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Reconfigurable high-power Kerr optical parametric oscillators with sub-hertz linewidths

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Abstract

Integrated coherent light sources combining broad wavelength tunability, narrow-linewidth, and high output power are essential for precision spectroscopy, coherent communications, and quantum information processing, yet remain challenging to realize simultaneously. Kerr microresonator optical parametric oscillators (OPOs) provide coherent wavelength access beyond conventional gain media, but their oscillating signal-idler pairs are typically fixed by the dispersion and loss of the fabricated resonator, while pump-noise transfer and nonlinear mode competition limit coherence and power scaling. Here, we demonstrate post-fabrication reconfiguration of Kerr OPOs through coherent feedback enabled by mode-selective sideband self-injection locking, without the need for resonator redesign. By tuning the relative effective gain of competing parametric channels, coherent feedback makes a selected signal-idler pair dominant over the free-running state. At a fixed pump wavelength, our method enables stepwise sideband selection across 1.27 THz and continuous tuning over 202.17 GHz, while joint tuning of the pump and feedback-selected sideband extends the accessible span beyond 23 nm. The same feedback reduces the intrinsic linewidth of the selected sideband to sub-hertz, corresponding to a ~30,000-fold reduction from the free-running OPO and suppresses cluster-comb formation to deliver more than 42 mW on-chip sideband power. Our work establishes coherent feedback as a new control degree of freedom for reconfiguring nonlinear oscillation states in integrated Kerr photonics.

Introduction

On-chip coherent light sources combining wide wavelength tunability, low frequency noise, and high output power are essential for coherent optical communications^{1, 2}, precision sensing and ranging³⁻⁵, microwave/terahertz photonics^{6, 7}, and quantum information processing⁸. These capabilities serve complementary functions. Wide tunability enables agile access to distinct spectral windows and communication channels, whereas ultralow frequency noise preserves the phase coherence and spectral purity underlying precision measurements and coherent information processing, and high output power provides the photon flux required for extended transmission, high-dynamic-range detection, and efficient driving of nonlinear optical processes. Combining these properties within a single integrated source remains difficult because wavelength selection, coherence and power scaling are constrained by distinct physical mechanisms that are often strongly coupled and competing.

Self-injection-locked semiconductor lasers and integrated external-cavity lasers represent two established routes to narrow-linewidth integrated sources⁹⁻¹² (Fig. 1(a)). Self-injection locking (SIL) to a high-Q microresonator can strongly suppress semiconductor-laser frequency noise¹³, yet the continuous mode-hop-free tuning range within a single resonance is typically limited by the narrow resonant-feedback bandwidth and laser–resonator dynamics^{14, 15}. Integrated external-cavity lasers provide broader wavelength tuning, while their narrowest linewidths generally requires long, low-loss cavities and stable control of multiple wavelength-selective sections, with thermorefractive fluctuations ultimately imposing a frequency-noise floor¹⁶. More fundamentally, both approaches remain tied to the gain spectrum of the active medium, making broad spectral access from the visible to the mid-infrared difficult within a single source platform.

Kerr microresonator optical parametric oscillators (OPOs) provide a distinct route to coherent light generation. By generating signal-idler pair through four-wave mixing (FWM) rather than direct stimulated emission, they extend wavelength access beyond the gain bandwidth of conventional lasers¹⁷⁻²³ (Fig. 1a(iii)). Their operation, however, remains subject to three coupled constraints. First, under a fixed pump, the oscillating sidebands are restricted is normally selected by the dispersion, loss and detuning conditions of the fabricated resonator, leaving the output wavelengths difficult to change after fabrication²⁴.

Second, the generated sidebands inherit pump-frequency noise through the parametric interaction, limiting their spectral purity^{25, 26}. Existing noise mitigation approaches, such as external reference locking based on high-Q bulk Fabry–Pérot (FP) cavity, can pump-frequency noise, but introduce additional optical hardware and stabilization requirements²⁷. Third, at elevated pump powers, secondary FWM frequencies and cluster-comb formation divert energy from the primary sidebands and limit power scaling^{24, 28}. Recent advances based on hybrid-mode-family, photonic-crystal, loss-engineered and dispersion-reconfigurable resonators have improved conversion efficiency or wavelength flexibility^{22, 28-30}. These approaches act primarily by prescribing or modifying the cavity-mode spectrum. Sideband injection locking has also been used to stabilize selected microcomb lines³¹, but has not been established as a means of reselecting the primary oscillation state of a high-power Kerr OPO while suppressing competing cluster-comb channels. A post-fabrication strategy control mechanism that acts directly on parametric mode competition is therefore still lacking.

Here we demonstrate coherent feedback through mode-selective sideband SIL as a post-fabrication control mechanism for widely tunable, low-noise and high-power reconfigurable Kerr OPOs (Fig. 1(b),(c)). By tuning the relative effective gain of competing parametric channels, coherent reinjection suppresses the free-running sidebands and makes the selected signal-idler pair dominant. This brings nonlinear mode selection and energy transfer under active feedback control. At a fixed pump wavelength, this mode-selective feedback provides stepwise sideband selection across 1.27 THz, corresponding to approximately 10 nm in the C band. Thermal tuning further provides continuous wavelength tuning over 202.17 GHz, while joint tuning of the pump and feedback-selected sideband extends the accessible wavelength span beyond 23 nm. The same feedback narrows the intrinsic linewidth of the selected sideband to sub-hertz (approximately 0.62 Hz), an approximately 30,000-fold reduction from the free-running state. Moreover, sideband SIL suppresses cluster-comb formation and redirects power towards the selected parametric channels, yielding more than 42 mW of on-chip first-order sideband power (Fig. 1(c)). These results extend sideband SIL beyond the stabilization of an existing spectral line, establishing it as a means of reconfiguring the oscillation state and controlling

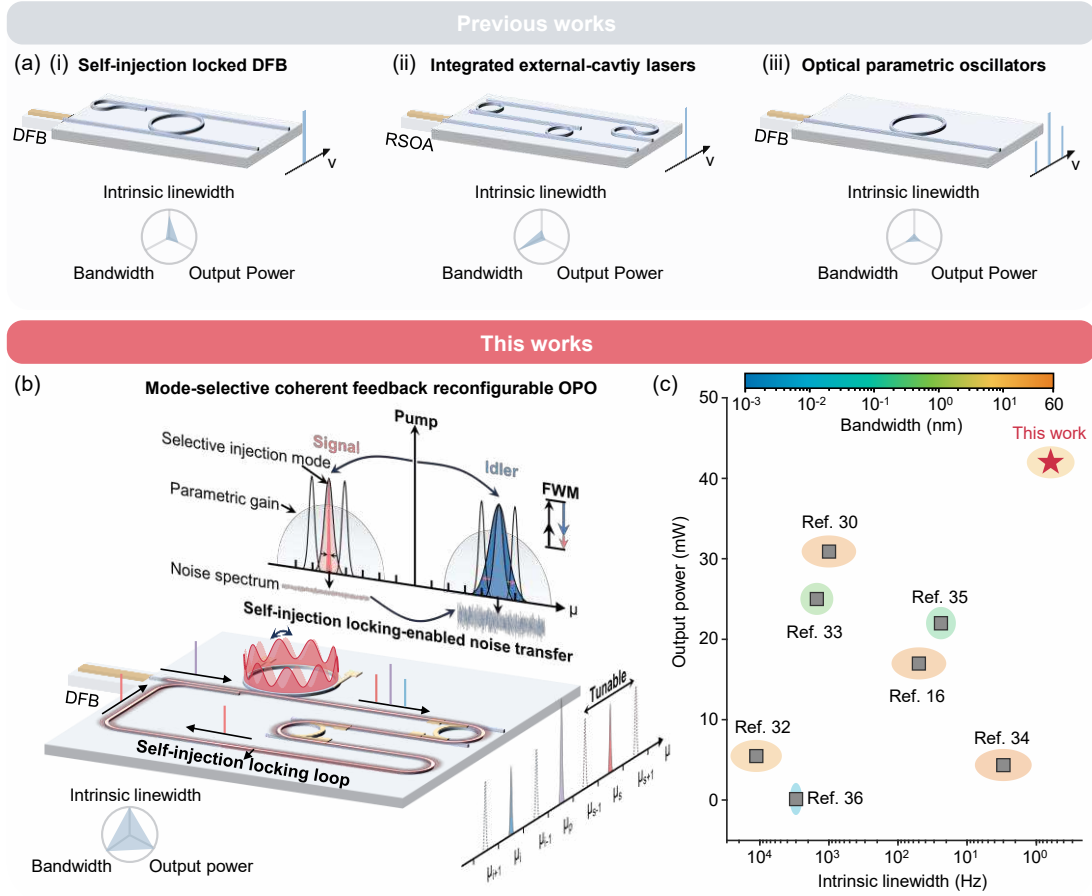


Fig. 1. Concept of sideband SIL for reconfigurable Kerr OPOs. (a) Concept and performance comparison of (i) SIL distributed feedback (DFB) laser, (ii) integrated external-cavity laser, and (iii) conventional OPO. (b) Device schematic and operating principle of the sideband SIL OPO. (c) Comparison of this work with multiple on-chip light sources in output power, bandwidth at a fixed pump wavelength, and intrinsic linewidth^{16, 30, 32-36}.

Principle

To describe the injection locking dynamics in the OPO, we have developed an appropriate theoretical model in the form of the Lugiato-Lefever equation (LLE)³⁷⁻⁴⁰, with modifications introduced to account for the influence of the feedback field on the cavity dynamics:

$$t_R \frac{\partial A_\mu}{\partial t} = \left(-\frac{\alpha}{2} - i\delta_0 - it_R D_{int}(\mu) \right) A_\mu + i\gamma L \sum_{m,n} A_m A_n A_{m+n-\mu}^* + \sqrt{\theta} E_{in} \delta_{\mu,0} + \sqrt{\theta} E_F \delta_{\mu,\mu_s}, \quad (1)$$

$$E_F = \sqrt{\beta} A_{n-l} e^{-i\phi_F}, \quad (2)$$

Here, A_μ represents the field amplitude of mode μ , whereas α and $D_{int}(\mu)$ denote the total round-trip losses and integrated dispersion, respectively. γ is the nonlinear coupling

coefficient, θ is the coupling coefficient, ϕ_F is the feedback phase, and t_R represents the cavity round-trip time, with $t_R = \frac{1}{\text{FSR}}$, where FSR denotes the free spectral range. E_{in} and E_F refer to the input and feedback fields, respectively. The delay l in the feedback loop governs the effective photon lifetime of the injected mode (Supplemental Material, Section 1). The feedback injection ratio β can be quantified as the on-chip power ratio between the feedback field re-injected into the microring (P_μ^F) and the emitting optical field (P_μ), i.e., $\beta = P_\mu^F / P_\mu$.

Traditional OPO formation requires anomalous dispersion, and the sidebands typically emerge at the frequency corresponding to the maximum parametric gain for fixed pump conditions ($|E_{\text{in}}|^2$ and $\delta\omega$, top panel in Fig. 2(a)). Here, we propose a sideband SIL scheme that overcomes this constraint by reshaping the gain landscape within the parametric bandwidth. By injecting a selected mode with tunable feedback gain, we tune the relative effective gain of competing parametric channels so that its effective gain exceeds that of the intrinsic maximum-gain mode, enabling continuous wavelength tuning across the full parametric gain bandwidth (bottom panel in Fig. 2(a)). Numerical simulations based on Eq. (1, 2) show that, once injection locking is activated, the initial OPO sidebands are suppressed, the selected mode (A_{μ_s}) becomes dominant, and generated new sidebands ($A_{\mu_{\pm s}}$) through FWM process (top panel in Fig. 2(b)), the corresponding injected-mode power then rises to the parametric oscillation threshold as the original signal decays rapidly (bottom panel in Fig. 2(b)). In addition, shifting the injection mode away from the intrinsic parametric-gain peak can suppress the competing cluster combs and enhance sideband power. This behavior is attributed to the increased effective photon lifetime of the injected mode under optical feedback for loss compensation⁴¹, which enables the injected mode to dominate intracavity energy transfer, facilitates FWM between the pump and primary sidebands, and suppresses parasitic nondegenerate FWM involving adjacent modes (Supplemental Material Fig. S1).

Beyond tunability, the proposed sideband SIL loop can also effectively suppress the frequency noise of the injected OPO sidebands. For sidebands satisfying the relation $\nu_{s,i} = \nu_p \pm \Delta\nu_{\text{FWM}}$, where $\Delta\nu_{\text{FWM}}$ denotes the excess noise introduced by the FWM process and

scales linearly with the frequency offset of the signal and idler relative to the pump (top panel in Fig. 2(c)). While the sideband noise can feature distinct behavior when a selected sideband ν_s (ν_i) is extracted and re-injected into the microresonator via a feedback loop. This loop effectively prolongs the photon lifetime of the injected mode A_{μ_s} , which can be interpreted as a reduction in its effective cavity loss rate ($\kappa_{\mu_s} < \kappa_{\mu_i}$). This reduction leads to a narrower linewidth for the injected mode, satisfying $\Delta\nu_{\mu_s} < \Delta\nu_p < \Delta\nu_{\mu_i}$ (Fig. 2(c)).

Within the framework of the elastic-tape model^{42, 43}, the injected sideband redistributes the pump noise through nonlinear interactions, leading to a directional transfer of noise from the injected sideband to the non-injected counterpart. We quantitatively investigate this noise transfer through numerical simulations of the phase noise dynamics. The frequency noise power spectral density (PSD) $S_{\Delta\nu_{p,s,i}}$ relates to the phase-noise PSD $S_{\Delta\phi_{p,s,i}}$ as^{44, 45}:

$$S_{\Delta\nu_{p,s,i}} = f^2 S_{\Delta\phi_{p,s,i}}(f), \quad (3)$$

where f denotes the frequency offset from the optical carrier. In the free-running OPO regime, the frequency noise of the pump, signal, and idler are comparable. Upon injection locking the signal ν_s , the pump frequency noise remains nearly unchanged, whereas the signal exhibits a substantial noise suppression (> 60 dB). However, the frequency noise of the idler is markedly elevated relative to the free-running state (Fig. 2(d)).

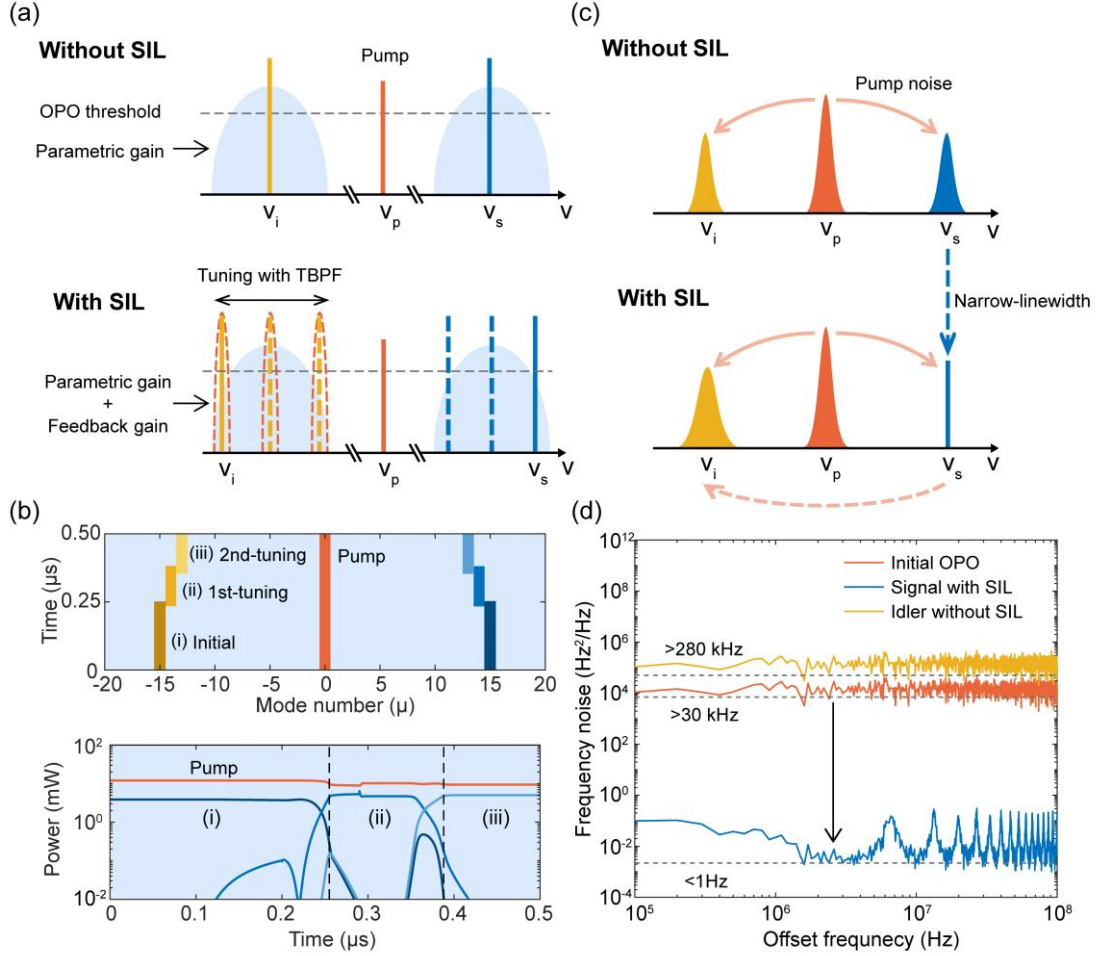


Fig. 2. Principle of sideband SIL for reconfigurable Kerr OPOs. (a) Schematic of injection-locked wavelength tuning. The blue shaded region indicates parametric gain bandwidth; the orange dashed curves are the parametric gain combined with the feedback gain; the blue and yellow lines indicate free-running signal and idler, respectively. (b) Simulated tuning dynamics. Top, output field evolution: the initial sidebands at ± 15 FSR are suppressed, the selected mode dominates, and new sidebands emerge through FWM. Bottom, power evolution of sidebands (i)-(iii). (c) Linewidth narrowing via injection locking. Orange arrows, pump-noise transfer; blue line, linewidth compression of the injection-locked signal. (d) Simulated linewidth narrowing. Injection-locked signal shows lower noise than the free-running OPO.

Results

Wavelength tuning of the injection-locked OPO

We experimentally validate the mechanism of an injection-locked OPO on a silicon nitride (Si_3N_4) microring resonator. The microring has a radius of $R = 115 \mu\text{m}$, with a waveguide cross-section of $W \times H = 1.8 \mu\text{m} \times 0.72 \mu\text{m}$. The device adopts a pulley waveguide coupling scheme, with a 700 nm coupling gap between the microring and the pulley waveguide (inset, Fig. 3(a)). By fitting the transmission spectrum of the fundamental TE_{00} polarization mode, we extract an intrinsic quality factor of the pump mode as $Q_i \approx 1.2$

× 10⁶ (Supplemental Material Fig. S2).

With the pump frequency and power fixed, the feedback-selected sideband is chosen using a tunable bandpass filter (TBPF), enabling stepwise switching of the injection-locked signal across a span of ~10 nm (Fig. 3(a), experimental setup in Supplemental Material Fig. S3). Controlling the overall chip temperature provides thermal tuning across approximately 202.17 GHz (~1.58 nm, Fig. 3(b)). We further demonstrate integrated electrical tuning over 23.5 GHz (Supplemental Material Fig. S4), along with continuous frequency sweeps under electrical modulation for potential LiDAR applications (Supplemental Material Fig. S5). The present electrical tuning range is limited by the maximum voltage applicable on chip and could be extended through process modifications such as local undercut etching⁴⁶. Furthermore, joint tuning of the pump and feedback-selected sideband extends the total accessible wavelength span beyond 23 nm (Fig. 3(c)). We also characterize the dependence of the injection-locked OPO wavelength tuning performance on the feedback injection ratio β (Supplemental Material Fig. S6). The original and new sidebands coexist at the lower feedback injection ratio ($\beta = 0.471$), but only the new sideband remains as the ratio increases ($\beta = 0.734$).

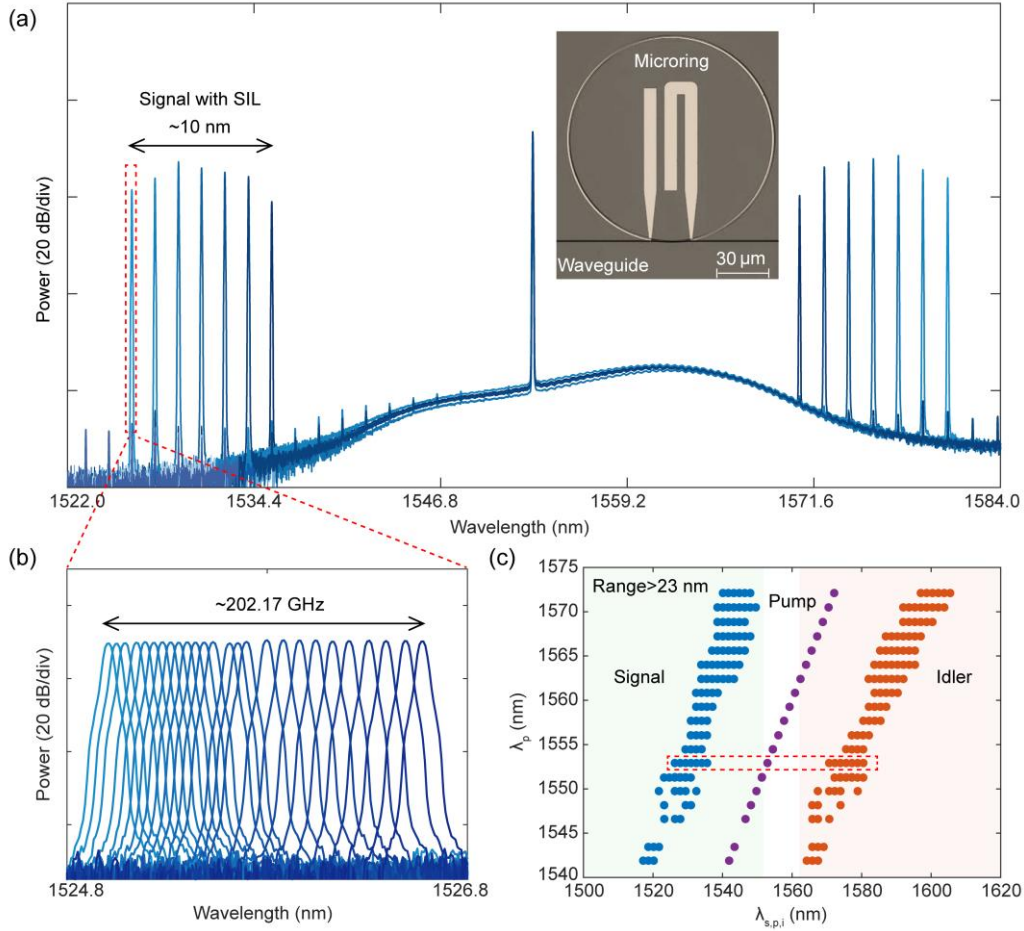


Fig. 3. Wavelength tunability of injection-locked OPO. (a) Extended tuning of the injection-locked signal, achieving a tuning range of ~10 nm. Inset: optical micrograph of the Si₃N₄ microring resonator. (b) Continuous tuning of the signal across 202.17 GHz (~1.58 nm) by controlling the overall chip temperature. Dashed lines mark selected sidebands. (c) Sideband frequencies as a function of pump wavelength, together with injection-locked tuning under corresponding conditions. The accessible tuning range exceeds 23 nm. The dashed line indicates the corresponding details shown in (a).

Noise suppression under injection locking

We systematically characterize the noise suppression of the injection-locked OPO as a function of the feedback injection ratio β using delayed self-heterodyne measurements (inset, Fig. 4). At low feedback (Regime I), the sideband linewidth remains close to that of the free-running OPO. Increasing β leads to progressive noise suppression in Regime II, followed by pronounced linewidth narrowing in Regime III, where the intrinsic linewidth falls below 1 Hz, corresponding to a reduction factor of ~30,000 relative to the free-running case (Fig. 4). As β approaches unity, the system enters Regime IV, where coherence collapse causes the frequency noise and linewidth to increase again^{47, 48}. The measured frequency noise PSD for each wavelength is presented (Fig. 4). The measured dependence on β

agrees well with numerical simulations (Supplemental Material Fig. S7). Simulations further indicate that the noise suppression is only weakly dependent on the feedback phase over the stable locking regime (Supplemental Material Fig. S8).

We further examine noise suppression under injection-locked wavelength tuning, in which the signal is locked while the idler remains free-running (Supplemental Material Fig. S9). A direct comparison shows substantial linewidth narrowing for the signal, whereas the idler exhibits no suppression and instead degrades. This arises because the intrinsic OPO noise scales with the frequency detuning $\Delta\nu$, whereas the noise suppression factor under a given injection condition remains constant. We note that the low-frequency noise remains elevated, because the system operates without active stabilization at ambient conditions. Further reduction is expected by referencing the oscillator to a stable passive cavity, such as an on-chip ultrastable resonator^{49, 50}.

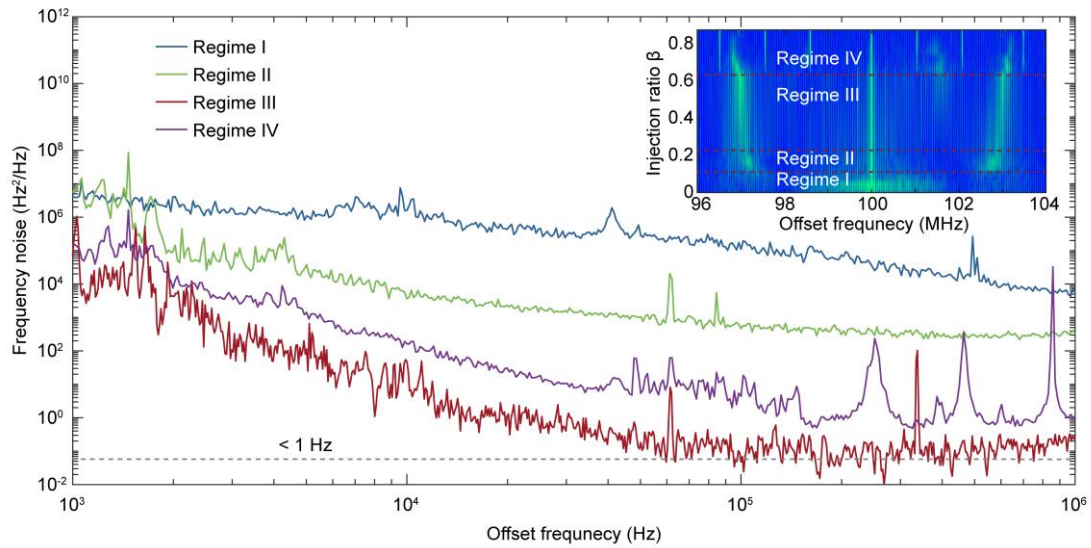


Fig. 4. Frequency-noise spectra. Injection locking reduces the intrinsic linewidth of the signal, with the strongest narrowing (<1 Hz) occurring in Regime III. Inset: beat-note spectra measured under different feedback injection ratios β , revealing distinct injection regimes.

Sideband SIL suppresses nonlinear mode competition

At elevated pump powers, secondary four-wave-mixing processes around the primary OPO sidebands can drive cluster-comb formation, diverting energy from the targeted signal-idler pair and limiting both conversion efficiency and sideband power²⁸. We therefore investigate whether sideband SIL can suppress this nonlinear mode competition. To quantify the relationship between pump power and sideband output, we define the total

241 OPO conversion efficiency as $\eta = (P_s + P_i)/P_p$ under the three-mode interaction
 242 approximation. Here, P_p denotes the on-chip pump power, while P_s and P_i represent the
 243 on-chip signal and idler powers, respectively. Without SIL, a maximum conversion
 244 efficiency of $\sim 37\%$ is achieved at a pump power of 124.74 mW (inset, Fig. 5(a)),
 245 corresponding to signal and idler powers of 20.98 and 25.18 mW, respectively.

246 Further increasing the pump power drives the free-running OPO into a cluster-comb
 247 state, reducing the power carried by the primary sidebands (Fig. 5(d)). When a sideband
 248 at 1526.76 nm, displaced from the free-running OPO sideband at 1523.54 nm, is selected
 249 for feedback, sideband SIL reshapes the mode competition and suppresses cluster-comb
 250 formation. As a result, the first-, second-, and third-order sideband powers are enhanced
 251 by approximately 0.72 dB, 11.20 dB, and 17.60 dB, respectively (Fig. 5(e)). The
 252 corresponding maximum powers for the first three sideband orders with injection locking
 253 can reach up to 42.03 mW, 4.88 mW, and 0.76 mW, respectively (Figs. 5(a)–5(c)). Hybrid-
 254 mode and photonic-crystal microrings can also suppress cluster-comb formation by
 255 tailoring the sidebands to operate within the normal-dispersion regime^{28, 49}. However, they
 256 require the relevant phase-matching conditions to be encoded in stringent dispersion
 257 engineering and complex fabrication. In contrast, sideband SIL concentrates optical power
 258 in the selected parametric channels by suppressing competing cluster-comb formation,
 259 without modifying the microresonator structure.

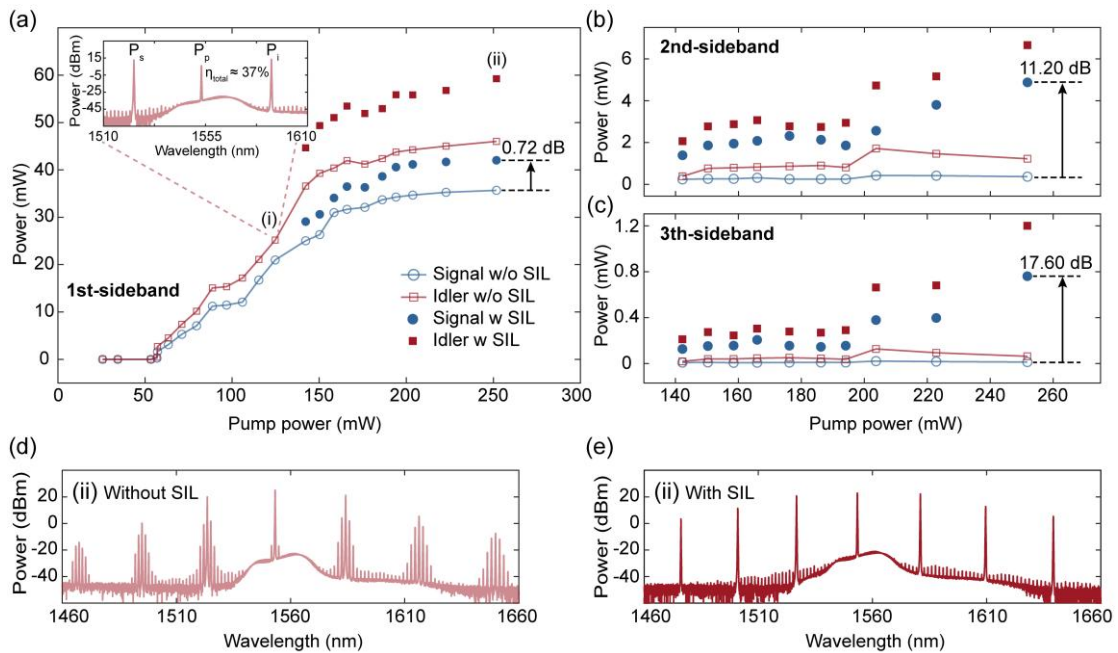


Fig. 5. Highly efficient and high-power OPO. (a-c) Power evolution of the first-, second-, and third-order sidebands with and without injection locking. Inset: high-conversion-efficiency OPO operation without SIL. (d) Cluster combs form above the threshold (~ 251.77 mW) and limit sideband power scaling. (e) Suppression of mode competition via injection locking. Cluster combs are eliminated (~ 251.77 mW), leading to enhanced sideband power.

Discussion

In conclusion, we have demonstrated mode-selective sideband SIL as a post-fabrication control approach for reconfiguring the nonlinear oscillation state of a Kerr OPO. Unlike conventional OPOs, in which the oscillating signal-idler pair is determined by the fixed dispersion, loss and phase-matching conditions of the fabricated microresonator, coherent reinjection introduces an additional feedback-controlled gain channel that reshapes competition among parametric oscillation modes. As a result, a selected signal-idler pair can replace the free-running oscillation state without modifying the resonator structure. This feedback-controlled reconfiguration enables sideband selection across 1.27 THz at a fixed pump wavelength, continuous wavelength tuning over 202.17 GHz, and an accessible spectral span beyond 23 nm through joint pump and feedback tuning. The same mechanism suppresses cluster-comb formation and enhances energy transfer into the selected parametric channels, enabling sub-hertz intrinsic linewidth (~ 0.62 Hz) and more than 42 mW on-chip first-order sideband power.

This operating principle differs fundamentally from recent SIL approaches in microcomb systems. The SIL of soliton microcomb has produced sub-hertz intrinsic linewidths across multiple comb lines, but relies on the preparation and stabilization of a pre-existing soliton state³¹. Cascaded SIL can further suppress thermorefractive-noise-induced fluctuations and transfer coherence among existing comb modes⁵¹. In these approaches, feedback primarily stabilizes spectral components that are already supported by the underlying nonlinear state. In contrast, sideband SIL in the present work acts directly on the mode competition governing Kerr OPO formation. By modifying the relative dominance of competing parametric channels, coherent feedback enables the selection of a different signal-idler pair and suppresses nonlinear pathways responsible for cluster-comb formation. Therefore, wavelength reconfiguration, linewidth narrowing and power enhancement arise as coupled consequences of feedback-controlled nonlinear mode

selection and energy transfer under active feedback control rather than independent optimization of individual device parameters.

The combination of fixed-pump spectral reconfigurability, coherence and output power also distinguishes the present scheme from other integrated coherent sources. Heterogeneously integrated SIL and external-cavity semiconductor lasers can reach hertz- or sub-hertz-level intrinsic linewidths, but their spectral coverage remains bounded by the gain medium and generally requires tuning of the laser cavity. Integrated stimulated Brillouin lasers have demonstrated an intrinsic linewidth of 31 mHz together with an output power of 41 mW⁵², but their operating wavelength is ultimately determined by the pump frequency and Brillouin frequency shift, while the cavity design must satisfy stringent phase-matching conditions. In contrast, sideband-selective feedback provides an additional control degree of freedom after fabrication, allowing the generated OPO wavelength to be reconfigured within the available parametric-gain bandwidth without encoding each operating wavelength into a dedicated dispersion profile or mode-coupling design.

The current implementation still relies on fiber -based filtering, amplification and delayed feedback (Fig. 6). Extending this concept towards a fully integrated architecture would require the co-integration of the nonlinear OPO resonator with low-loss delay lines, wavelength-selective elements, optical gain and integrated pump sources. Heterogeneous integration of Er:Si₃N₄ gain sections with passive Si₃N₄ circuits provides a promising route to replace fibre-based amplification while maintaining the low-loss and high-Q characteristics required for nonlinear feedback systems⁵³. Recent advances in ultralow-loss passive Si₃N₄ waveguides and microresonators, including propagation losses below 0.2 dB/m and intrinsic quality factors exceeding 1.6×10^8 , further support the feasibility of compact low-noise feedback circuits⁵². Such reconfigurable coherent sources could enable future applications in precision spectroscopy, coherent ranging, optical communications, and quantum photonics.

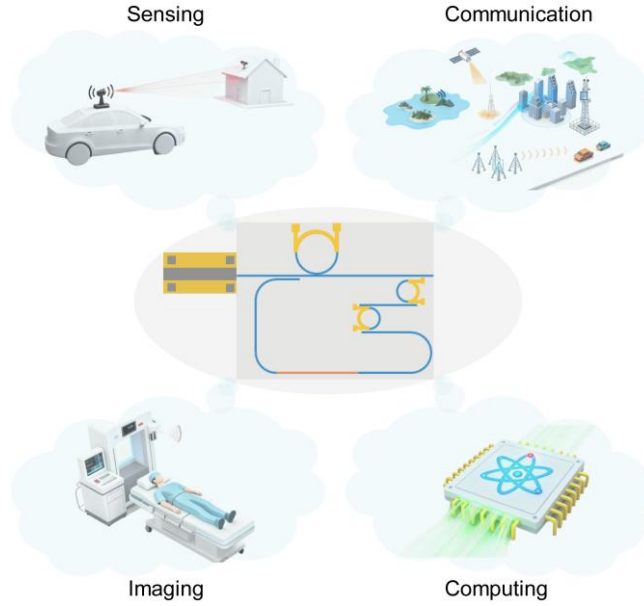


Fig. 6. Conceptual illustration of monolithically integrated OPO injection locking and prospective applications.

Methods

Fabrication and resonator characteristics

A 4- μm -thick SiO_2 layer is formed by thermal oxidation of a crystalline silicon wafer and serves as the bottom cladding. A 720-nm-thick Si_3N_4 film is deposited by low-pressure chemical vapor deposition (LPCVD) and annealed. Device patterns are defined by electron-beam lithography and transferred into the Si_3N_4 layer by inductively coupled plasma reactive-ion etching (ICP-RIE) with $\text{CHF}_3/\text{N}_2/\text{O}_2$ chemistry. To reduce sidewall roughness, a SiO_2 hard mask is used and the O_2 flow is increased. An additional anneal in argon at 1200 °C suppresses N-H absorption. For the top cladding, we first deposit a thin layer of high-temperature oxide, followed by a second thicker layer of SiO_2 deposited by plasma-enhanced chemical vapor deposition. A 300-nm-thick gold layer is then sputtered and patterned into integrated heaters by lift-off. The radius of the microresonator used for the experiment is 115 μm . The width and the height of the Si_3N_4 waveguide are 1800 nm and 720 nm, respectively. The ring is coupled to a pulley waveguide through a 700-nm gap. Fitting the transmission spectrum of the fundamental TE_{00} mode yields an intrinsic quality factor of $Q_i \approx 1.2 \times 10^6$ for the pump mode. Lensed fibers are used for coupling into and out of the Si_3N_4 chip. The total coupling loss is about 5.05 dB.

Theoretical modeling of injection-locked Kerr OPO

The dynamical evolution of the OPO in a microresonator is governed by three nonlinearly interacting fields—the pump A_P , signal A_B , and idler A_C —whose intracavity dynamics are described by the coupled-mode equations:

$$t_R \frac{dA_P}{dt} = -\frac{\alpha}{2} A_P - i\Delta_P A_P + i\gamma L_R (|A_P|^2 + 2|A_B|^2 + 2|A_C|^2) A_P + i2\gamma L_R A_P^* A_B A_C + \sqrt{\theta} E_{in}, \quad (4)$$

$$t_R \frac{dA_B}{dt} = -\frac{\alpha}{2} A_B - i\Delta_B A_B + i\gamma L_R (2|A_P|^2 + |A_B|^2 + 2|A_C|^2) A_B + i\gamma L_R A_P^2 A_C^*, \quad (5)$$

$$t_R \frac{dA_C}{dt} = -\frac{\alpha}{2} A_C - i\Delta_C A_C + i\gamma L_R (2|A_P|^2 + 2|A_B|^2 + |A_C|^2) A_C + i\gamma L_R A_P^2 A_B^*, \quad (6)$$

Here, α is the total round-trip losses, and Δ_P , Δ_B , and Δ_C denote the detunings of the pump, signal, and idler, respectively. L_R is the cavity length, and $t_R = 1/\text{FSR}$ is the round-trip time. γ is the Kerr nonlinear coefficient, θ is the coupling coefficient, and E_{in} is the input field.

To capture the injection-locked wavelength-tuning dynamics of the OPO while maintaining analytical clarity, we restrict the model to three-wave interactions among the pump, signal, and idler, neglecting Raman scattering and higher-order dispersion. The system is formulated within the LLE framework, augmented by a feedback term E_F to account for injection locking:

$$t_R \frac{\partial A_\mu}{\partial t} = \left(-\frac{\alpha}{2} - i\delta_0 - it_R D_{int}(\mu) \right) A_\mu + i\gamma L \sum_{m,n} A_m A_n A_{m+n-\mu}^* + \sqrt{\theta} E_{in} \delta_{\mu,0} + \sqrt{\theta} E_F \delta_{\mu,\mu_s}, \quad (7)$$

Here, A_μ denotes the field amplitude of mode μ , and $D_{int}(\mu)$ is the integrated dispersion. $\delta_{\mu,0}$ and δ_{μ,μ_s} are Kronecker delta functions selecting the pump and injected sideband modes, respectively. To reduce model complexity, the feedback field is approximated as a delayed replica of a selected sideband, $E_F = \sqrt{\beta} A_{n-l} e^{-i\phi_F}$, where β is the feedback injection ratio, ϕ_F is the feedback phase and l represents the feedback-loop delay.

Experimental setup

We pump the OPO via a DFB laser, which is amplified by an EDFA, passes through a polarization controller (PC1), and enters one port of a 50:50 coupler. Light is coupled into and out of the Si₃N₄ chip through lensed fibers, with a facet coupling loss of ~5.05 dB, and the pump is aligned to the fundamental TE₀₀ mode to excite the OPO. The OPO output is

split by a 90:10 coupler, with 90% of the power sent to an optical spectrum analyzer (OSA, AQ6370D-01-L-0/FC/RFC) for real-time spectral monitoring and the remaining 10% routed into the feedback loop, where a TBPF selects the injection sideband. The selected sideband is amplified by a second EDFA (small-signal gain ≈ 45 dB), polarization-conditioned by PC2, attenuated by a variable optical attenuator (VOA), and re-injected into the microcavity through a 90:10 coupler, with $\sim 90\%$ of the power coupled back; tuning the VOA varies the injection ratio for quantitative analysis of injection-locked wavelength tuning. To characterize noise suppression with and without injection locking, the selected OPO signal is amplified, filtered, and measured with a delayed self-heterodyne interferometer: the signal is split by a 50:50 coupler, one arm is frequency-shifted by an acousto-optic modulator (AOM, 100 MHz) and delayed by ~ 100 m of single-mode fiber, and the resulting beat note centered at 100 MHz is recorded to extract the PSD of the signal.

Data availability

The data that support the plots within this paper are available. Source data are provided with this paper.

Code availability

The codes that support the findings of this study are available from the corresponding authors upon request.

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Author contributions

The experiments were conceived by X. Zhao D. Xia, L. Luo, and B. Zhang. Measurements were performed by X. Zhao, with assistance from L. Luo, D. Xia, N. Yang, L. Wang, and X. Zhou. The device was fabricated by L. Wang and G. Wang. The device was designed by X. Zhao, D. Xia, L. Luo. Numerical simulations were performed by X. Zhao, with assistance from D. Xia, L. Wang, N. Yang, and L. Luo, X. Zhao, D. Xia, R. Huang, D. Tang, X. Zheng and B. Zhang contributed to writing the manuscript. The project was supervised by Z. Li, H. Jing, and B. Zhang.

Supplementary Material

See Supplemental Material at xxx.

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