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Spectral Self-Compression of Partially Coherent Pulses

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Abstract: We numerically studied the nonlinear effect of spectral self-compression: the spectral analogue of temporal self-compression. The study is done for pulses with random modulations of amplitude and phase, and for pulses that have random modulations of both amplitude and phase.

Keywords: Ultrafast laser optics, Fiber optics, Soliton-type processes, Spectral compression

1. Introduction

Temporal compression of pulses using media with nanostructures or photonic liquid crystals has wide applications nowadays. Recently, compression down to one-two cycle pulses was achieved in the process of pulse self-compression [1-4]. Spectral compression (SC) [5-8], the nonlinear process in which the pulse spectrum compresses, is the spectral analogue of pulse temporal compression. SC occurs when ultrashort laser pulses first travel through a dispersive medium with negative sign of dispersion, and then are impacted by nonlinearity in a second medium, for example, through self-phase modulation (SPM) [9]. This is usually done by passing the pulse through a fiber. The dispersive impact stretches the pulse and applies linear chirp (with negative sign). This chirp is then compensated by the nonlinear impact in fiber, and results in an output pulse with compressed spectrum. Spectral compression demonstrates large variety of applications in different fields, based on the space-to-time analogy and the time lens concept [10,11]. Pulse self-compression can occur in a fiber, under the combined impact of strong phase modulation and weak group velocity dispersion (GVD) [12,13]. Spectral self-compression (SSC), the analogue of temporal self-compression, occurs under the combined effect of strong GVD and weak nonlinear self-phase modulation. Dispersion delay line applies negative chirp to the pulse, while self-phase modulation compensates the chirp, enhancing the compression of pulses [14,15].

The effect of SSC was simulated for pulses with initial Gaussian temporal profile [16]. SSC was experimentally demonstrated for noisy supercontinniuum radiation, where a compression factor of 4x was demonstrated [17].

We report the possibility of SSC for noisy pulses. Here, we numerically simulated SSC of pulses with random phase and amplitude modulations. Also, it is demonstrated that the noisy components of the pulses are suppressed by to nonlinear effect of SSC.

2. Analytics

We analytically examine the process of SSC by comparing the effects of GVD in spectral domain and nonlinear self-phase modulation in temporal domain. For slowly varying amplitude (A) of the pulse, and its Fourier transform $\tilde{A}$, this comparison clearly shows that GVD modulates the phase in a parabolic way:

$$\tilde{A}\left(\omega, z\right) = \tilde{A}\left(\omega, 0\right)\exp[-i\omega^2(z / L_D) / 2] \tag{2.1}$$

Analogically to the phase of a self-phase modulated bell-shaped pulse:

$$A\left(t, z\right) \approx A\left(t, 0\right)\exp(iz / L_{NL})\exp[-it^2(z / L_{NL})] \tag{2.2}$$

Modulation step for GVD is the dispersion length $L_D \equiv (\beta_2\Delta\omega_0^2)^{-1}$, whereas the self-phase modulation step is the nonlinear length $L_{NL} \equiv [\beta_0 n_2 \,|\, A(0,0)\,|^2]^{-1}$. Here, t and ω are the “running” time and central frequency respectively, Δt_0 and $\Delta\omega_0$ are the normalized duration and spectral width of initial pulse, n_2 is the coefficient of the second order nonlinearity, β_2 is the coefficient of the second order of dispersion and z is the spatial coordinate.

The effect of temporal self-compression occurs under the combined impact of strong self-phase modulation and weak negative GVD which compensates the chirp. Thus, the condition necessary for the temporal self-compression can be expressed as $L_{NL} < L_D$. For SSC, the situation is the opposite. Strong negative GVD first chirps the pulse, which is then compensated by the impact of weak self-phase modulation, resulting in a self-compressed spectrum. Hence, the condition of $L_{NL} > L_D$ must be kept for SSC.

3. Numerical study

To study the effect of SSC for pulses with noisy nature, we carried out numerical studies based on the non-analytical solution of nonlinear Schrödinger equation, taking into account only dispersive and nonlinear effects respectively.

In our studies, we applied noise on top of a regular pulse, and used the result as a test pulse. Here, we added randomly modulated amplitude, phase and combined modulations to initial secant hyperbolic pulse. To study the SSC process for those modulated pulses, we constructed 3D graphics, where the evolution of the temporal and spectral profiles are demonstrated. We carried out numerical simulations for different nonlinear coefficients in optical fibers, as well as different fiber normalized lengths, up to $\zeta = 500$ ($\zeta = z / L_D$ is its normalized value of dispersion).

Firstly, we took into consideration the following amplitude modulation model: $A(t) = A_0(t)[1+\sigma\xi(t)]$, where $A_0(t)$ is the secant hyperbolic pulse, $\xi(t)$ is the white noise, and σ is the amplitude of the noise. The 3D maps of evolution of temporal and spectral profiles of the pulse are shown in Fig. 1(a) and (c), for $\zeta = 500$ normalized length of fiber. The dynamics of the change of spectral profile for up to $\zeta = 100$ is demonstrated in Fig. 1(b). This numerical study was carried out using the following parameters: nonlinear coefficient of $R = L_D / L_{NL} = 0.015$, normalized length of optical fiber of $\zeta = 500$, coherence time of $\tau = 1/3\Delta t_0$ and noise amplitude of $\sigma = 0.1$. As one can see, the pulse is periodically stretched and compressed during the propagation through the fiber. Stretching of the pulse corresponds to the compression of the spectrum and vice versa. For above-mentioned parameters, the first spectral compression point (9x compression factor) corresponds to $\zeta = 80$. In Fig. 1(b), $z = 0$ corresponds to the initial spectrum, $z = 50$ to the first SSC point and $z = 100$ to the second compression point. It is clear, that the noisy component of the pulse is suppressed throughout the SSC process in the central energy-carrying part of the pulse.

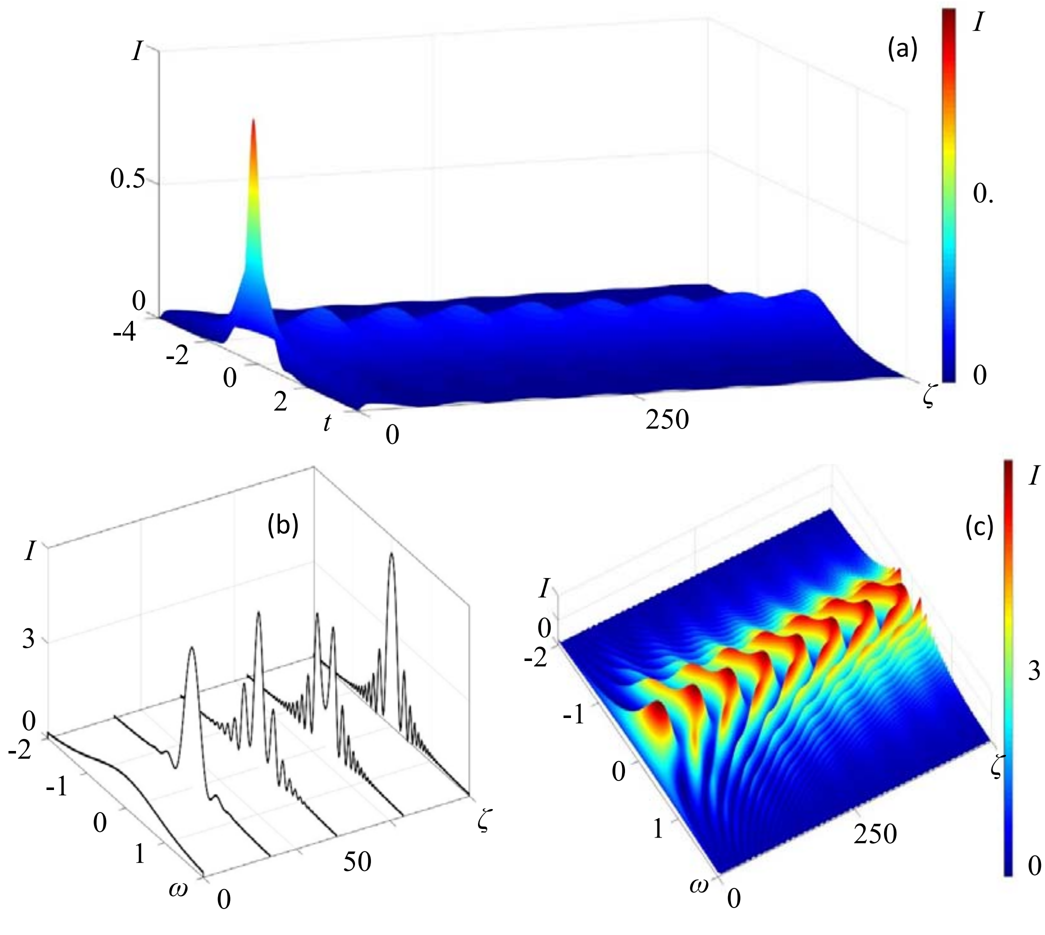

Figure 1: The SSC of pulse with random amplitude modulation: 3D map of temporal profile evolution (a); dynamics of spectrum evolution (b); 3D map of spectrum evolution (c).

Second, we studied pulses with phase modulation $A(t) = A_0(t)[\exp(i\sigma\xi(t))]$. $A_0(t)$ is the secant hyperbolic pulse, $\xi(t)$ is the white noise, σ is the amplitude of the noise. Temporal and spectral profiles of the pulse throughout propagation in the medium are shown in Fig. 2(a) and (c), for $\zeta = 500$ normalized length of fiber. The dynamics of the spectral profile for fiber length of up to $\zeta = 160$ is demonstrated in Fig. 2(b).The following parameters were used in this simulation: nonlinear coefficient of $R = 2.2$, normalized length of optical fiber of $\zeta = 500$, coherence time of $\tau = 1/3\Delta t_0$ and noise amplitude of $\sigma = 1.5$. Here, 3D graphs show the periodic nature of SSC: the spectrum compresses and stretches, while the temporal profile stretches and compresses on opposite points throughout propagation across the medium. The first spectral compression point (17x compression factor) corresponds to $\zeta = 80$.

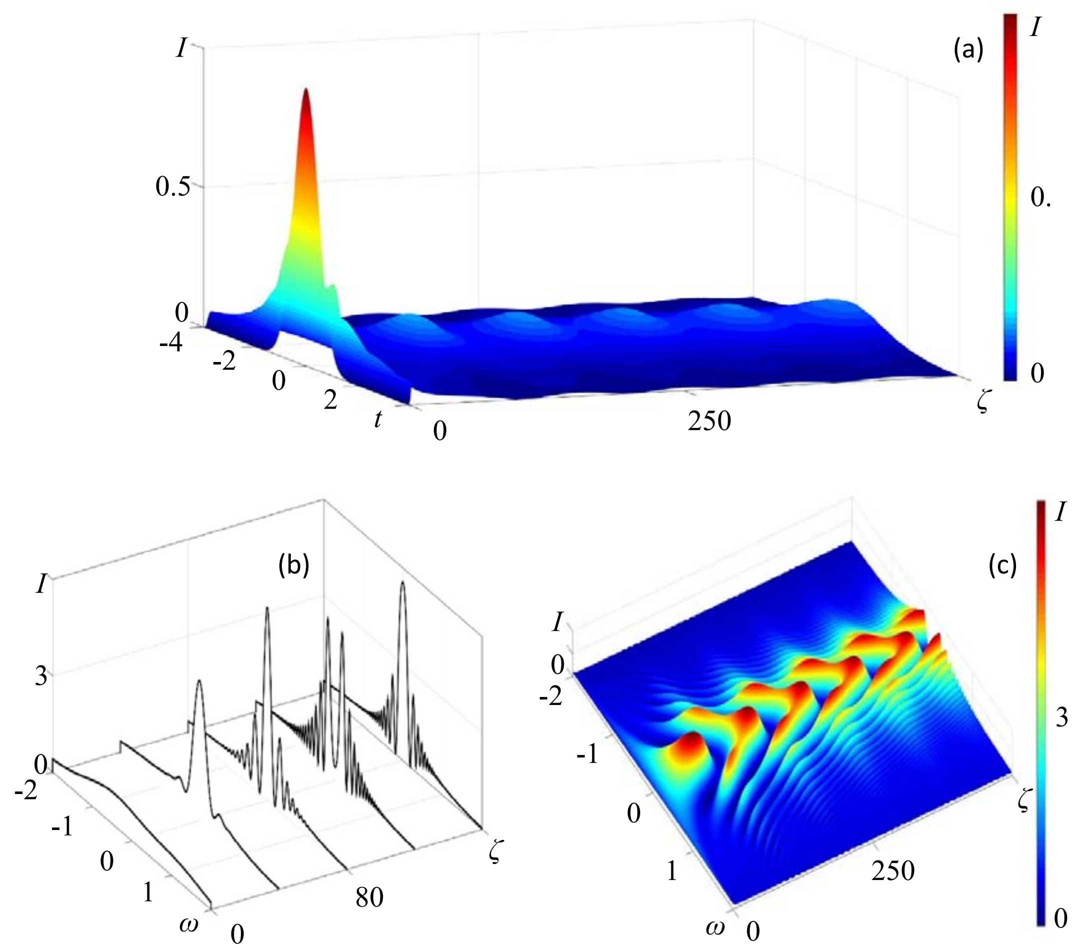

Figure 2: The SSC of pulse with random phase modulation: 3D map of temporal profile evolution (a); dynamics of spectrum evolution (b); 3D map of spectrum evolution (c).

Lastly, $A(t) = A_0(t)[1+\sigma\xi(t)]$ amplitude and phase modulation model was used. Here, $A_0(t)$ is the secant hyperbolic pulse, $\xi(t) = \xi_1(t) + i\xi_2(t)$ is the complex noise, where $\xi_1(t)$ and $\xi_2(t)$ are white noises, σ is the amplitude of the noise. The 3D maps of evolution of temporal and spectral profiles are shown in Fig.3 (a) and (c) respectively, for $\zeta = 500$ normalized length of fiber. Fig.3 (b) demonstrates the spectral profile on different propagation distances up to $\zeta = 70$. Here we used the following parameters: nonlinear coefficient of $R = 0.195$, normalized length of optical fiber of $\zeta = 500$, coherence time of $\tau = 1/3\Delta t_0$ and noise amplitude of $\sigma = 0.5$. On the length of $\zeta = 35$ spectrum self-compresses for the first time, with a compression factor of 13x.

Our numerical simulations show the solitonic nature of SSC. The pulse and its spectrum are compressed and stretched in opposite points, while the noisy modulations are suppressed: the coherence of the pulse increases in central, energy-caring part.

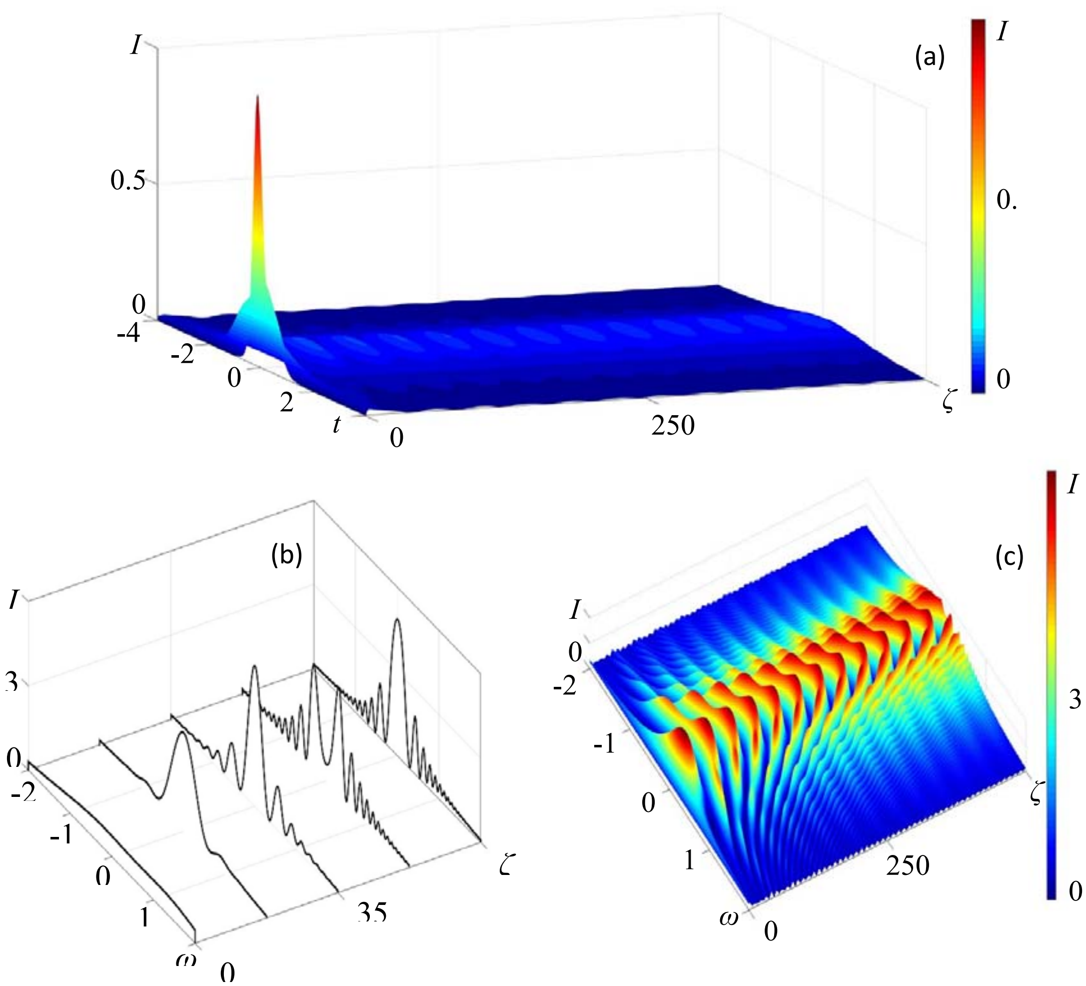

Figure 3: The SSC of pulse with random amplitude and phase modulation: 3D map of temporal profile evolution (a); dynamics of spectrum evolution (b); 3D map of spectrum evolution (c).

4. Conclusion

To conclude, we numerically demonstrated the SSC process for pulses with random noisy modulations of phase and amplitude. Furthermore, it is demonstrated that the nonlinear effect of SSC suppresses the noisy components of pulses, increasing the coherency of pulses in the central energy-carrying part.

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