Editor's Focus

Bright photon-pair source based on a silicon dual-Mach-Zehnder microring

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Single photons and photon pairs are typically generated by spontaneous parametric down conversion or quantum dots; however, spontaneous four-wave mixing (SFWM) in silicon microring resonators [1] is also an appealing source of entangled photons, offering a strong cavity-enhanced nonlinear interactions while maintaining features, such as compact, simple to fabricate, and allowing for thermal tuning. However, silicon ring-resonators usually suffer from a trade-off between providing a high pair generation rate (PGR) and high extraction efficiency. To achieve high PGR, devices are generally operated with the signal and idler photons in the undercoupling regime and pump photons at the critical coupling point, while high extraction rates require the converted photons to be overcoupled. Therefore, the optimal conditions for achieving maximal output photon pair flux are critical coupling for the pump photons and overcoupling for the converted photons [2, 3]. However, it is not easy to approach such optimal coupling conditions with traditional single-bus waveguide-coupled resonators and double-bus resonators because they do not allow the coupling conditions for the pump and converted photons to be controlled independently.

Herein, we propose to use dual asymmetric Mach-Zehnder

Interferometers (AMZIs) as waveguides coupled to a ring resonator to optimize the output photon pair flux. In 1995, Barbarossa et al. [4] demonstrated that a single AMZI-coupled ring-resonator could suppress certain resonant modes via interference between the two arms of the AMZI. This design has since been used to tune the bandwidths of ring-resonator-based filters [5, 6] and as an ingenious sensor [7]. Recently, several studies [8–10] have also adopted this design to adjust the quality factors of the interacting beams in SFWM to either concentrate the photon pairs, resulting in emission from one of the ports of an add-drop structure, or enhance the photons' spectral purity. Herein, we use a dual-AMZI-coupled resonator to control the coupling conditions of the pump, signal, and idler photons independently, conducting experiments to approach the optimal coupling conditions by fabricating a series of dual-AMZI-coupled resonators with different coupling parameters. We are able to use this ensemble to achieve and characterize bright photon sources.

For continuous-wave (CW) SFWM in a microring resonator, it has been proven theoretically that the generated photon pair flux scales with the quality factor as follows [2, 3]:

$$N_{cc} = \frac{16V_g^4 \gamma^2 P_p^2 Q_p^4 Q_s^2 Q_i^2}{\Omega_p^3 \pi^2 R^2 Q_{ext,p}^2 Q_{ext,s} Q_{ext,i} (Q_s + Q_i)}, \quad (1)$$

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where v_g is the resonator's group velocity, γ is the nonlinearity parameter, P_p and Ω_p are the pump photons' power and resonant frequency, respectively, and R is the ring radius. Additionally, Q_p and $Q_{\text{ext},p}$ are the pump photons' total and extrinsic quality factors, respectively. Likewise, Q_s , Q_i , $Q_{\text{ext},s}$, and $Q_{\text{ext},i}$ are the signal and idler photons' total and extrinsic quality factors, respectively, given as follows:

$$\frac{1}{Q} = \frac{1}{Q_{\text{int}}} + \frac{1}{Q_{\text{ext}}}, \quad (2)$$

where Q_{int} is related to the total round-trip loss α ($Q_{\text{int}} = \frac{\omega}{v_g \alpha}$) and Q_{ext} is determined by the power-coupling coefficient k for the coupling between the waveguide and ring ($Q_{\text{ext}} = \frac{2\pi R \omega}{v_g k}$).

Assuming that the converted photons' quality factors are identical and independent of those of the pump photons, to maximize the output photon pair flux, the resonator should be operated at the pump photons' critical point, namely $Q_{\text{ext},p} = Q_{\text{int},p}$, and the converted photon pairs' overcoupling point, namely $Q_{\text{int},s/i} = 2Q_{\text{ext},s/i}$, where $Q_{\text{ext},s/i}$ and $Q_{\text{int},s/i}$ are the converted photons' extrinsic and intrinsic quality factors, respectively. As shown in Figure 1, the normalized output photon pair flux drops off in both the undercoupling and overcoupling regimes for the pump photons, and also decreases if the converted photons deviate from their overcoupling point.

Figure 2(a) shows a schematic of the proposed dual-Mach-Zehnder microring. The performance of this design depends on the properties of three individual components, namely a ring resonator and two AMZIs. In the ring cavity, the optical mode should satisfy the resonant condition, namely $2\pi R n_{\text{eff}} = m\lambda$ ($m = 0, \pm 1, \pm 2, \dots$), with the free spectral range (FSR) satisfying $\omega_{\text{FSR}} = \frac{v_g}{R}$. The AMZI's interference spectrum is sinusoidal relative to the difference in optical path length between its long and short arms, and its FSR is given by $\Delta L n_{\text{eff}} = n\lambda$ ($n = 0, \pm 1, \dots$), where ΔL is the path difference between two arms and wavelength-dependent n_{eff} is the effective refractive index of the silicon resonator. Therefore,

Figure 1 (Color online) N_{cc} versus the intrinsic to extrinsic quality factor ratios for both the pump photons and converted photon pairs.

Figure 2 (Color online) (a) Schematic of a dual-AMZI-coupled microring. Resonator spectra for the (b) input side (green) and (c) drop side (red), tuned by the AMZI spectrum (gray).

if ΔL equals half the ring's round-trip length, the AMZI's FSR is twice that of the cavity, making it possible to suppress every other cavity resonance. The resonant wavelength and the point of constructive interference between the two AMZIs can be tuned by thermal-optic phase shifters. Therefore, this design couples the pump photons to the ring and does not allow them to be decoupled from the ring through the add port, while the photon pairs generated at resonance only escape from the drop port. Figure 2(b) and (c) shows the theoretical spectra for the input and output sides, respectively.

This configuration has three main advantages. First, the coupling conditions of the pump and signal/idler photons can be controlled separately, which is the main motivation of this work. Second, this design prevents the converted photons generated in the straight waveguide from entering the resonator and suppresses the pump beam in the drop port, ensuring that no photons are generated from the straight output waveguide. Third, it has higher collection efficiency because it suppresses the number of generated photons in the through port.

We fabricated a sample comprising a series of 12 dual-Mach-Zehnder microrings on a single silicon-on-insulator chip with the waveguides' cross-section heights and widths of 220 and 500 nm, respectively. Each microring was designed with a radius of 28 μm to facilitate an FSR of approximately 3.2 nm to match the 200 GHz channel spacing of commercial dense wavelength division multiplexing (DWDM). In addition, we integrated heaters into the tops of the rings and long AMZI arms to precisely tune the resonant wavelengths and adjust the AMZIs' phase differences. All 12 resonators had different coupling gaps, including 180, 210, and 240 nm gaps for the pump photons and 120, 150, 180, and 210 nm gaps for the signal/idler photons; therefore, both the pump and converted photon beams experienced overcoupling, critical coupling, and undercoupling. The cascaded resonator connections ensured identical coupling losses for all resonators.

Figure 3 illustrates our experimental setup for generating and detecting photon pairs via SFWM. A tunable CW laser (Yenista Tunics T100s with a tuning range of 1500–1630 nm and linewidth of 0.4 MHz) was used as the pump and its polarization state was controlled by a polarization controller

(PC). A DWDM was used to suppress sideband noise in the pump beam before it reached the chip. The pump laser was coupled to and decoupled from the silicon chip by coupling fiber arrays (FAs) to the waveguide grating array on the chip with a total insertion loss of 7.13 dB. A pump wavelength of 1551.0 nm was chosen to match the DWDM's CH33, while the signal and idler photons were measured at 1554.2 and 1547.8 nm, respectively, matching CH37 and CH29. The residual pump photons from the through port were also decoupled from the chip and sent to a power meter (PM) to monitor the pump in a resonant state. Meanwhile, the converted photon pairs from the drop port were separated and filtered by a second DWDM. The photons were detected by two superconducting nanowire single-photon detectors with dark count rates of 800 Hz and detection efficiencies of 73 and 75%, respectively. Finally, the coincidence rates were calculated using a time-tagging unit with a resolution of 78 ps.

Figure 4 shows the experimental and calculated coincidence rates for each resonator. The coupled pump power delivered to the chip was 156 μ W, which was low enough to reduce the nonlinear loss. Herein, we give the loss-subtracted

Figure 3 (Color online) Schematic of the experimental setup, where CW is continuous wave; PC is polarization controller; DWDM is dense wavelength division multiplexing; FA is fiber array; PM is power meter; and SPD is superconducting nanowire single-photon detector.

Figure 4 (Color online) Coincidence rates of the 12 dual-AMZI resonators. Herein, the horizontal axis indicates the resonator number based on the order given in Table 1.

coincidence rates, which account for the waveguide propagation loss (measured to be 4.23 dB/cm). The calculated counts were obtained by substituting the measured quality factors into eq. (1). Ranking the experimental and calculated coincidence rates for each resonator in order from high to low, the experimental and calculated results were in good agreement. The quality factors for the pump, signal, and idler photons were calculated from the measured transmission spectra on the input and drop sides of the microring resonator, respectively. When calculating the source's spectral brightness in Table 1, we accounted for the escape efficiency [3], propagation loss, grating coupling loss, and detection efficiency.

The highest measured coincidence rate (3596 Hz) was recorded for the ring with gaps of 210 and 120 nm for the pump and signal/idler photons, respectively. Large propagation losses in such cascaded connecting designs should be subtracted from the raw data; therefore, we obtained a final rate of 15604 Hz. The source's maximum spectral brightness approached 2.4×10^9 pairs $s^{-1} nm^{-1} mW^{-2}$ when the gaps on both sides of the AMZI were 240 nm, higher than those achieved by bulk second-order nonlinear optical crystals [11] and typical second-order nonlinear chips, such as ion-exchange lithium niobate waveguides [12, 13], but not including lithium-niobate-on-insulator designs [14]. The raw measured coincidence rates in Table 1 are among the highest results reported [2, 3, 15–21]. In addition, we found that photon pairs were escaping from the through port at 3.2 Hz, a much lower rate than the drop port's 3596 Hz, indicating that our dual-AMZI resonator's collection efficiency was high [10].

To analyze the optimal coupling conditions for the pump and converted photons individually, we now focus on a key parameter, namely the ratio between the intrinsic and extrinsic quality factors. We selected coincidence data from three resonators with input-side gaps varying from 180 to 240 nm

Table 1 Key parameters of the 12 AMZI resonators, showing their quality factors ($\times 10^4$), measured coincidence rates N_{cc} (Hz), loss-subtracted coincidence rates N_{ls} (Hz), and source spectral brightnesses B ($\times 10^7$ pairs $s^{-1} nm^{-1} mW^{-2}$)

Gap (nm)	$Q_p, Q_{ext,p}$	$Q_s, Q_{ext,s}$	$Q_i, Q_{ext,i}$	N_{cc}	N_{ls}	B
180, 120	3.5, 6.6	1.6, 1.9	1.6, 2.0	1429	4594	6.2
210, 120	5.6, 9.7	1.5, 1.8	1.9, 2.2	3596	15604	20
240, 120	4.8, 21.4	1.7, 2.0	2.0, 2.3	470	2754	4.1
180, 150	4.1, 7.4	2.5, 3.3	2.7, 3.4	903	7136	18
210, 150	4.4, 7.8	2.4, 3.1	2.5, 3.4	650	6931	18
240, 150	6.0, 18.1	2.5, 4.0	2.5, 3.3	480	6902	21
180, 180	3.7, 5.9	3.2, 5.6	3.0, 4.8	353	6851	35
210, 180	5.1, 11.0	3.0, 5.9	3.8, 5.7	344	9021	52
240, 180	5.0, 21.0	3.9, 6.2	4.0, 6.3	62	2195	13
210, 210	3.3, 6.3	4.7, 10.1	4.6, 9.6	61	2928	36
240, 210	4.7, 21.0	2.8, 4.2	4.6, 9.6	20	1287	8.2
240, 240	6.8, 14.1	6.9, 16.4	6.3, 16.2	120	10395	240

with the drop-side gap fixed at 180 nm, and calculated the coincidence rates by deducting the contributions of the pump photons' intrinsic quality factor and the converted photons' quality factors. The results, shown in Figure 5(a), agree well with the theoretical curve.

Turning now to the converted photons, we selected three resonators where the input-side gap was fixed at 210 nm and the drop-side gap varied from 120–180 nm. Figure 5(b) shows the coincidence rate versus the $Q_{\text{int},s}/Q_{\text{ext},s}$ ratio, calculated by deducting the contributions from the pump photons' scale factor and converted photons' total quality factor. This indicates that the device should be operated with the converted photons in the overcoupling regime if their total quality factor is fixed.

Finally, if the photon pairs have equal quality factors and the intrinsic quality factor is fixed, the optimal coupling condition is $Q_{\text{int},s/i}/Q_{\text{ext},s/i} = 2$, as shown by the black line in Figure 5(c). These results were obtained for three resonators with the same input-side gap of 180 nm and drop-side gaps varying from 120 to 180 nm by deducting the contributions of the pump photons' scale factor and the photon pairs' intrinsic quality factor. The fluctuations seen here mainly originated from the difference in the signal and idler photon Q factors for a single resonator.

We believe this is the first experimental validation of the output photon pair flux of resonators. Although the resonator with 240-nm gaps on both the input and drop sides was slightly undercoupled, it still yielded a high output photon pair flux, with a loss-subtracted coincidence rate of 10395 Hz owing to its relatively high quality factor.

In conclusion, we have designed a series of dual-AMZI resonators that allow the quality factors of the pump and converted photons to be controlled and have demonstrated that the pump and signal/idler photons should be in the critical coupling and overcoupling regimes, respectively, to optimize SFWM efficiency. This work provides a guideline for creating highly efficient resonator-based photon-pair sources via SFWM, which will be valuable as practically feasible

Figure 5 (Color online) Coincidence rate versus (a) $Q_{\text{int},p}/Q_{\text{ext},p}$, (b) $Q_{\text{int},s}/Q_{\text{ext},s}$, and (c) $Q_{\text{int},s/i}/Q_{\text{ext},s/i}$ (assuming the converted photons' quality factors are equal).

quantum light sources for on-chip quantum information processing.

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