A comparison between waveguide and microresonator single-photon sources in silicon photonics

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ABSTRACT

For useful photonic quantum information protocols, such as quantum computing, quantum simulation, quantum machine learning, we need integrated photonic circuits to accommodate interaction of a large number of qubits [1], [2], [3], [4]. A key resource of the interaction of qubits is quantum interference. For high interference visibility, the single-photons that construct the qubits have to be indistinguishable. Measuring indistinguishability between two independent single-photon sources, we can determine the fidelity of the qubit interaction in a photonic platform. With such measurements in silicon, we have found microresonators more suitable than waveguides for such applications as it has 72% visibility without any spectral filtering. For both structures, photon number purity drastically affects the raw indistinguishability.

Keywords: Single-photon source, non-linear optics, silicon photonics, four-wave mixing, quantum computing.

1 INTRODUCTION

In general, indistinguishable single-photons correspond to the spectral purity of the single-photons: each of

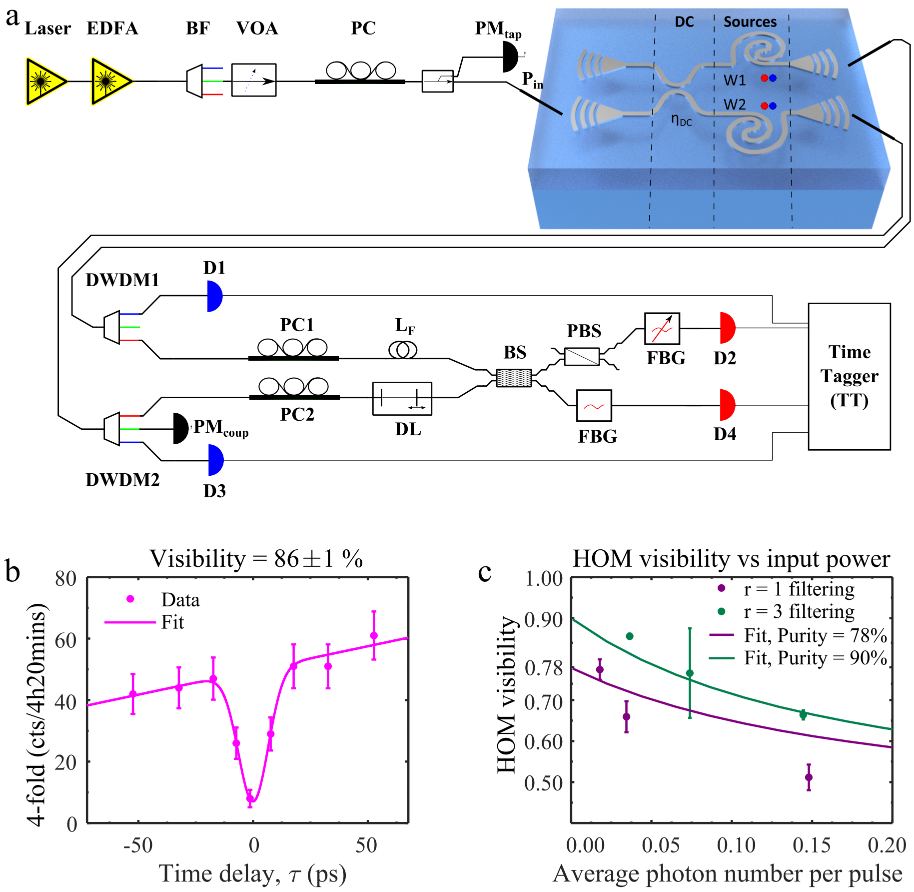

Figure 1. PIM of strip waveguide HSPSs. (a) Experimental setup for off-chip PIM. (b) HOM interferogram of heralded photons (red) from independent strip waveguides. With $r = 3$ spectral filtering and about 0.04 mean photon number 86% visibility is achieved. (c) Increase of the HOM visibility for lower mean photon number per pulse shows the detrimental effect of photon number purity. BF: Broadband Filter, VOA: Variable Optical Attenuator, DL: delay line, BS: Beam Splitter, FBG: Fibre Bragg Graiting, D: Single-photon Detector.

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the photons is emitted in a single optical (spectro-temporal) mode. In heralded single-photon sources, photon-pairs are emitted through a nonlinear optical process and detecting one photon of the pair herald the presence of the other photon, thus acting as a heralded single-photon source (HSPS). In silicon, the third-order nonlinear optical process, spontaneous four-wave mixing, absorbs two pump photons (λ_p) and produce a photon-pair historically called signal-idler (λ_s, λ_i). Detecting the idler photon projects the signal photons into specific spectro-temporal modes. For the heralded signal photons to be identical (i.e. spectrally pure), the spectral shapes have to be the same, and the joint spectral density has to be separable [5].

Once all the physical qubits have near unity spectral purity, a large number of qubit interaction is feasible. In reality, spectral purity has trade-offs with photon-number purity (ratio between single-photon state and multi-photon state), heralding efficiency and the brightness (amount of photons/s). Therefore, an HSPS for scalable quantum computing/communication is characterised by a set of metrics: spectral purity (P); photon-number purity; heralding efficiency and brightness. A desired interaction among physical qubits requires these metrics to be high. All of these metrics are captured by a single experiment of photon indistinguishability measurement (PIM). In a PIM with two HSPSs, we detect the idler photons from each HSPS to herald the signal photons, which then interferes in a Hong-Ou-Mandel interferometer [6] or a Mach-Zehnder interferometer [7] as four-fold coincidences. The raw visibility of the interference indicates the indistinguishability of the heralded single-photons in the presence of the photon-number impurity and spectral impurity. The raw brightness of the four-fold coincidence indicates the heralding efficiency, loss of the device and the detection efficiency. Thus, a PIM coefficient ($\mathbb{C}_{\mathrm{PIM}}$) can be defined which efficiently captures the metrics of the HSPSs and their scalability:

$$\mathbb{C}_{\mathrm{PIM}} = \mathrm{B} \times \mathrm{V} \div \mathrm{T} \tag{1}$$

where, T is the required time for a PIM and raw brightness B captures the actual brightness, heralding efficiency and system loss. Higher the value of the $\mathbb{C}_{\mathrm{PIM}}$, better the HSPS is.

Here, we have compared the PIM of silicon waveguide and micro-resonator HSPSs. We have chosen silicon because of high component density, demonstration of electronic and photonic integration [8], low loss optical delay lines [9], high-speed electro-optic switches [10], and other necessary criteria for a linear optical quantum computing. If near ideal HSPSs are achieved in silicon, it will lead to an early demonstration of quantum advantages.

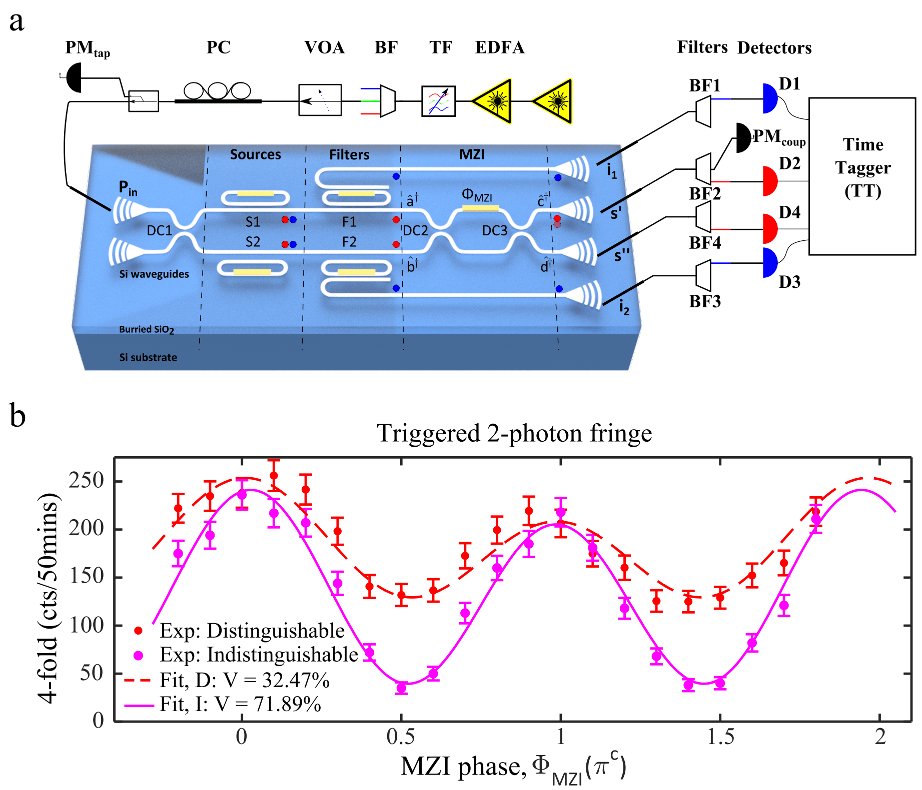

Figure 2. PIM of micro-resonator HSPSs. (a) Experimental setup for on-chip PIM. (b) Mach-Zehnder interferogram of completely distinguishable (red events) and indistinguishable (magenta events) heralded photons. Due to photon-number impurity, the raw visibility reduces to 72% from the theoretical value of 92%.

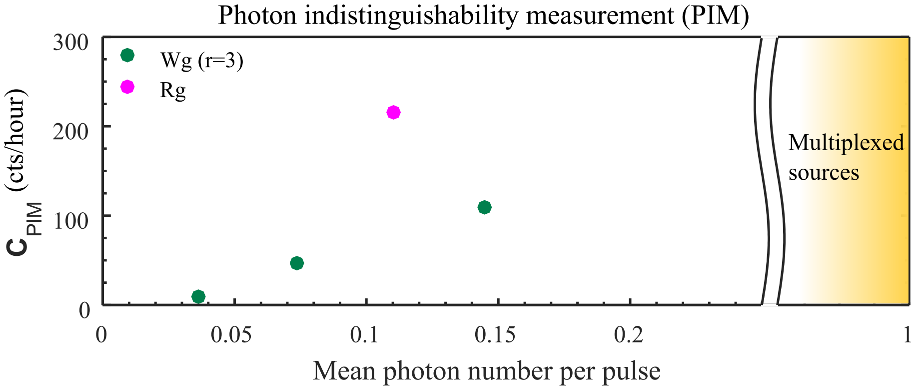

Figure 3. Comparing PIM between strip waveguide and microresonator.

2 RESULTS

We have interfered heralded single-photons, generated from strip waveguides, in an off-chip HOMI (Fig. 1) and recorded a set of interferogram for equal filtering ($r = 1$) and three times narrow filtering ($r = 3$) of the heralded photons with respect to the pump ($r = \Delta\lambda_p/\Delta\lambda_s$). We have reduced the input power in both cases (Fig. 1(c)) and observed improved raw visibility (max V $= 86\%$) due to improved photon-number purity at the expense of brightness and drastically increased integration time. Here, the y-intercept specifies the maximum achievable visibility determined by the spectral purity.

Integrating the spectral de-multiplexer and a MZI on-chip significantly reduced the complexity while improving the stability of the PIM (Fig. 2) for the microresonators. We have achieved V $= 72\%$ without any spectral filtering with high brightness due to resonant enhancements. The reduction of visibility from 92% theoretical limit is due to the photon-number impurity [11].

3 DISCUSSION AND OUTLOOK

The $\mathbb{C}_{\text{PIM}}$ for waveguides and microresonators are plotted in Fig. 3 as a function of mean photon-number per pulse ($\bar{n}$). Our HSPSs are on the lower values of $\bar{n}$ emphasising their probabilistic nature. A near ideal single-photon source achieved by lossless active multiplexing (or demultiplexing) will be on the top-rightmost side of this graph. From our observation, the microresonators are more suitable candidates as HSPSs in silicon photonics. These results promises near term integration of 10+ photon experiments in SOI photonics even without multiplexed sources.

We have also observed that the integration of photonics components increases the ease of performing PIM which will be desirable for a larger photonic chip with an array of HSPSs. These PIM measurements give an understanding of the performances of HSPSs on the scalability of silicon HSPSs as it shows the basic interaction between two single-photons (i.e. two qubits). This is our first attempt to quantify the performance of HSPSs for photonic quantum information processing. It can be further improved in future by having a more complete theoretical basis from where $\mathbb{C}_{\text{PIM}}$ naturally emerges.

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