# Soliton-effect Spectral Self-compression for Different Initial Pulses

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Our numerical studies demonstrate a spectral analogue of soliton-effect self-compression for different initial pulses. The evolution of transform-limited pulses during the propagation in a single-mode fiber with anomalous dispersion is studied. It is shown that the spectral analogue of soliton-effect self-compression is realized in the case of different initial pulses: periodicity of the spectral compression and stretching is different for different initial pulses. The approximation of curves introducing the frequency of the spectral compression and stretching dependence on nonlinearity parameter is implemented.

## 1 Introduction

The spectral compression (SC) process has numerous interesting applications in ultrafast optics and laser technology [1–5], such as the spectrotemporal imaging of ultrashort pulses by means of Fourier transformation [1]. In [5], the authors offer to apply SC in a fiber laser instead of strong spectral filtering. This allows to obtain transform-limited pulses and benefits the laser's power efficiency. As another practical application of SC, it is important to mention the transfer of femtosecond pulses without distortion at a relatively large distance [6]. Diverse applications of SC remain urgent in relation to the development and analysis of new effective compression systems. For example, in [7] the compression efficiency is improved by means of amplitude modulation.

The traditional spectral compressor consists of prism as a dispersive delay line, where the pulse is stretched and negatively chirped, and single-mode fiber (SMF) with the normal group-velocity dispersion, where nonlinear self-phase modulation leads to the chirp compensation and spectral narrowing. At the wavelength range of $<1.3\,\mu$m, the group-velocity dispersion is positive for standard silica fibers. The role of the normal dispersion in SC of subpicosecond laser pulses is analyzed in [8]. As it is known, the combined impact of negative dispersion and the nonlinear self-phase modulation leads to the formation of solitons in SMF [9, 10], when the impact of dispersion and nonlinear self-phase modulation balance each other out. The pulse self-compression phenomenon is also known [11], which is obtained when the impact of the nonlinear self-phase modulation exceeds the dispersion. 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 [12] and studied [13]. In this work, we carried out detailed numerical studies on the process of soliton-effect self-SC for different initial pulses. Simulations were carried out for initial Gaussian and secant-hyperbolic pulses. We have shown the soliton-effect self-SC in the fiber "directly", without dispersive delay line, in the fiber with anomalous dispersion for different initial pulses. It is shown that there is an analogy between the processes of soliton self-compression and soliton-effect self-SC for different initial pulses: the periodicity of the process changes in the case of different initial pulses. The studies show that the periodicity of the process decreases when the nonlinearity parameter reduces. Our detailed study has shown that the frequency of compression has polynomial and exponential approximations.

## 2 Numerical studies and results

In the SMF, the pulse propagation is described by the nonlinear Schrödinger equation for normalized complex amplitude of field, considering only the influence of group-velocity dispersion and Kerr nonlinearity [14]:

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

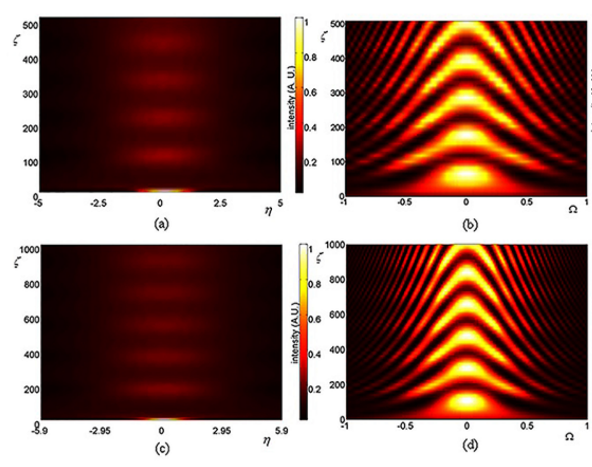

Fig. 1: The 3D map of the propagation of Gaussian (a, b) and secant-hyperbolic (c, d) pulses and its spectra. $\Omega = (\omega - \omega_0)/\Delta\omega_0$.

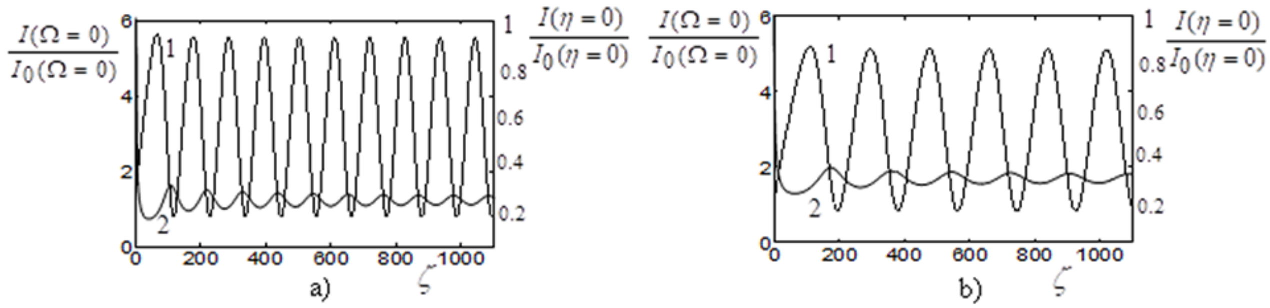


Fig. 2: The peak values of spectra (1) and pulses (2) vs fiber length for initial Gaussian (a) and secant-hyperbolic (b) pulses.

where $\zeta = z/L_D$ is the dimensionless propagation distance, $\eta = (t - z/u)/\tau_0$ is the running time, which are normalized to the dispersive length $L_D = \tau_0^2/|k_2|$ ($k_2$ is the coefficient of second-order dispersion), and initial pulse duration $\tau_0$, 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, $I_0$ is the peak intensity. The first and second terms of the right side of (1) describe the impact of group-velocity dispersion 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 [15, 16].

The objective of our numerical studies is the soliton-effect self-SC, which takes place when the dispersive length in the fiber is shorter than the nonlinear length ($L_D < L_{NL}$, i.e. $R < 1$). Therefore, at first, the group-velocity dispersion stretches the pulse by acquiring a chirp. Afterwards, the accumulated impact of nonlinear self-phase modulation leads to the compensation of the chirp. As a result, the spectrum is compressed. The process has periodic character. We study the pulse behavior in a fiber with negative group-velocity dispersion for different initial pulses and different values of the nonlinearity parameter and fiber length.

Fig. 1 illustrates the process of propagation of Gaussian (a, b, $R = 0.6$) and secant-hyperbolic (c, d, $R = 0.4$) pulses and their spectra. In this case, we study the process for short fiber lengths where the efficiency of the process is high for the nonlinearity parameter values of $R = 0.6$ (Gaussian pulse) and $R = 0.4$ (secant-hyperbolic pulse). It can be observed that the pulse is stretched and the spectrum is compressed in the initial propagation step. Afterwards, the width of central peak of the spectrum decreases and the main part of the pulse energy goes to the spectral satellites. At the certain fiber length, the reverse process starts the pulse self-compression.

The process can be explained in the following way: in the initial propagation step the spectrum is compressed, which leads to the decreasing of dispersion impact. As a result, the dispersive length increases, therefore, the nonlinearity parameter also increases. When the condition $R > 1$ is satisfied ($L_D > L_{NL}$), the pulse is compressed. Then, the spectrum is

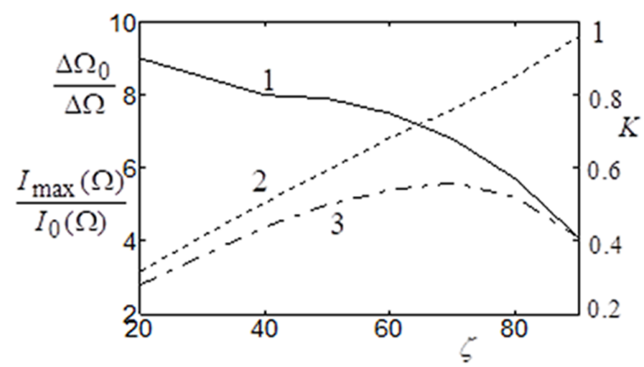


Fig. 3: The $K$ (1) and self-SC ($\Delta\Omega_0/\Delta\Omega$) (2), $I_{max}(\Omega)/I_0(\Omega)$ (3) vs fiber length for initial Gaussian pulse.

stretched, which leads to the increasing of dispersion impact (the decreasing of $L_D$ and $R$). When the condition $R < 1$ is satisfied ($L_D < L_{NL}$), the spectrum is compressed.

The process, which is described above has periodic character, but in the case of every next cycle, the quality of the SC is worse than in the case of the previous SC as spectral satellites increase within propagation.

Fig. 2 shows the peak value of spectra (1) and pulses (2) for initial Gaussian (a) and secant-hyperbolic (b) pulses, which shows that the process has a periodic character not only for Gaussian pulses but also for secant-hyperbolic pulses. The difference between Gaussian and secant-hyperbolic pulses is the speed of the process: as we see in Fig. 2, every next spectrum compression occurs in the short distance in the case of Gaussian pulses in comparison with the case of secant-hyperbolic pulses.

As we see in Fig. 2, the peak value decreases within the distance which is conditioned by the fact that the energy of spectral satellites increases. This fact is proved by the coefficient of SC quality, $K$, (the ratio of the energy in the central part of pulse to the whole energy). As we see in Fig. 3, the coefficient of SC quality decreases within the fiber length.

In the process of propagation, the behavior of the spec-

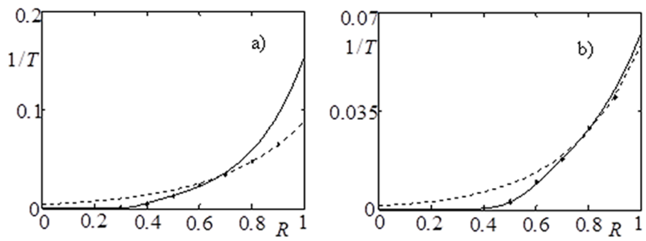


Fig. 4: The frequency vs nonlinearity parameter for initial secant-hyperbolic (a) and Gaussian (b) pulses. The points correspond to the numerical investigations, solid lines introduce the approximation of results (Eqs. 2, 3) by all points, while the dotted lines correspond to the approximation by last 3 points (Eqs. 4, 5).

trum is similar to the pulse behavior in the case of the soliton compression. As it is known, the propagation of the high-order solitons have periodic character with a $(\pi/2)L_D$ periodicity. On the distance equal to the periodicity, at first pulse is compressed, then it is stretched taking initial shape. In our case, the spectrum has similar behavior. However, due to the incomplete cancellation of the chirp, the changing of the spectrum does not have the strict periodic character. The process is different from soliton compression due to the fact that spectrum changes depend on a nonlinear phase, which depends on the shape of the pulse. In the case of soliton propagation, the changes of the pulse depend on a dispersive phase, which depends on neither spectral nor temporal shape of the pulse.

The study shows that the periodicity of the SC and stretching decreases with the reduction of nonlinearity parameter (Fig. 4). It is shown that there are polynomial (Eqs. 2, 3) and exponential (Eqs. 4, 5) approximations of the curve introducing nonlinearity parameter dependent frequency (Fig. 4), which is the frequency of the SC and stretching.

$$1/T = 1/\left(1.6 \times 10^{7} \times 10^{-30R} + 7821 \times 10^{-4.79R}\right) \tag{2}$$

$$1/T = 1/\left(5.09 \times 10^{6} \times 10^{-19.8R} + 731.3 \times 10^{-3.83R}\right) \tag{3}$$

$$1/T = 1/\left(0.004 \times e^{3.08R}\right) \tag{4}$$

$$1/T = 1/\left(0.001 \times e^{3.73R}\right) \tag{5}$$

## 3 Conclusion

Through the detailed study, we study the soliton-effect self-SC for initial Gaussian and secant-hyperbolic pulses. The process is realized in the fiber with a negative group-velocity dispersion. The study shows that there is an analogy between soliton self-compression and soliton-effect self-SC processes. We show that the periodicity of the process decreases when the nonlinearity parameter reduces. It is shown that the frequency dependence on the nonlinearity parameter has polynomial and exponential approximations.

**Acknowledgements**

The authors acknowledges Prof. R. Hakobyan for fruitful discussions and help during the work.

Received on December 4, 2017

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