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Citation: Chin. Phys. B . 2020, 29(11): 114201 . **doi:** 10.1088/1674-1056/abbb28
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RAPID COMMUNICATION

Near 100% spectral-purity photons from reconfigurable micro-rings*

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(Received 21 September 2020; revised manuscript received 21 September 2020; accepted manuscript online 24 September 2020)

We propose an on-chip reconfigurable micro-ring to engineer the spectral-purity of photons. The micro-ring resonator is designed to be coupled by one or two asymmetric Mach–Zehnder interferometers and the coupling coefficients hence the quality-factors of the pump and the converted photons can be dynamically changed by the interferometer's internal phase-shifter. We calculate the joint-spectrum function and obtain the spectral-purity of photons and Schmidt number under different phases. We show that it is a dynamical method to adjust the spectral-purity and can optimize the spectral-purity of photons up to near 100%. The condition for high-spectral-purity photons is ensured by the micro-ring itself, so it overcomes the trade-off between spectral purity and brightness in the traditional post-filtering method. This scheme is robust to fabrication variations and can be successfully applied in different fabrication labs and different materials. Such high-spectral-purity photons will be beneficial for quantum information processing like Boson sampling and other quantum algorithms.

Keywords: spectral-purity, micro-ring, Mach–Zehnder interferometer

PACS: 42.50.–p, 42.65.–k, 42.65.Wi **DOI:** 10.1088/1674-1056/abbb28

Deterministic source of single photons is a vital resource for photonic quantum technologies such as boson sampling,[1] state discrimination,[2] and foundations of quantum mechanics.[3] From the requirement of practical experiments, single-photon sources should emit photons on-demand and indistinguishable in all degrees of freedom. Two primary directions are developed enormously to generate such sources: single emitters such as quantum dots or color centers, and the heralded single-photon sources via spontaneous parametric nonlinear processes.[4] With the progress of solid-state technologies, the quantum dot is considered as an attractive candidate for quantum experiments which can provide high-quality single photons.[5–9] However, it remains a chanllenge to fabricate identical emitters at the nanoscale.[10] As an alternative approach, parametric sources have specific advantages in spectral tunability and integration.[11–13]

Photon pairs can be produced on the integrated photonic chip[14,15] via nonlinear process such as the spontaneous four-wave mixing (SFWM) process in the $\chi^{(3)}$ silicon[16] and in the $\chi^{(2)}$ lithium niobate.[17,18] For heralded single-photon sources, one photon in a pair is detected to herald the existence of its partner. The on-chip micro-ring resonator has been fabricated to enhance the SFWM process.[19] However, because of the energy conservation in nonlinear processes, parametric photon pairs have unavoidable spectral correlation which cause the impurity of the heralded single photons.[20] A 93% bound of spectral purity[21,22] from a common one or double straight-waveguide coupled micro-ring is given since the spectra of four interacting beams are approximated. Experimentally, a heralded two-photon Mach–Zehnder interference between two silicon rings is demonstrated with $72\% \pm 3\%$ visibility.[23] Adding a narrow-band filtering (much narrower than the pump's linewidth) to both signal and idler photons is a simple way to improve the purity of the source, but it will seriously reduce the number of valid single photons. An elegant improvement by overcoming the tradeoff between the purity and efficiency was proposed in Ref. [24] and realized recently in Ref. [12] wherein two asymmetric Mach–Zehnder interferometers (AMZIs) are used as the coupler for the pump and signal/idler to control their quality factors, respectively. Such quality-factor-tunable microsing structure also has an ability to optimize the efficiency of the stimulated four-wave mixing process[25] and the photon pairs' productive rate of the SFWM process.[26] However, the quality factors of the pump and the

*Project supported by the National Basic Research Program of China (Grant Nos. 2017YFA0303700 and 2019YFA0308700), the National Natural Science Foundation of China (Grant Nos. 61632021 and 11690031), and the Open Funds from the State Key Laboratory of High Performance Computing of China (HPCL, National University of Defense Technology).

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signal/idler photons in this design are fixed, hence the purity of the sources is fixed after the manufacture of the chip and one can hardly guarantee that one can obtain the ideal purity of photons after the first fabrication run. So, many similar structures should be designed for the purity requirements in different applications, which is troublesome and resource-wasting, especially for the applications in the large-scale quantum information process. On the other side, a tunable spectral-purity is desired when disclosing the relation of Boson sampling's fidelity with photon's distinguishbility[27] and other quite a lot of multiphoton interference effects.

In this work, we propose a method to dynamically adjust the quality factors of the micro-ring resonator for tunable and extremely high spectral-purity photons. We propose two types of micro-rings either coupled by one or two AMZIs. The quality factors of the pump and signal/idler can be adjusted by the internal phase of the interferometers and the spectral-purity of photons can be optimized dynamically close to 100%. This scheme is robust under fabrication variations and can be successfully applied in different fabrication labs and different materials. Such high-spectral-purity photons will be beneficial for quantum information processing like Boson sampling and other quantum algorithms.

Although the micro-ring proposed in this work is applicable to both $\chi^{(3)}$ and $\chi^{(2)}$ materials, we take the silicon-on-insulator (SOI) micro-ring as the example. In general the normalized two-photon state produced by the SFWM process can be represented as

$$|\psi\rangle = \iint \mathrm{d}\omega_\mathrm{s}\mathrm{d}\omega_\mathrm{i}\phi(\omega_\mathrm{s},\omega_\mathrm{i})\, a^\dagger_{\omega_\mathrm{s}} a^\dagger_{\omega_\mathrm{i}} |0\rangle, \tag{1}$$

where $a^\dagger_{\omega_\mathrm{s}}$ and $a^\dagger_{\omega_\mathrm{i}}$ represent the creation operators for the signal and the idler photons, respectively. The detection of one of the converted photons heralds the existence of the other one. If the signal and idler are correlated in frequency, this heralded single photon is in a mixed state.[24] The spectral-purity of this heralded photon is related to the separability of the joint spectral function which follows the form

$$\begin{aligned}\phi(\omega_\mathrm{s},\omega_\mathrm{i}) = &\int \mathrm{d}\omega_\mathrm{p} a(\omega_\mathrm{p})\, a(\omega_\mathrm{s}+\omega_\mathrm{i}-\omega_\mathrm{p}) \\ &\times l(\omega_\mathrm{p})\, l(\omega_\mathrm{s}+\omega_\mathrm{i}-\omega_\mathrm{p})\, l(\omega_\mathrm{s})\, l(\omega_\mathrm{i}),\end{aligned} \tag{2}$$

where $a(\omega_\mathrm{p})$ is the normalized distribution of pump laser's spectrum (usually Gaussian), and $l(\omega)$ is a Lorentzian spectrum representing one of the resonances of pump, signal, and idler. This joint spectral function is narrowly peaked at $\Omega_\mathrm{s}+\Omega_\mathrm{i} = 2\Omega_\mathrm{p}$ wherein Ω_s, Ω_i, and Ω_p are the central frequencies of the signal, idler, and pump resonances, respectively, thus a highly anti-correlated energy exists if the pump spectrum width is narrow.[20] Broadening the pump spectrum brings more terms to satisfy the phase-matching, relaxing the strict anti-correlation between the converted photons, thus supplying the possibility to engineer the spectrally uncorrelated photons, namely, spectrally pure photons. However, the spectrum of pump for conversion is filtered when it enters the resonator and the quality factor determines the filter width that the smaller quality factor corresponds to the boarder resonance. Therefore, the pump quality factor must be small, while the signal and the idler's quality factors should be large, for a high-purity single photon source.[12,24] The purity of the heralded photon can be calculated as $p = 1/K$, where K is the Schmidt number[28] of the heralded single-photon state and $K = X^2/Y$, with $X = \int \mathrm{d}\omega_\mathrm{s} \int \mathrm{d}\omega_\mathrm{i} |\phi(\omega_\mathrm{s},\omega_\mathrm{i})|^2$ and $Y = \int \mathrm{d}\omega_\mathrm{s} \int \mathrm{d}\omega_\mathrm{i} \int \mathrm{d}\omega'_\mathrm{s} \int \mathrm{d}\omega'_\mathrm{i} [\phi(\omega_\mathrm{s},\omega_\mathrm{i})\phi(\omega'_\mathrm{s},\omega'_\mathrm{i})\phi^*(\omega_\mathrm{s},\omega'_\mathrm{i})\phi^*(\omega'_\mathrm{s},\omega_\mathrm{i})]$.

The purity is determined by the ratio $Q_{\mathrm{s/i}}/Q_\mathrm{p}$, as numerically shown in Fig. 1. Higher purity can be achieved by increasing ratio $Q_{\mathrm{s/i}}/Q_\mathrm{p}$, and will be closer to 1 when the ratio gets larger. For example, when $Q_{\mathrm{s/i}}/Q_\mathrm{p} = 1$, the upper bound of the purity is $\sim 93\%$. A purity of 99% requires the ratio to be 3. In this paper, we propose a purity of 99.9% which will require the ratio to be 8. For a high-fidelity multiphoton interference such as in the Boson sampling, the spectral purity is a vital parameter and determines the interference visibility. A near 100% purity source is an ideal source competent for many quantum tasks. Therefore, one must figure out how to increase $Q_{\mathrm{s/i}}/Q_\mathrm{p}$. In the aforementioned discussion, we have explained that the narrowband filtering of the signal and idler photons after they emitting from the ring is not a good solution since it will decrease the photons rate. The better strategy is to make the pump and signal/idler photon's quality factors be naturally different and let $Q_{\mathrm{s/i}}/Q_\mathrm{p}$ reach a certain ratio without sacrificing the photons' flux.

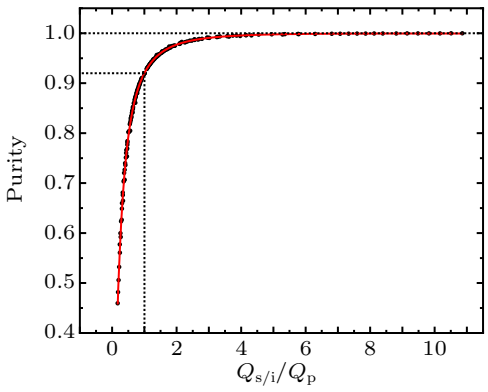


Fig. 1. The theoretical spectral purity as a function of $Q_{\mathrm{s/i}}/Q_\mathrm{p}$.[24]

Now we will introduce our strategy. In the common four-port micro-ring resonator[29,30] (see in Fig. 2(a)), the quality factor of the pump is equal to the signal/idler's, so that the purity is limited to less than 93%. We propose two updated micro-ring structures which can generate purity-tunable and close to 100% photons. The first structure is designed to be coupled by one AMZI as shown in Fig. 2(b). For such a ring, the total quality factors include the intrinsic quality factor which is determined by the optical transmission loss in the

ring, and the extrinsic quality factor which depends on the effective coupling coefficient $\kappa_{\rm eff}$ as

$$Q_{\rm ext} = \frac{\omega l}{v_{\rm g}\left|\kappa_{\rm eff}\right|^2}. \tag{3}$$

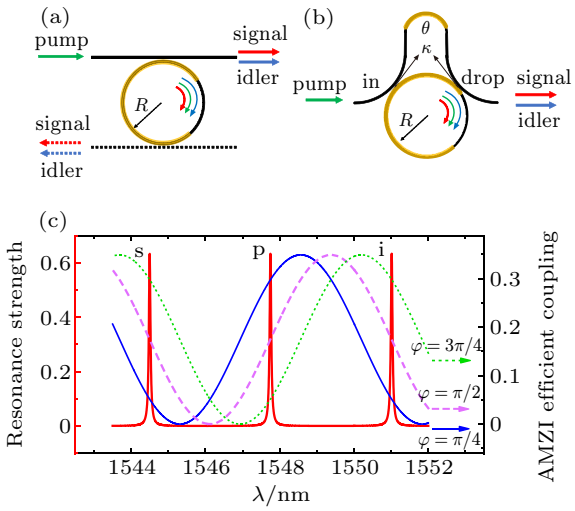


Fig. 2. Schematic of (a) a common single or double-side-coupled micro-ring resonator and (b) a single-AMZI-coupled micro-ring resonator. (c) The resonance strength of the single-AMZI-coupled micro-ring and the AMZIs' efficient cross-coupling strength with different settings of the phase φ.

The effective coupling coefficient can be calculated from the transmission matrix of the AMZI which follows

$$\begin{aligned} U_{\rm AMZI} &= \begin{bmatrix} t & {\rm i}\kappa \\ {\rm i}\kappa & t \end{bmatrix} \begin{bmatrix} {\rm e}^{-{\rm i}(\beta_{\rm p(s/i)}\Delta l+\theta)} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} t & {\rm i}\kappa \\ {\rm i}\kappa & t \end{bmatrix} \\ &= \begin{bmatrix} -\kappa^2 + t^2 {\rm e}^{-{\rm i}(\beta_{\rm p(s/i)}\Delta l+\theta)} & {\rm i}t\kappa + {\rm i}t\kappa {\rm e}^{-{\rm i}(\beta_{\rm p(s/i)}\Delta l+\theta)} \\ {\rm i}t\kappa + {\rm i}t\kappa {\rm e}^{-{\rm i}(\beta_{\rm p(s/i)}\Delta l+\theta)} & t^2 - \kappa^2 {\rm e}^{-{\rm i}(\beta_{\rm p(s/i)}\Delta l+\theta)} \end{bmatrix}, \end{aligned} \tag{4}$$

where $\kappa(t)$ is the cross-coupling (transmission) coefficient of a coupling point in the AMZI that $|\kappa|^2 + |t|^2 = 1$, $\beta_{\rm p(s/i)}$ is the transmission constant of the pump (signal/idler), and Δl is the length difference between the long and short arms of the AMZI. Thus, the effective cross-coupling coefficient $\kappa_{\rm eff,p(s/i)}$ satisfies

$$\begin{aligned} \left|\kappa_{\rm eff,p(s/i)}\right|^2 &= \left|t\kappa + t\kappa {\rm e}^{-{\rm i}(\beta_{\rm p(s/i)}\Delta l+\theta)}\right|^2 \\ &= 2\kappa^2(1-\kappa^2)\left[1+\cos(\beta_{\rm p(s/i)}\Delta l+\theta)\right]. \end{aligned} \tag{5}$$

The path difference of $\Delta l = \pi R$ is set in the AMZI that it gives a relative phase $\left|\beta_{\rm p} - \beta_{\rm s/i}\right|\Delta l = (2n+1)\pi$ (n is an integer) between the photons at pump's and signal/idler's resonance frequencies, i.e., if the pump resonance is set to be maximally coupled into (out from) the ring, the signal and idler resonance will be suppressed. Assuming that all the intrinsic quality factors are equal for the pump and signal/idler, the quality factors of the single-AMZI-coupled micro-ring can be expressed as

$$\frac{1}{Q_{\rm p}} = \frac{1}{Q_{\rm int}} + \frac{1}{Q_{\rm ext,p}}, \quad \frac{1}{Q_{\rm s/i}} = \frac{1}{Q_{\rm int}} + \frac{1}{Q_{\rm ext,s/i}}. \tag{6}$$

We define that $\varphi = \beta_{\rm p}\Delta l + \theta$. A constant α is introduced, representing the ratio of the instrinsic ($Q_{\rm int}$) and the maximal extrinsic ($Q_{\rm ext,p,\varphi=0}$) quality factors, i.e., $1/Q_{\rm ext,p,\varphi=0} = \alpha/Q_{\rm int}$. According to Eqs. (3), (5), and (6), the quality factor ratio of signal/idler and pump follows

$$\frac{Q_{\rm s/i}}{Q_{\rm p}} = \frac{\dfrac{1}{Q_{\rm int}} + \dfrac{1}{Q_{\rm ext,p}}}{\dfrac{1}{Q_{\rm int}} + \dfrac{1}{Q_{\rm ext,s/i}}} = \frac{2+\alpha(1+\cos\varphi)}{2+\alpha\left[1+\cos(\varphi+\pi)\right]}. \tag{7}$$

By adjusting the phase shifter θ to change $\varphi \in (0,\pi)$, the quality factor ratio of signal/idler and pump can be set in the range of $(1/(1+\alpha), 1+\alpha)$. We choose the case of $\alpha = 7$ for example. In this case, the purity of idler as a function of the setting of the phase φ is numerically shown in Fig. 3.

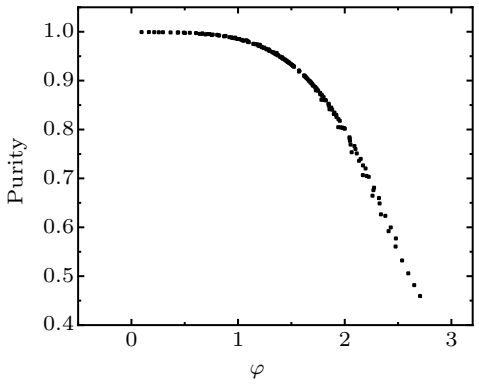


Fig. 3. Simulated spectral purity of the idler photons from the single-AMZI-coupled micro-ring resonator as a function of the phase φ.

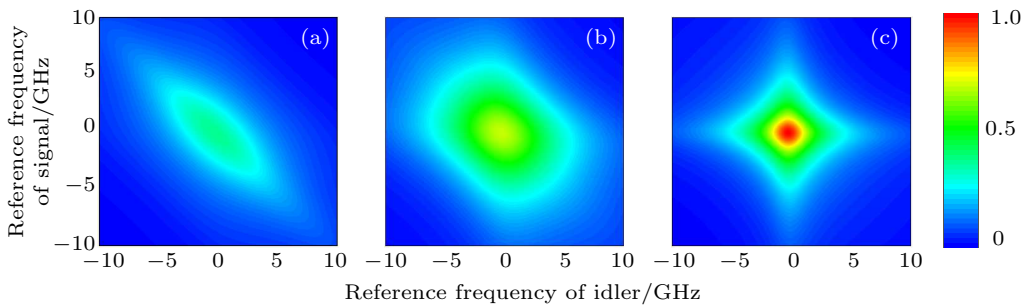


Fig. 4. Simulated signal–idler joint spectral function profiles of the single-AMZI-coupled micro-ring resonator in the cases of (a) $\varphi = 3\pi/4$, (b) $\pi/2$, (c) $\pi/4$.

The simulated signal–idler joint spectral function profiles[31] with $\varphi = 3\pi/4, \pi/2, \pi/4$ are depicted in Fig. 4, revealing the ability of purity adjustment. We can find the purity variation in these joint spectral function profiles, increasing with the phase φ. The purity is calculated to be 78.5%, 95.1%, and 99.3% respectively for the cases of $\varphi = 3\pi/4$, $\pi/2$, and $\pi/4$. When φ decreases to less than $\sim 0.07\pi$, the purity will be higher than 99.9%. However, the major of pump from the in-port waveguide with a board spectrum is transmitted through the AMZI which will produce noise photons in the subsequent waveguide. As a further improvement, the micro-ring coupled two AMZIs (see Fig. 5(a)) can solve this problem, and simultaneously, further widen the adjustment range.

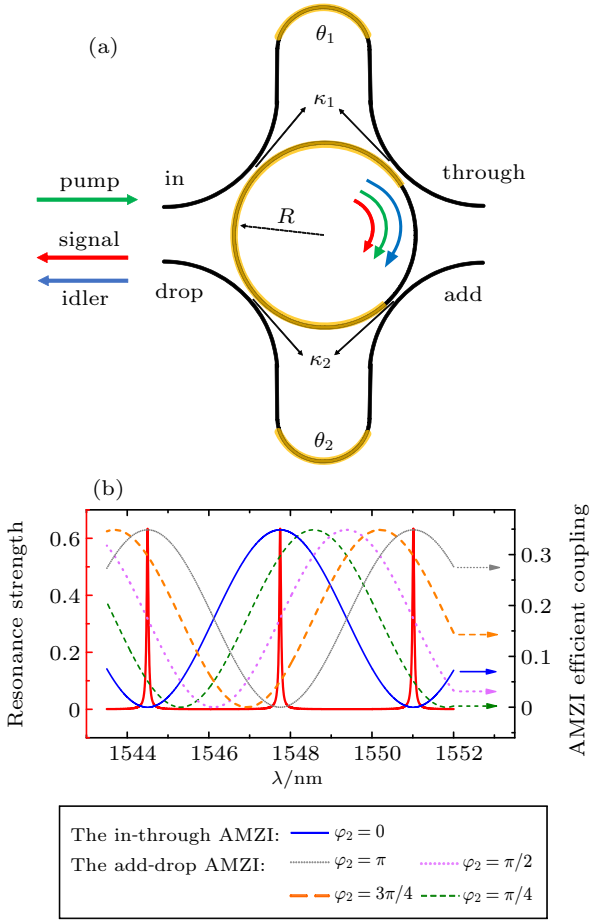


Fig. 5. (a) Schematic of a dual-AMZI-coupled micro-ring resonator. (b) The resonance strength of the dual-AMZI-coupled micro-ring and the two AMZIs' efficient cross-coupling strength with different settings of the phases φ_1 and φ_2.

The total quality factor of the dual-AMZI-coupled micro-ring resonator includes three parts: the intrinsic quality factor Q_{int}, and two extrinsic parts Q_{ext1} and Q_{ext2}, depending on the coupling coefficient of the in-through AMZI and the add-drop AMZI, respectively. The quality factors can be expressed as

$$\begin{aligned}\frac{1}{Q_{\text{p}}} &= \frac{1}{Q_{\text{int}}} + \frac{1}{Q_{\text{ext1,p}}} + \frac{1}{Q_{\text{ext2,p}}},\\ \frac{1}{Q_{\text{s/i}}} &= \frac{1}{Q_{\text{int}}} + \frac{1}{Q_{\text{ext1,s/i}}} + \frac{1}{Q_{\text{ext2,s/i}}}.\end{aligned} \tag{8}$$

The path difference of each AMZI leads to a π relative phase between pump and signal/idler in this micro-ring structure as well. We define that $\varphi_1 = \beta_{\text{p}}\Delta l + \theta_1$ and $\varphi_2 = \beta_{\text{p}}\Delta l + \theta_2$. The in-through AMZI is set to suppress the coupling of the converted photons that $\varphi_1 = 0$, while the other AMZI is dynamically tunable. Two constants γ and δ are introduced to stand for the ratios of the intrinsic quality factor to the maximal extrinsic quality factors from the in-through AMZI and the add-drop AMZI, respectively, i.e., $1/Q_{\text{ext1,p}} = \gamma/Q_{\text{int}}$ and $1/Q_{\text{ext2,p}} = \delta/Q_{\text{int}}$. Then the ratio of $Q_{\text{s/i}}$ and Q_{p} can be expressed as

$$\begin{aligned}\frac{Q_{\text{s/i}}}{Q_{\text{p}}} &= \frac{\dfrac{1}{Q_{\text{int}}} + \dfrac{1}{Q_{\text{ext1,p}}} + \dfrac{1}{Q_{\text{ext2,p}}}}{\dfrac{1}{Q_{\text{int}}} + \dfrac{1}{Q_{\text{ext2,s/i}}}}\\ &= \frac{2+2\gamma+\delta(1+\cos\varphi_2)}{2+\delta\,[1+\cos(\theta_2+\pi)]}.\end{aligned} \tag{9}$$

By choosing appropriate offsets of the phase-shifter θ_2 on the add-drop AMZI to adjust the phase $\varphi_2 \in (0, \pi)$, the tunable range of this ratio is $[(1+\gamma)/(1+\delta), 1+\gamma+\delta)$. In the case of $\gamma = \delta = 5$, the purity as a function of the phase's setting is shown in Fig. 6.

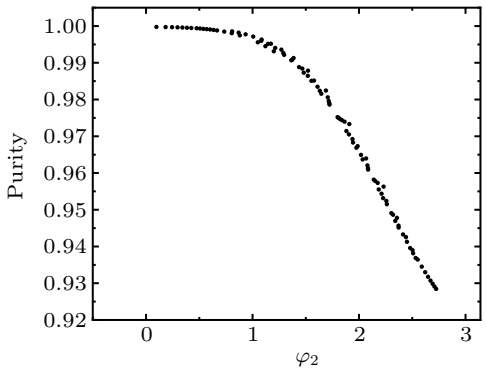


Fig. 6. Simulated spectral purity of the idler photons from the dual-AMZI-coupled micro-ring resonator as a function of the phase φ_2.

Similarly, the simulated signal–idler joint spectral function profiles with $\varphi_2 = \pi$, $3\pi/4$, $\pi/2$, and $\pi/4$ are depicted in Fig. 7. A visible frequency anti-correlation exists when $\varphi_2 = \pi$, and the correlation decreases when φ_2 decreases. The purity of the joint spectral function profiles in Figs. 7(a)–7(d) is calculated to be 95.4%, 96.1%, 97.8%, and 99.3%, respectively. By a further calculation, when φ_2 decreases to less than 0.19π, the theoretical purity of such source will be higher than 99.9%.

The constants α, γ, and δ here are determined by the gaps between the ring and the external waveguides. The precision of the actual fabrication is limited, which leads to unavoidable errors. Our strategy is robust against such fabrication errors owing to the purity-adjustability. In practical design, one can choose appropriate gaps to make the constants a bit larger for a wide adjustment range of purity which covers the required

value. And actually, the high-purity photon pairs not only can be used for heralded single-photon source, but also can be regarded as the essential two-photon state for constructing multiphoton states.[32–34]

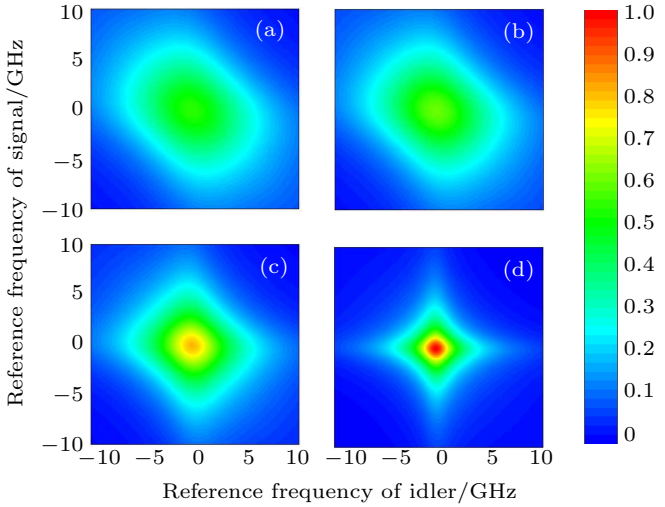


Fig. 7. Simulated signal–idler joint spectral function profiles of the dual-AMZI-coupled micro-ring resonator in the cases of (a) $\varphi_2 = \pi$, (b) $3\pi/4$, (c) $\pi/2$, and (d) $\pi/4$.

In conclusion, we propose two types of micro-rings: the single-AMZI-coupled micro-ring and the dual-AMZI-coupled micro-ring, for a high-spectral-purity heralded single-photon source. The coupling coefficients of the pump and the converted photons are adjusted by the on-AMZI phase shifters, leading to the change of the quality factors. The purities of both sources are adjustable within a certain range and can be higher than 99.9%. Both schemes have their own advantages that the single-AMZI-coupled structure is simpler and the dual-AMZI-coupled microring produces less noise and has a larger adjustment range. Pure photons will be beneficial for the fidelity of quantum operations and the adjustability of the sources makes them more flexible in practical experiment. We expect that they can promote the further development of quantum information processing.

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