Polarization-Insensitive Ultralow-Power Second-Harmonic Generation Frequency-Resolved Optical Gating

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Abstract: We demonstrate polarization-insensitive ultralow-power second-harmonic generation (SHG) frequency-resolved optical gating (FROG) measurements with a fiber-pigtailed, aperiodically-poled lithium niobate (A-PPLN) waveguide by scrambling the polarization much faster than the measurement integration time.

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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-femtosecond optical pulses in the telecommunication band. The measurement sensitivity (the minimum peak-power-average-power product) was $2.0 \times 10^{-6}$ mW, approximately 5 orders of magnitude better than previous published results. This allows high quality pulse measurements at nW to tens of nW 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 [4]. The large nonlinear coefficient of PPLN together with the enhanced intensity made possible by the waveguide geometry are responsible for unprecedented sensitivity, while an appropriately designed aperiodic (chirped) poling pattern broadens the phase-matching bandwidth from <0.2 nm to ~25 nm, which is broad enough for accurate measurement of pulses a few hundred femtoseconds in duration. Since the waveguide only supports a single polarization, 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, we carefully controlled the input SOP and attempted to eliminate 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 length, 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 paper, we overcome this serious polarization sensitivity by scrambling [5] the input SOP at a rate much faster than the measurement integration time. We report polarization-insensitive characterization of ~360-femtosecond optical pulses at 50-MHz repetition rate with 5.2-nW coupled average fundamental power.

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-femtosecond pulses with 50-MHz repetition rate and 1550-nm central wavelength. The SOP of the pulses is then scrambled uniformly on the Poincare sphere with a wideband fiber-pigtailed polarization scrambler (General Photonics Corporation, PCD-104), with more than 100-nm operating range centered at 1550 nm, and 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 (DCF). The SHG spectrum for each delay is recorded by a spectrometer and an intensified CCD camera with 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 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.

Fig. 1. Scheme of polarization insensitive FROG.

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For our first measurements, we compared the fundamental power coupled through the A-PPLN waveguide and the generated SHG power with the polarization scrambler turned on and off (in the off state, the input SOP was aligned for maximum coupling). We used a power meter to measure the fundamental power and a PMT together with a lock-in amplifier to measure the SHG power. The measurement integration time was 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 Poincare sphere, where SOP is described by a 3x1 vector \([s_1, s_2, s_3]^T\). Since the waveguide only supports the vertical polarization, the ratio of the coupled fundamental power with the scrambler on and off (but with optimized input SOP) can be written as 

\[
\frac{1}{4\pi} \int \int \int \frac{1-s_3}{2} dS,
\]

which results in 1/2. The ratio of the SHG power can be calculated with 

\[
\frac{1}{4\pi} \int \int \int \left(\frac{1-s_3}{2}\right)^2 dS,
\]

which is 1/3. The measurement yielded coefficients of 0.505±0.004 and 0.341±0.005, respectively, which is very close to the calculation.

We first perform FROG measurement with the scrambler off using a maximum of 19-nW fundamental power coupled through the waveguide. To enhance the polarization fluctuation effects, we randomly adjust the SOP from the source by hand with a polarization controller (PC). Fig. 2 shows the measurement results. The grid size is 128x128 throughout the paper. The measured FROG trace exhibits random power fluctuation with time, and the retrieved FROG trace differs significantly from the measured one. Furthermore, the retrieved spectrum does not agree with the spectrum recorded by the OSA. All of these indicate problems with the measurement.

In conclusion, we have demonstrated polarization-insensitive SHG FROG measurements operating at ultralow power by scrambling the input state of polarization (SOP) much faster than the measurement integration time.

References