Ultrasensitive Nonlinear Measurements of Femtosecond Optical Pulses at 1.5 mm by Aperiodically Poled Lithium Niobate Waveguides

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Abstract: Ultraweak, ~300-fs pulses at 1.5 μ m are measured by second-harmonic generation intensity autocorrelation and frequency-resolved optical gating using aperiodically poled LiNbO₃ waveguides. Our reference-free scheme can retrieve complex fields with 120-aJ coupled pulse energy, corresponding to a sensitivity of 2× 10⁻⁶ mW², ~5 orders of magnitude better than the previous record.

Measuring the time duration or amplitude-phase profiles of femtosecond optical pulses is essential in a wide variety of applications, such as high bit-rate telecommunication transmissions, coherent control, and nonlinear-optical material characterizations. The demanding requirement of time resolution is normally achieved by nonlinear optical gating schemes for lack of fast electronic response in the terahertz regime. However, the typical nonlinear conversion efficiency of short pulse in traditional bulk crystals is fairly low due to the short interaction length limited by diffraction and phase-matching (PM) bandwidth (BW) [1]. We proposed to use aperiodically poled LiNbO₃ (A-PPLN) waveguide as second-harmonic (SH) generator in femtosecond pulse measurement, for the waveguide structure can tightly confine the optical beam for a long interaction length without diffraction and the longitudinally varying poling period can phase match a broad optical BW. As a result, we succeeded in measuring intensity autocorrelation (IA) function and amplitude-phase profiles by second-harmonic generation (SHG) frequency-resolved optical gating (FROG) technique for 1.5- μ m, 50-MHz, ~300-fs pulse train at energies of 52 aJ and 120 aJ per pulse, respectively [1-3]. The corresponding quadratic sensitivities (defined as the peak power – average power product for the minimum detectable input) are 3.2×10^{-6} mW², improving on the previous records of self-referenced schemes by three and five orders of magnitude, respectively [4-5]. We also measured pulses with specified spectral phases to verify the accuracy of our A-PPLN waveguide approach.





As shown in Fig. 1, we used a passively modelocked fiber laser to generate a 50-MHz, ~300-fs pulse train at ~1.55- μ m wavelength. A collinear-type Michelson interferometer (MI) split and recombined each input pulse to form a pulse pair with delay t, which was coupled into an A-PPLN waveguide for SHG. The waveguide has a 5.95-cm-long, linearly chirped poling region, resulting in a ~6.3-THz-wide PM power spectrum with rippled structure [1-3]. We measured the average SH power or power spectrum for each t (could be fast dithered by a piezoelectric transducer in the MI to suppress the interferometric fringes), and numerically processed the data to obtain the IA function or complex field of the input pulse.



Fig. 2 illustrates two IA functions measured by our A-PPLN waveguide. The energies per pulse coupled into the waveguide (referring to the total of those from both MI arms) are 12 fJ (solid) and 52 aJ (dashed), respectively. In the presence of a 23-dB input power difference (46-dB difference for SH powers), these two curves still agree extremely well. The 52-aJ measurement corresponds to a record sensitivity of 3.2×10^{-7} mW² [1]. We also measured chirped Gaussian pulses (delivered by the source and a Fourier-transform pulse shaper) with 9-nm spectral intensity full-width at half maximum (FWHM) and different cubic spectral phases: $\mathbf{g} \times (\lambda'/9.2 \text{ nm})^3$, where λ' is the wavelength detuning from 1.54 μ m and g represents the cubic phase strength. As shown in Fig. 3, the deconvolved pulse durations obtained by IA measurement (crosses, deconvolution factor is 1.41) are close to the simulated values (circles, assuming infinite PM BW), proving the integrity of the A-PPLN waveguide approach. Fig. 4 illustrates the retrieved complex fields without (a-b) and with (c-f) cubic phase modulation. Measurement sensitivity for nearly chirp-free pulse (a-b) is $\sim 2 \times 10^{-6}$ mW². The retrieved spectral phases in (c,e) show clear cubic dependence on the wavelength, and the fitted cubic coefficients are in good agreement with those imposed by the pulse shaper: 0.93×10^{-2} ps³ (1.19×10⁻² ps³), and 1.90×10^{-2} ps³ (2.13×10⁻² ps³), respectively. The mainlobe broadening and asymmetric oscillatory tails of the temporal intensity profiles in (d,f) are signatures of the cubic spectral phase modulation. These measurements directly prove that our A-PPLN waveguide scheme can correctly reconstruct the complex field of the unknown pulse with extremely low power requirement.



Fig. 4. Complex fields without (a-b) and with (c-f) cubic phase modulation retrieved by SHG FROG using A-PPLN waveguide.

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