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High-Sensitivity Polarization Gating Frequency-Resolved Optical Gating (PG-FROG) Using Highly-Nonlinear Dispersion-Shifted Fiber

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Abstract

We experimentally demonstrate a frequency-resolved optical gating (FROG) system in pulse characterization at 1.55 μm by using cross-phase modulation (XPM) in highly nonlinear dispersion-shifted fiber (HNL-DSF), with over 6-times sensitivity improvement.

1. Introduction

Complete characterization of ultrashort pulse includes the waveform and phase information. A well-established method to implement this is called frequency-resolved optical gating (FROG) [1], which gates the pulse with a variably delayed replica of the pulse itself in a medium with instantaneous response time, and then spectrally resolves the gated pulse [2]. The interaction usually involves several nonlinear processes, including second-harmonic generation (SHG), third-harmonic generation (THG), polarization gating (PG), and self-diffraction (SD) [1,2]. Among them, SHG-FROG is a sensitive method, and therefore, is most commonly used [2,3]. Besides, fiber-based third-order nonlinear process in PG-FROG also has the potential in providing high sensitivity, without any direction-of-time ambiguity [4]. One of the applications attracting many interests is the pulse characterization in the wavelength band of 1.55 μm, especially for the ultrafast optical communication. Previous work based on dispersion-shifted fiber (DSF) has achieved peak power down to 12 W [4]. In this paper, we have achieved 6-times higher sensitivity using a highly-nonlinear dispersion-shifted fiber (HNL-DSF) in PG-FROG system, with peak power as low as 2 W.

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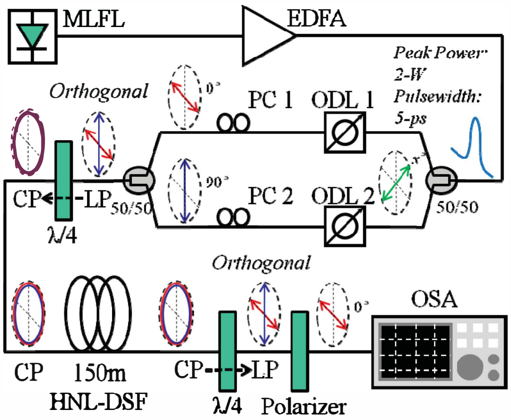

Fig. 1. Experimental setup of HNL-DSF based FROG system.

2. Principle and Experimental Setup

Cross-phase modulation (XPM) is based on the $\gamma^{(3)}$ nonlinearity in an optical fiber. Increasing the nonlinear coefficient of a fiber waveguide, the fiber FROG system gives higher sensitivity [5]. The interaction in the HNL-DSF could be expressed by the autocorrelation equation (1), where γ is the nonlinearity coefficient, L is the fiber length, and τ refers to the variable time delay. Two terms show the effect of self-phase modulation (SPM) and XPM separately, and the XPM term provided a phase-gating mechanism. The corresponding FROG trace is shown in equation (2), and $I_{sig}(\omega,\tau)$ is the intensity getting from the spectroscopy with delay of τ [2]. Many standard retrieval algorithms could recover the waveform and phase information from this FROG trace.

$$E_{sig}^{Fiber}(t,\tau)=E(t)\exp\left\{i\gamma L\left[\frac{2}{3}\left|E(t)\right|^2+\frac{4}{3}\left|E(t-\tau)\right|^2\right]\right\} \quad (1)$$

$$I_{sig}(\omega,\tau)=\left|\int_{-\infty}^{+\infty}E(t)\exp\left\{i\gamma L\left[\frac{2}{3}\left|E(t)\right|^2+\frac{4}{3}\left|E(t-\tau)\right|^2\right]\right\}\exp(i\omega t)dt\right|^2 \quad (2)$$

The experimental setup of the HNL-DSF based FROG system is shown in Fig. 1. A mode-lock fiber laser (MLFL) generated 5-ps short pulses with center wavelength at 1554.8 nm. There were two optical delay lines (ODL), one was to match the two arms to be the same, while the other one with fine precision helped to match the delay between the two arms. Polarization controller (PC) 1 and PC2 changed the input state of polarization (SOP) to linear-polarized (LP) fields with 0° and 90°, respectively, which could be monitored by a polarimeter. At the input and the output of the HNL-DSF, there were two l⁄4 wave plates. The first one converted LP field into counter-rotating circular-polarized (CP) field; the other turned it back, by keeping it at the 45° of fast or slow axis. The CP field helped maximize the XPM effect inside the HNL-DSF. Finally, one of the orthogonal LP field was selected by the polarizer, and detected by the optical spectrum analyzer (OSA).

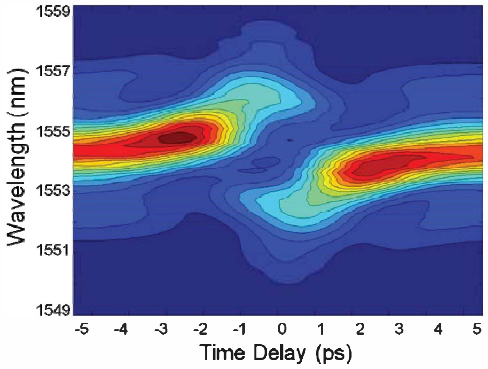

Fig. 2. Measured PG-FROG trace based on HNL-DSF.

3. Results and Discussion

Figure 2 and 3 show the typical fiber FROG trace and the retrieved pulse characteristics, respectively. The FROG trace is spectrally resolved by a generalized-projections (GP) algorithm from the nonlinear signal $I_{sig}(\omega,\tau)$. It can be observed from Fig. 3(a) that the peak power is 0.45 W, with pulse width of 4 ps. This shows the full features of $E(t)$. After Fourier transform, the full characterization of the frequency-domain could be recovered (Fig. 3(b)). The GP retrieval algorithm can help to convert back to the input pulse $E(t)$. It uses the multi-dimensional minimization to find the optimal approximation of the measured pulse, and in our case, 100 iterations could get the convergent result.

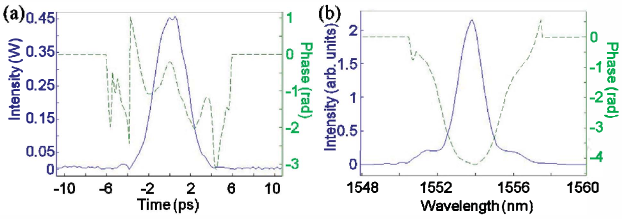

Fig. 3. Retrieved result: (a) Retrieved pulse shape and phase information in time-domain; (b) Retrieved spectra and phase information in frequency-domain.

The power requirement and the operating wavelength range are essential factors of the fiber FROG. In our configuration: L = 150 m, $\beta_2 = -4.5\times10^{-5}$ ps^2/m, β_3 = 5.8×10^{-5} ps^3/m, and $\gamma = 3\times10^{-2}$ $W^{-1}m^{-1}$. First, the dispersion should be negligible, provided that $L \leq 0.05\times\min\{L_D, L'_D\}$ = 1000 m ($L_D = 1/(|\beta_2|\Delta\omega^2)$, $L'_D = 1/(|\beta_3|\Delta\omega^3)$ are the GVD and TOD dispersion lengths). On the other hand, the fiber length should be long enough that the phase shift due to XPM is measurable, provided that $L \geq 0.1\times L_{NL}$ = 6.67 m (peak power of 0.5 W, considering the 6-dB low pre-stage loss, the input peak power should be 2 W) [5]. With certain fiber length (150 m), the dispersion slope would limit operating range (15 nm); for the second condition, the minimum interaction peak power should be 22 mW, with corresponding input peak power of 100 mW.

4. Conclusion

In summary, we have experimentally demonstrated a PG-FROG based on HNL-DSF, with high-sensitivity and low peak power requirement (2W), which is potentially as low as 100mW. The 15-nm operating range could be further enhanced by using dispersion flattened fiber with lower dispersion slopes [2].

5. References

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