

Tunable mid-infrared frequency combs from nanophotonic parametric oscillators

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Abstract: We demonstrate mid-infrared frequency combs from synchronously-pumped optical parametric oscillators in nanophotonic lithium niobate at 19 GHz. With a picosecond pump at $\sim 1 \mu\text{m}$, the output can be tuned between 1.5 and $3.3 \mu\text{m}$ supporting sub-picosecond pulses. © 2022 The Author(s)

On-chip generation of frequency combs in the mid-infrared is of utmost importance for the field deployment of photonic devices that cater to a plethora of applications including spectroscopy, metrology, and quantum optics. Optical parametric oscillators (OPOs) based on bulk nonlinear optical crystals have been the mainstay for accessing tunable coherent radiation in the mid-IR spectral region. Efforts to miniaturize mid-IR frequency comb sources rely primarily on supercontinuum generation, and/or difference frequency generation [1, 2]. Not only do these nonlinear processes require a femtosecond pump as their input (which has its own challenges for efficient on-chip manifestation), they also suffer from the limitation that the power spectrum is distributed over a wide frequency range, including undesired spectral bands. Engineered semiconductor devices, like quantum cascade lasers, have successfully been demonstrated in the mid-infrared; however, they are inherently narrowband and exceedingly difficult to operate in the ultrashort pulse regime. On the other hand, OPOs enjoy high tunability that can be manipulated at will by engineering the phase matching requirement. Four-wave mixing based on Kerr-nonlinearity can lead to tunable broadband radiation but is contingent on demanding resonator quality factor requirements.

The emergence of the thin-film lithium niobate platform provides access to strong $\chi^{(2)}$ nonlinearity, enabling the recent realization of integrated continuous wave (CW) OPOs [3, 4]. The ability to control the phase-matching via periodic poling combined with dispersion engineering enables wide-range tunability exceeding an octave [4]. Here, we report the generation of a tunable frequency comb from an OPO in lithium niobate nanophotonics. The demonstrated frequency comb covers the typical communication bands and extends into the mid-infrared spectral region beyond $3 \mu\text{m}$ and operates at a repetition rate near 19 GHz.

Our device is a doubly-resonant OPO [4], represented schematically in Fig. 1(a). The waveguides are patterned on a 700-nm-thick MgO-doped lithium niobate layer on top of a silica buffer layer. The nonlinear interaction takes place in the poled region of the waveguide (5-mm long). Multiple devices with poling periods from $5.55 \mu\text{m}$ to $5.7 \mu\text{m}$ (in 10-nm increments) have been fabricated to phase-match different signal-idler combinations as shown in Fig. 1(b). The parametric gain curve of one of these OPOs is shown in Fig. 1(c), showing an idler lying in the mid-infrared. The waveguide dimensions (width of $2.5 \mu\text{m}$, etch depth of 250 nm) are chosen such that it can support guided modes in the mid-infrared (see inset of Fig. 1(c)). The designed adiabatic couplers couple only the long wavelengths (signal and idler), allowing the short wavelengths (pump) to pass through the poled region with minimum coupling to the resonator. The OPO is synchronously pumped by 1-ps-long pulses around 1060 nm operating at a repetition rate of approximately 19 GHz. The pump is generated from an electro-optic frequency comb using cascaded intensity and phase modulators [5] followed by a spectral wave-shaper and amplified by a combination of semiconductor optical amplifier and ytterbium doped fiber amplifier.

Figure 1(d) shows the broad spectral coverage extending up to $3.3 \mu\text{m}$ obtained from a single chip. Wide tunability can be accessed by choosing a different OPO with slightly different poling period, while fine tunability can be obtained by changing the pump wavelength. The comb lines can be resolved by the optical spectrum analyser (OSA) and can be seen in the inset, where the separation of the peaks correspond to the applied repetition rate. We further evaluate the coherence of the output frequency comb by performing a linear field cross-correlation (FCCR) of the output signal light, where each OPO pulse is interfered with another pulse delayed by 10 roundtrips. The presence of the interference fringes, combined with the consistency of the Fourier transform of the cross-correlation trace and the signal spectrum obtained using an OSA, serve as evidence for the coherence of the output frequency comb over the entire spectrum. The on-chip threshold amounts to approximately 1 mW of average power. The OPO output corresponds to a sub-picosecond transform-limited temporal duration (~ 800 fs) for the

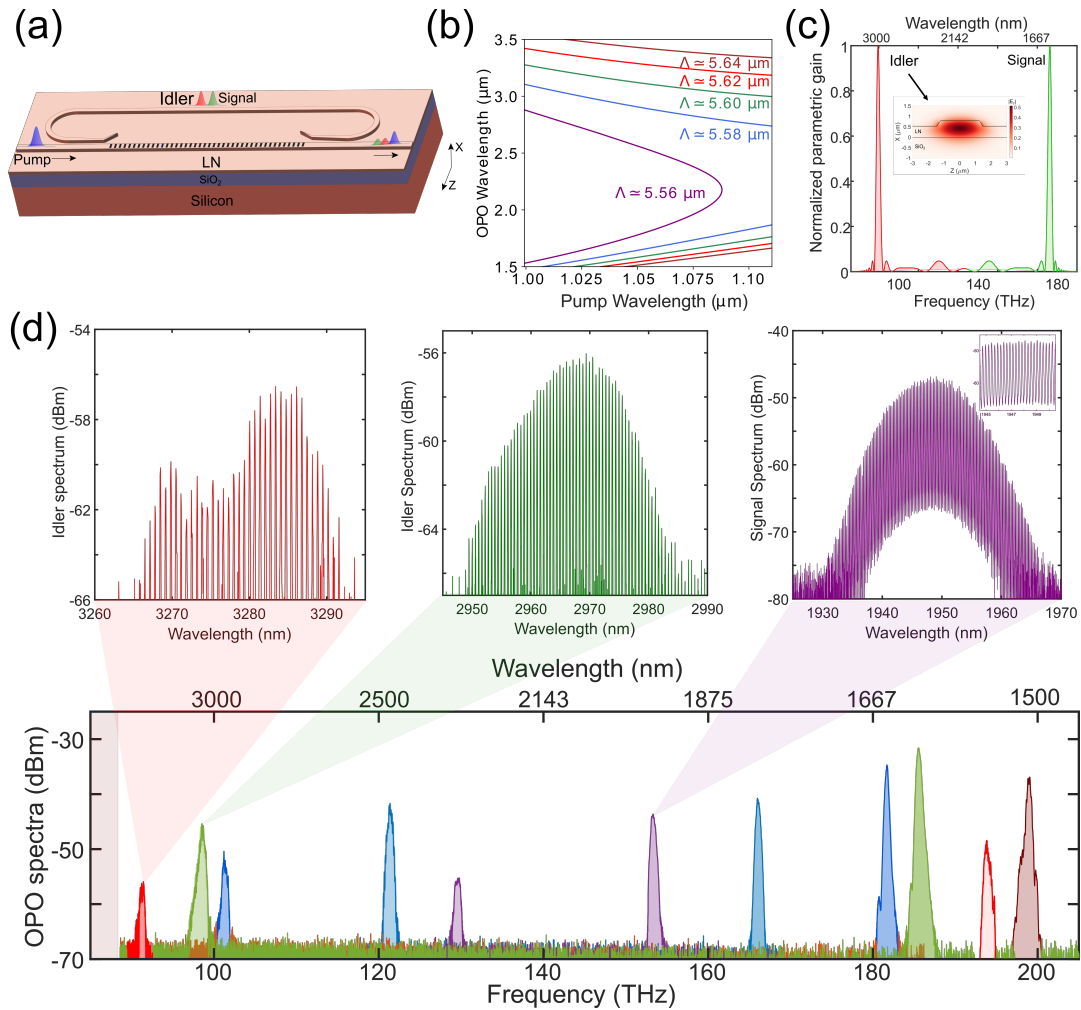


Fig. 1. a) Schematic of the synchronously pumped integrated OPO, b) Tuning the phase-matching curve with different poling periods c) Parametric gain in the mid-infrared by quasi-phase matching, d) Broadband tunability resulting from the spectral coverage of the OPOs extending up to $3.3\ \mu\text{m}$. Zoomed in versions display the comb line structure for a few examples.

signal and idler pulses. The occurrence of other quadratic nonlinear processes, namely second harmonic and sum-frequency generation, leads to frequency comb formation in the visible spectral region. The tunability aspect can also be observed in the visible counterpart, which represent an opportunity for a universal tunable frequency comb covering visible to mid-IR.

In summary, we have shown tunable mid-infrared frequency combs from lithium niobate-based integrated optical parametric oscillators, paving the way for the development of on-chip spectroscopic platforms. Lithium niobate has a transparency window that extends beyond $4.5\ \mu\text{m}$, which, combined with near-IR electro-optic comb generation on the same chip [6], promises future fully integrated frequency comb sources deep into the mid-infrared. With proper dispersion engineering, our OPO design can additionally achieve quadratic soliton formation followed by significant pulse compression [7], enabling the generation of femtosecond mid-infrared frequency combs in nanophotonics.

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