Integrated Quantum Photonics on Silicon Chips

(Invited paper)

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ABSTRACT
Quantum technology that utilizes single-photons as information carriers promises more efficient computing and higher security in communication. The realization of such novel photonic quantum information processing systems requires the implementation of large numbers of single-photon sources, linear optical circuitry and efficient single-photon detectors. To overcome scalability limitations and interface with established telecommunication architecture, we develop a nanophotonic quantum technology platform on silicon chips, employing standard semiconductor thin-film processing. We generate non-classical photon-pairs at telecom wavelengths via spontaneous parametric down conversion in aluminum nitride micro-ring resonators. Antibunching of heralded single-photons with high modal purity highlights the suitability of this second-order nonlinear source for nanoscale quantum optics. Further, we developed a toolbox of nanophotonic components for integrated quantum circuits. Employing balanced directional couplers we demonstrate quantum interference with 97% visibility when measuring photon statistics with waveguide-coupled detectors directly on-chip. Embedding superconducting nanowire single-photon detectors with nanophotonic circuits enables us to count individual photons with high efficiency, negligible dark count rate and high timing accuracy, as desired for applications in quantum technology. Advanced nanofabrication routines allow for straightforward replication of such sources, circuits and detectors in large numbers on silicon chips, thus paving the way for scalable integrated quantum photonics.

Keywords: quantum interference, superconducting single-photon detectors, spontaneous parametric down conversion, nanophotonic waveguides.

1. INTRODUCTION

Single photons are ideal carriers of quantum information and allow for realizing a broad range of applications in quantum communication, quantum computation and quantum sensing. The implementation of corresponding quantum photonic processing units require the generation, manipulation and detection of single photons. While proof-of-principle demonstrations were realized with bulk optic components the stability and scalability demands of complex quantum photonic circuitry will require an integrated solution. This can be achieved with nanophotonic waveguides and superconducting single-photon detectors on a silicon chip. Modern nanofabrication techniques then allow for replicating and combining functional units for photon generation, manipulation and detection in large numbers on a chip, thus enabling the construction of a programmable photonic quantum information processing system.

Here we employ aluminium nitride microring resonators that feature strong second-order optical nonlinearity to demonstrate the generation of single photons in pure quantum states. Nanophotonic circuit components allow for realizing high-visibility quantum interference of indistinguishable photons, which underlies the implementation of crucial quantum gate operations. Current-biased superconducting nanowires enable efficient detection of single photons with high signal-to-noise ratio. The integration of all these building blocks on a silicon chip holds great promise for photonic quantum technology.

2. PHOTON PAIR GENERATION IN MICRORING RESONATORS

Sources of indistinguishable photons are a key prerequisite for any quantum photonic information processing system. The generation of suitable photon pairs has recently been realized via the third-order nonlinear process of spontaneous four wave mixing (SFWM) in silicon waveguides. However, in SFWM schemes it is not straightforward to separate the resulting correlated signal and idler photons from the co-propagating classical pump field directly on chip, casting a fully integrated quantum photonic solution with waveguide-coupled single-photon detectors into doubt. Here we realize the generation of photon pairs in the second-order nonlinear process of spontaneous parametric down conversion instead, because larger spectral separation between pump und signal (idler) fields benefits efficient filtering.

We achieve phase-matching between higher-order visible-wavelength (775 nm) transverse magnetic pump modes and telecom-wavelengths (1550 nm) signal and idler fields in aluminium nitride (AlN) microring resonators via geometric dispersion engineering. The strong intrinsic second-order nonlinear of the AlN material system allows for generating degenerate photon pairs within 1.1 GHz bandwidth at rates of 3 MHz per milliwatt pump power. We confirm the quantum nature of the down-converted photons by analysing their statistical properties in time-correlated single-photon counting experiments [1]. A measurement of the second order auto-correlation function of idler photons heralded by the detection of their alleged signal partner photon shows high-visibility antibunching with $g^{(2)}(\tau=0) = 0.09$, which has no classical analogue. We further find high modal purity of the generated idler photons in a self-correlation measurement yielding a Schmidt number of K = 1.07, thus underlining the benefits of nanophotonic waveguide implementations for quantum photonics.

3. NANOPHOTONIC CIRCUIT COMPONENTS

Linear optic circuits are sufficient for implementing universal quantum information processing if they can be combined with single-photon sources and efficient detectors, as envisioned here. Crucial circuit components that allow for realizing quantum logic gate operations include beam splitters and optical phase shifters [2]. The latter can be realized via electrostatic actuation of optomechanical nanophotonic devices, which is preferable over thermo-optic and carrier-injection based methods that are challenging the integration with superconducting detectors and single-photons in dielectric waveguides, respectively. On-chip beam splitters on the other hand can be realized as directional couplers of evanescently coupled waveguides allowing for precisely controlled splitting ratios.

Here we show quantum interference of telecom wavelength photons from spontaneous parametric down conversion on a directional coupler fabricated from silicon nitride waveguides. Controlling the pump field characteristics allows for tuning the degree to which signal and idler photons are spectrally distinguishable via phase matching conditions. We observe two-photon interference with visibility of up to 97% using superconducting nanowire single-photon detectors embedded directly within the photonic integrated circuit [3]. Such high-visibility quantum interference will benefit the implementation of two-qubit quantum logic gate operations, which are a prerequisite for realizing universal quantum computing.

4. SUPERCONDUCTING NANOWIRE SINGLE-PHOTON DETECTORS

The overwhelming part of optical quantum technologies critically relies on the detection of single-photons in order to extract information from a quantum system. To perform such measurements both efficiently and accurately detectors are required that count single-photons with low noise, high timing accuracy and speed as well as high detection efficiency. Integrated quantum technology further benefits from efficient interfaces between detectors and nanophotonic circuits as well as operation at telecom wavelengths.

Here we show how superconducting nanowires are coupled with optical waveguides in traveling wave geometry for detection of near-infrared single-photons [4]. Efficient absorption of photons along their direction of propagation and high internal quantum efficiency nanowires biased close to their critical current yield on-chip detection efficiencies above 80%. Short nanowire length further allows for operation speed up to GHz rates, jitter performance of tens of picoseconds and sub-Hz dark count rates. We exploit these highly attractive performance characteristics for detecting quantum signatures of correlated single-photons directly on chip. High yield of hundreds of superconducting nanowire single-photon detectors on a single chip highlights the suitability of our approach for scalable quantum technology.

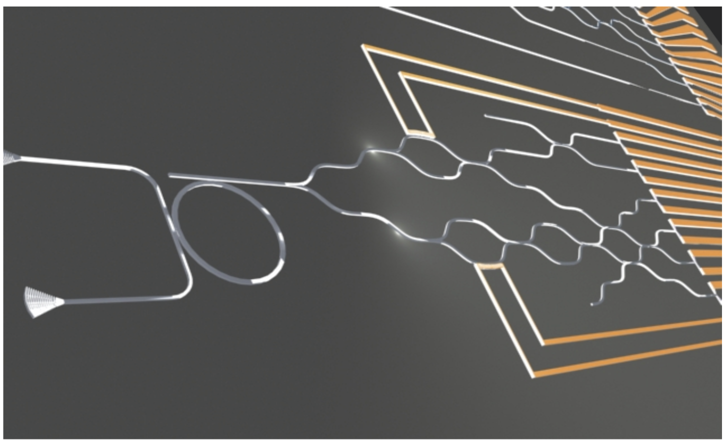

Figure 1. Schematic of quantum photonic circuits on a silicon chip.

5. CONCLUSIONS

We realize a quantum light source based on the second-order nonlinear process of spontaneous parametric down conversion in a microring resonator on a silicon chip. High visibility quantum interference in photonic integrated circuits and efficient single-photon counting with waveguide-coupled superconducting nanowire detectors demonstrates the suitability of our platform for integrated quantum optics. We have taken first steps towards the integration of large numbers of non-classical light sources, nanophotonic circuit components and single-photon detectors on a monolithic silicon chip (see Fig. 1) that satisfies the stability and scalability requirements of complex quantum technology. Future work will rely on these building blocks for realizing quantum logic gates that can be combined into a quantum algorithm as well as quantum communication and sensing schemes.

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