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Microarticle

Single-shot reconstruction of a subpicosecond pulse from a fiber laser system via processing strongly self-phase modulated spectra

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ABSTRACT

The single-shot reconstruction of an ultrashort pulse from a fiber laser system by the method based on recording and numerical processing of two self-phase modulated spectra after a nonlinear fiber is demonstrated experimentally. The 0.7-ps asymmetrical signal with an energy of ~1 μJ retrieved by this method without time direction ambiguity is in good agreement with independent measurements by second harmonic generation frequency-resolved optical gating (SHG FROG) technique.

Introduction

Measurements of the shape and phase of optical signals are of great importance for numerous applications [1]. For obtaining these data, different techniques and approaches have been developed with various advantages and disadvantages, degrees of complexity of their hardware and software implementation, areas of workability and limitations [1–3]. Several reconstruction methods were demonstrated for single-shot pulses [1], but for them, the problem is much more challenging than for signals having high repetition rates. For retrieving the intensity profile and phase of TW- and PW-class power single-shot pulses, a very simple method of measuring the fundamental (initial) pulse spectrum and two spectra transformed due to self-phase modulation (SPM) in elements with Kerr nonlinearity (plastic films) was recently proposed [4]. Based on this method, techniques for measuring optical pulses with low energies of order 1 nJ and high repetition rates using silica fibers as nonlinear elements were implemented by independent research teams [5,6]. To the best of our knowledge, for fiber laser systems, single-shot pulse retrieval by this method has not been reported yet. Recently we showed that the peak power and duration of an ultrashort pulse can be estimated by measuring a single SPM spectrum in a single-shot regime [7]. Here we demonstrate the possibility of characterization of a single-shot pulse from a fiber laser system with a peak power of about 1 MW and sub-ps duration by processing strongly SPM spectra.

Results and discussion

The experimental scheme is presented in Fig. 1(a). The fiber laser system at 1.56 μm similar to that reported in [7] consists of a mode-locked Er-doped fiber master oscillator, a fiber stretcher, an acousto-optic modulator to reduce pulse repetition rate, a powerful amplifier, and a dispersive compressor based on diffraction gratings. This system generates pulses with an energy of ~1 μJ, a duration of < 1 ps, and estimated peak power of ~1 MW at a repetition rate of 100 kHz. The pulse shape was retrieved from single-shot SPM spectra. Spectral broadening due to SPM occurred in a GeO_2-doped silica nonlinear fiber (NLF) with normal dispersion to prevent higher-order soliton dynamics [8]. The initial pulse was divided by a beam splitter into two replicas with different energies which were launched into two 2-cm long pieces of NLF (NLF_1 and NLF_2, see Fig. 1(a)) where the spectra were broadened significantly. The high *B*-integrals [4] were chosen to ensure a much larger nonlinear pulse phase due to SPM than the initial pulse phase. We assumed that the pulse phase at the output of our optimized compressor was less than π. We neglected Raman nonlinearity, dispersion, and self-steepening in the used $NLF_{1,2}$ (and confirmed the validity of this assumption by numerical simulations). The resulting complex electric field amplitudes at the $NLF_{1,2}$ outputs were [8]:

$$E_{1,2}(t) = |E_0(t)| \exp[iB_{1,2}|E_0(t)|^2], \quad (1)$$

where $E_0(t)$ is the initial complex electric field amplitude, t is time, and $B_{1,2}$ are corresponding *B*-integrals. The spectral amplitudes after conversion in $NLF_{1,2}$ are:

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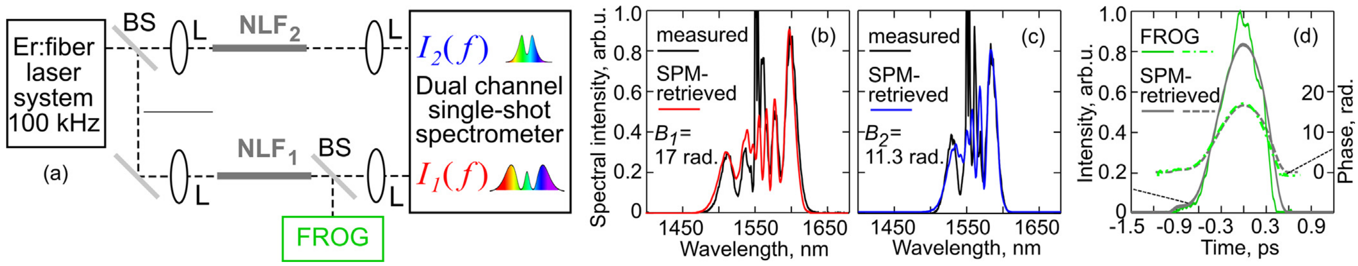

Fig. 1. The experimental scheme, BS: beam splitter and L: lens (a). SPM-spectra measured directly and reconstructed by the proposed method after NLF_1 (b) and after NLF_2 (c). Intensity profiles and phases retrieved independently from SPM spectra and FROG measurements.

$$\tilde{E}_{1,2}(f) = \int_{-\infty}^{\infty} E_{1,2}(t)\exp(i\cdot 2\pi f\cdot t)dt, \tag{2}$$

where frequency f is counted from the optical carrier frequency. The numerical algorithm is aimed to find $E_0(t)$ minimizing the difference Δ between the retrieved SPM spectra and the spectra $I_{1,2}(f)$ measured by a single-shot two-channel spectrometer [7] (CCD array):

$$\Delta = \left\{\sum_{k=1}^{N}[I_1(f_j) - |\tilde{E}_1(f_j)|^2]^2 + \sum_{k=1}^{N}[I_2(f_j) - |\tilde{E}_2(f_j)|^2]^2\right\}, \tag{3}$$

where N is the number of points, each point is designated by j.

We directly measured SPM spectra for $B_1/B_2 = 1.5$ (see Fig. 1(b, c), black curves) and applied the differential evolution algorithm similar to that reported for d-scan traces in the paper [9]. We assumed that the phases $\varphi_{1,2}(t)$ were proportional to the intensities $|E_{1,2}(t)|^2 = |E_0(t)|^2$ (see Eq. (1)). The exact value of B_1 was not known a priori, and we used exhaustive search for B_1 to find the value minimizing Δ [4,5]. The best agreement between directly measured and retrieved SPM-spectra was obtained for $B_1 = 17$ rad. The retrieved intensity profile and phase of the pulse are demonstrated in Fig. 1(d) by the grey curves. The retrieved SPM spectra are shown in Fig. 1(b, c) by red and blue curves, respectively. We also measured pulses after the NLF_1 by SHG FROG home-made apparatus [5]. We had no opportunity to implement single-shot FROG, so the intensity profile and phase shown in Fig. 1(d) by the green curves were retrieved for the 100 kHz repetition rate. The pulse shapes and phases obtained by the reported single-shot SPM-based technique and by FROG were similar. The slight discrepancy between the profiles retrieved by the two techniques may be due to FROG data averaging for many nonidentical pulses [7,10] and a nonideal adjustment of the nonlinear crystal for SHG affecting phase-matching. Note also that the method based on processing SPM spectra has no time direction ambiguity [4,5] in contrast to SHG FROG (when the FROG traces are the same for replacement: $t \to -t$, $\varphi(t) \to -\varphi(t)$) [1,2]. However, in the reported experiment we excluded this ambiguity for FROG pulses because we knew the sign of the phase $\varphi_1(t)$ after NLF_1 resulting from strong SPM. The high black peaks near 1.56 µm of the measured spectra in Fig. 1(b, c) are due to noncompressed and non-retrieved pedestal (this pedestal was not retrieved from FROG-measurements either). So, for pulse characterization of the reported single-shot fiber laser system the method based on SPM spectra processing is more simple, robust, and reliable.

Conclusions

The experimental single-shot reconstruction of a sub-ps pulse from a fiber laser system demonstrates that the reported ultrafast metrology method is a promising tool for characterization of similar classes of fiber laser systems when implementation of other single-shot techniques can be a challenge due to not very high energy and necessity of using complex and expensive equipment and precision adjustment. This method has benefits thanks to its simplicity, absence of time direction ambiguity and low cost.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Walmsley IA, Dorrer C. Characterization of ultrashort electromagnetic pulses. Adv Opt Photonics 2009;1:308–437.
[2] Trebino R. Frequency-resolved optical gating: the measurement of ultrashort laser pulses. Springer Science & Business Media; 2012.
[3] Nibbering ETJ, Franco MA, Prade BS, Grillon G, Chambaret JP, Mysyrowicz A. Spectral determination of the amplitude and the phase of intense ultrashort optical pulses. J Opt Soc Am B 1996;13:317–29.
[4] Anashkina EA, Ginzburg VN, Kochetkov AA, Yakovlev IV, Kim AV, Khazanov EA. Single-shot laser pulse reconstruction based on self-phase modulated spectra measurements. Sci Rep 2016;6:33749.
[5] Anashkina EA, Andrianov AV, Koptev MYu, Kim AV. Complete field characterization of ultrashort pulses in fiber photonics. IEEE J Sel Top Quantum Electron 2018;24:8700107.
[6] Baudin K, Audo F, Finot C. Fiber-based measurement of temporal intensity and phase profiles of an optical telecommunication pulse through self-phase modulation. Microw Opt Technol Lett 2018;60:882–6.
[7] Andrianov AV, Anashkina EA, Koptev MYu, Kim AV. Method for real-time measurement of fluctuations of the ratio of peak power to duration of high-repetition-rate ultrashort pulses. Quantum Electron 2019;49:322–9.
[8] Agrawal GP. Nonlinear fiber optics. Academic Press; 2019.
[9] Gerth D, Escoto E, Steinmeyer G, Hofmann B. Regularized differential evolution for a blind phase retrieval problem in ultrashort laser pulse characterization. Rev Sci Instrum 2019;90:043116.
[10] Ratner J, Steinmeyer G, Wong TC, Bartels R, Trebino R. Coherent artifact in modern pulse measurements. Opt Lett2874 2012;37.