Parallelizing Single-Photon Detection for Ultra-Fast Quantum Key Distribution

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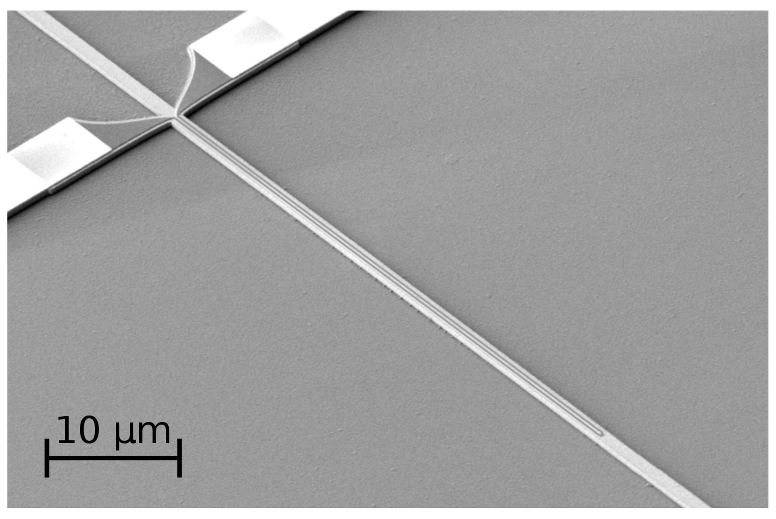
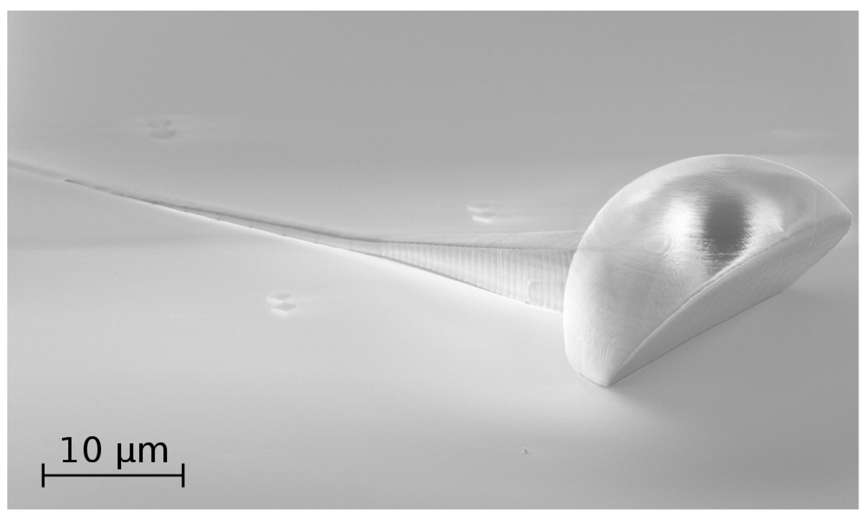
Quantum key distribution (QKD) protocols using photon states to transmit information promise secure communication over large distances. However, even in low loss optical fibers the attenuation of optical signals over long distances limits the secret key rates to a few kbit/s. To overcome this problem we parallelize established quantum cryptography schemes to larger numbers of channels and employ arrays of individually addressable low noise waveguide-integrated superconducting nanowire single-photon detectors that enable ultra-fast QKD. Our detectors operate at 3 K, feature detection efficiencies up to 50 %, dark counts rates below 100 Hz and a timing accuracy of up to 100 ps. Furthermore, the compact design allows for the integration with arbitrary passive and active nanophotonic devices on a single chip, e.g. delay lines, wavelength filters or phase modulators.

Integrated photonics and single-photon detection

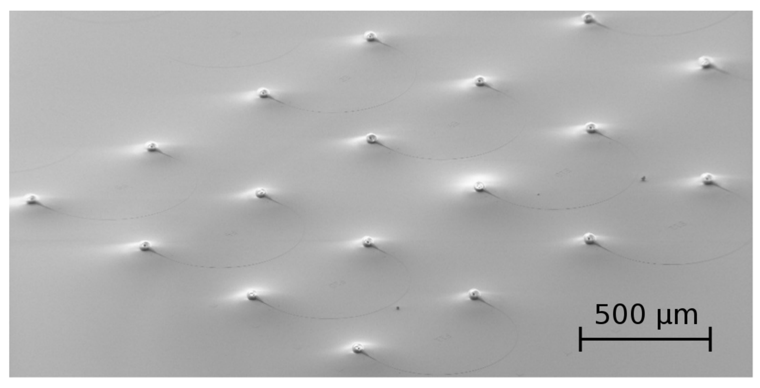
- In integrated photonics, nanoscale structures for guiding, manipulating and detecting light are patterned on small monolithic silicon chips in CMOS-compatible fabrication processes. This not only allows for a high scalablity and reproducibility but also provides a highly stable platform for the operation of on-chip passive and active photonic devices, including waveguide-integrated single-photon detectors[1].
- In addition to 2D in-plane devices, 3D polymeric structures fabricated using direct laser writing (DLW) are employed to efficiently couple light from optical fibers into on-chip photonic waveguides[2]. This approach is especially interesting when working with photonic platforms for which established out-of-plane coupling methods provide only limited coupling efficiency and bandwidth.

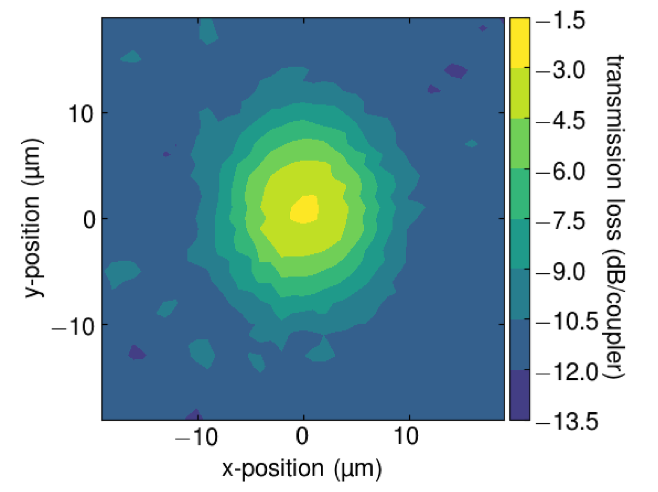


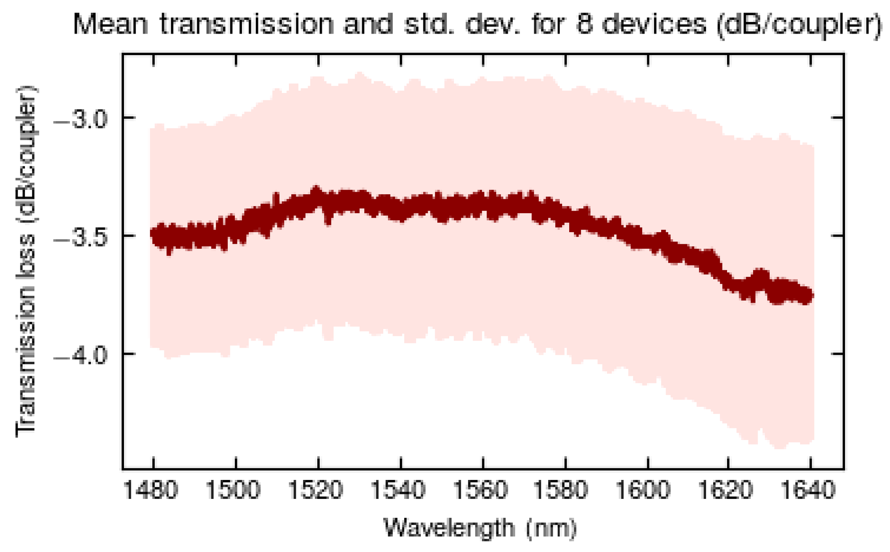


Optical interface

- 3D polymeric structures interfaced with nanophotonic waveguides present a highly efficient, broadband fiber-to-chip coupling solution.
- The high placement accuracy and reproducibility make the devices ideal for large scale applications.
- A mechanically stable and highly symmetric 90 ° out-of-plane design enables the coupling from 2D fiber arrays in a cryogenic environment.



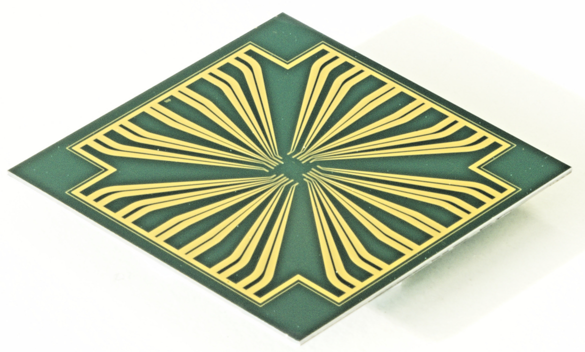


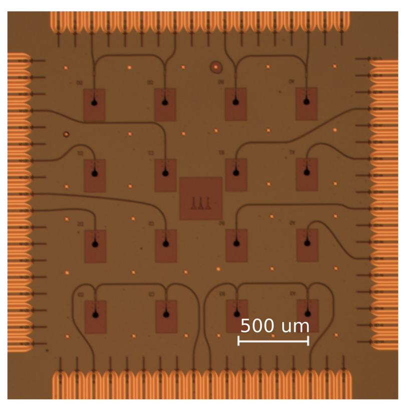


Chip fabrication

- The fabrication of the multi-channel detector chip is done in five steps from a 30 mm x 30 mm silicon nitride on insulator die.

1. Deposition of the superconducting film in a rf sputter process.
2. Patterning of contact pads and alignment markers using electron beam lithography (EBL).
3. Pattering of the nanowires using EBL.
4. Pattering of the photonic structures using EBL.
5. Direct laser writing of the coupling structures.

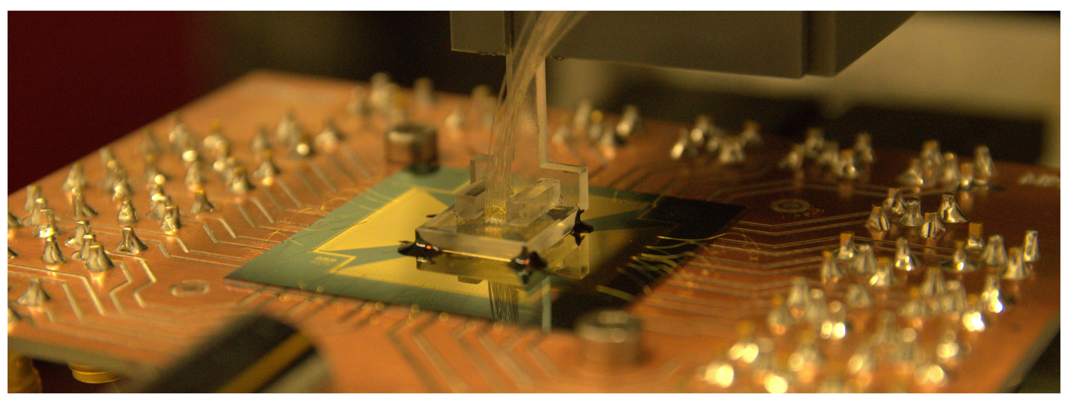




Packaging

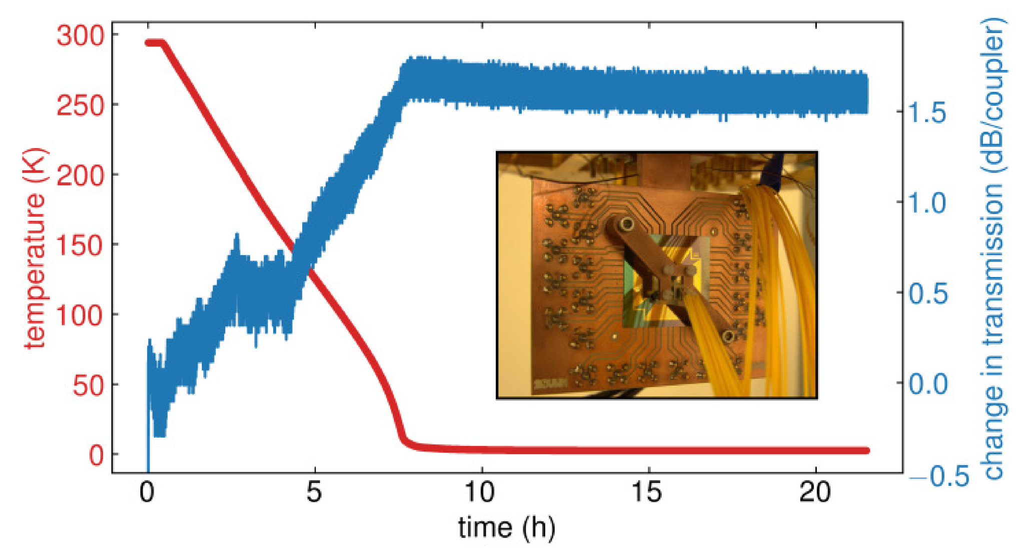
- After the fabrication, electrical and optical connections to the chip are established.

1. For individual electrical bias and readout of the detectors, the chip is mounted on and connected to a custom-made PCB featuring 16 SMA connectors via wirebonds.
2. For individual optical access of the detectors, a 2D fiber array featuring 16 channels is precisely aligned with respect to the 3D coupling structures on the chip using dedicated alignment structures, and mechanically fixed using a cryogenic epoxy.



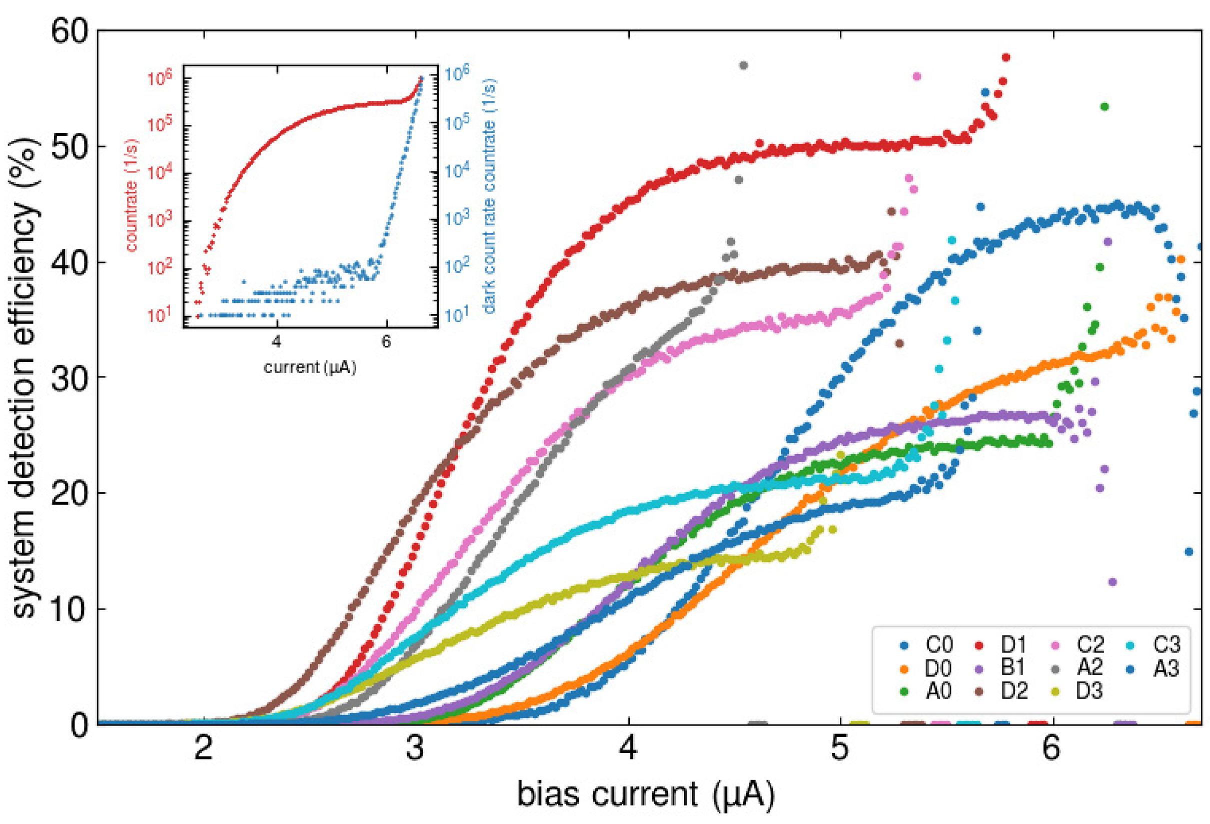
Cryogenic setup

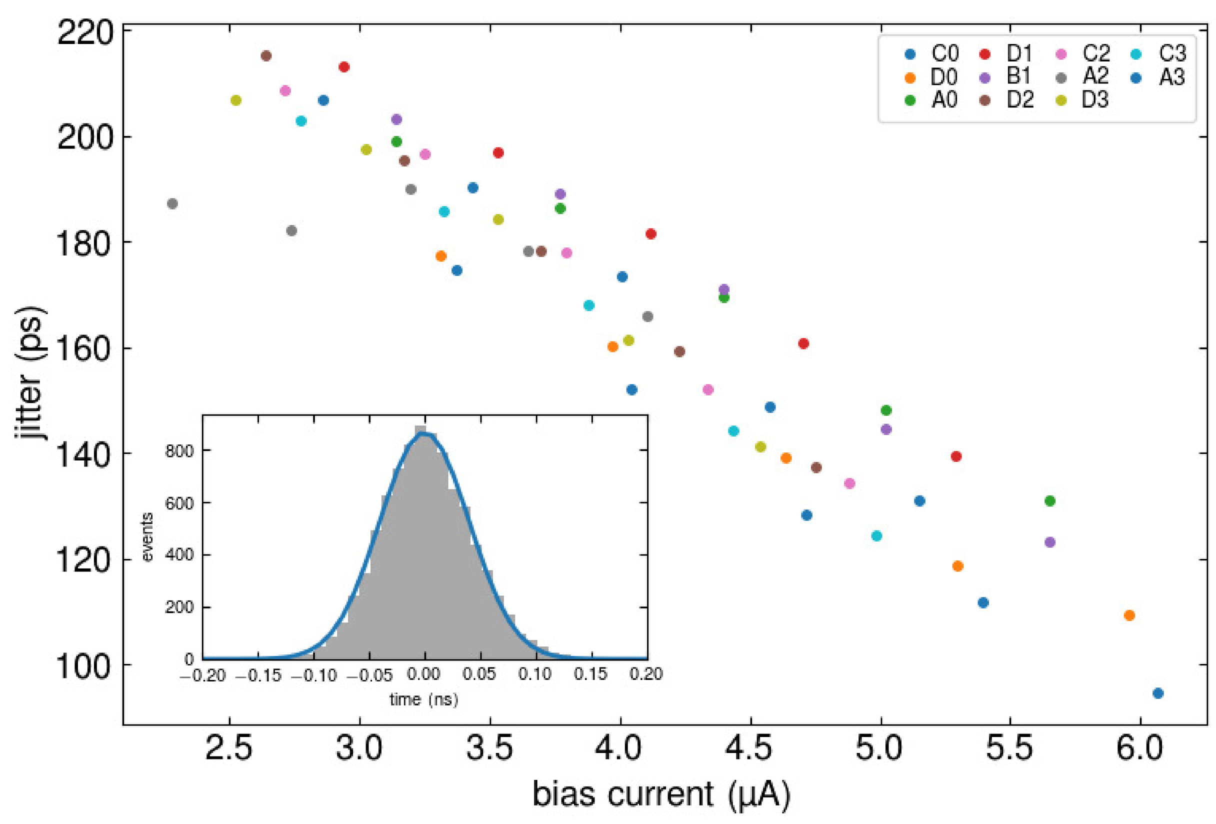
- The PCB is mounted on the 3 K stage of a closed-cycle 4He cryostat and electrically interfaced using flexible, high bandwidth multi-channel coaxial cables.
- The mechanical stability at cryogenic temperatures is analyzed via a transmission measurement of dedicated structures on the chip.



Experimental results

- We characterize the detectors at 2.7 K and find system detection efficiencies up to 50 % and dark count rates below 100 Hz.
- The timing uncertainty of the detectors is mainly limited by electronic jitter and ranges between 100 ps and 220 ps.





Results and Outlook

- We fabricated, packaged and characterized a matrix of fiber-coupled SNSPDs integrated with low-loss silicon nitride nanophotonic waveguides.
- Our nanophotonic approach allows for the realization of a compact, broadband QKD receiver for GHz clock rates (Fabian Beutel et al., contributed talks 4a).
- We work towards the realization of a single chip featuring a 64 detector array including state-of-the-art bias and readout electronics for multi-channel QKD experiments.

References

[1] Simone Ferrari et al. In: *Nanophotonics* 7 (2018).

[2] Helge Gehring et al. In: *Optics Letters* 44 (2019).

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