

Ultrafast Single-Photon Detectors for On-Chip QKD

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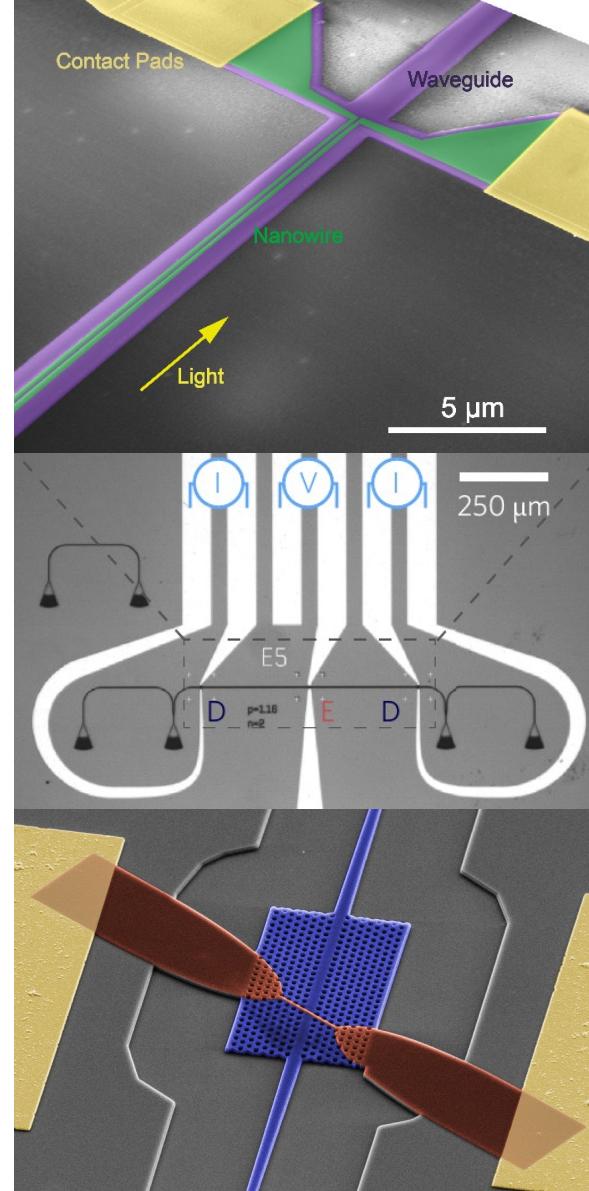


Table 1 | Comparison of single-photon detectors.

Detector type	Operation temperature (K)	Detection efficiency, η	Jitter time, Δt (FWHM)	Dark count rate, D (ungated)	Figure of merit	Max. count rate	Resolves photon number?	Class of report
PMT (visible-near-infrared) ³¹	300	40% @500 nm	300 ps	100 Hz	1.33×10^7	10 MHz	Yes	†
PMT (infrared) ³²	200	2% @1,550 nm	300 ps	200 kHz	3.33×10^2	10 MHz	Yes	†
Si SPAD (thick junction) ³⁸	250	65% @650 nm	400 ps	25 Hz	6.5×10^7	10 MHz	No	†
Si SPAD (shallow junction) ⁴¹	250	49% @550 nm	35 ps	25 Hz	5.6×10^8	10 MHz	No	†
InGaAs SPAD (gated) ⁵⁵	200	10% @1,550 nm	370 ps	91 Hz	2.97×10^5	10 kHz	No	‡
InGaAs SPAD (self-differencing) ⁵⁷	240	10% @1,550 nm	55 ps	16 kHz	1.14×10^5	100 MHz	Yes	‡
Frequency up-conversion ⁶⁵	300	9% @1,550 nm	400 ps	13 kHz	1.7×10^4	10 MHz	No	‡
Frequency up-conversion ⁶⁵	300	2% @1,550 nm	40 ps	20 kHz	2.5×10^4	10 MHz	No	‡
VLPC ⁶⁹	6	88% @694 nm	—	20 kHz	—	—	Yes	§
VLPC*	6	34% @633 nm	270 ps	7 kHz	1.83×10^5	—	Yes	§
TES ⁷⁶	0.1	50% @1,550 nm	100 ns	3 Hz	1.67×10^6	100 kHz	Yes	‡
TES ²⁰	0.1	95% @1,550 nm	100 ns	—	—	100 kHz	Yes	§
SNSPD (meander) ⁹⁰	3	0.7% @1,550 nm	60 ps	10 Hz	1.16×10^7	100 MHz	No	‡
SNSPD (new) ⁸⁷	1.5	57% @1,550 nm	30 ps	—	—	1 GHz	No	§
QD (resonant tunnel diode) ⁹⁶	4	12% @550 nm	150 ns	2×10^{-3} Hz	4×10^9	250 kHz	No	§
QD (field-effect transistor) ⁹³	4	68% @805 nm	—	—	—	1 Hz	Yes	§

The class of report indicates the conditions under which the detector characteristics were measured: † represents a commercial product specification, ‡ represents the use of the detector in a practical experiment and § represents a measurement of device performance. *Unpublished data, Byun Baek, NIST, USA, 2009.

Key measures

- Efficiency
- Dark count rate
- Dead time
- Jitter
- Footprint
- Continuous operation
- Photonic integration

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NATURE PHOTONICS DOI: 10.1038/NPHOTON.2009.230

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→ Superconducting Nanowire SPDs

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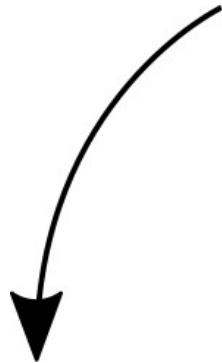
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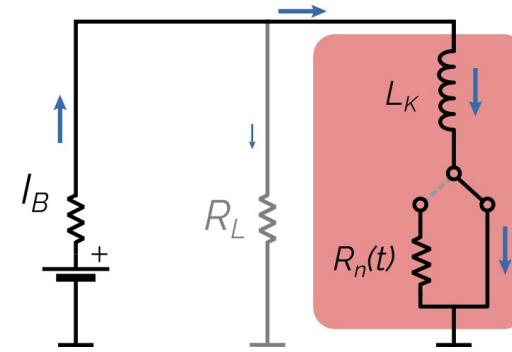
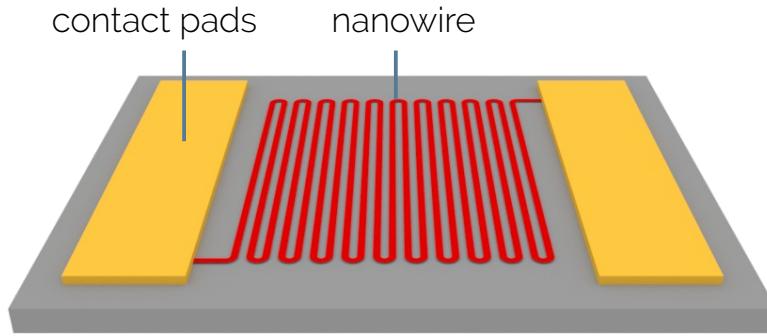
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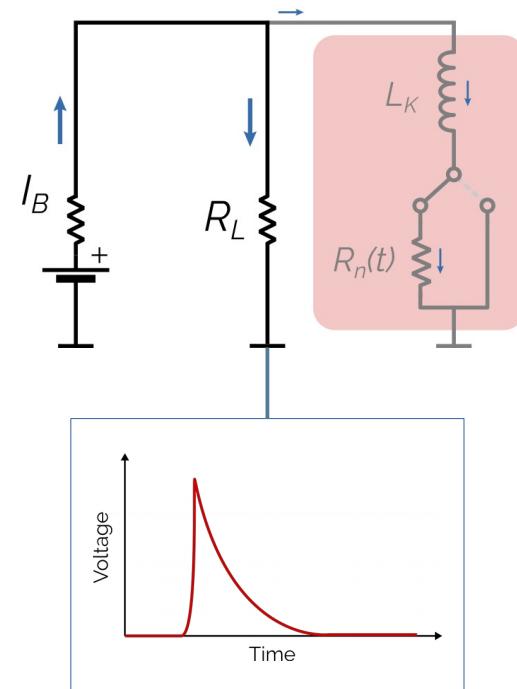
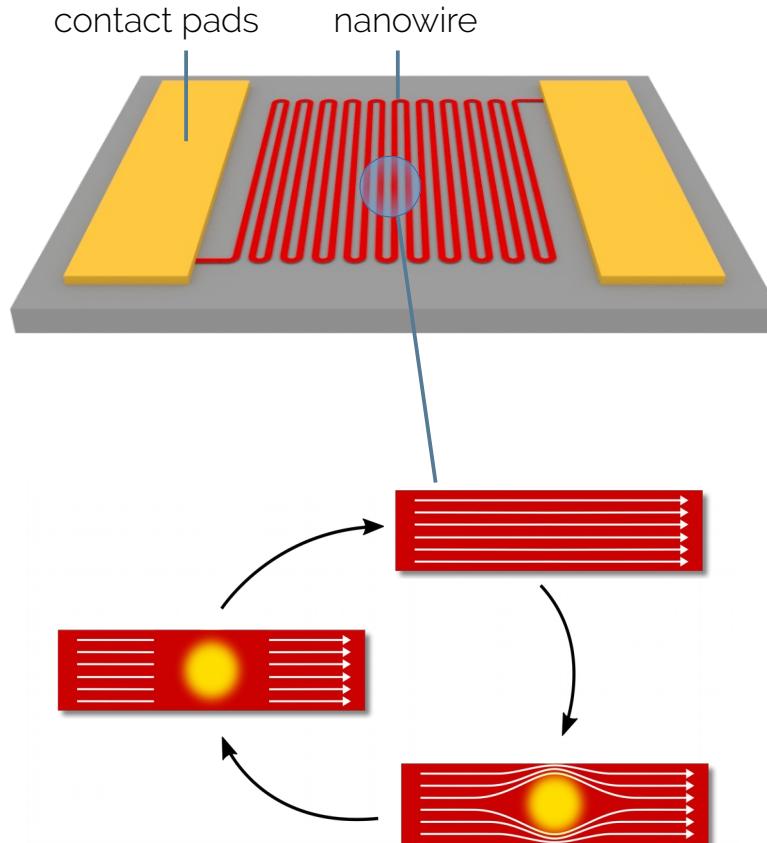
Nanowire
(original size)



Superconducting Nanowire SPDs



Superconducting Nanowire SPDs





Specifications

Optimization wavelength	800 nm	1550 nm
System detection efficiency	$\geq 85\%$	$\geq 80\%$
Dark count rate	≤ 10 Hz	typ. 300 Hz
Standard timing jitter	≤ 40 ps	≤ 50 ps
Optional low timing jitter	≤ 15 ps	≤ 25 ps
Dead time ¹	≤ 10 ns	≤ 30 ns
Maximum count rate ²	≥ 80 MHz	≥ 20 MHz
Output pulse height	≥ 500 mV	≥ 200 mV

Possible range of system's characteristics:

Spectral range	Quantum efficiency referred to optical input	Dark counts rate	Output voltage signal	Counting rate (dead time)	Jitter
0.6÷2.5μm	$\geq 85\%$	≤ 10 cps	≥ 150 mV*	≥ 100 MHz (≤ 10 ns)	≤ 45 ps



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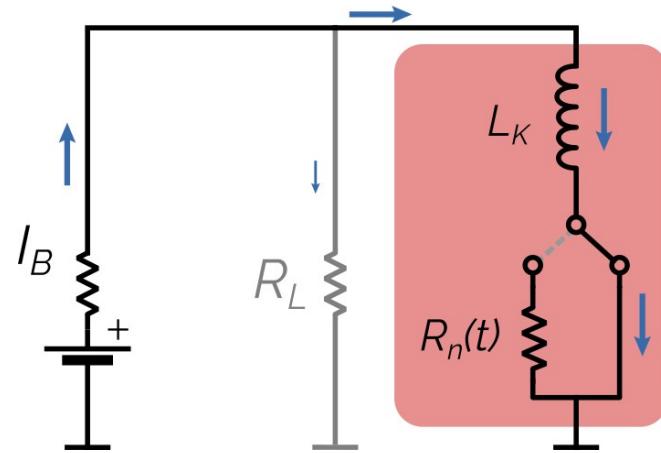
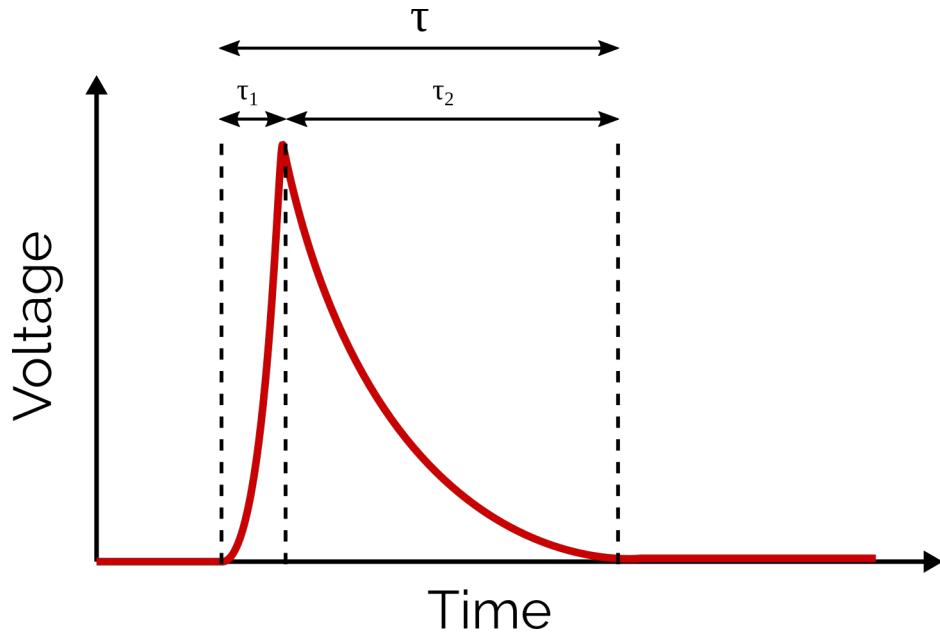
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0.6÷2.5μm	≥ 85 %	≤10 cps	≥150 mV*	≥ 100MHz (≤10ns)	≤ 45ps

SNSPD器件

参数	典型值	最优值
探测效率	1550 nm	≥ 70% ≥ 90%
	1064 nm	≥ 70% ≥ 80%
	850 nm	≥ 70% ≥ 80%
	532 nm	≥ 70% ≥ 80%
暗计数率	≤ 100 Hz ≤ 1 Hz	
时间抖动	40–70 ps ≤ 20 ps	
计数率	≥ 20 MHz ≥ 100MHz	

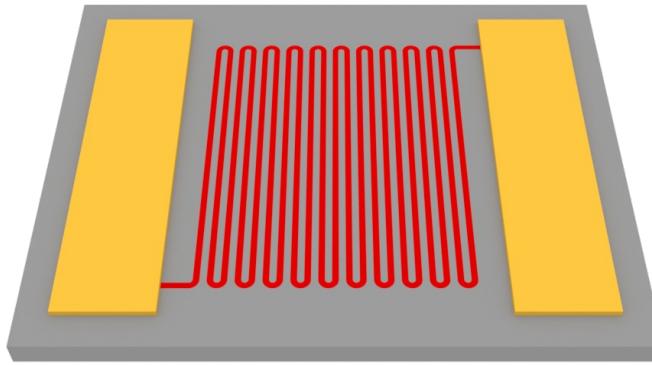
① 所有性能参数为 2.2 K 工作温度下测试结果
 ② 探测效率为针对特定波长定制器件结果
 ③ 可定制：根据用户特定性能需求

Recovery time

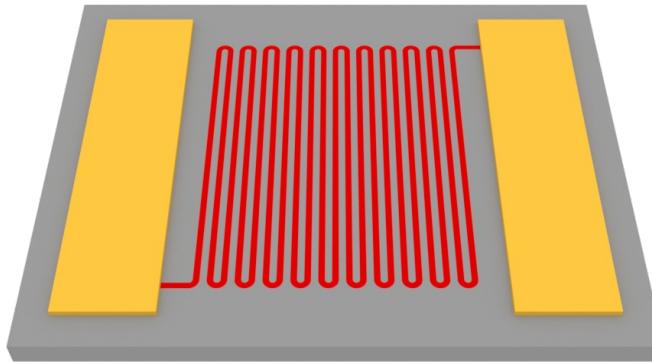


$$\tau_1 = \frac{L_K}{R_L + R_n(t)} \approx \frac{L_K}{R_n(t)} \quad \tau_2 = \frac{L_K}{R_L}$$

$$L_K \sim \frac{l}{h \cdot w}$$

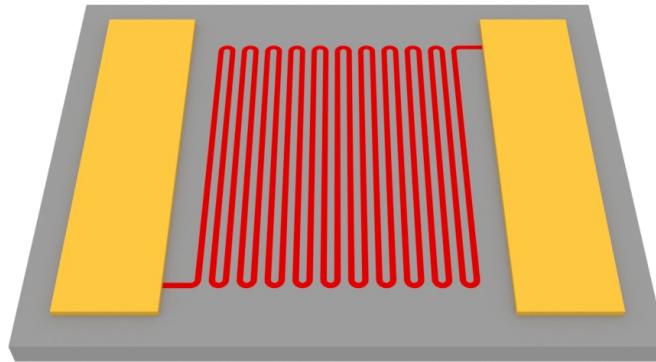


✗ Long dead time



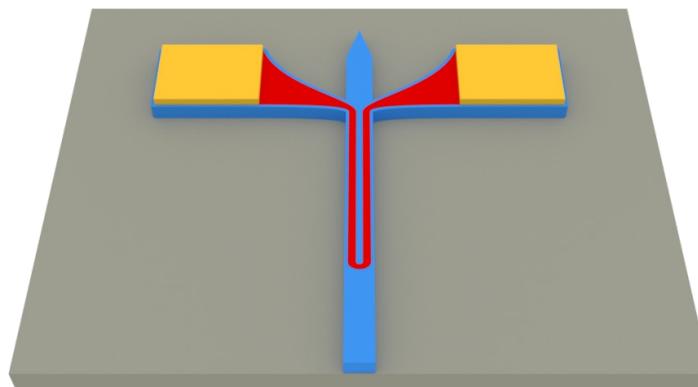
✗ Long dead time

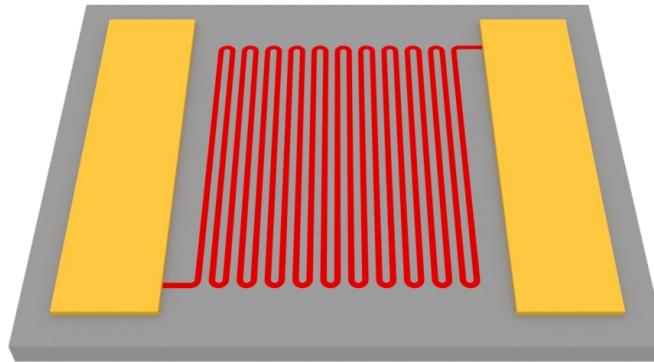
✗ No photonic integration



✗ Long dead time

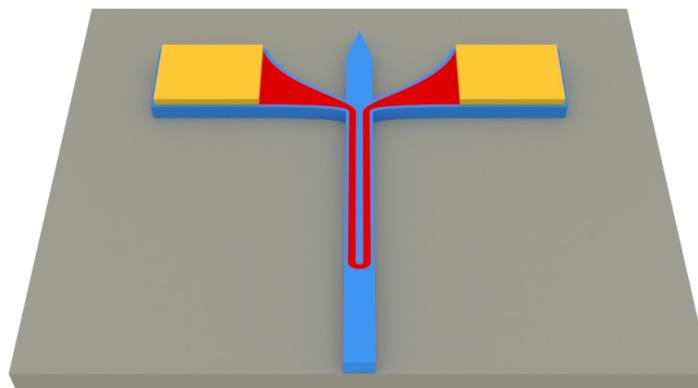
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✗ Long dead time

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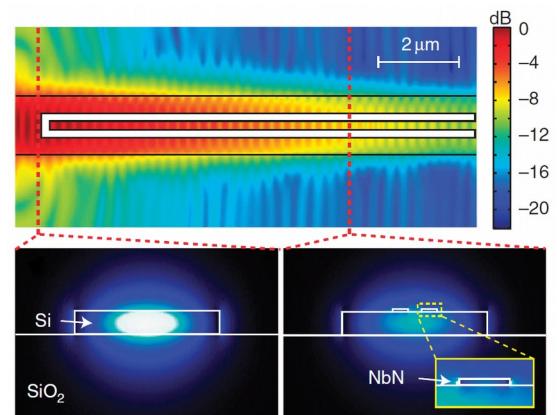
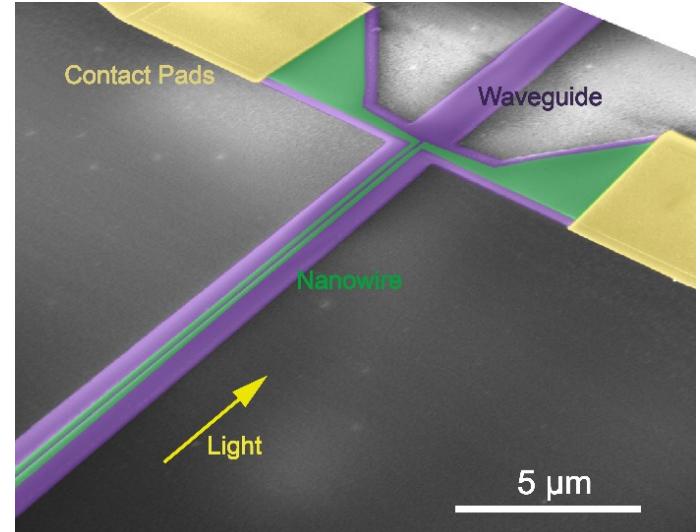
✓ 85 % detection efficiency (on-chip)

✓ 35 ps jitter

✓ < 1 Hz dark count rate

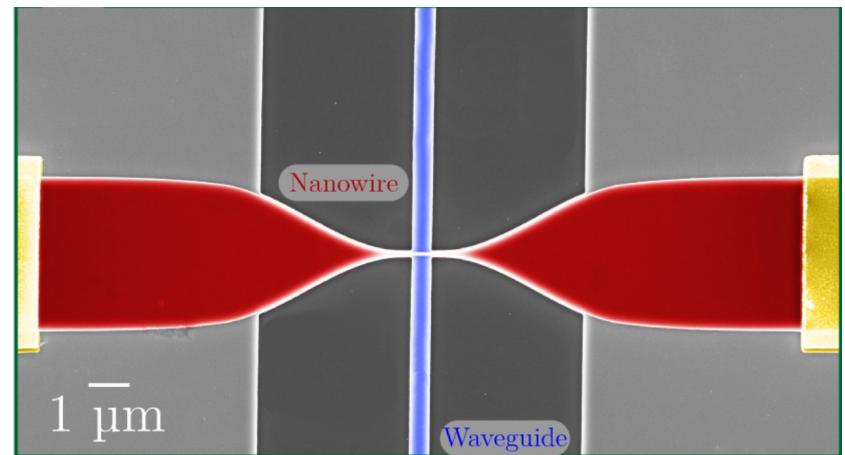
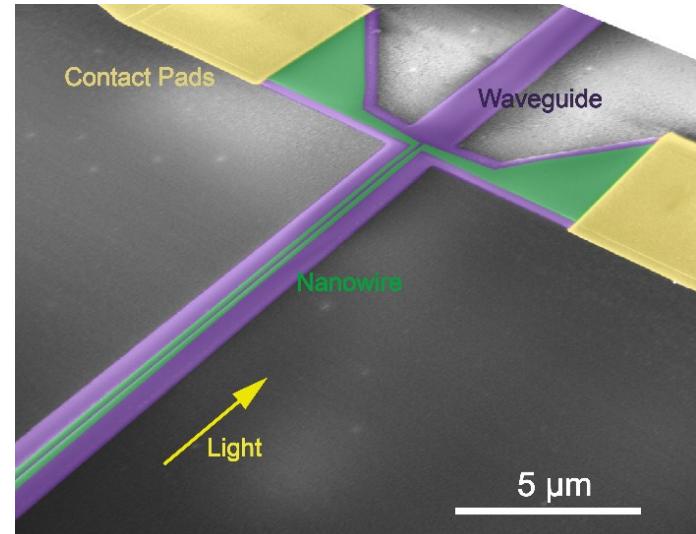
✓ Reduced dead time (~5 ns)

Waveguide-integrated SNSPDs



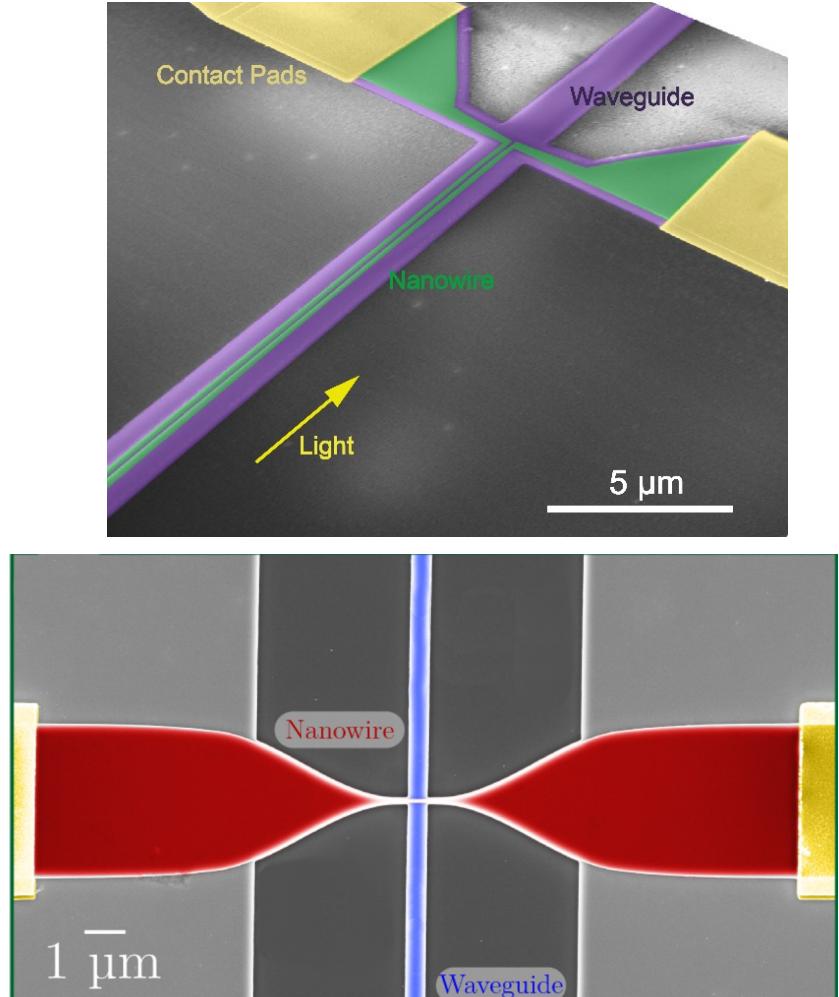
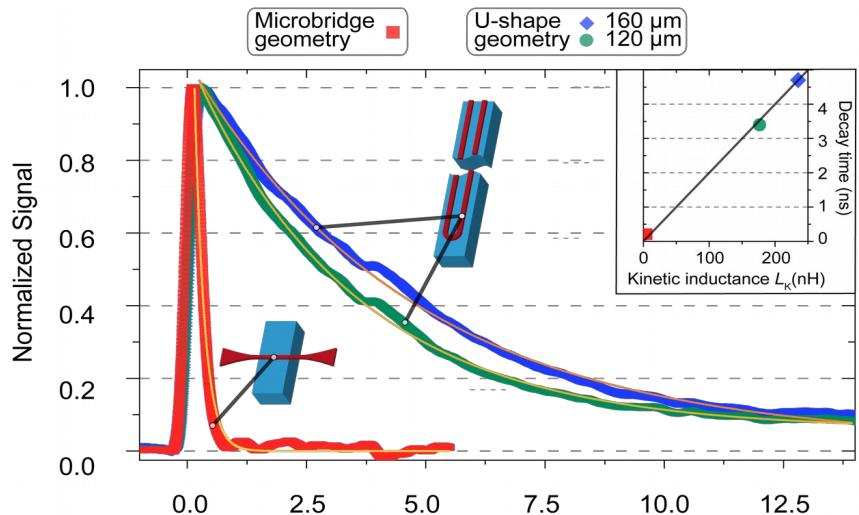
Waveguide-integrated SNSPDs

- Further reduce wire length



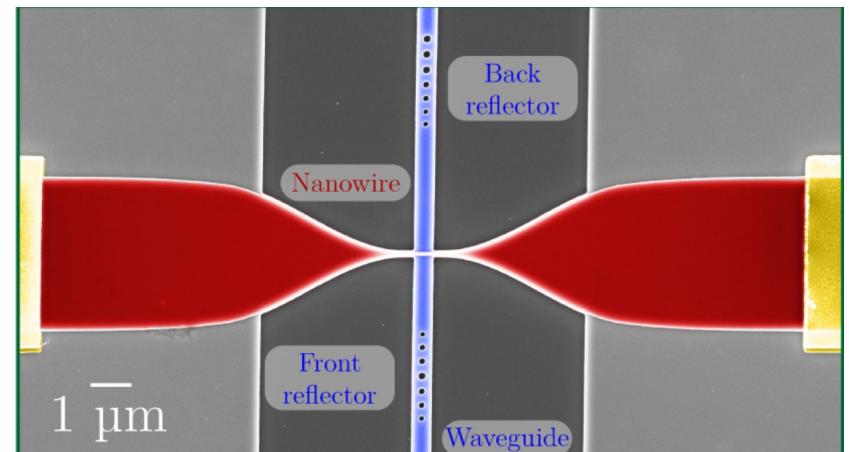
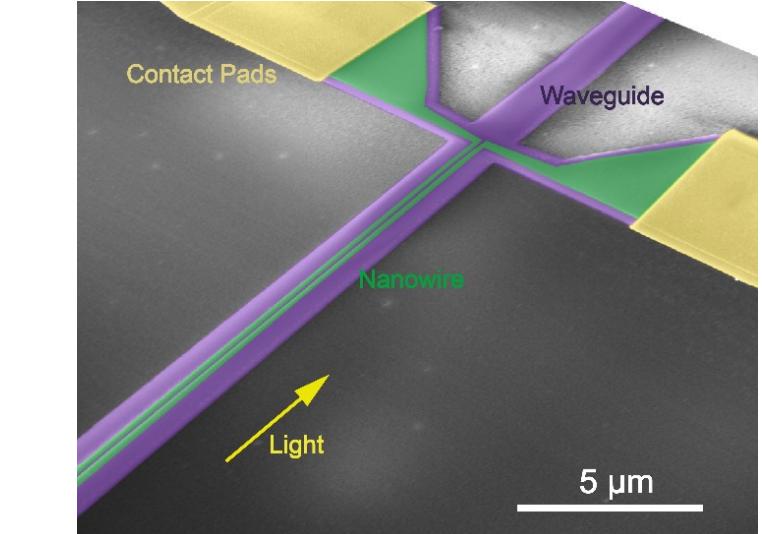
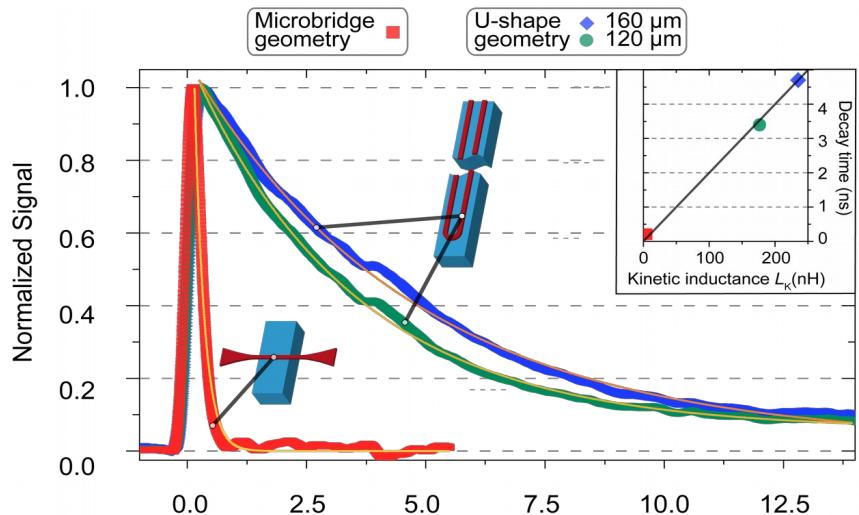
Waveguide-integrated SNSPDs

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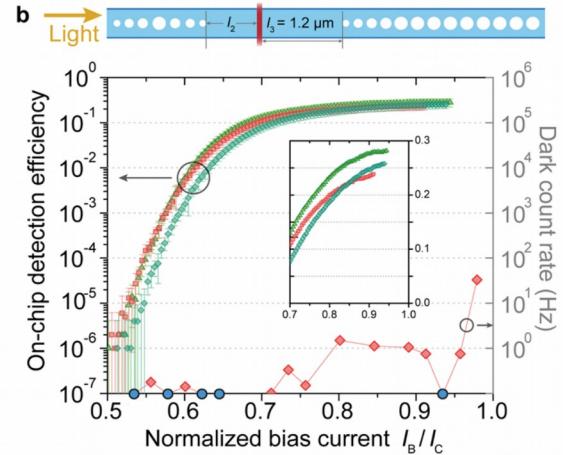
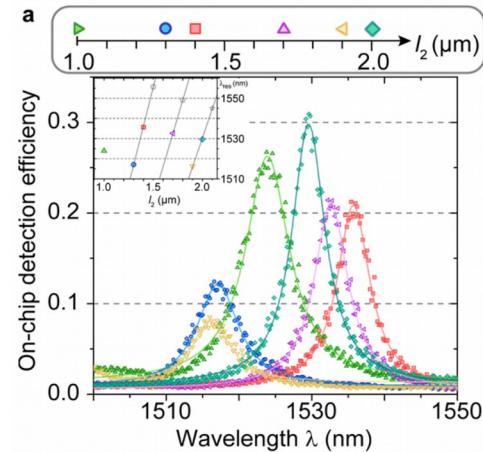
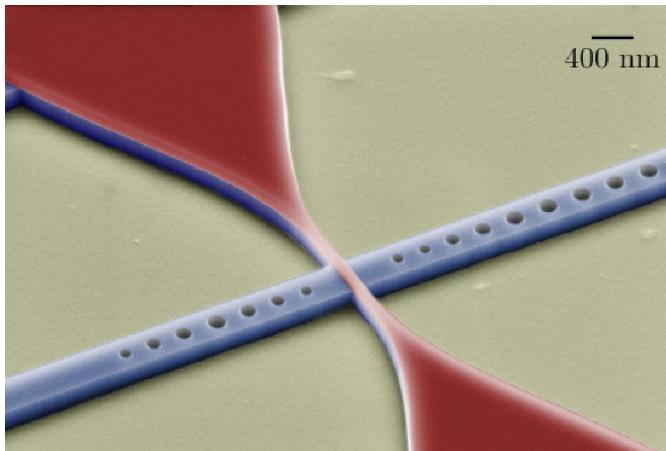
Waveguide-integrated SNSPDs

- Further reduce wire length
- Add photonic crystal cavity



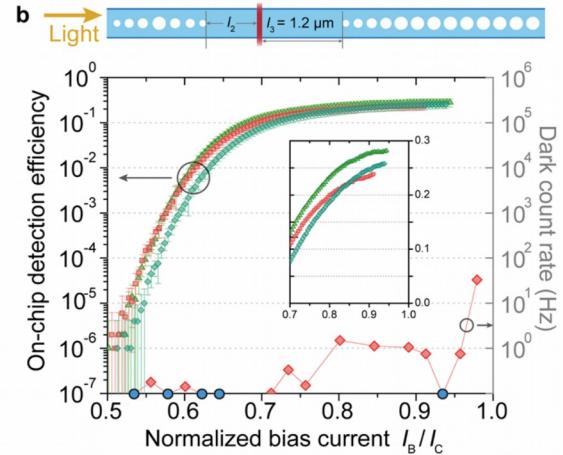
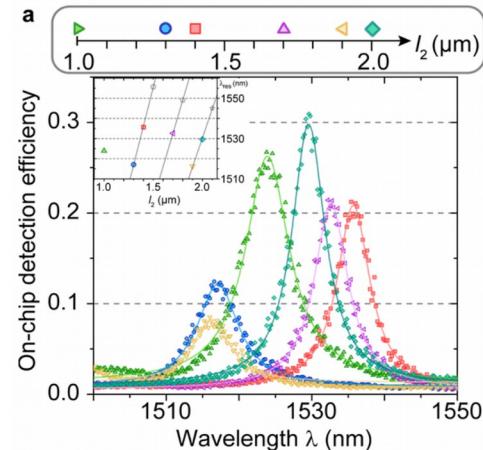
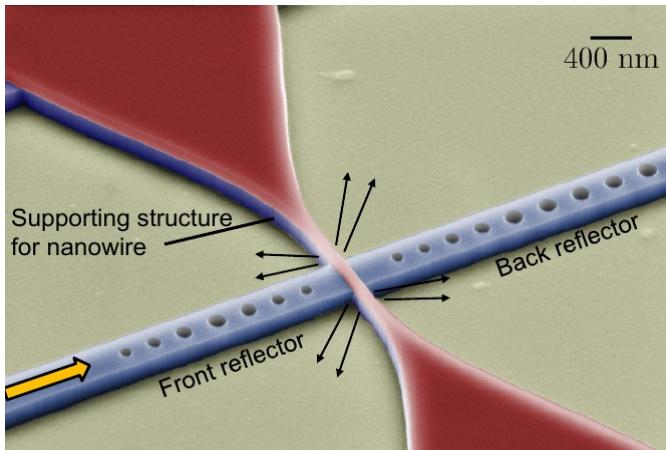
1D-cavity enhanced SNSPDs

- 30 % OCDE
- Small recovery time (500 ps)
- Lower dark count rate (resonance filter, small active area)

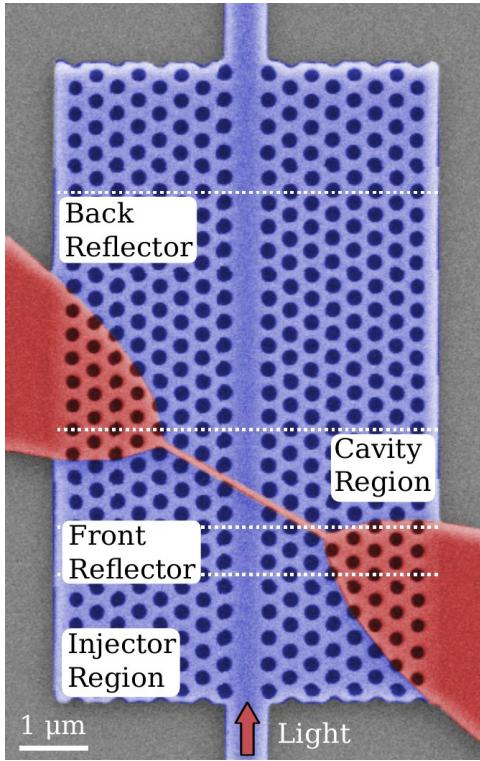


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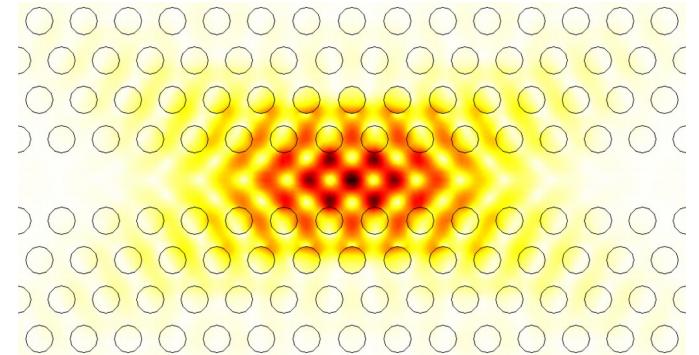
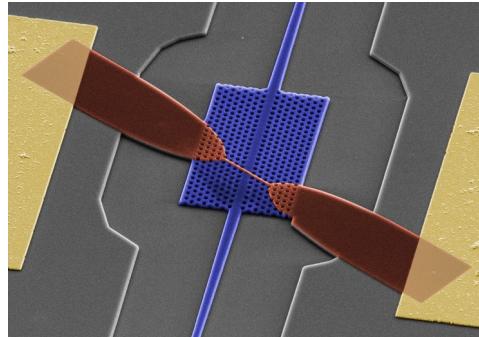
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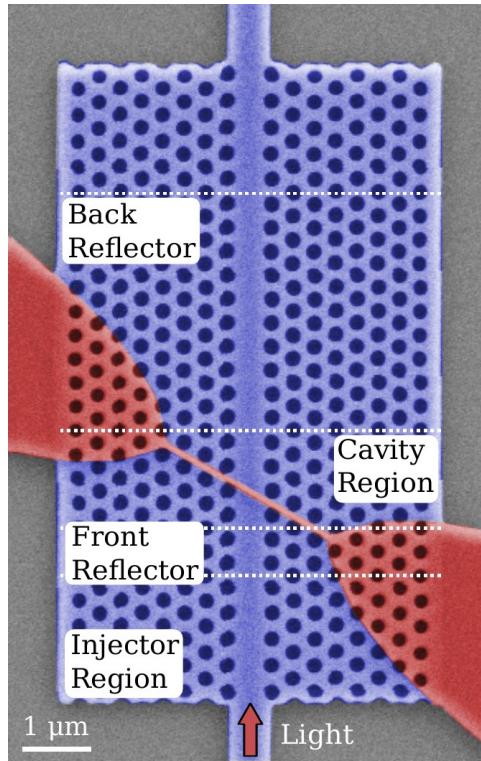
2D-Cavity SNSPDs



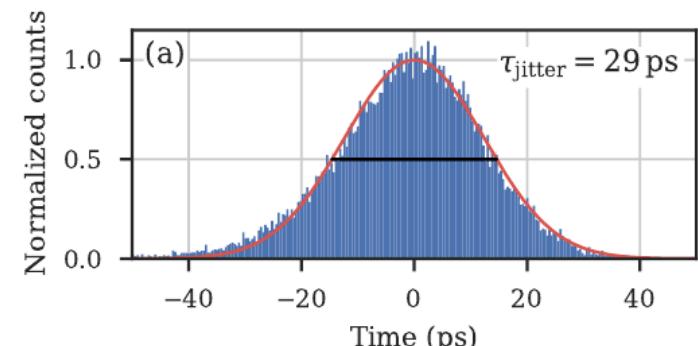
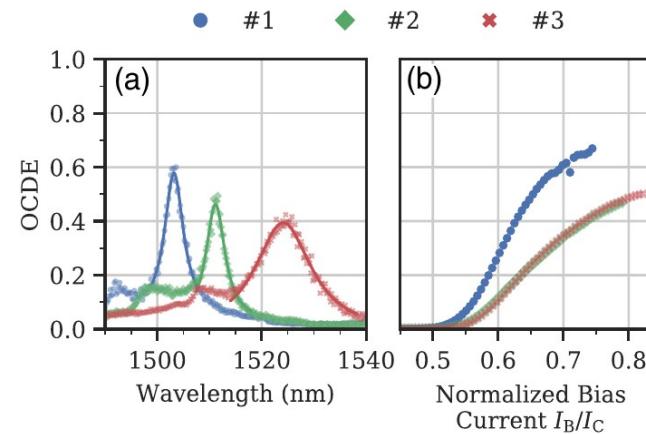
- Efficiency: 67 % at 1504 nm
- < 0.1 mHz dark count rate
- 29 ps jitter



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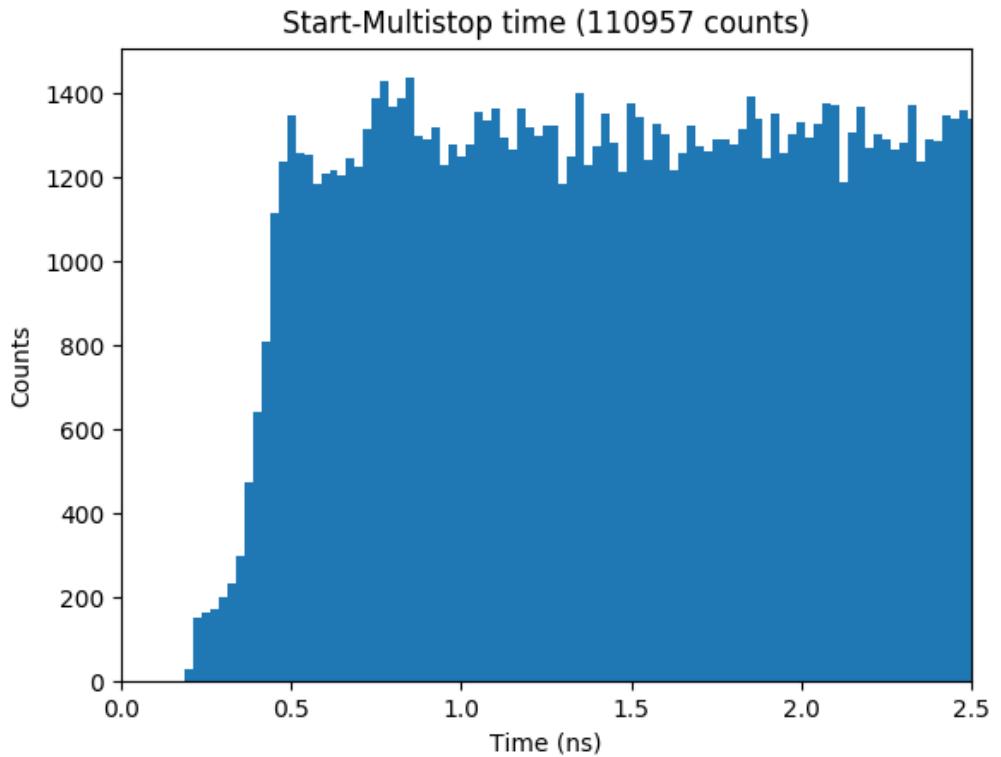


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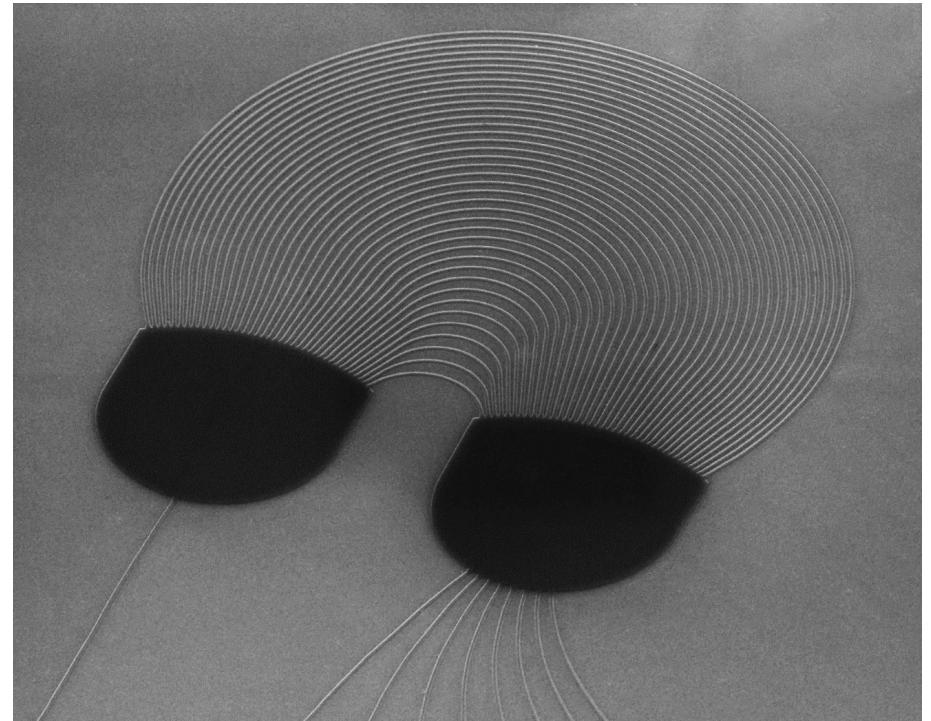
Recovery time

- Full recovery after 0.5 ns
- Clicks are registered again starting from 250 ps



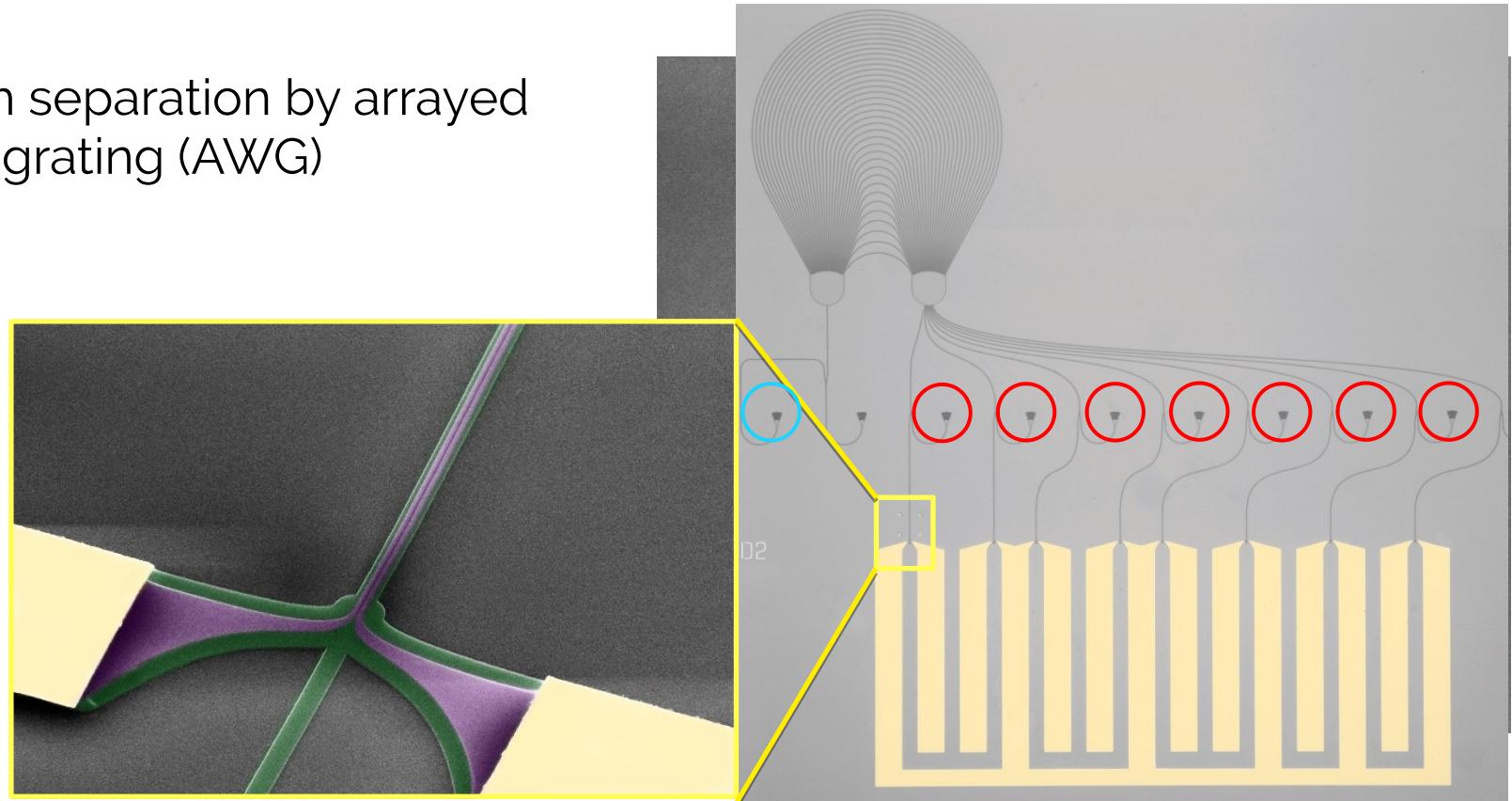
Applications: On-Chip Spectrometer

Wavelength separation by arrayed waveguide grating (AWG)



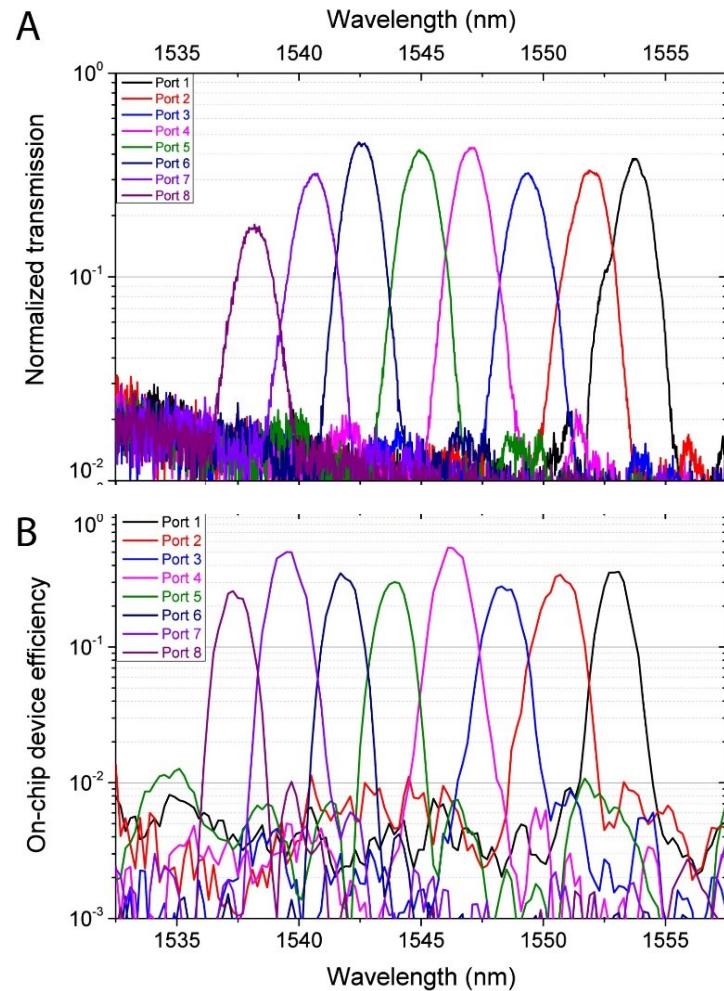
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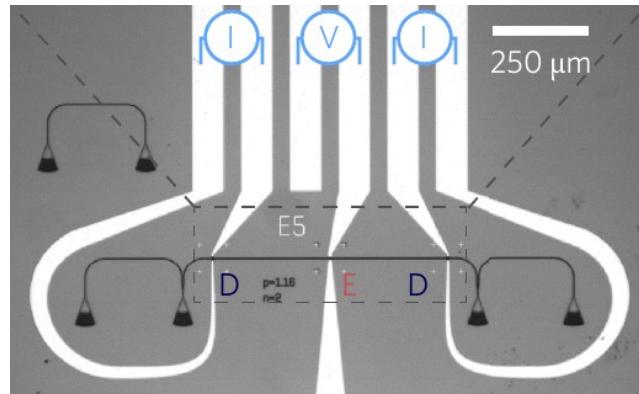
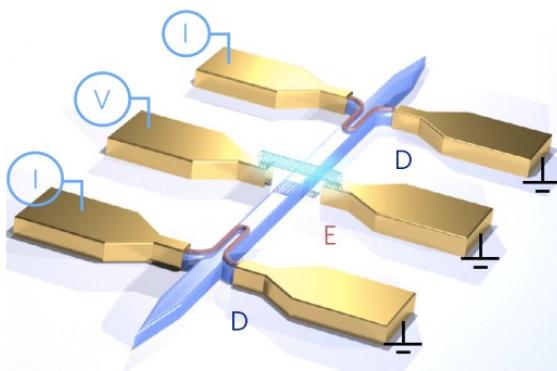


On-Chip Spectrometer

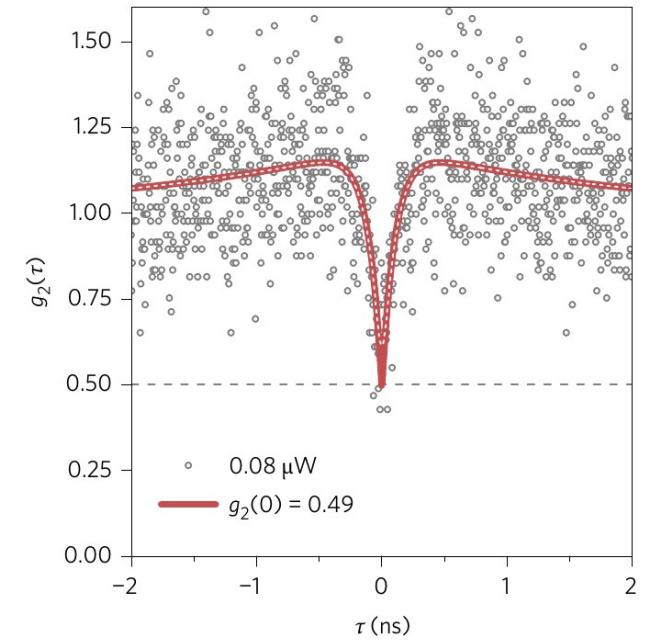
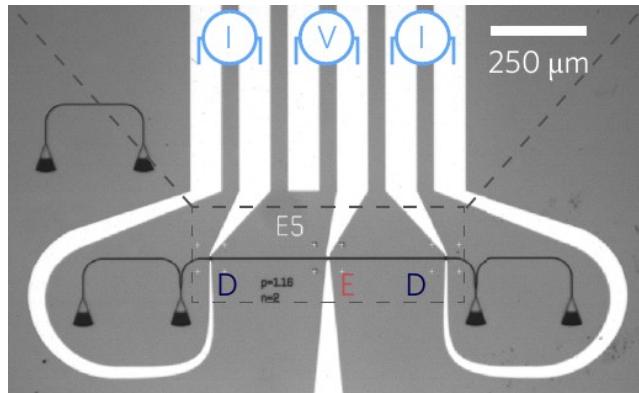
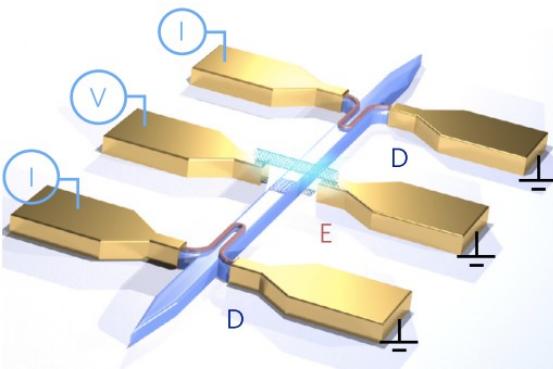
- 8-Port spectrometer
- 2 nm channel bandwidth
- -18 dB crosstalk
- OCDE ~20%
- Demonstrated for 1550 nm and 740 nm



Single-photon source and detectors on a single chip



Single-photon source and detectors on a single chip



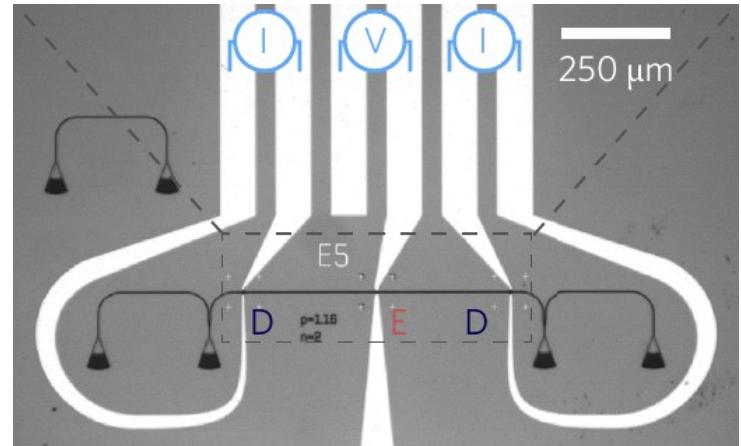
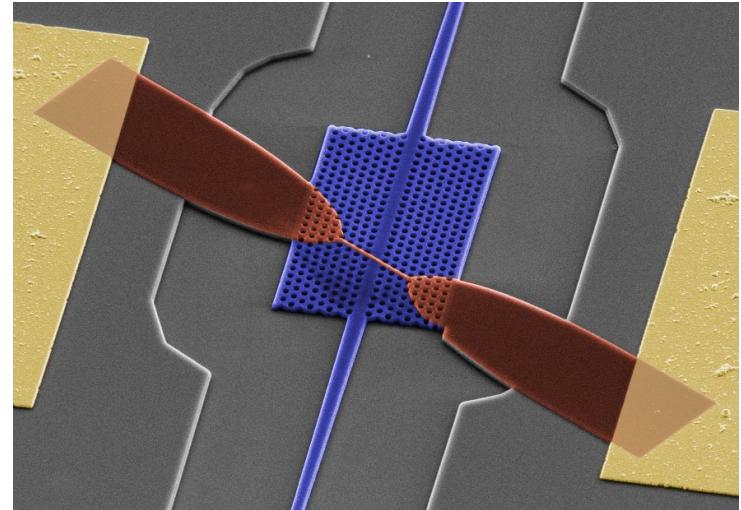
Summary

High-performance SNSPDs

- < 500 ps dead time (2 GHz)
- 67 % detection efficiency
- < 0,1 mHz dark count rate

Photonic integration

- On-chip spectrometer
- On-chip single photon source characterization



Thank you for your attention!



DFG Deutsche
Forschungsgemeinschaft



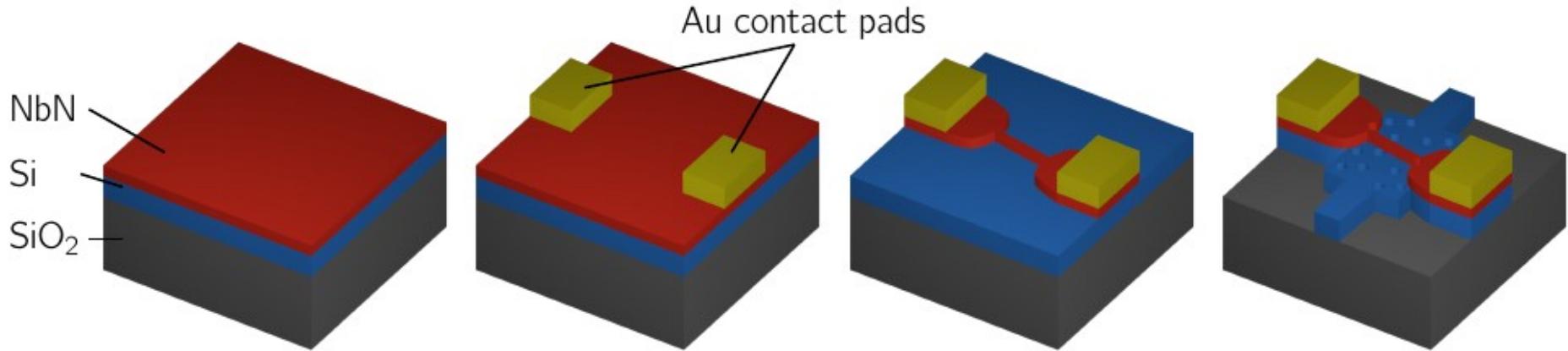
EMPIR  
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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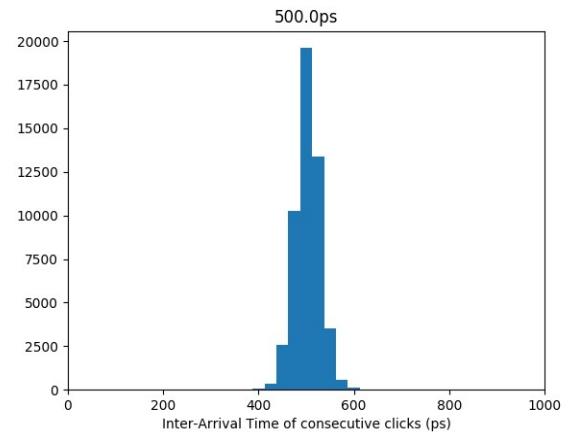
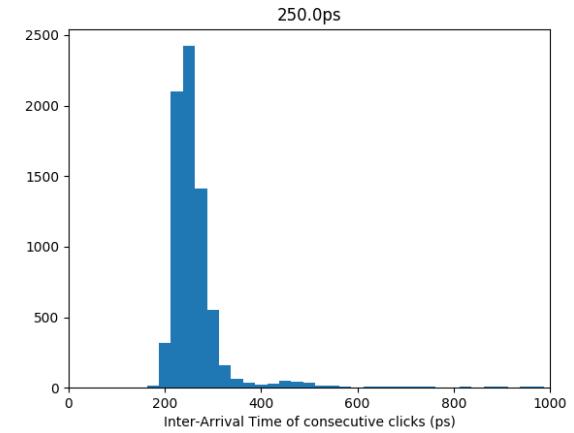
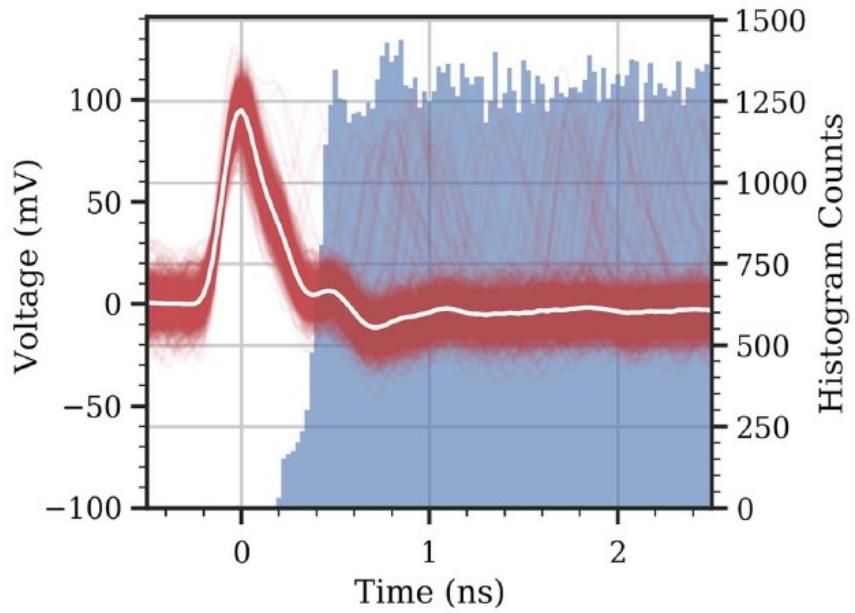


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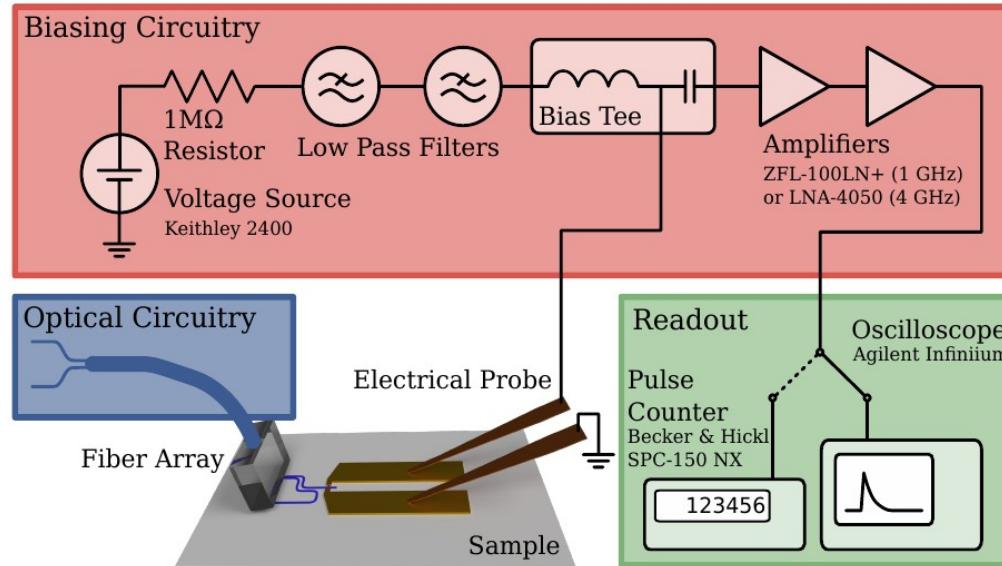
Fabrication



Recovery time



Setup



Fully integrated quantum photonic circuit with an electrically driven light source