pathway to get 1dB/um absorption rate

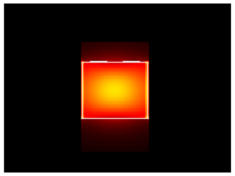
Evanescent field should be large and decay fast

- High index contrast is key
- Air cladding is most desirable
- Aspect ratio, polarization are important



Waveguide	Si/air	GaAs/air	Si_3N_4/air
Index contrast	3.48/1	3.37/1	2.0/1
Absorption rate	1dB/um	1dB/um	0.6dB/um

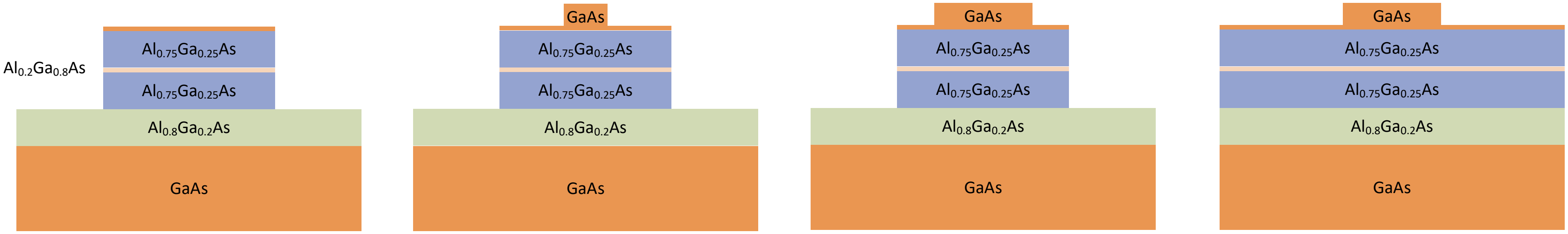




60nm*6nm NbTiN
on suspended GaAs
waveguide with different
thickness

Best results:
3.7dB/um for TM
2.3dB/um for TE

High efficiency suspended GaAs waveguide



$Al_{0.75}Ga_{0.25}As$

$Al_{0.2}Ga_{0.8}As$

$Al_{0.75}Ga_{0.25}As$

$Al_{0.8}Ga_{0.2}As$

GaAs

GaAs

$Al_{0.75}Ga_{0.25}As$

$Al_{0.75}Ga_{0.25}As$

$Al_{0.8}Ga_{0.2}As$

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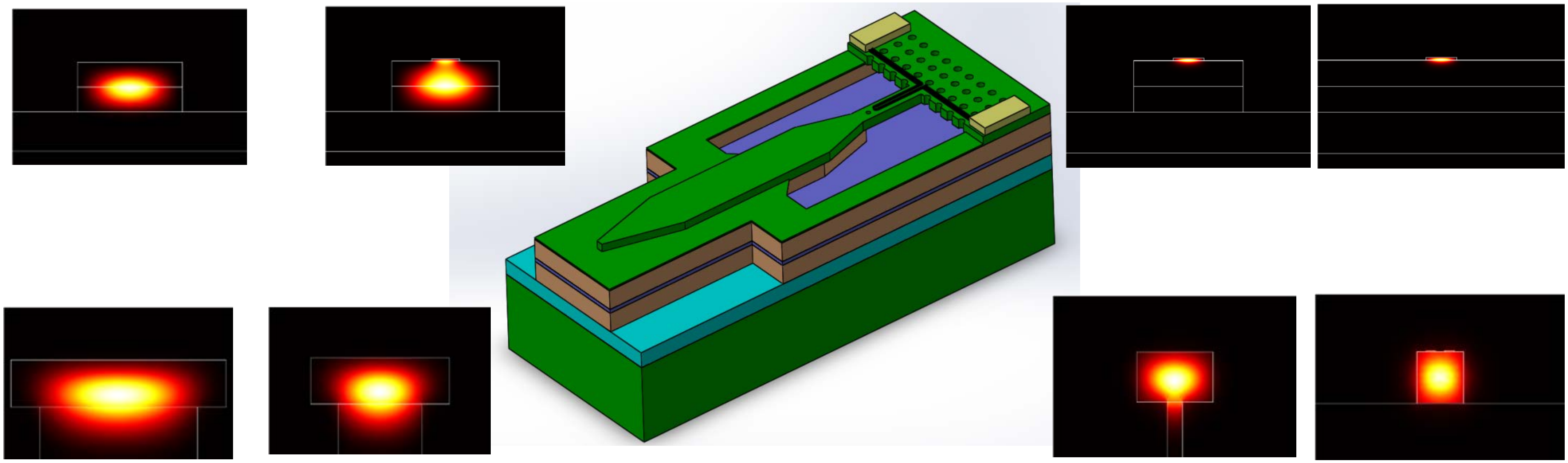
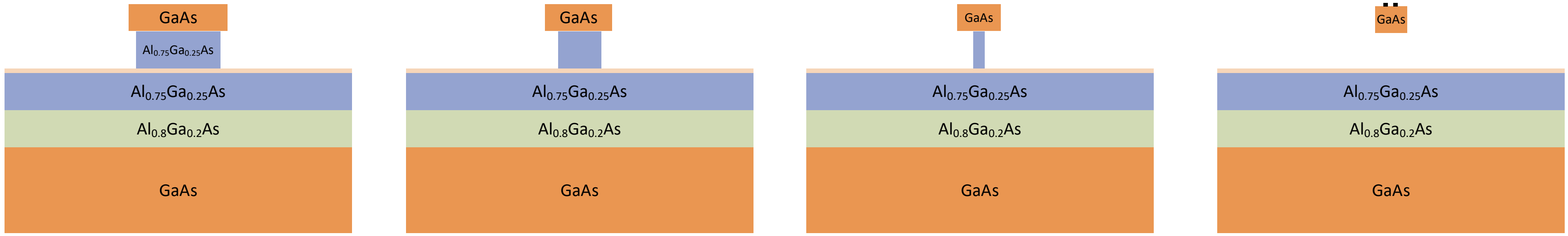
GaAs





GaAs

$Al_{0.75}Ga_{0.25}As$

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$Al_{0.8}Ga_{0.2}As$

GaAs

GaAs

$Al_{0.75}Ga_{0.25}As$

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GaAs

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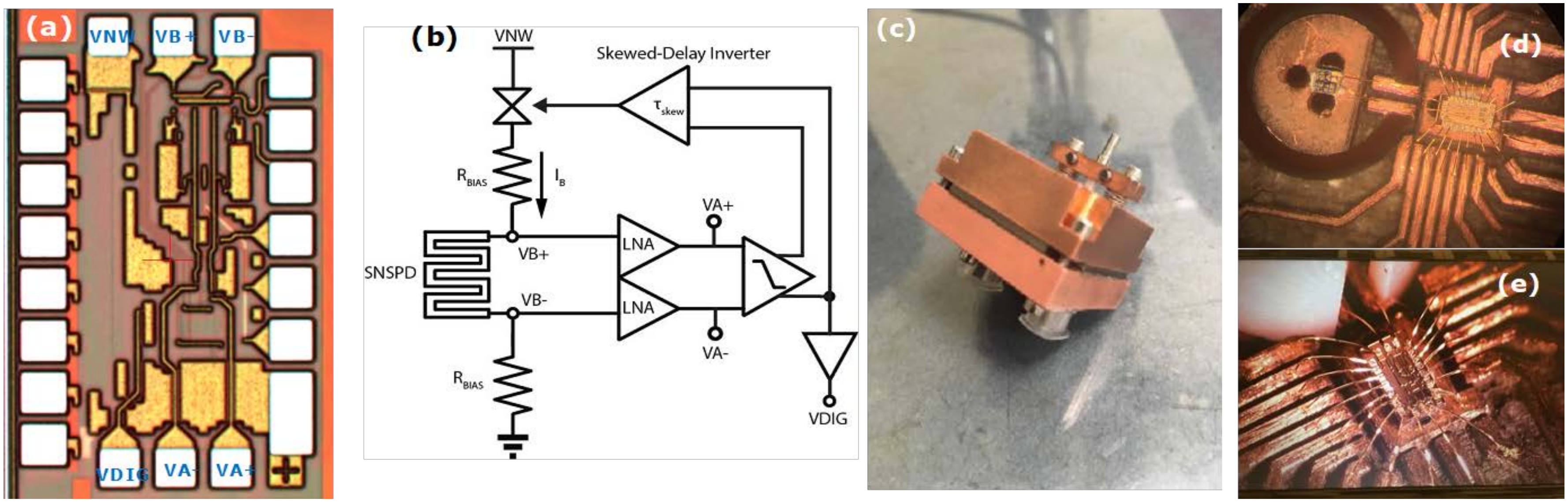
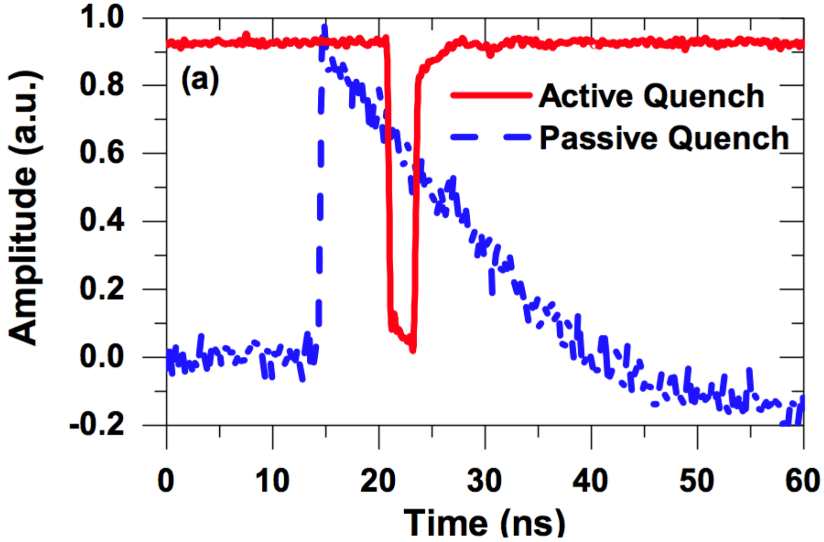
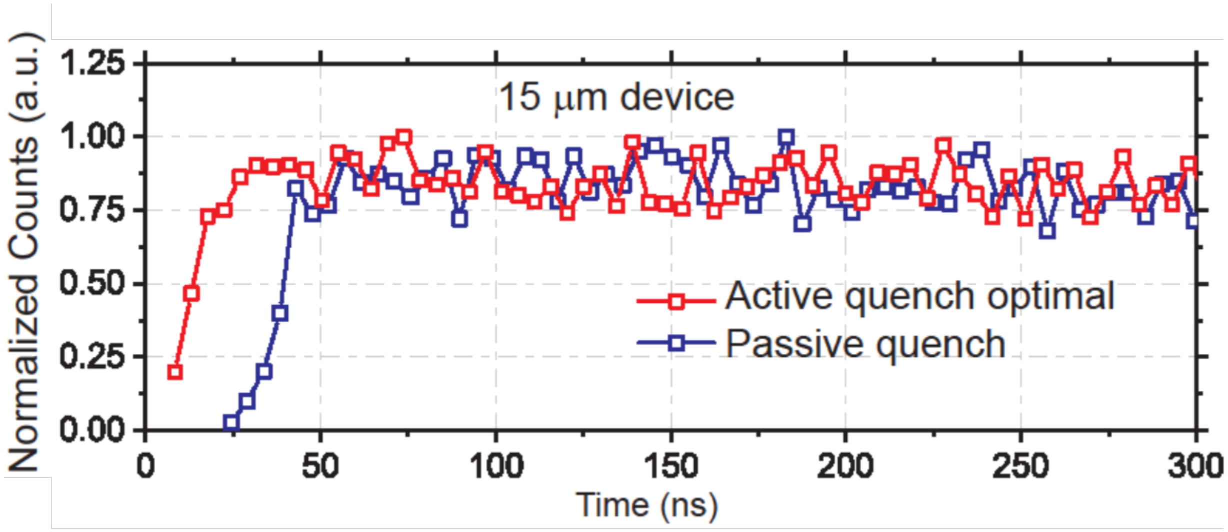
$Al_{0.8}Ga_{0.2}As$

GaAs

Integrated detector readout







P. Ravindran, R. S. Cheng, H. X. Tang, J. C. Bardin, Optics Express, to be published.

Summary

Powered by superconductor/photonics co-integration

❑ **Waveguide integrated micro-SSPD**

- Detector length ~10um: high efficiency, speed, low jitter
- Integration in quantum photonic circuits
- v-ODTR

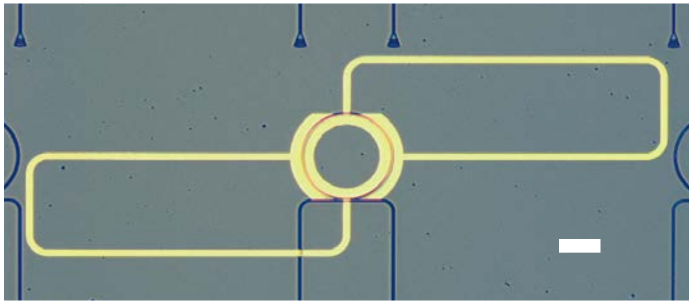
❑ **Waveguide integrated nano-SSPD**

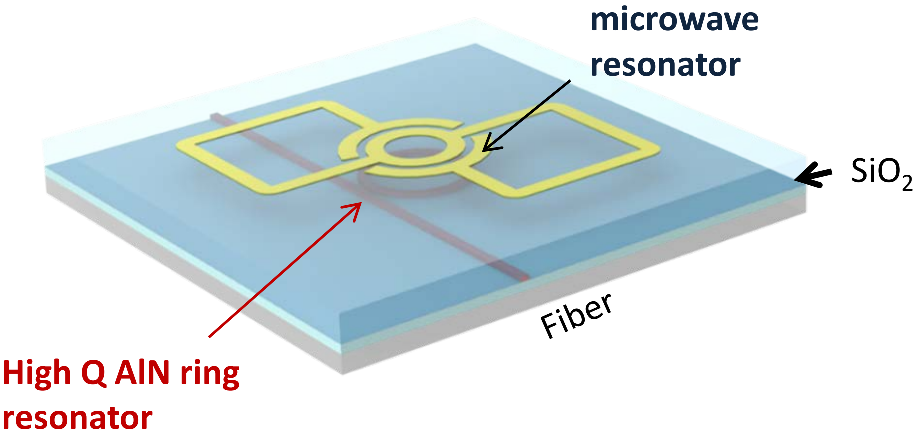
- Detector length ~1um, promising even higher speed

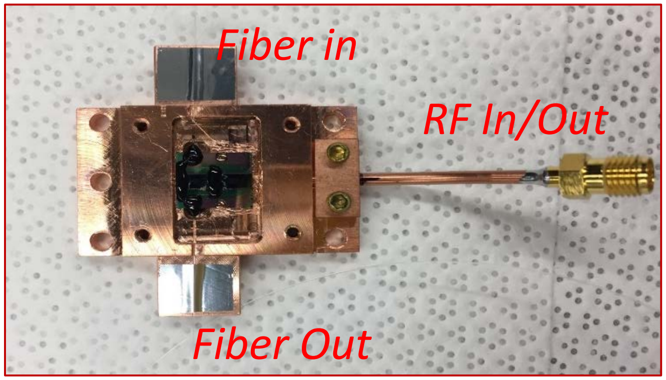
❑ **Detector semiconductor chip integration**

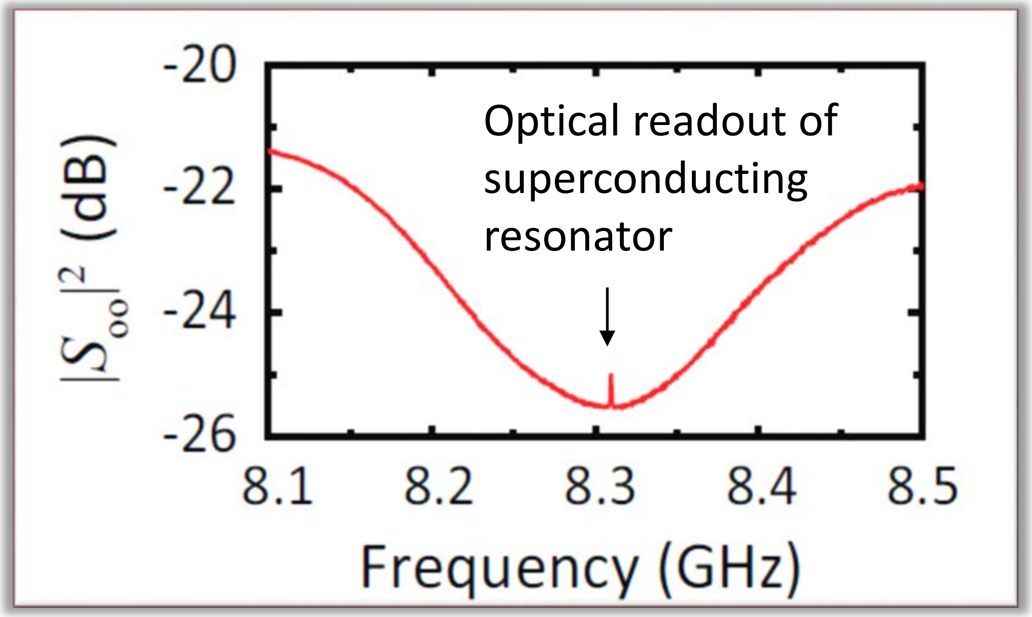
- Higher scalability, High counting rate

Can we photodetect microwave photons?









L. R. Fan, C. Zou, R. Cheng, X. Guo, X. Han, Z. Gong, S. Wang, H. Tang, Science Advance, 4, 4994 (2018)

Photodetect microwave photons

- Detection is already quantum limited
- No need for squid or JPA
- Current efficiency 2-26%
- Projected efficiency limited by coupling loss

Thank you!

Risheng Cheng

Carsten Schuck (Assistant Prof., University of Munster), Xiaosong Ma (Professor Nanjing University), Wolfram Pernice (Professor, University of Munster)

Collaborators: Joseph Bardin (UMass), Zubin Jacobs (Purdue)

Funded by: DARPA (DETECT), NSF, Packard Foundation