Ultraviolet to Near-infrared Frequency Comb Generation in Lithium Niobate Nanophotonic Waveguides with Chirped Poling

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Abstract: We demonstrate thin-film lithium niobate waveguides with chirped poling periods for efficient supercontinuum via $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities. With picojoule energies, we generate gap free frequency combs spanning 330 to 2400 nm.

While lithium niobate (LN) has a long history as one of the most widely-used nonlinear optical materials, recent developments in nano-scale fabrication open new opportunities to engineer waveguides for integrated supercontinuum and frequency comb generation at picojoule (pJ) pulse energies [1–5]. In this paper, we introduce nonlinear waveguide designs in thin-film lithium niobate that leverage the combined $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities to enable frequency combs spanning the full transparency window of LN. Significantly, our designs employ longitudinal chirped poling in nanophotonic LN waveguides pumped at 1550 nm to demonstrate gap-free and coherent frequency comb spectra from 330 nm to beyond 2.4 μm.

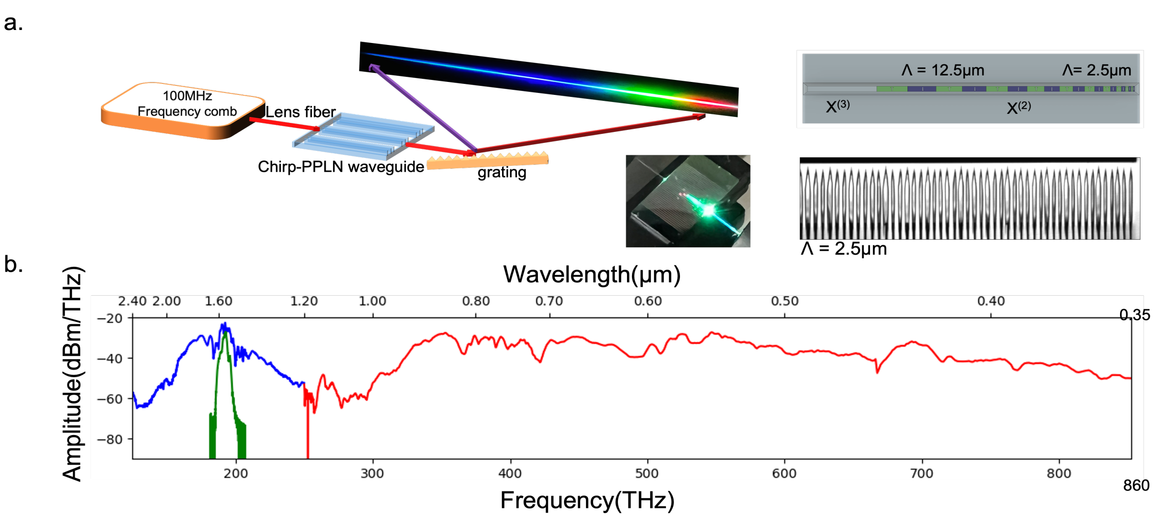

Fig. 1. (a) Experimental setup for UV to infrared comb generation. A photo of the dispersed visible region of the comb is shown along with a schematic of the waveguide and an image of the poled region. (b) The input spectrum of the waveguide at 1.55 µm is shown by the green line. Broadband frequency comb spectra generated in the LN waveguides with chirped poling is shown in blue and red.

Figure 1a shows a schematic of the experiment. We employ waveguides etched from a 700 nm film of LN on oxide to be 350 nm high and 1700 nm wide, with a mode area of about 1 µm^2. The waveguides are 6.6 mm long and the initial 3 mm section is designed without poling for $\chi^{(3)}$ self-phase modulation (SPM) to spectrally broaden the input pulse. In the remaining 3.6 mm, we implement a linearly chirped poling period, ranging from Λ =12.5

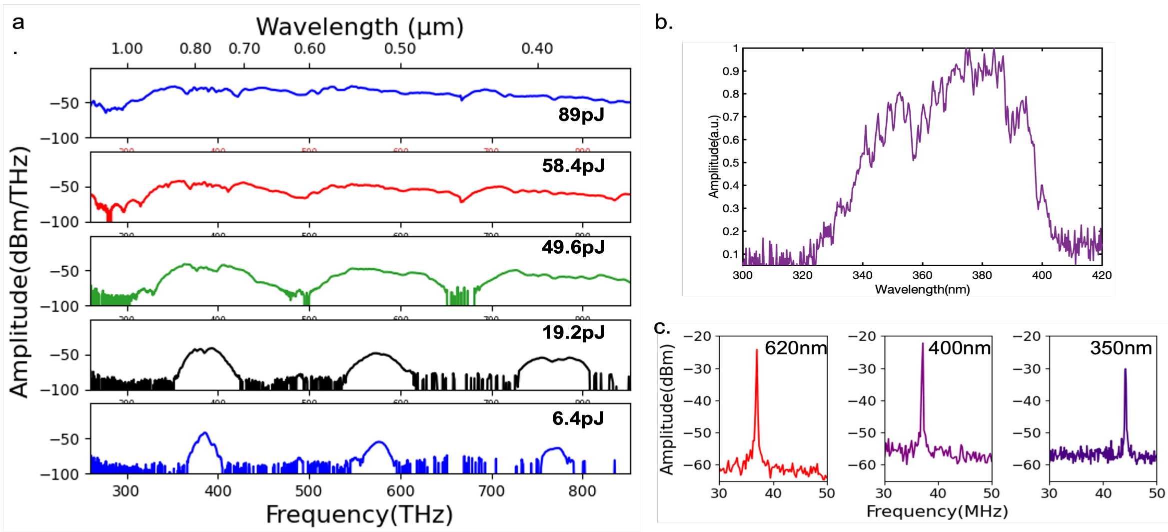

Fig. 2. (a) Power spectral density of broadband LN supercontinuum with different input driving pulse energies. (b) UV spectrum measured after a UV bandpass filter to eliminate any light at longer wavelengths. (c) f_{ceo} beatnote observed directly at wavelengths across the visible and UV. The SNR of f_{ceo} is greater than 35dB with 10 kHz RBW.

μm to Λ =2.5 μm, that expands the near-infrared light to the visible and ultraviolet.

We pump the waveguides with sub-100fs pulses from an amplified 100-MHz frequency comb that outputs 100 mW of average power. The full spectrum from the waveguide when pumped with 95 mW (9 mW coupled into the waveguide) is shown in Fig. 1b, and the progression of the spectral expansion is shown in Fig. 2a. The input pulse optical bandwidth is broadened from 30 nm to 400 nm in the first 3 mm of the waveguide. It is estimated by the simulation results with different propagation length of waveguide. In the next 3.6 mm, the $\chi^{(2)}$ nonlinearity generates second harmonic (2f), third harmonic (3f) and forth harmonic (4f) with a driving pulse energy of only a few pJ. Furthermore, our simulations show that the cascaded $\chi^{(2)}$ induces an effective $\chi^{(3)}$ to broaden the harmonic spectra as the pulse energy increases to 10's of pJ [6]. In particular, for pulse energies higher than 50pJ, the 2f, 3f and 4f start to overlap, and with $\sim$ 90 pJ (9 mW on chip) the spectrum is nearly uniform. Figure 2b shows the spectrum measured through a UV bandpass filter (max wavelength 400 nm), indicating that the waveguides generated down to about 330 nm. The average power of blue light (470 nm - 330 nm) is 0.65 mW in the waveguide with 89 pJ pump power. This implies an approximate comb mode power of 0.29 nW per comb mode.

In this case of spectral overlap between the harmonics, the f_{ceo} beatnote can be detected on a photodiode that follows a grating spectral filter. Figure 2c shows the f_{ceo} beatnote detected across the visible and ultraviolet spectrum with signal-to-noise ratio (SNR) near the shot noise limit. Depending on the available light, the SNR is greater than 35 dB (400nm). The heterodyne beatnote in the ultraviolet (350 nm) provides the direct evidence of the coherence of the ultra-broad frequency comb generated with this unique chirped poling in thin-film LN waveguides. Our numerical propagation models predict all major features of the observed supercontinuum leading to spectrally-tailored frequency combs for optical clocks, astronomical spectrograph calibration, and spectroscopic sensing.

References

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