

Soliton Pulse Compression in Lithium Niobate Nanophotonics

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Abstract: We show that soliton pulse compression in lithium niobate nanophotonics can enable formation of few-cycle pulses. We experimentally confirm such nonlinear dynamics and measure chirped 44-fs output pulses consistent with numerical simulations.

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Ultrashort pulses are crucial for myriad applications, ranging from fundamental studies of electronic motion in atoms and molecules [1,2] to extreme nonlinear optics [3,4]. Synthesis of ultrashort pulses is generally done in two stages. Firstly, one must produce an ultrabroadband coherent spectrum, typically via supercontinuum generation. Secondly, dispersive optics are used to compress the pulse in time [5]. This results in a large system complexity for generation of few- and single-cycle pulses. One path towards circumventing these requirements is to use soliton pulse compression, where the nonlinear phase accumulated due to self-phase modulation (SPM) in the spectral broadening process is directly compensated by the dispersion of the mediating material [6–8]. As the SPM arising from the third-order nonlinearity results in normal dispersion, a material with anomalous dispersion is required. Additionally, careful design of the dispersion, pump energy, and propagation length is necessary to avoid soliton fission and other nonlinear effects which can distort the temporal shape of the pulse, limiting the achievable pulse widths in such systems without an additional compression stage [9].

In addition to cubic nonlinear media, supercontinuum generation has been achieved through spectral broadening from phase-mismatched nonlinear interactions in quadratic nonlinear media [10]. Soliton pulse compression in such phase-mismatched second-harmonic generation (SHG) has also been observed down to the few-cycle regime and has the additional advantage of being achievable for both anomalous and normal dispersion [11,12]. However, bulk nonlinear optical crystals have inflexible dispersion profiles and thus face fundamental limitations in their potential for achieving arbitrary pulse compression due to the effects of group-velocity mismatch (GVM) between the fundamental and second harmonic as well as higher-order dispersion [13]. More recently, progress in lithium niobate (LN) nanophotonics has facilitated generation of multi-octave coherent supercontinuum leveraging phase-mismatched SHG [14] as well as optical parametric oscillation (OPO) [15] while requiring modest pump pulse energies in the pJ and fJ range, respectively. Here, we show that the dispersion engineering capabilities afforded by the nanophotonic platform can enable soliton pulse compression in such phase-mismatched nonlinear interactions, offering a flexible pathway towards on-chip generation of few- and even single-cycle pulses.

The on-chip pulse compression scheme is illustrated in Fig. 1a. Pulses at the fundamental are coupled into the slightly quasi-phase-mismatched waveguide on the nanophotonic chip, and phase-mismatched interaction with the generated second harmonic results in large pulse compression over the course of propagation. In our experiment, 35-fs pulses at the fundamental wavelength, 2090 nm, are generated in a free space optical parametric oscillator (OPO) pumped by a Yb-fiber mode locked laser (MLL) and coupled into the chip via a reflective objective. Experimental characterization of the input and output pulses is done using a home-built frequency-resolve optical gating (FROG) setup based on non-collinear SHG and sum-frequency generation (SFG) in a 50- μ m BBO crystal [16]. Our chip consists of x-cut, 700-nm thin-film LN on a SiO₂ buffer layer. The designed waveguide has a width of 2500 nm and an etch depth of 250 nm, resulting in a group velocity dispersion of 62.7 fs²/mm at 2090 nm and 138 fs²/mm at 1045 nm as well as a GVM of 35.5 fs/mm. A 5-mm periodically poled region facilitates the phase-mismatched second harmonic generation in the waveguide [17].

Figures 1b-i show the simulated soliton pulse compression in the fabricated device. Our simulations utilize a single-envelope equation to model the pulse evolution inside the waveguide [18]. Here, we consider a pump pulse energy of 7 pJ and a poling period of 5.598 μ m, 40 nm larger than the calculated phase-matched period of 5.558 μ m, parameters which are readily realizable experimentally. As can be seen in Figs. 1b and 1f, the spectrum around both the fundamental at 143 THz and the second harmonic at 286 THz is seen to rapidly broaden, resulting in multi-octave supercontinuum generation. In the time domain (Figs. 1c-e), we see that the balance of dispersion and nonlinear phase as well as walk-off and nonlinear acceleration facilitates localization and compression for both the fundamental and second harmonic over the course of their propagation. The resulting pulses (Figs. g-i)

have widths as small as 7 fs for the fundamental and second harmonic as well as 3.5 fs for their combined output, suggesting soliton pulse compression to the single-cycle regime is possible.

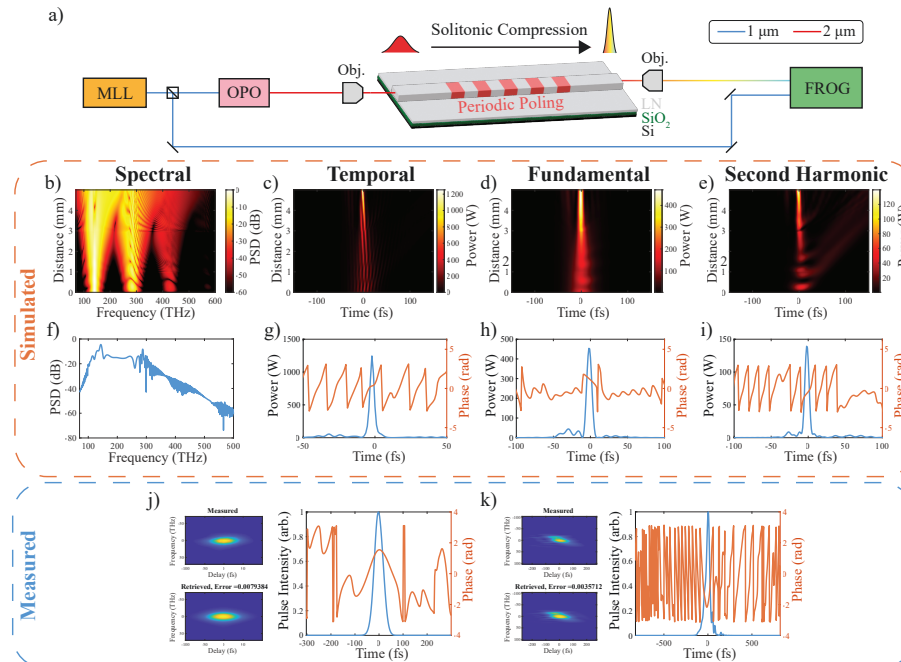


Fig. 1. Soliton pulse compression in nanophotonic LN. (a) Experimental setup. (b) Simulations of the expected spectral broadening and (c) temporal compression as the pulse propagates through the waveguide. Following several back-and-forth conversions, the (d) fundamental at 143 THz and (e) second harmonic at 286 THz are both seen to compress and co-propagate. (f) The output spectrum and (g-i) temporal profiles for the simulated propagation demonstrate broadband supercontinuum generation and temporal widths as short 7 fs for the fundamental and second harmonic components and 3.5 fs for their combined output, indicating the potential for compression to the single-cycle regime. (j) Experimental FROG trace of the OPO output. (k) Example second-harmonic from chip, measured in an X-FROG geometry gated by the MLL output. MLL, mode-locked laser; OPO, optical parametric oscillator; FROG, frequency-resolved optical gating; Obj., reflective objective.

Our experimental results are shown in Figs. 1j-k. Figure 1j shows our SHG FROG characterization of the 35-fs pulses at 2090 nm output by the free-space OPO. With a Fourier grid size of 512, the algorithm converges with a retrieved error of 0.008, giving a chirped 44-fs pulse. This result is in good agreement with our expected pulse shape, as the 35-fs OPO output traverses several optical elements including a neutral-density and long-pass filter before entering the FROG setup. Besides pumping the OPO, a portion of the MLL output is also used to gate the weaker off-chip signal in an X-FROG geometry. Figure 1k illustrates a typical measured pulse out of the nanophotonic chip; here, specifically, the second harmonic output is measured. While the transform-limited pulse width is seen to narrow, consistent with the expected spectral broadening from supercontinuum generation, compression to the few- or even single-cycle regime is yet to be observed, with the measured pulses exhibiting similar pulse widths to the input. Better compression is expected through improved dispersion management in the measurement setup and better thermal stabilization of the chip for precise phase matching and tuning.

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