Two-Octave Frequency Comb from a Nanophotonic Parametric Oscillator

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Abstract: We demonstrate a synchronously pumped OPO in nanophotonic lithium nio-bate with a 4-ns-roundtrip cavity generating two octaves of continuous and coherent spec-trum from the visible to mid-IR with only 126 fJ of pump energy.

Nanophotonic sources of broadband frequency combs are highly desirable for on-chip spectroscopy, communication, and pulse synthesis [1–3]. Previous demonstrations of chip-based broadband combs include dispersive-wave generation in Si_3N_4 waveguides pumped with >100 pJs of on-chip energy [4], as well as two-octave-spanning $\chi^{(2)}$ supercontinuum generation in periodically-poled lithium niobate (PPLN) waveguides pumped with >10 pJs of energy at 2 μm [5]. Here we demonstrate a synchronously (sync-) pumped degenerate optical parametric oscillator (OPO) generating a two-octave frequency comb at $\sim$ 100 fJ of pump, representing the lowest-energy realization of such a broadband frequency comb. As shown in Fig. 1a, our device is pumped at 1 μm with a repetition rate (f_{rep}) of 250 MHz, thus requiring a cavity length of 0.53 m for the cavity-round-trip time of 4 ns to match the repetition rate of the pump. In a sync-pumped degenerate OPO, the phase-sensitive gain in the PPLN region locks the phase and frequency of the down-converted signal frequency comb to the pump [6].

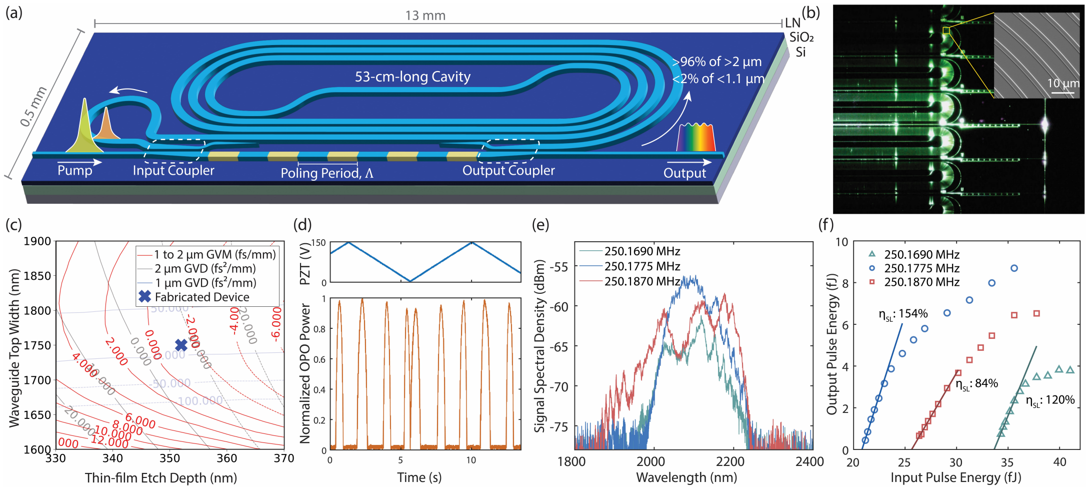

Fig. 1. (a) Illustration of the sync-pumped nanophotonic OPO on X-cut, 700 nm-thick lithium niobate. It is pumped by a 75-fs-long, 250-MHz, Yb mode-locked laser (MLL) centered at 1045 nm. The poled region is 10.8-mm long. The input and output adiabatic couplers are identical and are designed to couple over 96% of wavelengths > 2 μm and less than 2% of wavelengths < 1.1 μm. (b) Microscope image of several devices with an inset showing a SEM image of the spiral region. (c) Dispersion engineering of the OPO waveguide, with the measured parameters of our device indicated by the cross. (d) Oscillation peaks of our OPO as the pump repetition rate is modulated by a piezoelectric transducer (PZT) in the pump laser cavity at 600 Hz. (e) Signal spectrum at 35.6 fJ of pump energy for three different repetition rates, and (f) the corresponding OPO signal growth as a function of pump energy. The linear regimes are fitted and labeled by their slope efficiencies, η_{SL}.

The fabricated chip contains several OPOs with different poling periods as shown in Fig. 1b, one of which is used for the results presented here. The simulated dispersion profile of our device is shown in Fig. 1c. From our geometric characterization of the waveguide, we confirmed that our device has near-zero group velocity mismatch

(GVM) between the pump (1045 nm) and signal (2090 nm), and near-zero group velocity dispersion (GVD) at both of these wavelengths. As demonstrated in [7], operating in this near-zero dispersion regime allows broadband and intense parametric gain. In Fig. 1d, we show the oscillation peaks of the OPO as the pump repetition rate is modulated. These peaks are characteristic of doubly-resonant operation [6]. We can dither and lock the pump repetition rate to the center of each of these peaks, and the near-threshold signal spectra of three such peaks at distinct repetition rates are shown in Fig. 1e. The pump repetition rate of 250.1775 MHz has the lowest threshold of the three peaks, as shown in Fig. 2f. Our waveguide has a total throughput loss of 45 dB, and in our previous works of coupling into similar waveguides with reflective objectives [7], we have measured the output coupling to consistently be below 10 dB. In this paper we assume an output coupling loss of 10 dB, thus yielding an OPO threshold power of $\sim$20.8 fJ.

In Fig. 2a we show the output spectra of our OPO at 126 fJ of pump energy. We have continuous spectra from 600 nm to 2710 nm, where the long wavelength side is limited by the absorption of the SiO_2 substrate. To measure the coherence of our comb we employ the scheme in Fig. 2b, where we beat the output of our on-chip OPO against that of a bulk free-space OPO pumped by the same laser. A degenerate OPO above threshold can have two possible carrier-envelope offset (CEO) frequencies which differ by $f_{\mathrm{rep}}/2$ depending on the oscillation peak [6]. When the free-space and on-chip OPOs operate with different CEOs and their signal pulse trains are spatially and temporally overlapped as shown in Fig. 2c, beatnotes at $f_{\mathrm{rep}}/2$ are observed. When both OPOs operate with the same CEO frequencies, no $f_{\mathrm{rep}}/2$ beatnote is observed, and as the delay arm in Fig. 2b is scanned, the detector sees fringes as in the blue curve in Fig. 2d, as the two OPOs constructively/destructively interfere. These interference measurements confirm that the down-converted comb is coherent with respect to the pump comb.

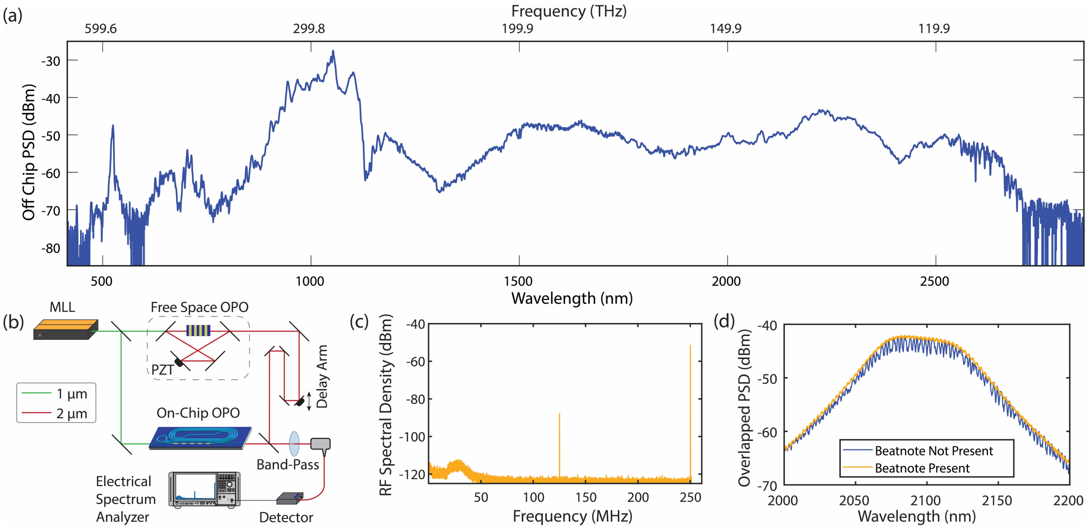

Fig. 2. (a) OPO output spectra at 126 fJ of pump energy with a repetition rate of 250.1775 MHz. (b) Setup for measuring the coherence of the comb. (c) The RF beatnote when the free-space OPO and on-chip OPO have different CEO frequencies. Here, the delay arm was fixed and both OPOs were locked to the pump. (d) The interference between the two OPO outputs on an optical spectrum analyzer when the delay arm in (b) was scanned and the OPOs have the same CEO frequencies. The band-pass was 48 nm wide centered at 2090 nm.

In summary, we have experimentally demonstrated a synchronously pumped nanophotonic OPO operating in the near zero-GVM, zero-GVD, ultra-high-gain regime resulting in an ultra-broadband output with only $\sim$100 fJ of energy. The two-octave frequency comb at the output enables unprecedented opportunities for numerous applications including wavelength division multiplexing [2], dual-comb spectroscopy [8], and frequency synthesis [1]. The recent advances in generating femtosecond combs in lithium niobate nanophotonics [9] combined with the ultra-low threshold of our OPO can lead to fully integrated ultra-broadband frequency comb sources.

References

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