Noise Properties of Microresonator-Based Optical-Parametric Oscillators

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Abstract: We theoretically and experimentally investigate the noise properties of four-wave mixing-based optical-parametric oscillators (OPOs) in silicon nitride microresonators. Such OPOs can operate at ultralow-noise levels and serve as a dual-point source for optical-frequency division.

Lasers can operate with low-frequency noise, which has enabled many applications in precision metrology, including the generation of ultra-low-noise microwave frequencies via optical frequency division (OFD). Traditional low-noise lasing is realized using stabilization cavities hosted in an evacuated chamber. Many miniaturization approaches have been demonstrated using whispering-gallery-mode cavities, including self-injection locking [1] and Brillouin lasing [2]. Such approaches are limited by thermorefractive noise (TRN) at lower offset frequencies and the Schawlow-Townes linewidth (STL) at higher frequencies and face challenges for further miniaturization due to incompatibility with the typical on-chip waveguides.

Here, we propose and demonstrate a new approach for generating low-noise optical frequencies on photonic chips using optical parametric oscillators (OPOs) based on four-wave mixing. We study the classical and quantum noise properties of OPO and show that it is a promising route toward applications requiring compact, integrated narrow-linewidth sources, especially for OFD based on dual-point sources.

Our OPO analysis for calculating the STL is based on the degenerately pumped four-wave mixing (DFWM) in $\chi^{(3)}$ microresonators, which can be realized in a broad array of materials. Our theory considers three cavity modes, namely the pump, signal, and idler modes, which is sufficiently accurate when cascaded four-wave mixing is weak. The cascaded modes can also be fully suppressed using methods such as Moiré gratings [3]. In semiconductor lasers, the linewidth is determined by carrier dispersion [4], and in Brillouin lasers, the Stokes oscillator linewidth is determined by the thermal occupation of phonons [2]. However, in OPOs, the linewidth is determined only by vacuum noise which allows the lowest possible STL. Our fully quantized analysis of STL yields,

$$\Delta f_{ST} = \frac{\hbar\omega_s\kappa\left[\alpha^2 + 4\left(\delta_s - 2\Gamma|A_{\mathrm{p}}|^2 - 2\Gamma|A_s|^2\right)^2\right]}{8\alpha P_s}, \tag{1}$$

where $\hbar$ is Planck's constant, ω_s is the signal frequency, κ is the bus-ring coupling rate, α is the total loss rate, δ_s is the signal detuning, Γ is the nonlinear coefficient, $\left|A_p\right|^2$ and $|A_s|^2$ are the intracavity pump and signal powers, respectively, and P_s is the output signal power. The term $4\left(\delta_s - 2\Gamma|A_{\mathrm{p}}|^2 - 2\Gamma|A_s|^2\right)^2$ is a result due to the dispersion and nonlinear phase shift which can be reduced to zero by controlling the pump detuning. In addition to quantum noise, thermorefractive and pump noise can also increase the OPO noise. For the case in which the signal and idler modes have identical loss rates, a concise result describing the phase evolution can be calculated to be,

$$\frac{d\psi_s}{dt} - \frac{d\psi_i}{dt} = -(\Delta\delta_s - \Delta\delta_i), \tag{2}$$

where ψ_s and ψ_i are the signal and idler phases, respectively, and $\Delta\delta_s$ and $\Delta\delta_i$ are the detuning fluctuations for the signal and idler due to TRN. Equation (2) indicates that when the loss rates of the signal and idler are matched, the pump noise is fully suppressed from the difference phase, which is due to the dynamics of the signal and idler fields being fully correlated [Fig. 1(b)]. Moreover, only the difference of the thermal fluctuations in the signal and idler contributes to the relative-phase noise, which is small since $\Delta\delta_s$ and $\Delta\delta_i$ are both proportional to temperature. Physically, the temperature fluctuations shift the resonances in the same direction. However, the signal and idler frequencies must shift oppositely due to energy conservation, which leads to a strong rejection of common-mode shifts [Fig. 1(c)]. In general, $\Delta\delta_s$ and $\Delta\delta_i$ are proportional to resonance frequencies and thus have a small but nonzero difference. We numerically simulate the classical OPO evolution with equal cavity loss rates, which is shown in Fig.

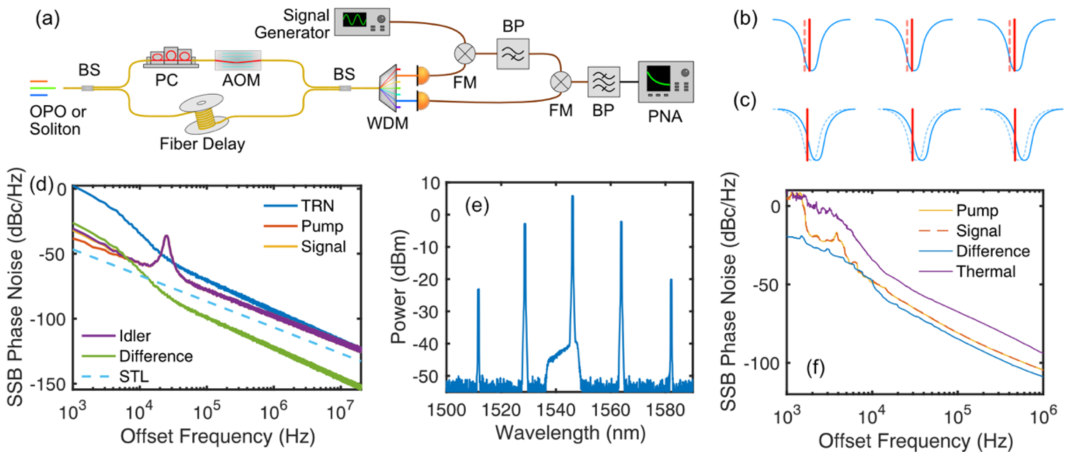

Fig. 1. (a) Delayed-heterodyne setup. Illustrations of pump (b) and TRN (c) rejections in OPO. (b) When the pump frequency shifts from the dashed-line to the solid-line locations, the signal and idler shift the same amount. (c) When the resonances shift from the dashed-line to the solid-line locations, energy conservation prevents the signal and idler from shifting. (d) Simulated OPO noise. (e) Measured OPO spectrum. (f) Measured OPO phase noise.

1(d). The signal and idler noise is limited by the thermal noise at low frequencies and pump noise at high frequencies. The relative phase noise between the signal and idler removes the pump noise and is significantly lower than the TRN. We also plot the STL as a dashed line which is not included in the classical simulation. This suggests that such an OPO is a promising on-chip system to reach the STL.

Experimentally, we use the modified delayed-heterodyne setup shown in Fig. 1(a) to measure the relative phase noise. We use a pump power of 9.7 mW at 1546.1 nm which generates OPO at 1528.5 nm and 1563.7 nm, respectively [Fig. 1(e)]. Figure 1(f) shows the measured phase noise of the pump, signal, and relative phase. In addition, we characterize the TRN of the pump mode using a homodyne method [5], which is also shown in Fig. 1(f). As predicted by theory, the relative phase noise is lower than the pump noise and TRN. Using Fig. 1(f), we infer a STL < 9.4 Hz for the signal and idler, and an equivalent STL of < 37 Hz as a dual-point reference. TRN can be reduced in cavities with a larger volume. Fig. 2(a) and 2(b) show the OPO generation in a 16-GHz-FSR cavity, which corresponds to a dual-point STL < 5.6 Hz. If we apply OFD on this 3-THz OPO to generate a 10-GHz microwave signal, it yields a phase noise of -116 dBc/Hz at the 10-kHz offset frequency. This is comparable to OFD with Brillouin lasers [6], which have larger footprints and operate with more restrictive materials and geometries. Further improvements can be achieved by tailoring the thermorefractive coefficient to achieve $\Delta\delta_s = \Delta\delta_i$ at the two wavelengths and engineering the dispersion to allow larger separation of the signal and idler. Finally, we point out that pump-noise suppression can also be achieved for the OPO-signal wavelength rather than the relative phase. Similar to Brillouin laser operation, we can increase the loss of the idler mode to allow lower phase noise in the signal. Figure 2(c) shows a simulation where the idler is 16× more lossy than the signal, which allows for a signal phase noise 6-dB lower than that of the pump.

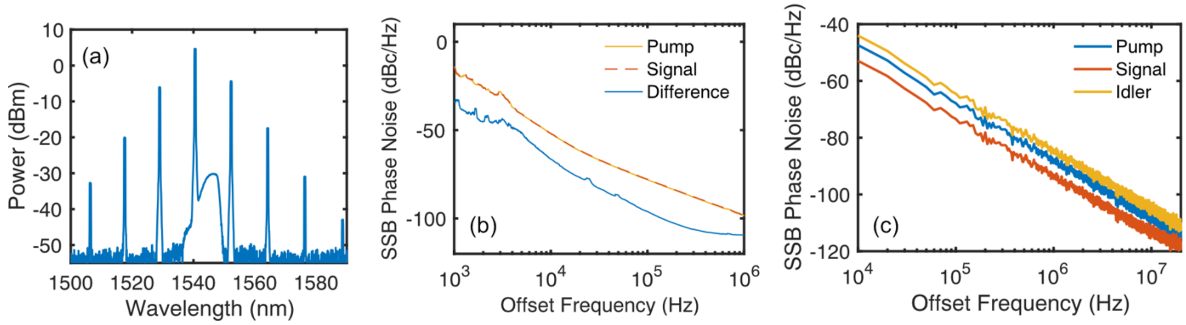

Fig. 2. Spectrum (a) and phase noise (b) noise OPO generated in a 16-GHz ring. (c) OPO with asymmetric loss rates

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