Ultrasensitive second-harmonic generation frequency-resolved optical gating using an fiber-pigtailed aperiodically poled lithium niobate waveguide at 1.55μm

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Abstract: We retrieve intensity and phase profiles of few hundred femtosecond optical pulses at 6 nW average power via second-harmonic generation FROG using a new fiber-pigtailed aperiodically poled lithium niobate waveguide with apodized design.

OCIS codes: (320.7100) Ultrafast measurements; (130.3730) Lithium niobate

Characterization of ultrashort pulses is important throughout the field of ultrafast optics. In many cases, including ultrafast optical communications and some types of spectroscopy, operation at low power levels is important. In previous work [1, 2], we demonstrated ultrasensitive autocorrelation and second-harmonic generation (SHG) frequency-resolved optical gating (FROG) measurements of subpicosecond optical pulses in the telecommunication band. Measurement sensitivities (the minimum peak-power-average-power product) of our autocorrelation and FROG measurements were 3.2×10^{-7} mW^2 and 2.7×10^{-6} mW^2, respectively, corresponding to factors of approximately 500 and 75,000 improved sensitivity compared to previous published results. This allows high quality pulse measurements at nW to tens of nW averages power for a laser at 50 MHz repetition rate. These results were obtained by using an aperiodically poled lithium niobate (A-PPLN) waveguide device. 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. In this paper we extend our ultralow power FROG experiments in several important ways. First, we use a new A-PPLN sample, which incorporates fiber-pigtailing (compared to free-space optical coupling) for improved stability. Second, the new device also introduces improved apodization of the quasi-phase matching (QPM) grating [3] that yields a more uniform phase matching curve. Third, we incorporate a programmable pulse shaper [4] into our setup so that we can test the FROG measurements for interesting input waveforms. We are able to demonstrate an improved measurement sensitivity of 2.0×10^{-6} mW^2 and successfully retrieve electric field profiles for pulses intentionally distorted by cubic spectral phase.

Our experimental setup is shown in Fig. 1. A passively mode-locked fiber ring laser and a bandpass filter are used to produce ~360 fs optical pulses with 50 MHz repetition rate and 1550 nm central wavelength. The pulses are first relayed through single-mode fiber into a reflective optical pulse shaper, where various amounts of cubic phase are imposed on to the spectrum. The shaped pulse train is then sent into a collinear free-space Michelson interferometer (MI) to produce pulse pairs with variable delays. The pulse pairs are coupled into the pigtailed A-PPLN waveguide via a pigtailed collimator to generate SHG signal. The dispersion of the fiber link is compensated with dispersion compensation fiber (DCF). The SHG power spectrum for each delay is recorded by a spectrometer and an intensified CCD camera with 800 ms exposure, which yields the raw FROG data. Commercial software (Femtosoft FROG) is employed to completely retrieve the intensity and phase profiles of the pulses.

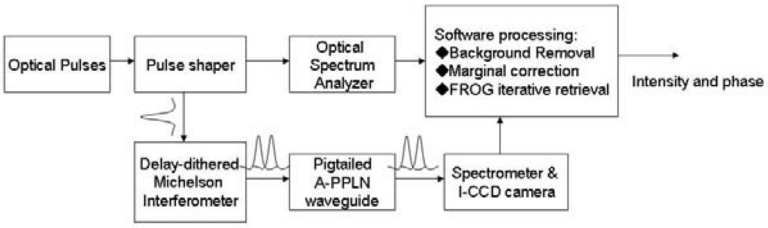

Fig. 1. Schematic diagram of the experimental setup: I-CCD, intensified charge-coupled device

We performed FROG measurements of nearly Fourier transform limited pulses (with coupled average power of 6 nW) and pulses with cubic spectral phase coefficients of 0.0119 and 0.0213 ps^3 (with coupled average power of 10 nW), where the cubic phase coefficient β is defined as: $\phi = \beta(\omega - \omega_0)^3$. Fig. 2 illustrates measured and retrieved FROG traces (grid size 128×128). The FROG errors for all the measurements are below 0.004. The symmetrisation of the FROG traces as a function of delay for the pulses with cubic spectral phase is expected according to the time-reversal ambiguity of SHG-FROG.

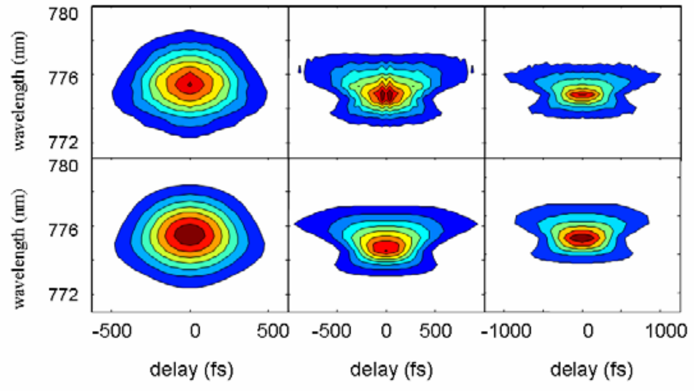

Fig. 2. Measured (Top) and retrieved (Bottom) FROG traces. From left to right, the cubic phase coefficients applied by the pulse shaper are 0 (input pulse), 0.0119, and 0.0213 ps^3, respectively.

Fig. 3 shows the retrieved pulses in the frequency and time domains. Independently measured input power spectra are plotted as dotted curves in Fig. 3 for comparison. The retrieved spectral intensity profiles closely approach these curves. The retrieved spectral phase curves display cubic nature and the estimated coefficients are -0.00969 (0.0119) and 0.0201 (0.0213) ps^3, respectively (for the two cases in which nonzero cubic phase is applied). The numbers in the parentheses are the applied values. The temporal intensity profiles clearly show oscillating tails caused by the cubic spectral phase modulation. The magnitudes of estimated coefficients agree well with values programmed in to the pulse shaper. Since time reversal ambiguity exists in SHG FROG, the sign of the spectral phase can not be determined uniquely, and the retrieved electrical fields are sometimes the time reversal of the actual fields (graphs in the middle position in Fig. 3 give a good example). But using the programmable pulse shaper, we can resolve this ambiguity, e.g., by programming an additional (known) phase and performing an additional measurement.

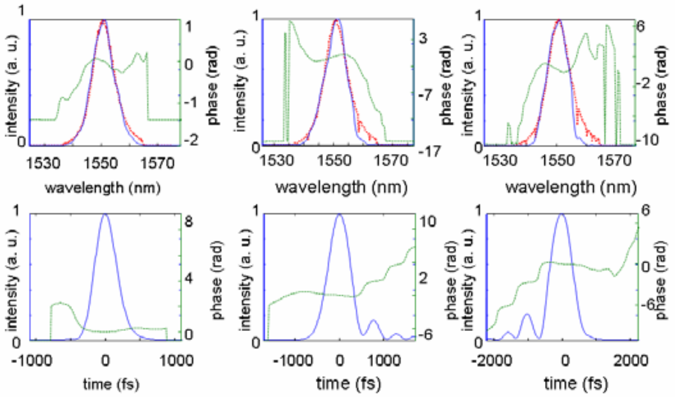

Fig. 3 Retrieved pulses depicted in the frequency domain (top) and the time domain (bottom). From left to right, the applied cubic phase coefficients are 0, 0.0119, 0.0213 ps^3, respectively. The retrieved spectral FWHM values are ~9nm. The retrieved temporal FWHM values are 366, 572 and 744 fs, respectively. Dash line: retrieved phase curves; solid line: retrieved intensity profiles; dot line: spectrum from optical spectrum analyzer.

The main advantages of the pigtailed A-PPLN waveguide sample are the flatness of the phase matching spectrum as well as the stable coupling efficiency, allowing reliable long term measurements resulting in improved spectral resolution. This also contributes to the faster convergence rate of the FROG traces acquired with the pigtailed waveguide. The phase matching curves of the pigtailed and free space samples are illustrated in Fig. 4. The amplitude apodization of the QPM grating was implemented to reduce the fluctuations of the conversion efficiency within the conversion bandwidth for both devices. Deleted-reversal method [4] and duty cycle engineering method were employed in the apodization of the pigtailed and free space waveguides, respectively. The improved apodization yields a more uniform phase matching curve for the pigtailed device.

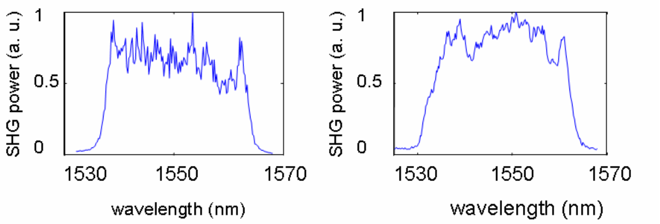

Fig. 4. SHG phase matching spectra of (left) previous free space A-PPLN waveguide device and (right) new fiber-pigtailed device

In conclusion, we performed ultrasensitive SHG FROG measurements with a fiber-pigtailed A-PPLN waveguide. We demonstrated an improved measurement sensitivity of 2.0×10^{-6} mW^2 and successfully retrieved pulse shapes for pulses intentionally distorted by cubic spectral phase.

References

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