Ultra-sensitive Second-Harmonic Generation Frequency-Resolved Optical Gating at 1.55 μm by Aperiodically Poled Lithium Niobate Waveguides

S.-D. Yang, and A.M. Weiner
School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907, USA
shangda@purdue.edu, amw@ecn.purdue.edu

K.R. Parameswaran
JDS Uniphase, Santa Rosa, CA 95407
krishp@stanfordalumni.org

M.M. Fejer
E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305, USA
fejer@stanford.edu

Abstract: We report ultrashort pulse measurement by second-harmonic generation frequency-resolved optical gating with 124-aJ coupled pulse energy using aperiodically poled lithium niobate waveguides. The sensitivity (2.7×10^{-6} mW^2) exceeds previous record by 5 orders of magnitude.

OCIS codes: (320.7100) Ultrafast measurements; (320.7110) Ultrafast nonlinear optics; (130.3730) Lithium niobate.

The comprehensive applications of ultrafast optics largely rely on the ability of fully characterizing the ultrashort (10^{-12}~10^{-15} sec) signal pulses, especially when nearly bandwidth-limited or precisely shaped pulses are involved, such as those in the high bit-rate telecommunication transmissions [1], optical code-division multiple-access systems [2], and nonlinear-optical material characterizations. To meet the requirements of limited power budget in optical communication systems, and weak (sub-femtojoule) signal pulses in material characterizations, several sensitive schemes have been proposed to retrieve complete intensity and phase information of ultrashort pulses. For example, linear spectral interferometry has been demonstrated to measure 42 zeptojoule (42×10^{-21} J) laser pulses [3], and optical-parametric-amplification (OPA) cross-correlation frequency-resolved optical gating (X-FROG) permits measurement of white-light continuum pulses at 50 attojoule (50×10^{-18} J) [4]. However, these techniques require strong, synchronized, and well-characterized reference pulses, which are not available at the intermediate and receiving ends in an optical communication link. Within the self-referenced regime, four-wave mixing (FWM) in 22-km dispersion-shifted fiber (DSF) has been employed to carry out FROG measurement with a sensitivity (defined as the peak power – average power product for the minimum detectable input) of 0.2 mW^2 [5], surpassing the conventional second-harmonic generation (SHG) FROG using bulk crystals by more than three orders of magnitude [6]. Nevertheless, this scheme is subject to the small dynamic range (~10 dB), and the sensitivity is still insufficient for optical communication monitoring. Alternatively, we have reported that SHG with chirped aperiodically poled lithium niobate (A-PPLN) waveguides is much more sensitive than other existing techniques, which enables intensity autocorrelation of 220-fs, 50-MHz, and 52-aJ optical pulses with a record sensitivity of 3.2×10^{-7} mW^2 [7]. In this work, we apply the A-PPLN waveguide to the more sophisticated SHG FROG technique for complete pulse retrieval. The accomplished sensitivity is 2.7×10^{-6} mW^2, substantially improving the record [5] by 5 orders of magnitude.

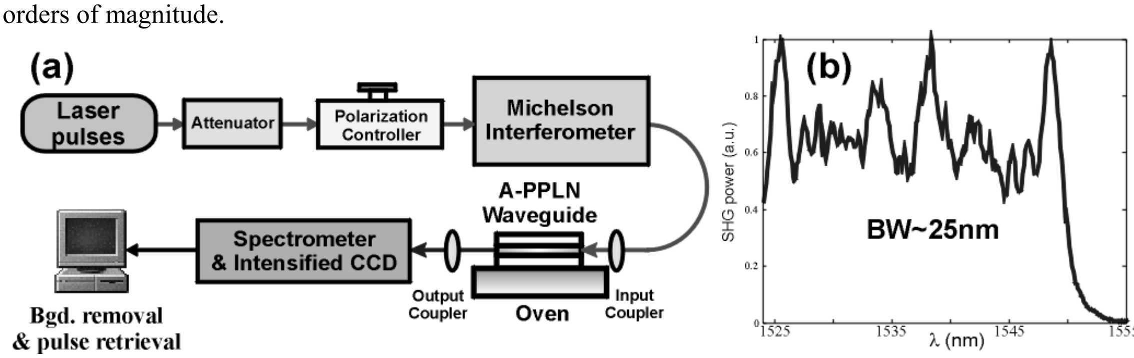

Fig. 1. (a) Experimental setup. (b) Room temperature phase-matching tuning curve of the A-PPLN waveguide.

Fig. 1a shows a schematic diagram of our experiments. We use a passively mode-locked fiber laser plus a band-pass filter to produce laser pulses with ~280-fs duration, 50-MHz repetition rate, 1538-nm central wavelength, and 11-nm spectral width. The pulses are relayed through a dispersion-compensated fiber link into a collinear-type free-space Michelson interferometer (MI). Instead of using a small delay increment and performing low-pass filtering in software [8], we dither one of the interferometer arms at 180 Hz by a few optical wavelengths to average out the interferometric fringes. The recombined pulse pair is then coupled into an A-PPLN waveguide with 5.95-cm-long poling region. Fig. 1b shows the phase-matching (PM) tuning curve (normalized SHG power as a function of input wavelength) at 21^{o}C temperature. Evidently, the chirped poling period greatly broadens the PM bandwidth (BW) from 0.17 nm (chirp-free PPLN) to ~25 nm. The irregular features resulting from the imperfect apodization of the poling grating can distort the generated SHG spectrum and the FROG trace. Fortunately, the procedure of frequency marginal correction from FROG [9] can eliminate the distortion (given there is no dark response in the band of interest) by making use of the input power spectrum measured by an optical spectrum analyzer. Since the waveguide made by annealed proton exchange process can only guide the TM mode, we use a polarization controller before the MI input to maximize the nonlinear yield. In principle, a fast polarization scrambler incorporated prior to the A-PPLN can remove the polarization dependence at the cost of small sensitivity degradation. The output SHG spectrum is recorded by the spectrometer and intensified CCD camera with 800-ms exposure for each delay step to get the spectrogram. For a scanning range of 2.6 ps with 20-fs delay increment, the data acquisition takes about 135 seconds. The residual signal background is removed by subtracting a spectrum measured at large delay. Commercial software (Femtosoft FROG) is employed to completely retrieve the intensity and phase of the pulses. The retrieval process normally converges within 1 minute.

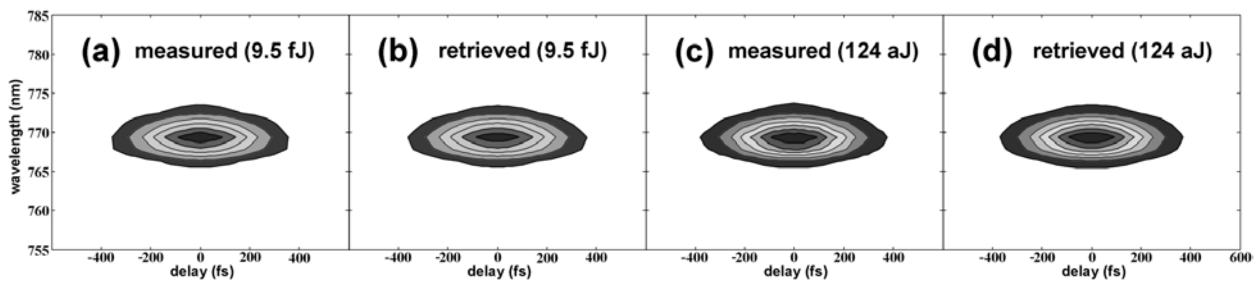

Fig. 2. FROG traces of (a) measured (b) retrieved at 9.5 fJ; and (c) measured (d) retrieved at 124 aJ.

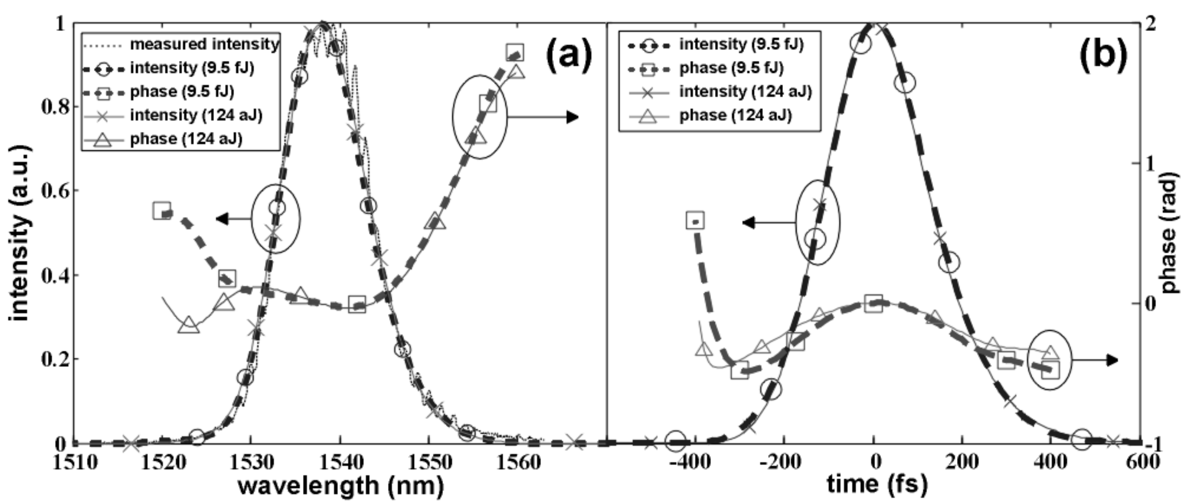

Fig. 3. Retrieved pulse depicted in: (a) frequency domain, and (b) time domain for both 9.5-fJ and 124-aJ coupled pulse energies. Dotted curve in (a) represents the independently measured power spectrum. The retrieved temporal FWHM is ~280 fs, and the residual dispersion is about 4.2 fs/nm.

Fig. 2 illustrates measured and retrieved FROG traces (grid size 64×64) using the nearly BW-limited pulses with coupled pulse energies of 9.5 fJ (a-b) and 124 aJ (c-d), respectively. The latter is equivalent to 0.44-mW peak power, and 6.2-nW average power, corresponding to an unprecedented FROG sensitivity of 2.7×10^{-6} mW^2. Even with a 19-dB input power difference (38-dB difference for SHG powers), the spectrograms agree well with one another. The FROG errors are 0.22 % and 0.32 %, respectively. Fig. 3 shows the retrieved pulses in (a) frequency, and (b) time domains for both input power levels. An independently measured input power spectrum is plotted as a dotted curve in Fig. 3a for comparison. The retrieved spectral intensities closely approach this curve, except for the oscillatory fine structures, which require more detailed sampling to be resolved. The spectral phases are fitted with cubic polynomials, and the resulting quadratic phase coefficients are 2.60×10^{-3} ps^2, and 2.71×10^{-3} ps^2. The retrieved temporal profiles also overlap well with each other, where the intensity FWHM values are essentially identical: 279 fs and 278 fs, respectively.

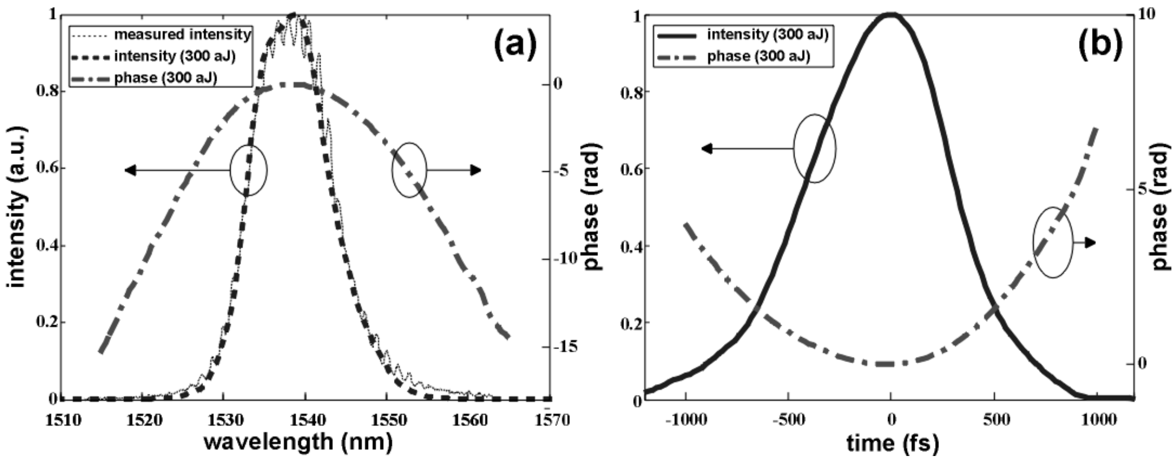

Fig. 4. Retrieved pulse depicted in: (a) frequency domain; and (b) time domain at 300-aJ coupled pulse energy. The retrieved temporal FWHM is 796 fs, and the dispersion is estimated as -70 fs/nm.

To further verify the measurement capability, we inserted a section of 5-meter-long single mode fiber (SMF) into the link to increase the quadratic spectral phase, and performed the FROG measurement. The retrieved intensity and phase profiles with coupled energy of 300-aJ per pulse are shown in Fig. 4. In addition to significant broadening of pulse duration (796 fs), both spectral and temporal phases are predominately parabolic, where the anomalous dispersion of SMF uniquely determines the sign of retrieved spectral phases (otherwise, ambiguity exists). Fitting the spectral phase profile gives a quadratic phase coefficient of -4.36×10^{-2} ps^2, corresponding to a dispersion of –70 fs/nm. Considering the small chirp on the input pulses (Fig. 3), the 5-m-long SMF is estimated to introduce an accumulated dispersion of –74 fs/nm, acceptably close to the value predicted by the SMF specification (-83 fs/nm) around 1538-nm band.

In conclusion, we have realized ultra-sensitive SHG FROG pulse measurement using a chirped A-PPLN waveguide. The sensitivity is 2.7×10^{-6} mW^2, considerably exceeding the previous record by 5 orders of magnitude. This promising technique enables characterization of ultraweak optical pulses without the need for a synchronized reference pulse, and can act as an efficient monitoring component to provide detailed pulse information for precise field control.

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