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10 GHz Frequency Comb Generation in Lithium Niobate Waveguides with Chirped Poling

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Abstract: We demonstrate efficient 10 GHz frequency comb generation using chirped periodically poled nanophotonic lithium niobate waveguides. Spectral coverage across the UV and visible is achieved with pulse energies less than 50 pJ.

Robust frequency combs with repetition rates of 10 - 20 GHz in the wavelength range (350 - 650 nm) are critical for achieving the high precision (< 10 cm/s) required for detecting exo-Earths through extreme-precision radial velocity (EPRV) measurements. However, blue frequency comb generation is challenging with gigahertz-rate frequency comb sources that have 100× lower pulse energy as compared to the more conventional mode-locked lasers with hundreds of MHz repetition rates. Additionally, the commonly used silica-based fibers for short wavelength generation are prone to damage from ultraviolet (UV) light within a few hours [1]. In order to address these challenges, we introduce nanophotonic waveguides with a wide transparency window based on poled thin film lithium niobate. These waveguides leverage the $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities of lithium niobate to achieve multi-octave frequency combs at low pulse energies in the tens of picojoules (pJ) range [2, 3]. Here, we demonstrate 10 GHz frequency combs spanning 350 - 1750 nm in dispersion-engineered periodically poled lithium-niobate (PPLN) waveguides pumped at 1550 nm with pulse energies as low as 40 pJ.

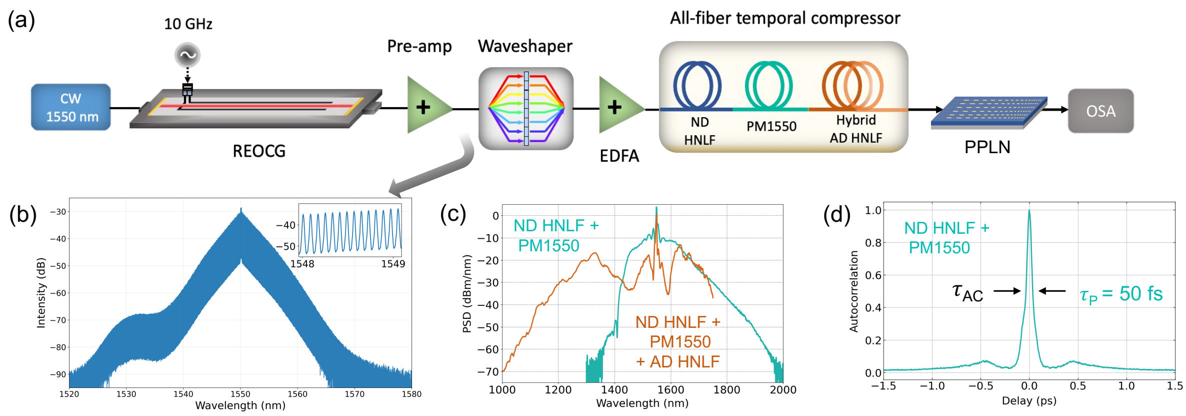

Fig. 1. (a) Experimental setup; (b) 10 GHz EOM comb spectrum and zoomed inset; (c) Optical spectra after temporal compression fiber (teal trace), and propagation through hybrid AD HNLF (orange trace); (d) Measured autocorrelation trace after the temporal compression fiber. The pulse duration (τ_P) is calculated from the autocorrelation width (τ_{AC}) considering a deconvolution factor of 1.41.

Fig. 1(a) shows the experimental setup. A 10 GHz frequency comb generated from a 1550 nm resonant electro-optic frequency comb generator (REOCG) is amplified to 3W using an erbium-doped fiber amplifier (EDFA), and propagated through an all-PM fiber temporal compressor consisting of 1.2 m of normal dispersion highly-nonlinear fiber (ND HNLF) and 22 cm of PM1550 to generate 50 fs pulses (Fig. 1(c) and 1(d)) with a peak power of 5.2 kW. The lengths of the fibers for this spectral broadening and temporal compression stage have been carefully designed by solving the nonlinear Schrodinger equation (NLSE) in PyNLO [4]. The details of the temporal compression can be found in [5]. These 50 fs pulses are then propagated through hybrid anomalous

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dispersion (AD) HNLF consisting of 12 cm of D = 2 ps/nm/km and 6.5 cm of D = 4.9 ps/nm/km fiber for spectral broadening to initiate more sum frequency generation processes in the waveguide. After spectral broadening, the average power is measured to be $\sim$ 2.1 W.

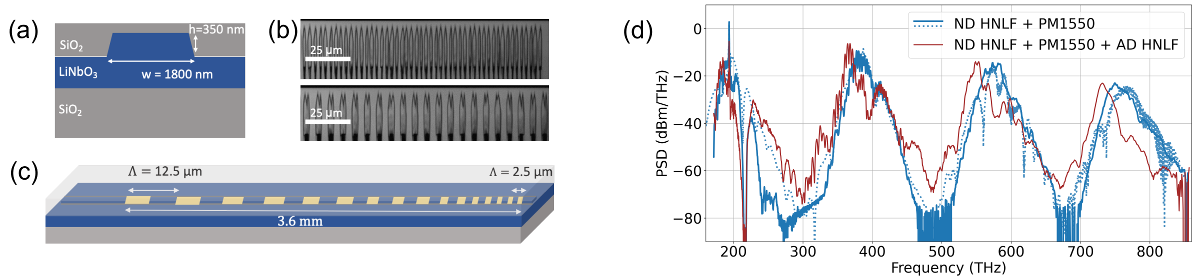

Fig. 2. (a) Schematic of the LN waveguide cross-section; (b) Microscopic images of the waveguide regions with poling periods of $\sim$ 2.7 μm and 7 μm; (c) Illustration of the chirped PPLN waveguide with 0.5 mm unpoled region followed by 3.6 mm segment with poling period varying from 12.5 μm to 2.5 μm; (d) Power spectral density plots of the broadband 10 GHz frequency comb generated in chirped PPLN waveguide. The dotted blue trace shows the simulated spectrum.

These compressed pulses are focused on a chirped PPLN waveguide etched from a 710 nm thick LN slab with an etch depth of 350 nm and width of 1800 nm (Fig. 2(a)). The initial 0.5 mm of the waveguide is unpoled and the rest 3.6 mm has a linearly varying poling period from 12.5 μm to 2.5 μm. The total insertion loss of the waveguide is measured to be $\sim$ 11 dB. The input pulse is further spectrally broadened in the initial unpoled region of the waveguide before it enters the chirped poling region. The range of poling periods has been chosen with the quasi-phase matching condition to generate the second, third, and fourth harmonics efficiently. Then the period and its step are finely tuned to induce a cascaded $\chi^{(2)}$ effect at higher pulse energies ($>$ 50 pJ) to spectrally broaden the harmonics and obtain a uniform multi-octave spectrum. The details of the waveguide design and demonstration of continuous spectral coverage across 350 nm - 2.4 μm using a 100 MHz Er:fiber comb can be found in [6]. Due to the large insertion loss, only pulse energy of $\sim$ 40 pJ and 14 pJ of the 10 GHz pulse after the temporal compression fiber and AD HNLF were coupled into the waveguide. The resulting broadband spectra obtained in both cases are shown in Fig. 2(d) with $\sim$ 1 μW per comb mode in the fourth harmonic. The spectral evolution in chirped PPLN is modeled with a single-mode unidirectional propagation equation including both second-order and third-order nonlinearities in PyNLO [4,7]. The simulation result (dotted blue trace in Fig. 2(d)) for a 50 fs, 10 GHz pulse with 40 pJ energy shows good agreement with the experiment.

In summary, we have demonstrated the generation of frequency combs with UV-near infrared spectral coverage at 10 GHz repetition rates using pulse energies less than 50 pJ. In order to obtain continuous spectral coverage at 10 - 20 GHz repetition rates across the UV and visible, it is necessary to reduce the required average power to more feasible levels. In future work, we plan to achieve this by improving the poling design to increase the nonlinear efficiency into the UV-visible region [6], and by reducing the waveguide coupling losses to 1-2 dB using inverse tapers [8]. These optimizations would enable the detection of the carrier-envelope offset frequency directly and open up new possibilities for achieving the unprecedented levels of precision required in visible EPRV instruments to detect Earth-Sun analogs.

References

1. Skuja, L. *et al.*, "Laser-induced color centers in silica," Proc. SPIE 4347 (2001).
2. Honardoost, A. *et al.*, "Rejuvenating a Versatile Photonic Material: Thin-Film Lithium Niobate," Laser Photonics Reviews 14, 2000088 (2020).
3. Jankowski, M. *et al.*, "Ultrabroadband nonlinear optics in nanophotonic periodically poled lithium niobate waveguides," Optica 7, 40–46 (2020).
4. PyNLO: Python Nonlinear Optics. `https://github.com/UCBoulder/PyNLO`.
5. Sekhar, P. *et al.*, "20 GHz fiber-integrated femtosecond pulse and supercontinuum generation with a resonant electro-optic frequency comb," arXiv:2303.11523 (2023).
6. Wu, T. *et al.*, "Visible to Ultraviolet Frequency Comb Generation in Lithium Niobate Nanophotonic Waveguides," arXiv:2305.08006 (2023).
7. Kolesik, M. *et al.*, "Nonlinear optical pulse propagation simulation: From Maxwell's to unidirectional equations," Phys. Rev. E 70, 036604 (2004).
8. Hu, C. *et al.*, "High-efficient coupler for thin-film lithium niobate waveguide devices," Opt Express 29, 5397–5406 (2021).