Spectral self-compression of randomly modulated pulses

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Abstract: Numerical studies show the possibility of the spectral self-compression for randomly modulated pulses in a fiber with anomalous dispersion. The study of the spectral self-compression process is carried out for the additive noise model. The peculiarities of the process for different values of the fiber length and the nonlinearity parameter is studied.

Keywords: spectral self-compression, randomly modulated pulse, correlation

1. Introduction

The nonlinear process of spectral compression (SC) in a dispersive delay line (DDL) followed by a nonlinear fiber demonstrates promising applications to the signal analysis-synthesis problems in ultrafast optics [1]. In the SC system, the pulse expands and obtains a negative phase in a DDL. This phase should be compensated by the positive phase acquired by nonlinear self-phase modulation (SPM) in a fiber with normal dispersion; as a result, the spectrum is compressed [2]. The impact of group velocity dispersion (GVD) on SC for sub-picosecond pulses in the range of normal dispersion, i.e. at wavelengths <1.3µm for standard silica fibers, is analyzed in [3] in view of shaping flattop pulses. In range of anomalous dispersion, i.e. at wavelengths \geq 1.3µm for silica fibers, the combined impact of GVD and SPM leads to the formation of solitons [4, 5], when the contributions of GVD and SPM balance each other. The pulse self-compression phenomenon arises when the impact of SPM exceeds the GVD, and high-order solitons are shaped [6].

Under the opposite condition, i.e. when the impact of dispersion exceeds the nonlinearity, we can expect spectral self-compression (self-SC) by the analogy of the pulse self-compression. Recently, the self-SC implementation directly in a fiber with negative group-velocity dispersion (at the wavelength range $\geq 1.3 \mu m$ for standard silica fibers) was proposed [7] and studied [8].

In this work, we carried out detailed numerical studies on the process of self-SC for randomly modulated pulses. The self-SC is shown in the fiber with anomalous dispersion, without dispersive delay line, when the impact of GVD in the fiber stronger than the influence of SPM.

2. Numerical Studies and Results

The pulse propagation in a single-mode fiber (SMF) is described by nonlinear Schrödinger equation for normalized complex amplitude of field, considering only the influence of GVD and Kerr nonlinearity [2]:

$$i\frac{\partial\psi}{\partial\zeta} = \frac{1}{2}\frac{\partial^2\psi}{\partial\eta^2} + R|\psi|^2\psi$$
(1)

where $\xi = z/L_D$ is the dimensionless propagation distance, $\eta = (t - z/u)/\tau_0$ is the running time, which are normalized to the dispersive length $L_D = \tau_o^2/|k_2| (k_2$ is the coefficient of second-order dispersion), and initial pulse duration τ_0 , respectively. The nonlinearity parameter *R* is given by the expression $R = L_D/L_{NL}$, where $L_{NL} = (k_0 n_2 I_0)^{-1}$ is the nonlinearity length, n_2 is the Kerr index of silica, and I_0 is the peak intensity. The first and second terms of the right side of Eq. (1) describe the impact of GVD and nonlinearity, respectively. We use the split-step Fourier method during the numerical solution of the equation, with the fast Fourier transform algorithm on the dispersive step [9, 10].

The initial pulses with random amplitude modulation are formed by the model of additive noise [11], and for Eq. (1) the initial conditions are given as follows:

$$\psi(0,\eta) = \psi_0(\eta) + \sigma\xi(\eta) \tag{2}$$

In Eq. (2), ψ_0 is the regular component of normalized amplitude, $\xi(\eta)$ is the stationary noise with a Gaussian correlation function, and σ is its amplitude.

The purpose of our work is to study the self-SC for randomly modulated pulses, which takes place when the dispersive length in the fiber is shorter than the nonlinear length ($L_D < L_{NL}$, i.e. R < 1). At first, the GVD stretches the pulse by acquiring a negative chirp. Afterwards, the accumulated impact of SPM leads to the compensation of the chirp. As a result, the spectrum is compressed. We study the pulse behavior in a fiber with negative GVD for different values of nonlinearity parameter and fiber length (the fiber length is less than 100).

The statistical parameters of radiation are determined by sampling of a large number realizations N = 150, which are solutions of Eq. (1). The studies are carried out for signals with the same value of the noise component amplitude $\sigma = 0.6$ and coherence time $\tau_c = 0.33$ ($\tau_c = \tau_0/3$).

A randomly modulated optical signal with higher coherency has a smoother shape than signal with a lower coherency. The period of oscillation is given by the coherence time, and their amplitude is given by the amplitude of noise component. Figure 1 illustrates two realizations of randomly modulated initial pulses with coherence time $\tau_c = 0.33$ ($\sigma = 0.6$).



Fig. 1. Two realizations of randomly modulated initial pulses.

The maximal value of the self-SC for different values of the nonlinearity parameter and the fiber length (the fiber length is less than 100) is studied. As shown in Fig. 2, the maximum value of the self - SC ($\Delta = \max(I(\Omega)/I_0(\Omega))$) is ≈ 3 , where the nonlinearity parameter and the fiber length equal to 0.4 and 65, correspondingly (Fig. 2).



Fig. 2. The maximal values of the self - SC vs nonlinearity parameter (for fiber lengths less than 100).

For comparison, self-SC for the regular Gaussian pulse and randomly modulated pulses in the system with the same parameters is implemented (the nonlinearity parameter and fiber length equal to 0.6 and 50, respectively). As we see on Figure 3 (a, b), the self-SC is ≈ 5.9 for initial Gaussian pulses meanwhile the self-SC is ≈ 2.5 for initial randomly modulated pulses Figure 3 (c, d).



Fig. 3. Spectral self-compression of initial Gaussian (a, b) and randomly modulated (c, d) pulses (the nonlinearity parameter and the fiber length equal to 0.6 and 50, respectively).

3. Conclusions

Thus, through detailed numerical study we show the possibility of spectral self-compression for randomly modulated pulses in the fiber "directly", without dispersive delay line. The study of the spectral self-compression process is carried out for different values of the fiber length and the nonlinearity parameter. We have shown that the maximal value of spectral self-compression is ≈ 3 for fiber lengths less than 100.

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