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SPECTROTEMPORAL IMAGING WITH “PRE-SIMILARITON” REFERENCE PULSE

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Abstract–The flat-top pulses are generated in a regime preceding the formation of nonlinear-dispersive similaritons. We demonstrate the possibility of using these “pre-similariton” flat-top pulses as reference pulses for diagnostics of femtosecond pulses by spectrotemporal imaging.

The signal analysis problem on the femtosecond time scale employs the powerful arsenal of contemporary optics, involving the methods of nonlinear and adaptive optics, Fourier optics and holography, spectral interferometry, etc. The nonlinear-optical techniques of FROG and its modifications [1], the most popular and commercialized, provide accurate and complete determination of the temporal amplitude and phase by recording high-resolution spectrograms, which are further decoded by means of iterative phase-retrieval procedures. The approach of spectral interferometry [2] and its developments to the methods of SPIDER [3], SPIRIT [4], and SORBETS [5] have the advantage of non-iterative phase retrieval. The recently developed and effectively applied MIIPS technique [6] operates with spectral phase measurement through its adaptive compensation up to transform-limited pulse shaping by using feedback from the second harmonic generation process. All these methods are based on the spectral phase determination, spectrum measurement, and reconstruction of a temporal pulse. The pulse direct measurement is possible by the transfer of temporal information to the space or frequency domain, or to the time domain with a larger - measurable scale. The method of pulse spectrotemporal imaging through temporal lensing is promising, having as a principal limit of resolution the ~1 fs nonlinear response time of silica [7,8]. Its recent modifications implemented in the silicon chip [9] and similariton-induced parabolic temporal lens [10] provide accurate, high-resolution direct measurement of a pulse in the spectrometer as in the femtosecond optical oscilloscope. The method proposed in [10] is based on the pulse spectrotemporal imaging in the similariton-induced temporal lens in the process of sum-frequency generation (SFG). The temporal lens was induced by the nonlinear-dispersive (NL-D) similariton, which was generated in a conventional uniform and passive (without gain) fiber under the combined impacts of Kerr-nonlinearity and dispersion [11]. Studies of this type of pulses showed the linearity of their chirp (parabolic phase), with a slope given only by the fiber dispersion [11].

The setup of SFG-spectrotemporal imaging is shown in Fig. 1. Splitting the signal beam, its part is injected into a fiber to generate the NL-D similariton-reference, with the complex spectral amplitude $\tilde{A}_f(\omega) = |\tilde{A}_f(\omega)| \exp[i\varphi_f(\omega)]$. In the spectral domain, the dispersive delay works as a parabolic phase modulator, and the signal $\tilde{A}(\omega)$ passed through is described as $\tilde{A}_d(\omega) = \tilde{A}(\omega)\exp(i\ddot{\phi}_d\omega^2/2)$ with the given coefficient $\ddot{\phi}_d \approx -\gamma_d^{-1}$ (γ is the chirp factor). In the fiber arm, we have NL-D similariton with the known parameters. Afterwards, these two pulses are directed to a nonlinear crystal for SFG, and thus we have the multiplication of the complex fields: $A_{SFG}(t) \sim A_f(t) \times A_d(t)$. In both arms of the setup, we have practically linearly chirped pulses, and under the conditions of the opposite and same value chirps

$$\gamma_f = -\gamma_d \equiv \gamma, \quad (1)$$

and constant similariton amplitude throughout the signal

$$|A_f(t)| = \text{const during } A_d(t), \quad (2)$$

the output SFG-spectrum displays directly the input temporal pulse: $S_{SFG}(\omega) = |\tilde{A}_{SFG}(\omega)|^2 \propto |A(t)|^2 = I(t)$, with the scale $\omega = \gamma t$ [10].

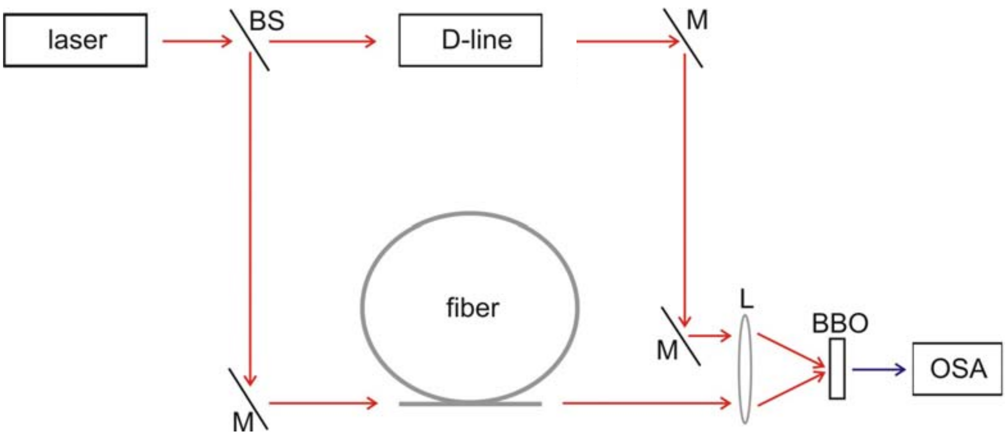

Fig. 1. Experimental setup: BS – beam splitter, M – mirrors, D-line – dispersive delay line, L – lens, BBO – crystal for SFG, OSA – optical spectrum analyzer.

Prior to the generation of NL-D similaritons in the fiber, pulses with nearly rectangular shape ("pre-similariton") are generated in case of initial bell-shaped pulses [11]. Following the generally accepted terminology, hereinafter we will call the pulses generated in this regime (i.e., certain ratio of the fiber length and initial intensity [12]) flat-top pulses, although in case of initial non-bell-shaped pulses they have more complicated form and are not rectangular. Similar to the similariton case, the spectral phase of such pulses at their central energy-carrying part is independent of the initial pulse parameters and has a parabolic shape with a coefficient $\alpha_R \equiv \gamma_R^{-1} = -\ddot{\phi}(\omega) \approx \beta_2 f$, where f is the fiber length, β_2 is the coefficient of second-order group velocity dispersion [11]. Provided that the fulfillment of the condition (2) takes place, these flat-top pulses can also be used as a reference in the method of spectrotemporal imaging.

Numerical simulations show that in case of initial bell-shaped pulses the condition (2) is satisfied almost always. This is expected result: both replicas of the pulse propagate through media with the same dispersion properties ($\left|\beta_2^d\right| d \approx \beta_2^f f$, d being the length of dispersive delay line), while the spectrum of the reference pulse is broadened in the fiber (in contrast to the spectrum of the signal pulse), resulting in stronger dispersive stretching of the reference pulse than that for the signal pulse. As for more complex pulses with multiple peaks, the condition (2) is well satisfied in this case too, provided that the distance between the peaks does not exceed the width of one peak. Figure 2 shows the simulation results in the typical case of symmetric two-peak pulse for the dimensionless fiber length of the $\varsigma \equiv \left|\beta_2\right| f / \tau_0^2 = 1.8$, where τ_0 is the half-width at the level $1/e$ of one of the peaks of the pulse under consideration. In the figure, the results are presented in dimensionless quantities $\Omega = (\omega - \omega_0)/\Delta\omega_0$ and $\eta = (t - z/u)/\tau_0$, where ω_0 is the center frequency, $\Delta\omega_0$ the initial spectral bandwidth, u the group velocity. The spectrum of the reference pulse (Fig. 2 (a)) has a rather complicated form, but the central part of the time profile of its intensity (Fig. 2 (b)) is flat and almost completely covers the signal pulse, which leads to the fulfillment of the condition (2).

Figure 3 shows the experimental demonstration of the spectrotemporal imaging for the case corresponding to the numerical simulation presented in Fig. 2, and implemented by the setup of Fig. 1.

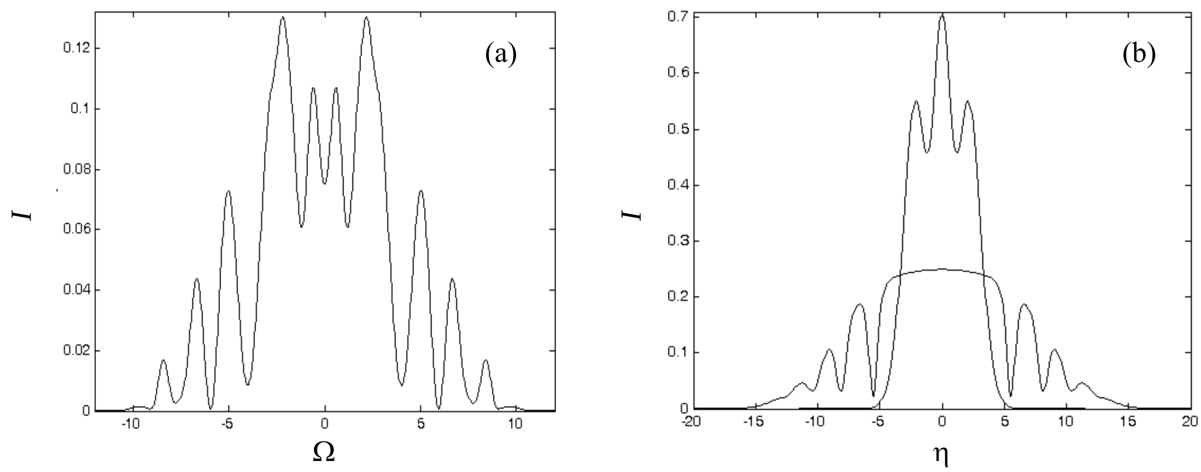

Fig. 2. Numerical simulation of spectrotemporal imaging in the regime of flat-top pulses: (a) spectrum of the reference pulse, (b) signal and reference pulses.

In the experiment, we use the Coherent Verdi10 + Mira 900F commercial femtosecond laser system with the following parameters of radiation: 100 fs pulse duration, 76 MHz repetition rate, 1.6 W average power, and 800 nm central wavelength. First, at the input of our system, we shape the pulses under test and measure them by a standard autocorrelator (APE PulseCheck). Afterwards, we split the radiation under test into two parts by means of a beam-splitter (80% + 20%). As a dispersive delay line we use the SF11-prism pair. We shape the reference flat-top pulse in a standard Newport F-SPF @820nm fiber. As a nonlinear crystal for non-collinear SFG, we use BBO type 1 (oo-e), 0.1 mm thick, with the 800 nm operating wavelength ($\theta = 29.2°$, $\varphi = 0°$). We measure the spectrum by the Ando AQ 6315 optical spectrum analyzer at the output of the system to register the spectrum of the SFG pulse. Having the spectrogram of the output as a spectrotemporal image of the pulse under test, we calculate its autocorrelation and compare it with the autocorrelation track measured at the input of the system, to check the performance of STI. There is a good quantitative agreement between the measured autocorrelation of the initial pulse and the calculated autocorrelation of the spectral image.

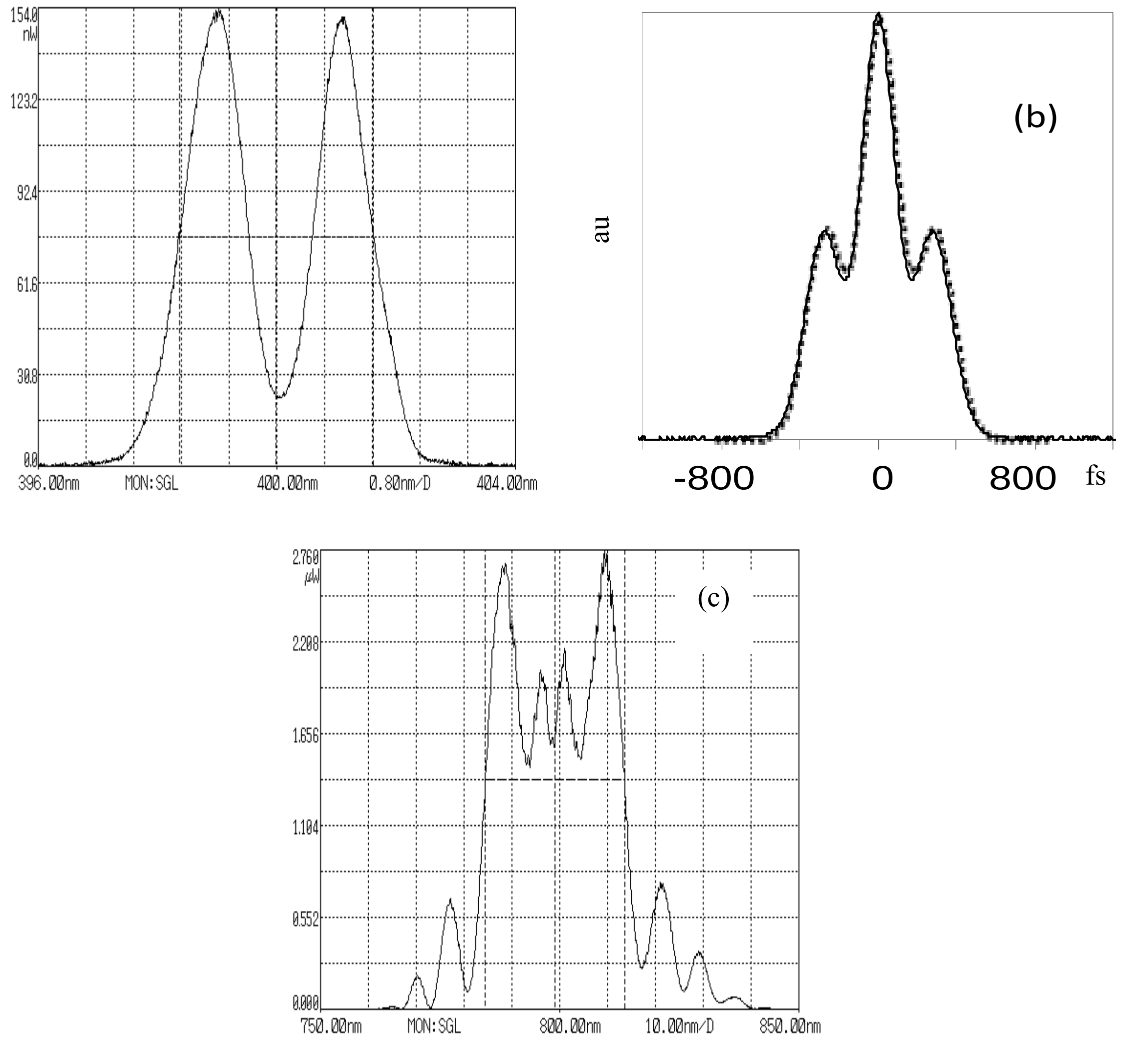

Fig. 3. Spectrotemporal imaging in the regime of flat-top pulses (experiment): (a) spectrotemporal image of two-peak pulse, (b) measured autocorrelation of the initial pulse (solid line) and calculated autocorrelation of the spectral image (dotted line), (c) spectrum of the reference pulse.

Concluding, we showed through numerical and experimental studies that the pulses generated from the pulse under test in the regime preceding the similariton formation can be used as a reference pulse in the method of spectrotemporal imaging. From the practical point of view, such a regime is of interest due to the fact that the flat-top pulses are generated at shorter fiber lengths, and, respectively, shorter dispersive delay line, which leads to more compact experimental setup. In addition, the obtained SFG spectra are wider in case of shorter fibers [10], which reduces the requirements on the resolution of the spectrometer used.

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