Photonic Integrated Circuits operating at the Single-Photon Level

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We present an approach to the full integration of active and passive single-photon devices on a single chip. Single-photon sources coupled to waveguides are realized by embedding InAs quantum dots (QDs) in photonic crystal (PhC) cavities. In order to control the QD-cavity coupling, devices for the electrical control of both the exciton energy and the cavity resonant wavelength are demonstrated. A waveguide single-photon detector is obtained by patterning superconducting NbN nanowires on top of the ridge waveguides, resulting in high efficiency and low jitter. This set of technologies opens the way to fully integrated quantum photonic circuits for quantum information processing based on photonic qubits.

I. INTRODUCTION

Quantum information processing (QIP) enables new protocols and functionalities in communication and computing. Quantum key distribution, allowing the secure exchange of cryptographic keys, is a first commercial application of QIP, while the tantalizing perspective of computational speed-up for a number of important problems has motivated much research in the direction of quantum computers. Single photons are one of the preferred implementation of quantum bits, since they can be transmitted at long distances with low loss and will form an integral part of any future QIP system. However, the production, processing and detection of single photons is still mostly realized using discrete, free-space or fiber-optic devices, resulting in unacceptable complexity and cost when circuits with several photons need to be built. The development of an integrated quantum photonic circuit is therefore the only possible solution to advance the state-of-the-art of photonic QIP in both science and applications. While passive quantum circuits have been demonstrated before [1], we are working on a concept which enables the full integration of active and passive devices, including sources and detectors of single photons. The main building blocks of this quantum photonic integrated circuit (Fig. 1) will be presented.

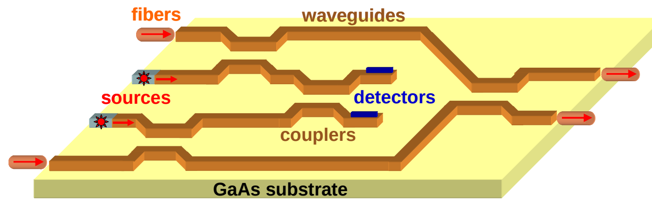

Figure 1 Schematics of a quantum photonic integrated circuit

II. WAVEGUIDE SINGLE-PHOTON SOURCES

Single-photon sources can be realized by using the radiative recombination from the excited state of a single two-level system, whereby one and only one photon is produced. Single QDs, due to their quantized energy structure, represent a good approximation of a two-level system at sufficiently low temperatures (<50 K). We use self-assembled InAs QDs on GaAs substrates, which have shown high radiative efficiency and relatively long coherence times. In order to efficiently funnel the QD emission into a waveguide a PhC cavity is patterned around the QD. This brings the additional advantage of shortening the radiative lifetime through the Purcell effect, which increases the emission rate and helps fighting decoherence. However this also contributes a major challenge: As the exciton/cavity coupling critically depends on their spectral alignment, a tuning method is required for either the cavity or the exciton. Tuning of the exciton energy is possible by applying an electric field to take advantage of the Stark effect. When several QD/cavity systems are needed, for example to produce several single photons in different waveguides, the cavities should all be resonant at the same wavelength, a major technological challenge. We have investigated two approaches to this problem. The first relies on the use of a short PhC waveguide, instead of a small cavity, as a broadband channel for photon emission. Indeed, in a PhC waveguide the suppression of in-plane emission due to the PhC bandgap results in efficient funneling into the guided mode over a large frequency range, making the fine control of the spectral resonance unnecessary [2]. We have demonstrated a spontaneous emission coupling factor β>80% in ≈20 μm-long waveguides, along with a small enhancement of the spontaneous emission rate[3]. The second approach is based on the electrical control of the PhC cavity wavelength. This is realized by having the PhC mode extend over two closely-spaced membranes, and varying their distance electromechanically. This results in a change of the mode wavelength, which can reach several tens of nm [4]. In a first experimental demonstration [5], we have shown electrical tuning over 10 nm with an applied voltage of only 6V (Fig. 2). This technique, differently from other PhC tuning methods, allows tuning also at low temperatures, as needed for integrated QIP applications.

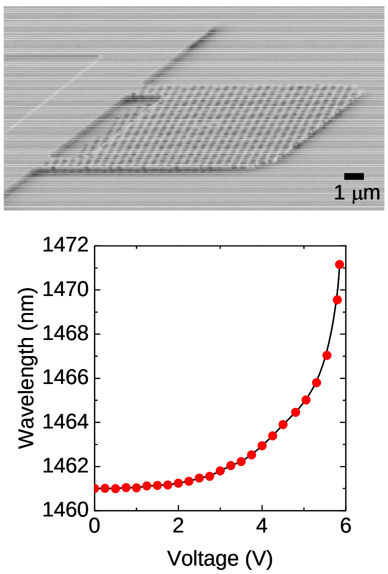

Figure 2 Top: Electron microscope image of a double-membrane tuneable PhC cavity. Bottom: Tuning curve

III. WAVEGUIDE SINGLE-PHOTON DETECTORS

Single-photon detection in GaAs waveguides can be obtained by using the "hot-spot" detection mechanism in superconducting nanowires. Ultrathin NbN films are deposited on top of a GaAs/AlGaAs ridge waveguide by sputtering, and then patterned as narrow wires (100 nm wide, tens of µm long). The evanescent field of the guided mode interacts with the wires, resulting in a modal modal absorption coefficient of several hundreds of cm^{-1}, ensuring nearly 100% absorptance. The device is cooled at 4 K and biased with a current close to the critical current of the superconducting wire. When the photon is absorbed, a region with a large population of electrons in the normal state forms, resulting in a resistance appearing in the wire, which produces a voltage pulse in the external circuit. With this structure we have demonstrated [6] waveguide detectors with quantum efficiency ≈20% and timing jitter ≈60 ps, which are very well suited for application in quantum photonic integrated circuits.

IV. CONCLUSION

We have demonstrated the main building blocks of a scalable quantum photonic integrated circuit. They are all based on the same GaAs/AlGaAs material basis and therefore can be integrated on the same chip. This should open the way to solid-state quantum processing of several tens of qubits.

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