Optimizing the spectral purity of photon sources from a nonlinear microring resonator by pump engineering *

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Abstract

Cavity-enhanced spontaneous four-wave mixing (SFWM) in microring resonators (MRRs) provides an efficient route to produce integrated photon sources. Despite the largely improved spectral purity without lossy filtering, standard MRR SFWM sources pumped by conventional single-pulses are still limited to 92% purity because all modes share the same Lorentzian lineshape, hindering their use in applications requiring near-unity purity. Here, we address this problem by proposing a pump-engineering scheme that uses a single Fabry–Pérot cavity to shape the pump by reflection. We show that the pump linewidth in the MRR is broadened well beyond the signal and idler linewidths and the spectral purity can approach unity. Our scheme is robust to MRR parameter deviations and can be applied to both all-pass and add-drop MRRs, offering a practical route to high-purity integrated photon sources.

Keywords: spontaneous four-wave mixing, microring resonator, spectral purity, pump engineering
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1. Introduction

Identical photon sources are indispensable for achieving high-visibility multiphoton interference, which is a cornerstone for quantum photonic technologies[1] and the optical demonstration of quantum computational advantage.[2–6] Spontaneous four-wave mixing (SFWM) is a promising approach for building high-quality photon sources owing to its room-temperature operation and compatibility with photonic integrated circuits.[7] It has been widely employed to generate large-scale entangled photonic states and squeezed states of light.[8–13]

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However, the intrinsic frequency correlation of SFWM photon pairs leaves each photon in a spectrally mixed state, which degrades their indistinguishability and thus poses a major obstacle to the realization of large-scale sources of identical photons.[14]

Narrowband spectral filtering is a straightforward method to extract spectrally pure photons from such frequency-correlated photon pairs, but at the cost of reduced brightness.[15] In contrast, spectral engineering provides a filter-free solution that preserves the source brightness while yielding spectrally pure photons.[16,17] One efficient route is cavity-enhanced SFWM in microring resonators (MRRs) pumped by spectrally broad pulses, but the conventional implementation is fundamentally limited to a maximum spectral purity of 92%, as all interacting fields share the same cavity-enhancement lineshape.[18] To achieve near-unity spectral purity, the quality factor of the pump resonance must be made substantially lower than those of the signal and idler resonances.[19] One strategy is to engineer the MRR, either by embedding it within Mach–Zehnder interferometers[12,19,20] or by employing two coupled MRRs,[13,21–23] but this approach inevitably adds system complexity and may introduce thermal crosstalk. Alternatively, temporal shaping and phase engineering of pump pulses have been explored to generate photons with near-ideal spectral purity from standard MRR SFWM.[24–27]

In this work, we propose a robust pump-engineering scheme that leverages the reflection effect of a Fabry–Pérot (FP) cavity to optimize the spectral purity of standard MRR SFWM sources. The pump linewidth is broadened to be significantly larger than those of the signal and idler modes in the MRR, thus enabling our scheme to break the 92% purity limit of a standard MRR SFWM source and asymptotically approach unity. Compared with previous methods,[25–27] our scheme eliminates the need for actively stabilized interferometers, making it particularly advantageous for long-term operation.

2. Theoretical method and principle

We first describe the operating principle of a standard MRR SFWM source, as shown in Fig. 1(a). We consider a frequency-degenerate SFWM process governed by the energy conservation condition $2\hbar\omega_{\mathrm{p}} = \hbar\omega_{\mathrm{s}} + \hbar\omega_{\mathrm{i}}$, where ω_{p}, ω_{s}, and ω_{i} are the frequencies of the pump, signal, and idler photons, respectively. The MRR is pumped by a pulsed laser with a spectral amplitude $\alpha_{\mathrm{p}}(\omega_{\mathrm{p}})$ and a central frequency tuned to an MRR resonance frequency at ω_{p0}. Signal and idler photons are then generated in pairs at resonant frequencies symmetric with respect to ω_{p0}. The generated photon pair state can be expressed as[24]

$$|\psi\rangle = R^{-1/2} \iint \mathrm{d}\omega_{\mathrm{s}}\mathrm{d}\omega_{\mathrm{i}}\, \mathcal{A}(\omega_{\mathrm{s}}, \omega_{\mathrm{i}})\, \hat{a}_{\mathrm{s}}^{\dagger}(\omega_{\mathrm{s}})\hat{a}_{\mathrm{i}}^{\dagger}(\omega_{\mathrm{i}})|0\rangle, \tag{1}$$

where $\mathcal{A}(\omega_{\mathrm{s}}, \omega_{\mathrm{i}})$ represents the joint spectral amplitude (JSA) and $\hat{a}_{\mathrm{s}}^{\dagger}(\omega_{\mathrm{s}})$, $\hat{a}_{\mathrm{i}}^{\dagger}(\omega_{\mathrm{i}})$ are the creation operators for the signal and idler photons. The factor $R = \iint \mathrm{d}\omega_{\mathrm{s}}\mathrm{d}\omega_{\mathrm{i}}|\mathcal{A}(\omega_{\mathrm{s}}, \omega_{\mathrm{i}})|^2$ denotes the probability of generating a photon pair per pump pulse. By spectrally isolating a single pair of symmetric signal and idler at resonant frequencies ω_{s0} and ω_{i0}, the JSA takes the form, up to an irrelevant proportionality factor,

$$\mathcal{A}(\omega_{\mathrm{s}}, \omega_{\mathrm{i}}) \propto \mathcal{I}_{\mathrm{p}}(\omega_{\mathrm{s}} + \omega_{\mathrm{i}})\, \mathcal{L}_{\mathrm{i}}(\omega_{\mathrm{i}})\, \mathcal{L}_{\mathrm{s}}(\omega_{\mathrm{s}}), \tag{2}$$

where the phase-matching function is omitted as it can be taken as approximately constant within the narrow bandwidth of a single resonance. Here, $\mathcal{I}_{\mathrm{p}}$ is given by the convolution

$$\mathcal{I}_{\mathrm{p}}(\omega) = \int \mathrm{d}\omega_{\mathrm{p}}\, \alpha_{\mathrm{p}}(\omega - \omega_{\mathrm{p}})\, \mathcal{L}_{\mathrm{p}}(\omega - \omega_{\mathrm{p}})\, \alpha_{\mathrm{p}}(\omega_{\mathrm{p}})\, \mathcal{L}_{\mathrm{p}}(\omega_{\mathrm{p}}). \tag{3}$$

The Lorentzian factor $\mathcal{L}_{\rm j}(\omega_{\rm j})$, with ${\rm j} = {\rm s}, {\rm i}, {\rm p}$, can be expressed as

$$\mathcal{L}_{\rm j}(\omega_{\rm j}) = \frac{1}{\gamma_{\rm j}/2 - {\rm i}(\omega_{\rm j} - \omega_{\rm j0})}, \tag{4}$$

where $\gamma_{\rm j} = \omega_{\rm j0}/Q_{\rm j}$ is the total decay rate with $Q_{\rm j}$ denoting the loaded quality factor and $\gamma_{\rm j}$ also representing the full width at half maximum (FWHM) in angular frequency.

The detection of one photon from a photon pair can herald the presence of the other. The spectral purity of the heralded photon can be evaluated via Schmidt decomposition of the JSA, given by[28]

$$\mathcal{A}(\omega_{\rm s}, \omega_{\rm i}) = \sum_k \sqrt{\lambda_k}\, u_k(\omega_{\rm s})\, v_k(\omega_{\rm i}), \tag{5}$$

where u_k and v_k form orthonormal sets, and the Schmidt coefficients $\lambda_k \geq 0$ satisfy $\sum_k \lambda_k = 1$. The Schmidt number $K \equiv 1/\sum_k \lambda_k^2$ quantifies the effective number of modes, and the spectral purity is given by

$$P \equiv \frac{1}{K} = \sum_k \lambda_k^2. \tag{6}$$

A fully factorable JSA yields a single non-zero Schmidt eigenvalue λ_k, giving $P = 1$. Any frequency correlation in the JSA gives $K > 1$ and thus $P < 1$. As pointed out previously, when pumped directly by a single pulsed laser, an ideal MRR SFWM source is limited to a spectral purity of 92%.[18] This limit can be understood qualitatively. When $\alpha_{\rm p}(\omega)$ is broad enough to be treated as a constant in Eq. (3), $\mathcal{I}_{\rm p}(\omega_{\rm s} + \omega_{\rm i})$ reduces to the convolution of two identical Lorentzians, which yields a new Lorentzian with a linewidth twice that of the signal and idler modes. This prevents the JSA from factorizing into independent signal and idler components.

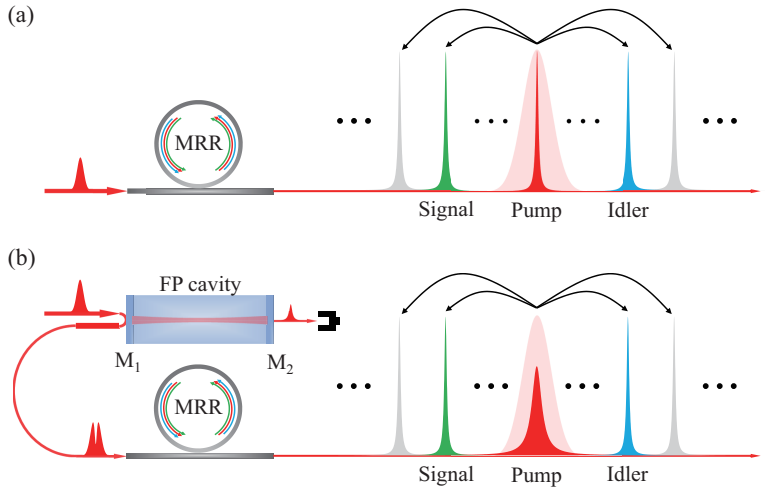


Fig. 1. (color online) Schematic of a microring resonator (MRR) spontaneous four-wave mixing (SFWM) source pumped by (a) standard pulses, and (b) pulses shaped via an off-chip Fabry–Pérot (FP) cavity formed by reflective coatings M_1 and M_2 on both sides of a crystal slice. In the right panel, the dark Lorentzian-shaped filled region represents the intracavity spectral density of states of the MRR resonant mode. Only a single pair of resonance modes is extracted.

To overcome this limitation, we propose a pump-engineering scheme where an MRR SFWM source is pumped with tailored pulses by an off-chip FP cavity, as shown in Fig. 1(b). The FP cavity is formed by a crystal slice with high-reflection coatings $\rm M_1$ and $\rm M_2$ on both ends, where the amplitude reflection and transmission coefficients $r_{\rm m}$ and $t_{\rm m}$ satisfy $r_{\rm m}^2 + t_{\rm m}^2 = 1$, $({\rm m} = 1, 2)$. A pulsed laser is first reflected by the

FP cavity and then injected into the MRR. Assuming negligible material losses, the amplitude reflection and transmission coefficients of the FP cavity are given by

$$r(\omega) = \frac{r_1 - r_2 e^{\mathrm{i}\phi(\omega)}}{1 - r_1 r_2 e^{\mathrm{i}\phi(\omega)}}, \tag{7}$$

$$t(\omega) = \frac{t_1 t_2 e^{\mathrm{i}\phi(\omega)/2}}{1 - r_1 r_2 e^{\mathrm{i}\phi(\omega)}}, \tag{8}$$

respectively, where $\phi(\omega)$ is the round-trip phase accumulated inside the FP cavity. For a high-finesse FP cavity, the field amplitude decay rates through end-coatings M_1 and M_2 can be written as

$$\Gamma_{\mathrm{m}} = -2\Delta f \ln r_{\mathrm{m}}, \tag{9}$$

where Δf is the free spectral range.

Near a resonance of the FP cavity, the amplitude reflection and transmission coefficients can then be expressed as

$$r_{\mathrm{p}}(\omega_{\mathrm{p}}) = \frac{(\Gamma_1 - \Gamma_2)/2 + \mathrm{i}(\omega_{\mathrm{p}} - \omega_{\mathrm{p0}})}{(\Gamma_1 + \Gamma_2)/2 - \mathrm{i}(\omega_{\mathrm{p}} - \omega_{\mathrm{p0}})}, \tag{10}$$

$$t_{\mathrm{p}}(\omega_{\mathrm{p}}) = \frac{\sqrt{\Gamma_1 \Gamma_2}}{(\Gamma_1 + \Gamma_2)/2 - \mathrm{i}(\omega_{\mathrm{p}} - \omega_{\mathrm{p0}})}, \tag{11}$$

where the FP cavity resonance frequency is tuned to the MRR resonance at ω_{p0} in our scheme. The transmission coefficient $t_{\mathrm{p}}(\omega_{\mathrm{p}})$ has the standard Lorentzian form with a FWHM of $\Gamma_1 + \Gamma_2$ in angular frequency. The Lorentzian form of Eqs. (10) and (11) is obtained by expanding the exact Airy function to first order around the FP resonance, which is valid in the high-finesse limit ($r_{\mathrm{m}} \geq 0.95$) and for frequency detunings much smaller than the FP FSR.[29] In our design, the pump pulse bandwidth is kept well below the FP FSR, so that only a single FP resonance is excited. Then, with the reflected field serving as the shaped pump for the MRR SFWM source, the pump spectral amplitude is given by

$$\alpha'_{\mathrm{p}}(\omega_{\mathrm{p}}) = r_{\mathrm{p}}(\omega_{\mathrm{p}})\, \alpha_{\mathrm{p}}(\omega_{\mathrm{p}}), \tag{12}$$

and Eq. (3) becomes

$$\mathcal{I}'_{\mathrm{p}}(\omega) = \int \mathrm{d}\omega_{\mathrm{p}}\, \alpha'_{\mathrm{p}}(\omega - \omega_{\mathrm{p}})\, \mathcal{L}_{\mathrm{p}}(\omega - \omega_{\mathrm{p}})\, \alpha'_{\mathrm{p}}(\omega_{\mathrm{p}})\, \mathcal{L}_{\mathrm{p}}(\omega_{\mathrm{p}}). \tag{13}$$

In our scheme, the FP cavity is designed to satisfy

$$\Gamma_2 - \Gamma_1 = \gamma_{\mathrm{p}}. \tag{14}$$

Consequently, combining Eqs. (4), (12), and (14), we have

$$\alpha'_{\mathrm{p}}(\omega_{\mathrm{p}})\, \mathcal{L}_{\mathrm{p}}(\omega_{\mathrm{p}}) = -\frac{\alpha_{\mathrm{p}}(\omega_{\mathrm{p}})}{(\Gamma_1 + \Gamma_2)/2 - \mathrm{i}(\omega_{\mathrm{p}} - \omega_{\mathrm{p0}})}, \tag{15}$$

which indicates that the original pump spectrum $\alpha_{\mathrm{p}}(\omega_{\mathrm{p}})$ is shaped by a broadened Lorentzian lineshape with a FWHM of $\Gamma_1 + \Gamma_2$, compared with the original γ_{p} of $\mathcal{L}_{\mathrm{p}}$. We define the ratio of the two FWHMs as

$$\kappa \equiv \frac{\Gamma_1 + \Gamma_2}{\gamma_{\mathrm{p}}}. \tag{16}$$

Using a pump with a spectrum that varies slowly over the broadened linewidth, the pump envelope can be regarded as constant, and the self-convolution in Eq. (13) yields

$$\mathcal{I}_{\mathrm{p}}(\omega_{\mathrm{s}} + \omega_{\mathrm{i}}) = \frac{2\pi \alpha_{\mathrm{p}}^2(\omega_{\mathrm{p0}})}{\kappa\gamma_{\mathrm{p}} - \mathrm{i}(\omega_{\mathrm{s}} + \omega_{\mathrm{i}} - 2\omega_{\mathrm{p0}})}, \tag{17}$$

which recovers the original pump term when $\kappa = 1$. For sufficiently large κ, the pump term varies slowly over the signal and idler linewidths and can be approximated as

$$\mathcal{I}_{\mathrm{p}}(\omega_{\mathrm{s}} + \omega_{\mathrm{i}}) \approx \frac{2\pi\alpha_{\mathrm{p}}^2(\omega_{\mathrm{p0}})}{\kappa\gamma_{\mathrm{p}}}. \tag{18}$$

In this case, the JSA given by Eq. (2) reduces to the separable form

$$\mathcal{A}(\omega_{\mathrm{s}}, \omega_{\mathrm{i}}) \propto \mathcal{L}_{\mathrm{s}}(\omega_{\mathrm{s}})\, \mathcal{L}_{\mathrm{i}}(\omega_{\mathrm{i}}), \tag{19}$$

and thereby the spectral purity approaches unity.

3. Results and discussion

To further illustrate the spectral purity enhancement, we numerically evaluate the JSA under typical experimental parameters. The pump, signal, and idler FWHMs are taken as $\gamma_{\mathrm{p}} = 2\pi \times 33.2$ GHz, $\gamma_{\mathrm{s}} = 2\pi \times 34.2$ GHz, and $\gamma_{\mathrm{i}} = 2\pi \times 31.8$ GHz, respectively. The pump pulse is assumed to have a Gaussian amplitude spectrum, $\alpha_{\mathrm{p}}(\omega_{\mathrm{p}}) \propto \exp[-(\omega_{\mathrm{p}} - \omega_{\mathrm{p0}})^2/(4\sigma'^2)]$, and the corresponding spectral intensity FWHM is $\sigma_{\mathrm{p}} = 2\sqrt{2\ln 2}\sigma'$. For convenience, we define the pump bandwidth parameter $\eta \equiv \sigma_{\mathrm{p}}/\gamma_{\mathrm{p}}$ and set it as $\eta = 8$ in the following simulation. The resulting normalized joint spectral intensities (JSIs), $|\mathcal{A}(\omega_{\mathrm{s}}, \omega_{\mathrm{i}})|^2$, of the MRR SFWM source pumped by original pulses ($\kappa = 1$) and the shaped pulses in our scheme ($\kappa = 4$) are shown in Fig. 2(a) and (b), respectively. It can be seen that the latter exhibits a symmetric profile, in clear contrast to the residual anti-correlation observed in Fig. 2(a). The corresponding spectral purity values, obtained by applying Schmidt decomposition to the JSA, are 91.6% and 99.1%, respectively.

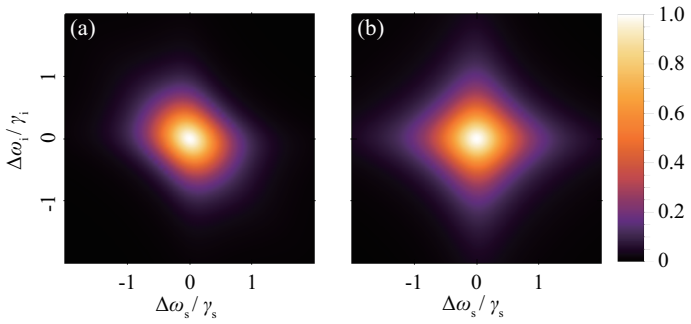


Fig. 2. (color online) Simulated joint spectral intensity (JSI) for (a) a standard microring resonator (MRR) spontaneous four-wave mixing (SFWM) source, and (b) the proposed MRR SFWM source. The axes represent the normalized detuning $\Delta\omega_{\mathrm{j}}/\gamma_{\mathrm{j}}$, where $\Delta\omega_{\mathrm{j}} = \omega_{\mathrm{j}} - \omega_{\mathrm{j0}}$, with $\mathrm{j} = \mathrm{s}, \mathrm{i}$, for the signal (s) and idler (i) modes.

We further characterize the effects of the broadening factor κ and the pump bandwidth parameter η on the purity enhancement. With $\eta = 8$, the purity as a function of κ is plotted in Fig. 3(a). It increases monotonically with κ, surpassing the 92% limit of a conventional MRR SFWM source and asymptotically approaching unity. Figure 3(b) further shows that a sufficiently large pump bandwidth η is required to suppress the anti-correlation arising from the self-convolution of the pump spectrum, which cannot be fully compensated by increasing κ alone. The saturation of the $\kappa = 1$ curve at approximately 92% corresponds to the intrinsic limit of a conventional microring source without pump broadening. For the representative case $\kappa = 4$, one suitable choice of mirror reflectivities is $r_1 \approx 0.98$ and $r_2 \approx 0.90$, which are readily achievable with standard dielectric coatings. These simulation results demonstrate that our scheme can substantially suppress the residual spectral correlation, generating photon pairs with near-unity spectral purity.

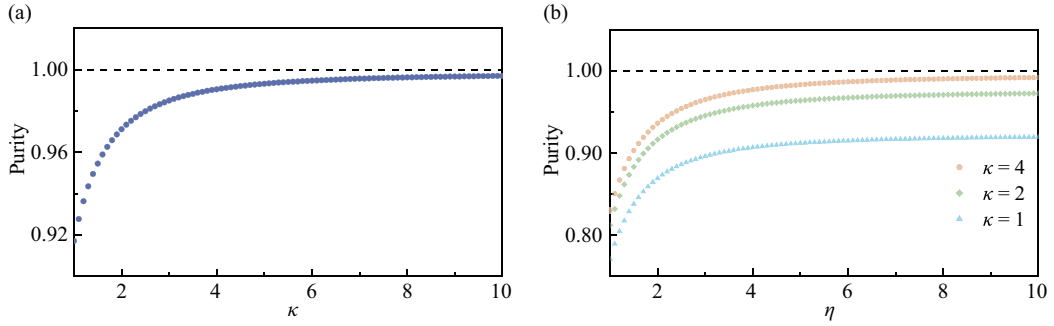


Fig. 3. (color online) Calculated spectral purity for the proposed source as a function of (a) the broadening factor κ, and (b) the pump bandwidth parameter η.

A notable advantage of our scheme is its robustness to fabrication variations. To quantify this, we introduce the relative linewidth deviation $\xi_{\mathrm{p}} = \gamma'_{\mathrm{p}}/\gamma_{\mathrm{p}}$, and the pump central frequency mismatch $\delta_{\mathrm{p}} = (\omega'_{\mathrm{p0}} - \omega_{\mathrm{p0}})/\gamma_{\mathrm{p}}$, where γ'_{p} and ω'_{p0} denote the linewidth and central frequency of the MRR after deviation, respectively. Here, γ_{p} is the reference pump linewidth specified by $\Gamma_2 - \Gamma_1 = \gamma_{\mathrm{p}}$, while γ'_{p} is the actual MRR linewidth. The condition $\Gamma_2 - \Gamma_1 = \gamma_{\mathrm{p}}$ ensures that the FP reflection notch suppresses the narrow Lorentzian peak of the pump mode, thereby broadening it into a Lorentzian of width $\Gamma_1 + \Gamma_2 = \kappa\gamma_{\mathrm{p}}$. When γ'_{p} deviates from γ_{p}, this suppression becomes incomplete, leaving residual spectral structure that degrades the factorability of the JSA. The resulting purity degradation is quantified as a function of $\xi_{\mathrm{p}} = \gamma'_{\mathrm{p}}/\gamma_{\mathrm{p}}$ in Fig. 4(a). Since thermal drifts of both the MRR and the FP cavity are equivalent to a change in the single parameter δ_{p}, the results in Fig. 4(b) directly quantify the tolerance of our scheme to such drifts. For $|\delta_{\mathrm{p}}| \leq 0.44\gamma_{\mathrm{p}}$, which is attainable under standard temperature stabilization, the spectral purity remains above 98%.

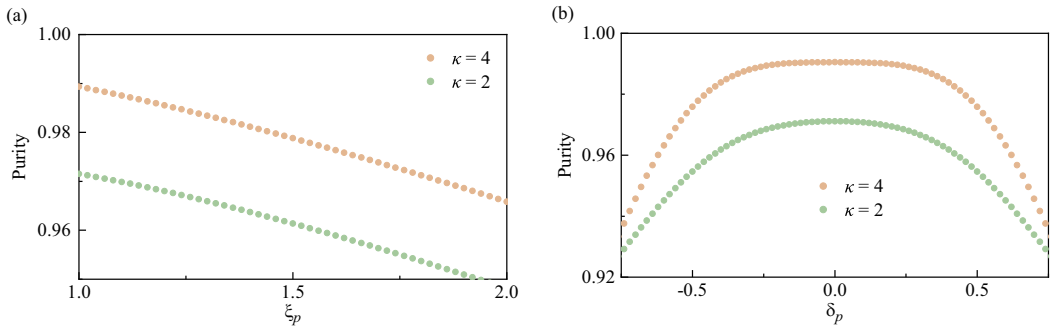


Fig. 4. (color online) Spectral purity of the proposed pump-engineering source as a function of (a) the relative linewidth deviation ξ_{p}, and (b) the pump central frequency mismatch δ_{p}.

Finally, it should be noted that the purity enhancement enabled by our pump-engineering scheme comes at the cost of a reduced pump power injected into the MRR. The pair generation rate (PGR) per pulse N scales as the squared modulus of the JSA integrated over all frequencies. In the limit where the pump spectrum is sufficiently flat over the relevant linewidth, the PGR scales as[30]

$$N \propto \frac{1}{\gamma_{\mathrm{p}}\gamma_{\mathrm{s}}\gamma_{\mathrm{i}}\left(\frac{\gamma_{\mathrm{s}}+\gamma_{\mathrm{i}}}{2} + \gamma_{\mathrm{p}}\right)}. \tag{20}$$

For a standard MRR source with equal mode linewidths ($\gamma_{\mathrm{p}} = \gamma_{\mathrm{s}} = \gamma_{\mathrm{i}} = \gamma$), this reduces to $N_0 \propto \gamma^{-4}$. In our FP-MRR scheme, only the pump linewidth is broadened from γ_{p} to $\kappa\gamma_{\mathrm{p}}$, while the signal and idler linewidths remain unchanged. Substituting the broadened pump Lorentzian into the above expression and evaluating the convolution integral yields

$$N_{\mathrm{FP}} \propto \frac{2N_0}{\kappa(\kappa+1)}. \tag{21}$$

This reduction can be compensated by increasing the pump pulse energy by a factor of $\sqrt{\kappa(\kappa+1)/2}$. Even after such compensation, the intracavity peak power remains comparable to that of a standard MRR source operating at the same generation rate. Since the scheme operates in the photon-pair regime and the overall power level is low, this does not introduce significant nonlinear noise or approach the optical damage threshold. However, with reduced cavity enhancement, the relative contributions of waveguide SFWM and Raman noise increase.[31] This contribution can be mitigated by limiting the waveguide length and filtering the residual pump on-chip.

This trade-off between purity enhancement and generation rate reduction is inherent in passive pump-engineering schemes.[24–27] A potential route to circumvent this limitation is to transform the spectral filtering function of the FP cavity into the time domain via temporal pulse shaping,[32,33] which can imprint the cavity reflection response onto the pump without discarding energy. This active approach could in principle maintain the high spectral purity without the power penalty, thereby representing an interesting direction for future work.

This work focuses on the numerical simulation of the proposed scheme. Nevertheless, compared with existing strategies, our passive FP reflection scheme offers a competitive alternative. Modifying the MRR structure itself requires precise on-chip coupling design and thermal tuning,[12,13,19–23] leading to high complexity and limited scalability. Temporal pulse shaping can realize complex spectra, but demands high-speed modulation and low-loss pulse-shaping equipment. In contrast, our scheme employs only a single coated FP cavity, thus introducing lower insertion loss than interferometric approaches, and can also be integrated on-chip.[34] The associated power penalty can be readily offset by amplifying the pump after pump engineering. With temperature stabilization, the tolerance to resonance drift is sufficient, and the scheme remains robust to MRR linewidth deviations, ensuring consistent high purity across different MRRs in a source array, thereby demonstrating the potential for practical deployment.

4. Conclusion

In conclusion, we have proposed a pump-engineering scheme for generating spectrally pure photon pairs via SFWM in a standard MRR. This scheme uses only a single off-chip FP cavity to shape a pulsed laser, with the reflected pulses injected into the MRR. The engineered pulse broadens the effective pump linewidth in the MRR well beyond those of the signal and idler modes. The resulting spectral purity can asymptotically approach unity, breaking the 92% limit of a standard MRR SFWM source. The scheme is robust against fabrication variations, maintaining high purity across a broad parameter range and thus enabling scalability to MRR arrays. It is compatible with both all-pass and add-drop MRRs, requires neither intricate coupling techniques nor additional interferometric circuits, and is thus particularly suitable for long-term operation and scalable photon-pair generation.

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