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Tunable frequency combs in nanophotonic parametric oscillators from visible to mid-IR

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Abstract: We demonstrate broadly-tunable synchronously-pumped optical parametric oscillators in nanophotonic lithium niobate. A picosecond 1-μm pump generates sub-picosecond signal/idler frequency combs tunable between 1.5 and 3.3 μm with up-conversion to the visible on the same chip.

On-chip generation of mid-infrared frequency combs is of paramount importance, thanks to its widespread applications in spectroscopy and metrology. Traditionally, tunable coherent mid-infrared radiation is obtained using optical parametric oscillators (OPOs) based on bulk nonlinear optical crystals. Attempts to miniaturize mid-IR frequency comb sources resort to supercontinuum generation, and/or difference frequency generation [1, 2]. These approaches face the challenge of requiring a femtosecond pump at their input, and also suffer from the limitation that the power spectrum is distributed over a wide frequency range, including undesired spectral bands. Quantum cascade lasers have been successfully deployed to operate in the mid-infrared, however attaining ultrashort pulse operation remains an outstanding challenge. On the other hand, tunable visible frequency comb realization is also challenging owing to the absence of suitable broadband gain medium, and the typical large normal dispersion at these wavelengths in most integrated photonic platforms. However, OPOs based on quadratic nonlinearity ($\chi^{(2)}$) enjoy high tunability that can be manipulated at will by engineering the phase matching requirement.

Strong ($\chi^{(2)}$) nonlinearity from the tight-confinement of the guided modes can be accessed in the emerging thin-film lithium niobate platform which led to 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 tunable frequency combs from on-chip OPOs in lithium niobate nanophotonics. The demonstrated frequency combs covers the typical communication bands and extends into the mid-infrared spectral region beyond 3 μm producing sub-picosecond pulses.

Our device is a doubly-resonant OPO [4] comprising of waveguides that are etched on an X-cut 700-nm-thick MgO-doped lithium niobate layer resting on top of a silica buffer layer, which is schematically represented in Fig. 1(a). The parametric nonlinear interaction takes place in a 5-mm-long poled waveguide region. The OPO-chip consists of multiple devices with poling periods ranging from 5.55 μm to 5.7 μm (in 10-nm increments) to phase-match different signal-idler combinations spanning from degeneracy to far non-degeneracy as shown in Fig. 1(b). This coarse tunability provided by multiple poling periods, can be coupled with fine tunability arising from the pump wavelength tuning and the temperature control. The waveguide dimensions (width of 2.5 μm, etch depth of 250 nm) are chosen such that it can support guided modes in the mid-infrared (see bottom of Fig. 1(a)). Doubly resonant operation is ensured by designing adiabatic couplers that preferentially couple only the long wavelengths (signal and idler), allowing the short wavelengths (pump) to pass through. 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 [5] followed by a wave-shaper assisted de-chirping stage and amplified by a combination of semiconductor optical amplifier and ytterbium doped fiber amplifier.

Figure 1(c) shows the broad spectral coverage extending up to 3.3 μm in the mid-infrared obtained from a single chip. 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 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 at degeneracy (Fig. 1(d)) corresponds to a sub-picosecond transform-limited temporal duration (~380 fs), representing a pulse compression factor exceeding 2 with respect to the pump. The occurrence of other quadratic nonlinear processes, namely second harmonic and

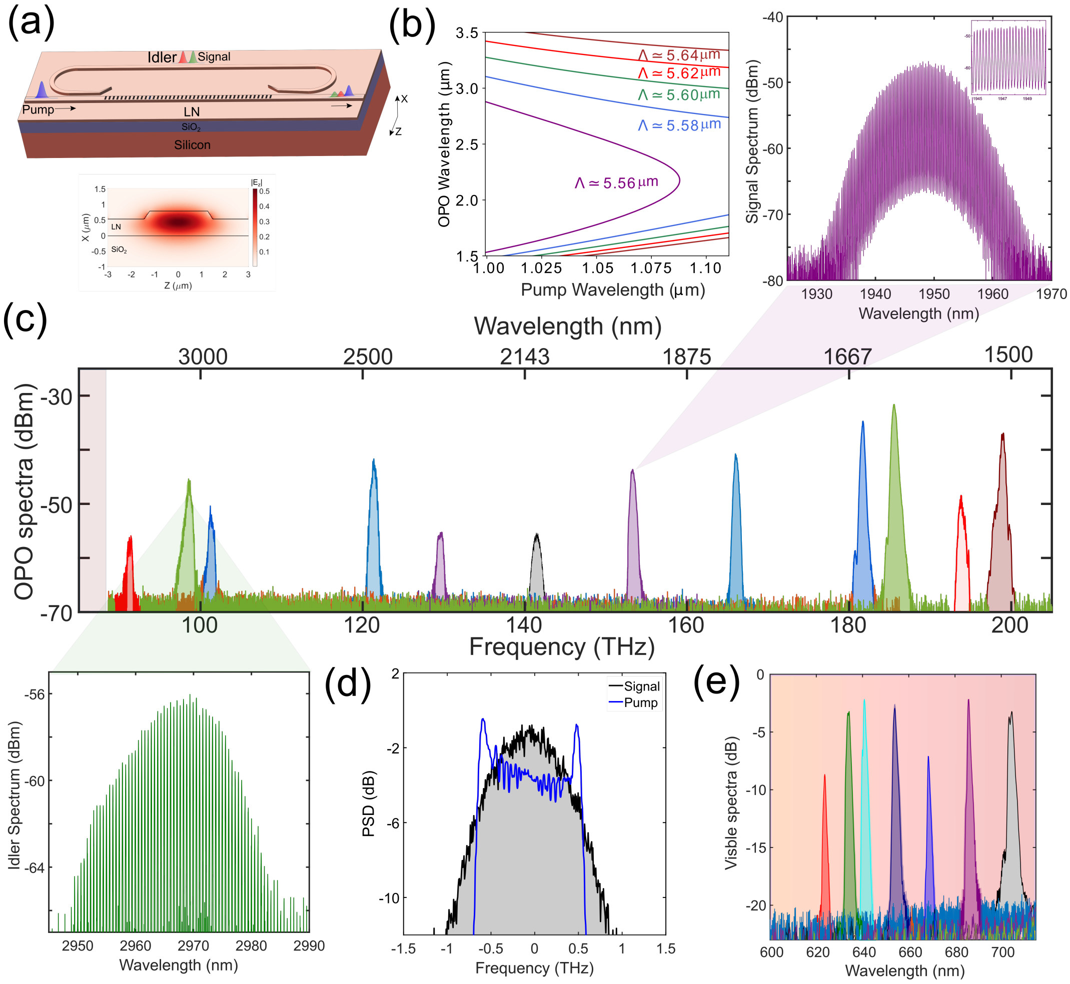

Fig. 1. a) Schematic of the synchronously pumped integrated OPO, b) Tuning the phase-matching curve with different poling periods, c) Broadband tunability resulting from the spectral coverage of the OPOs extending up to 3.3 μm. Zoomed in versions display the comb line structure. d) Spectral broadening of the OPO operating at degeneracy, e) visible frequency combs resulting from the up-conversion of the signal frequency comb.

sum-frequency generation, leads to frequency comb formation in the visible spectral region as shown in Fig. 1(e).

In summary, we have shown broadly tunable lithium niobate-based integrated optical parametric oscillators generating frequency combs from visible to the mid-IR, paving the way for the development of on-chip universal comb sources. The pump which is a near-IR electro-optic comb can be incorporated into the lithium niobate chip in the future [6], thereby promising a fully integrated solution for mid-infrared frequency comb generation with high coherence and high conversion efficiency. With proper dispersion engineering, our OPO design can additionally achieve large instantaneous bandwidth accompanied by significant pulse compression [7], enabling the generation of femtosecond frequency combs in nanophotonics in hard-to-access wavelength ranges.

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