Polarization-insensitive ultralow-power second-harmonic generation frequency-resolved optical gating

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We demonstrate polarization-insensitive ultralow-power second-harmonic generation frequency-resolved optical gating (FROG) measurements with a fiber-pigtailed, aperiodically poled lithium niobate waveguide. By scrambling the polarization much faster than the measurement integration time, we eliminate the impairment that frequency-independent random polarization fluctuations induce in FROG measurements. As a result we are able to retrieve intensity and phase profiles of few hundred femtosecond optical pulses with 50 MHz repetition rates at 5.2 nW coupled average power without control of the input polarization. © 2007 Optical Society of America

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Frequency-resolved optical gating (FROG) is a powerful technique for measurement of ultrashort pulses.[1] In previous work[2,3] we demonstrated ultralow-power second-harmonic generation (SHG) FROG measurements of ~360 fs optical pulses in the telecommunication band. The measurement sensitivity (the minimum peak-power–average-power product) was 2.0×10^{-6} mW^2, which allows high-quality pulse measurements at nanowatts to tens of nanowatts of average power (for a laser at 50 MHz repetition rate). Our results are obtained by using a fiber-pigtailed aperiodically poled lithium niobate (A-PPLN) waveguide device.[2–4] The reverse-proton-exchanged waveguides fabricated on a z-cut periodically poled lithium niobate (PPLN) substrate used in our experiments guide light polarized only along the crystal's z axis (i.e., TM). While this in general requires proper polarization state preparation of the coupled waves, access to the largest nonlinear coefficient in lithium niobate (d_{33}) allows efficient nonlinear mixing; the next largest nonlinear coefficient that involves nonlinear mixing of TE and TM modes (d_{31}) is approximately six times smaller. Nonlinear conversion efficiencies in excess of 100% (W cm^2) have been achieved for SHG of fundamental harmonic (FH) inputs in the telecommunication C-band, while FH propagation losses below 0.1 dB/cm are common for reverse-proton-exchanged waveguides. Since waveguides with 6-cm-long quasi-phase-matched gratings are easily fabricated, overall conversion efficiencies as large as 3.6%/mW are achievable. Furthermore, by applying appropriately designed aperiodic poling patterns, one can broaden the phase-matching bandwidth more than 100-fold to ~25 nm, which is needed for measurement of subpicosecond pulses. Since the waveguide supports only a single polarization (vertical), random fluctuations of the input state of polarization (SOP) arising from small birefringences of the optical fibers in the measurement loop will seriously degrade FROG measurements. In previous measurements eliminated polarization fluctuations by carefully taping all the fibers to the optical table. However, SOP fluctuations are very difficult to avoid in optical fiber systems of any significant distance, even for distances of only a few tens of meters, when fibers are used to connect between different optical tables or adjacent rooms.

In this Letter, we overcome this serious polarization sensitivity by scrambling[5] the input SOP at a rate much faster than the measurement integration time. We first derive expressions for the polarization-scrambling-induced waveguide coupling and SHG conversion loss and confirm our analysis by experiments. We then report polarization-insensitive characterization of an ~360 fs optical pulse at a 50 MHz repetition rate with 5.2 nW of coupled FH power. As a demonstration of the utility of our technique, we perform dispersion compensation experiments using a programmable pulse shaper[6] controlled by polarization-insensitive FROG measurements.

Figure 1 shows the scheme of the polarization-insensitive FROG setup. We use a passively mode-locked fiber ring laser together with a bandpass filter (spectral FWHM ~9 nm) to produce ~360 fs pulses with a 50 MHz repetition rate and 1550 nm central wavelength. The SOP of the pulses is then scrambled

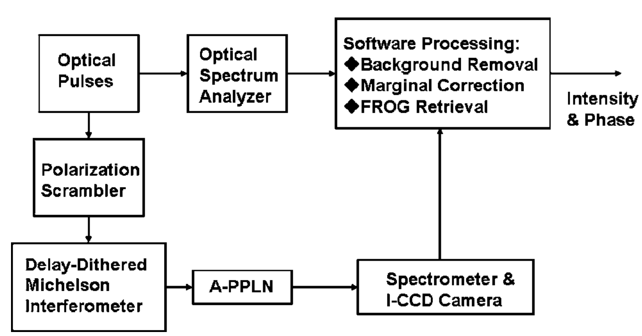

Fig. 1. Scheme of polarization-insensitive FROG.

uniformly on the Poincaré sphere with a wideband fiber-pigtailed polarization scrambler (General Photonics Corporation, PCD-104), with a more than 100 nm operating range centered at 1550 nm, and a 700 KHz scrambling frequency. The scrambled pulses are then launched into a Michelson interferometer to produce pulse pairs with various delays. One of the interferometer arms is dithered over a few optical cycles at a rate of 160 Hz to wash out the interference fringes. The pulse pairs are coupled into the A-PPLN waveguide with a fiber-pigtailed collimator to produce SHG signals. The dispersion of the fiber link is compensated with dispersion compensating fiber. The SHG spectrum for each delay is recorded by a spectrometer and an intensified CCD camera with an 800 ms exposure time, which yields the raw FROG data. To get a background-free FROG trace, a spectrum taken at a large delay is subtracted from the raw data.[2] The spectrum of the FH pulses is recorded separately by an optical spectrum analyzer (OSA) for frequency marginal correction.[1] We use commercial software (Femtosoft FROG) to completely retrieve the intensity and phase information of the pulses.

Polarization scrambling will result in the desired polarization-insensitive FROG measurement functionality when three key assumptions are satisfied: (1) the polarization scrambler is slow compared with the pulse duration; (2) the polarization scrambler is sufficiently fast compared with the detector integration time for which measurements yield ensemble average results corresponding to an input SOP distributed uniformly on the Poincaré sphere; (3) the input SOP is frequency independent. This implies that effects related to polarization-mode dispersion are small; specifically, the differential group delay arising from upstream optical elements must be much less than the pulse duration.[7]

For our first measurements, we compare the FH power coupled through the A-PPLN waveguide and the generated SHG power with the polarization scrambler on and with the scrambler off and the input SOP aligned for maximum coupling. We use a powermeter to measure the FH power and a photomultiplier tube together with a lock-in amplifier to measure the SHG power. The measurement integration time is tens of milliseconds in both cases, which is much greater than the scrambling period. The scrambled SOP can be treated as a uniform distribution on the Poincaré sphere, where the SOP is described by a 3×1 vector $[s_1\ s_2\ s_3]^T$. Since the waveguide supports only vertical polarization, the ratio of the coupled FH power with the scrambler on and off (but with optimized input SOP) can be written as $(1/4\pi)\oiint_S[(1-s_1)/2]\mathrm{d}S$, which results in 1/2. The ratio of the SHG power can be calculated as $(1/4\pi)\oiint_S[(1-s_1)/2]^2\mathrm{d}S$, which is 1/3. The measurement yields coefficients of 0.505 ± 0.004 and 0.341 ± 0.005, respectively, which are very close to the calculation.

In a first FROG experiment, we characterize nearly bandwidth limited, ~360 fs pulses at a 50 MHz repetition rate and 1550 nm center wavelength. To enhance the polarization fluctuation effects, we randomly adjust the SOP from the source by hand with a polarization controller. We first perform the FROG measurement with the scrambler off, using a maximum of 19 nW FH power coupled through the guide. Figure 2 shows the experimental results. The grid size is 128×128 throughout the Letter. The measured FROG trace exhibits random power fluctuation with time, and the retrieved FROG trace is totally different from the measured one. Furthermore, the retrieved spectrum is far from the spectrum measured by the OSA. All of these indicate a bad measurement.

Then we repeat this experiment with the scrambler on, while continuing to randomly adjust the input SOP. The measurement is performed at an average of 5.2 nW FH power coupled through the guide, which corresponds to the same SHG power as the measurement in Ref. 3. Figure 3 shows the measure-

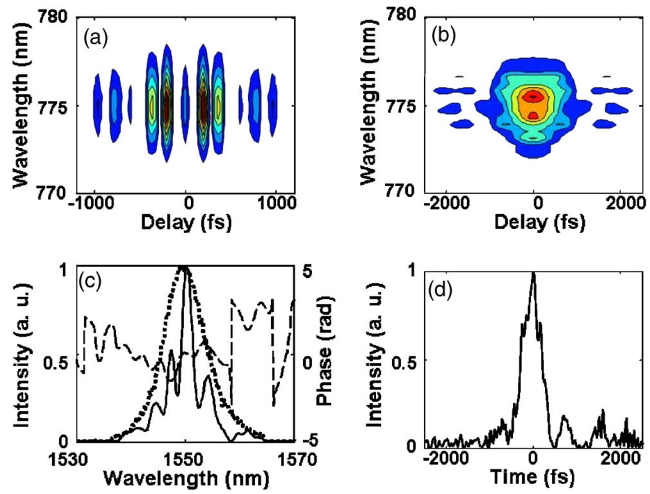

Fig. 2. (Color online) FROG data with time-varying polarization fluctuations intentionally introduced and scrambler off. (a) Measured FROG trace. (b) Retrieved FROG trace. (c) Retrieved spectral intensity and phase profiles. Dashed curve, spectral phase profile; dotted curve, spectrum recorded by OSA. (d) Retrieved temporary intensity profile.

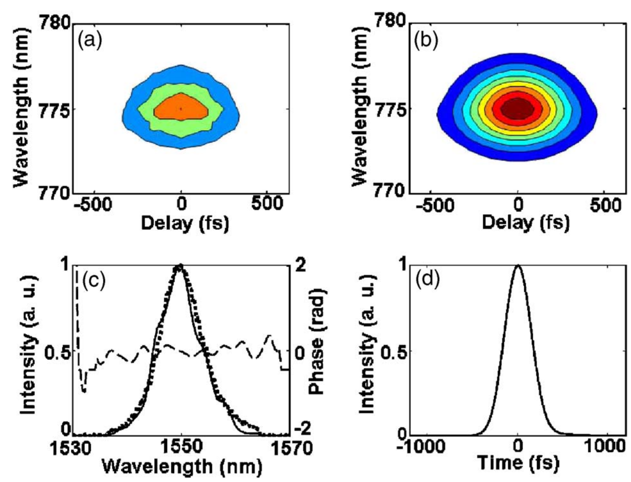

Fig. 3. (Color online) FROG data with time-varying polarization fluctuations intentionally introduced and scrambler on. (a) Measured FROG trace. (b) Retrieved FROG trace. (c) Retrieved spectral intensity and phase profiles. Dashed curve, spectral phase profile; dotted curve, spectrum recorded by OSA. (d) Retrieved temporary intensity profile.

ment results. The measured pulse FWHM is 352 fs, very close to that of the input pulses. The retrieved spectrum is very close to that measured by the OSA, and the FROG error is 0.0047. All of these points indicate a high-quality waveform retrieval. We have also performed additional measurements that show that our polarization-insensitive FROG scheme does not introduce additional FROG error compared with FROG measurements with a fixed, optimized input SOP, provided that the average SHG output is held constant.

As a further demonstration, we perform dispersion compensation experiments using a programmable pulse shaper controlled by our polarization-insensitive FROG setup. Figure 4 shows the experimental concept. The mode-locked pulse source located on one optical table is connected to the pulse shaper and FROG setup located on a second table. The spectral FWHM of the source is ~5 nm. There is a total of ~27 m of single-mode fiber [dispersion coefficient −17 ps/(km nm)] and 2 m of dispersion-compensating fiber [127.5 ps/(km nm)] in the link. None of the fibers are secured to any surface. The pulse shaper incorporates a two-layer, 128-element liquid-crystal modulator array to apply spectral phase. The two layers of the liquid-crystal modulator are programmed in common mode, resulting in a polarization-insensitive phase-only modulation functionality.[8] Figure 5 shows the measurement results with the pulse shaper inactive. The complex spectrum [Fig. 5(c)] clearly shows a quadratic phase profile. Then we use the pulse shaper to apply the inverse of the measured spectral phase and repeat

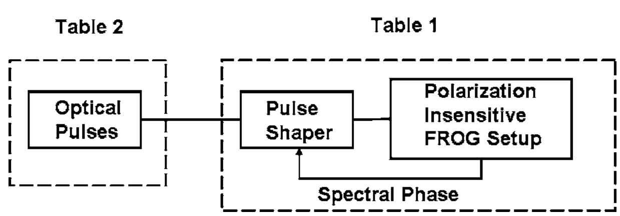

Fig. 4. Setup for dispersion compensation experiment.

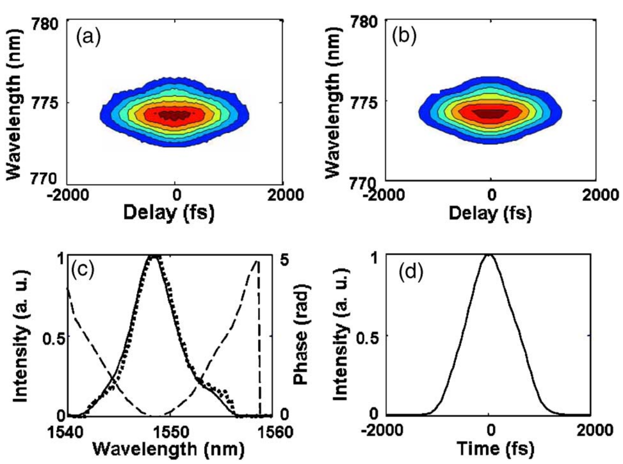

Fig. 5. (Color online) Data with pulse shaper inactive. (a) Measured FROG trace. (b) Retrieved FROG trace. (c) Retrieved spectral intensity and phase profiles. Dashed curve, spectral phase profile; dotted curve, spectrum recorded by OSA. (d) Retrieved temporary intensity profile.

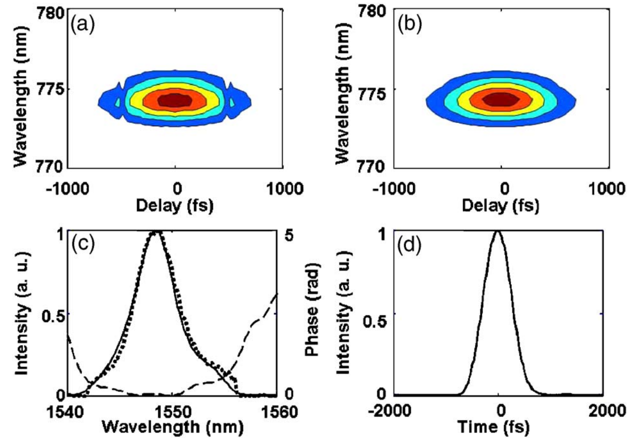

Fig. 6. (Color online) Data with pulse shaper programmed for phase compensation. (a) Measured FROG trace. (b) Retrieved FROG trace. (c) Retrieved spectral intensity and phase profiles. Dashed curve, spectral phase profile; dotted curve, spectrum recorded by OSA. (d) Retrieved temporary intensity profile.

the FROG measurement. Figure 6 shows the measurement. The pulses are compressed from 1.13 ps to 622 fs, which is near the bandwidth limit. The results further confirm the accuracy of our polarization-insensitive FROG technique. Note that we were unable to achieve satisfactory results without using the polarization scrambler.

In conclusion, we have demonstrated polarization-insensitive SHG FROG measurements operating at ultralow power by scrambling the input SOP much faster than the measurement integration time. We report full characterization of ~350 fs pulses at a 50 MHz repetition rate with 5.2 nW of average FH power coupled into the A-PPLN waveguide.

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References

1. R. Trebino, *Frequency-Resolved Optical Gating: The Measurement of Ultrashort Laser Pulses* (Kluwer Academic, 2000).
2. S. Yang, A. M. Weiner, K. R. Parameswaran, and M. M. Fejer, Opt. Lett. **30**, 2164 (2005).
3. H. Miao, A. M. Weiner, S. Yang, C. Langrock, R. V. Roussev, and M. M. Fejer, in *15th International Conference on Ultrafast Phenomena* (Springer, 2006), paper WC2.
4. J. Huang, X. P. Xie, C. Langrock, R. V. Roussev, D. S. Hum, and M. M. Fejer, Opt. Lett. **5**, 604 (2006).
5. L.-s. Yan, Q. Yu, and A. E. Willner, Opt. Commun. **249**, 43 (2005).
6. A. M. Weiner, Rev. Sci. Instrum. **71**, 1929 (2000).
7. H. Kogelnik, R. M. Jopson, and L. E. Nelson, in *Optical Fiber Telecommunications IVB-Systems and Impairments*, I. P. Kaminow and T. Li, ed. (Academic, 2002), p. 723.
8. R. D. Nelson, D. E. Leaird, and A. M. Weiner, Opt. Express **11**, 1763 (2003).