Integrated pump rejection filter for high-quality photonic quantum communication

Dorian Oser [1], Florent Mazeas [2], Carlos Alonso Ramos [1], Xavier Le Roux [1],
Laurent Vivien [1], Sébastien Tanzilli [2], Éric Cassan [1], Laurent Labonté [2]
[1] *Centre de Nanosciences et de Nanotechnologies, CNRS, Universié Paris-Sud, Université Paris-Saclay, C2N, Palaiseau, France*
[2] *Université Côte d'Azur, CNRS, Institut de physique de Nice, France*
e-mail: dorian.oser@c2n.upsaclay.fr

ABSTRACT

Combining quantum and integrated photonics gives the ability of generating, manipulating, and detecting individual quantum states on single chips. Nonlinear four-wave mixing in silicon micro-ring resonators has shown an immense potential for on-chip bright photon-pair generation. However, one of the major challenges of this approach is the on-chip rejection of the pump, which severely distorts the quantum signals generated by the nonlinear process. Here, we report the integration on a single substrate of a photon-pair generator and a pump-rejection filter showing photon pair generation with a rate of 480 pairs per second for two signal/idler pairs simultaneously, with a brightness of 390 pairs/s/MHz, and a remarkably high raw visibility exceeding 95 %. All wavelengths fall within the ITU channels thus rendering this photon-pair source compatible with off-the-shelf telecom components.

Keywords: ring resonator, photonics, SFWM, multimode, Bragg filters.

1 INTRODUCTION

An integrated photon source is a fundamental building block of any quantum circuit. Bright photo-pair sources have already been demonstrated in silicon photonics, by harnessing spontaneous four-wave (SFWM) mixing in micro-ring resonators [1], [2], [3]. We have already demonstrated its promising properties in SOI for signal/idler pairs generation in where we showed high visibility and brightness for multiple pairs simultaneously [3]. However the nonlinear process used, SFWM, has the disadvantage of requiring a pump wavelength close to those of the generated photon pairs. This makes proper on-chip pump suppression a challenging task, as a large rejection must be applied (>100dB) on a relatively small bandwidth (< 10 nm). Hence, the vast majority of reported photon-pair sources exploiting SFWM implement off-chip pump filtering. Indeed, the only demonstration of photon-pair generation with on-chip pump relayed on cascading two silicon chips chips [5]. Even if ultra-high on-chip rejection has already been demonstrated [4], [6], such filters require continuous monitoring and active tunning to achieve desired functionality, which compromise their feasibility as pump-rejection filters in complex quantum photonic circuits. Here, we present a novel approach for the implementation of ultra-high on-chip rejection without the need of any active tunning. We validate its feasibility for pump-rejection in silicon quantum photonics by experimentally demonstrating a silicon photon-pair source with a raw visibility exceeding 95 %.

2 DESIGN & FABRICATION

Waveguide Bragg gratings are widely used in silicon photonics for the implementation of advanced wavelength filtering functionalities. However, conventional Bragg filters exhibit a limited rejection capability, mainly due to phase errors arising from fabrication imperfections [7]. To overcome this limitation, we have developed a new strategy harnessing modal engineering of the waveguide gratings to minimize the sensitivity to relative phase errors, thus allowing ultra-high rejection, even in the presence of fabrication imperfections [8]. The proposed filter relies on non-coherent cascading of multi-mode gratings separated by single-mode waveguides (Fig. 1). Each grating section reflects the fundamental mode into a higher order mode, which is radiated away in the single-mode waveguide (shown in blue in Fig. 1) connecting successive Bragg filters. These properties finally allow to cascade filters by breaking the phase coherence between successive filters and thus avoiding the rejection saturation. Based on this approach we have demonstrated on chip rejection higher than 80 dB [8].

We have implemented a photon-pair source that comprises a silicon micro-ring resonator and the proposed modal-engineered Bragg filter. In this first demonstration the demultiplexing of the photon pairs (signal and idler) is done off-chip, with a filter providing 20 dB corsstalk. A multimode coupler was added before the first section of the filter to extract on a separate port the first reflection [9]. This gives easy information about the alignment of the pump laser and work as an alignment port when working at wavelength in the filter. This

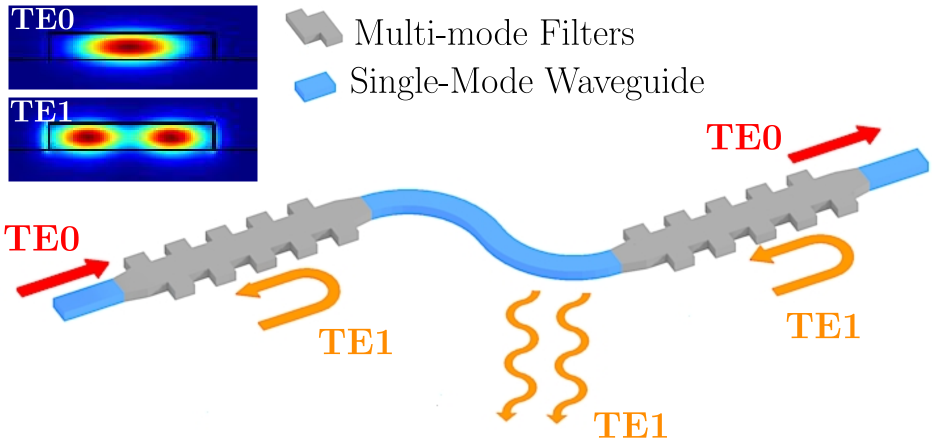

Figure 1. Schematic view of proposed cascaded filter. Fundamental mode (TE_0) is back-reflected into first order mode (TE_1). Single-mode waveguide sections separating adjacent filters radiate the back-reflected TE_1 mode away, precluding coherent interaction among different stages.

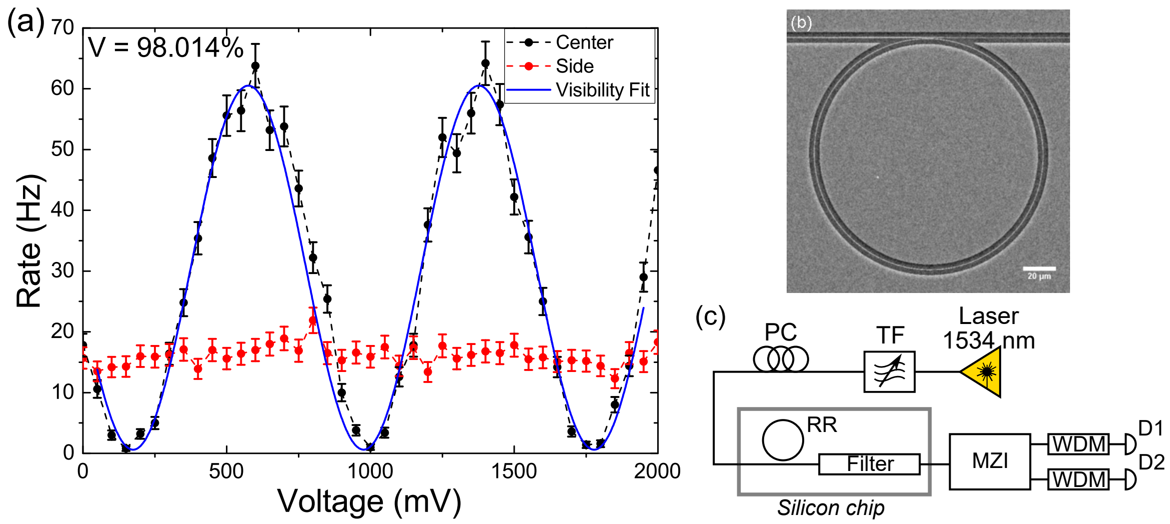

Figure 2. (a) Plots of the coincidence rate for the central (interference peak) and the average of the side peaks (coincidence peaks); each point was integrated for 5 seconds, the increment step is $50mV \sim \pi/8$, the side rate shows the stability of the measurement, the noise was not removed from the measurements. The noise is about 0.5 Hz, the error bars for all points come from Poissonian statistic of the pairs. (b) Scanning electron microscope image of the ring cavity used to make pairs of photons with SFWM. (c) Schematics of the setup used for the visibility experiments, PC is a polarization controller, TF is a tunable filter, MZI is a Mach-Zehnder interferometer, WDM is for wavelength demultiplexer, finally D1 and D2 are two photon counter detectors.

structure can generate pair of photons on all of the ring resonances and can be aligned to the telecom grid channel by carefully choosing the ring free spectral range.

Samples were fabricated on a silicon-on-insulator substrate with a silicon layer thickness of 220 nm. Electron beam lithography was used to print the patterns. The realized structure only required a single step of lithography for fabrication and no active tuning was needed. All filter sections were naturally aligned by the fabrication process.

3 RESULTS

The photon pairs produced by the source are genuinely energy-time entangled as they are produced by SFWM. Entanglement is analyzed using a folded Franson arrangement consisting of a single unbalanced fiber Michelson interferometer. In fig. 2a we plot the coincidence rate of photons coming from the interfering photon (Center), taking the same optical paths, and non-interfering photon (Side), taking different optical paths [3]. The side rate allows to see the stability of the photon generation which can be considered constant during the experiment. The interference pattern arise when changing the length of one arm of the interferometer with a piezo by applying a voltage. The visibility is measured then at destructive interferences. This shows a near perfect entanglements of the pairs generated as the visibility is close to unity. The visibility is limited by both the quality of the pairs generated but also by any residual noise. The visibility is degraded very quickly by any noise that get to the detector as we want the coincidence rate to be the closest to zero possible. This indicates that the pump is well filtered from the integrated multimode filter.

In addition to the good visibility, this integrated filter combined with a ring yields a rate of 480 pairs per seconds for two signal/idler pairs simultaneously and a brightness of $390\,\mathrm{pairs/s/M\,Hz}$. This was achieved by adding only a 20 dB-crosstalk de-multiplexing after the chip, on top of the integrated filter. The linear measurements of the on chip filter show a rejection of 70 dB, mainly limited by our current setup (limited sensitivity of the optical spectrum analyzer used for the analysis). However, quantum experiments suggest an even larger on-chip pump rejection.

4 CONCLUSION

We have demonstrated a new strategy using cascaded Bragg filters to reject the pump which is used for the non-linear processes. This all-passive photon-pair source, comprising on-chip pump-rejection filter, is an important step towards the full integration of an integrated heralding source. The low loss and simplicity of the proposed approach enable the implementation of photon-pair sources with a high generation rate, based on a single lithography step. The generated pairs yield a near unity visibility with no cost on the rate of the ring resonator. Only a single step of lithography is required for the fractionation This system strong promises for quantum key distribution networks as a cheap source of entangled photon pairs.

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