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Influence of gain coefficient on the self-similar pulses propagation in a dispersion-decreasing fiber

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ABSTRACT

This paper first investigates the influence of the dispersion-decreasing optical fiber structure on the self-similar pulses interaction and compression. The dynamic of the evolution of a pair of self-similar pulses in a dispersion-decreasing optical fiber with normal group-velocity dispersion (ND-DDF) under different gain coefficient g_0 of DDF is analyzed, and the chirp evolution is also studied to analyze the propagation characteristic of self-similar pulses. The numerical simulations show that the change of gain coefficient g_0 of DDF can impact directly on the linear chirp of the self-similar pulses. We find out that the smaller g_0 can generate better high-quality femto-second pulses than the higher g_0 after pulses compression. Finally, we got a pair of ultra-short pulses with a FWHM of 124 fs at $g_0 = 0.015\ \text{m}^{-1}$, indicating efficient and high-quality pulse compression.

1. Introduction

With the increasing demand of communication capacity, the requirements of high data transfer rate and distance of optical communication systems are put forward. The communication systems based on the optical solitons which have the advantage of ultra-high repetition rate and shape preserving transmission have become one of the popular solutions. Recently, another self-similar asymptotic solution of the nonlinear Schrodinger (NLS) equation has attracted great attentions because of their potential applications in optical soliton communication systems.

Self-similar pulse, generated in a dispersion-decreasing optical fiber [1] or fiber amplifier [2] with normal group-velocity dispersion, has attractive characteristics, such as resistance to optical wave breaking of soliton, self-similarity in shape, and enhanced chirp linearity [3–8]. The formation of the self-similar pulses for optical communication systems is associated with interactions between two adjacent slightly overlapped pulses. Although there are more and more studies on the generation and propagation of a single self-similar pulse, to date, there are still limited studies on the interaction between self-similar pulses. To our knowledge, all the works on interaction between parabolic pulses have been mostly based on fiber amplifier [9], dispersion-managed fibers [10] and nonlinear waveguides [11]. Recently, the properties of the self-similar parabolic pulses interaction in a ND-DDF are also investigated [12,13] too.

This paper further investigates the influence of the dispersion-decreasing optical fiber structure on the self-similar pulses interaction and compression. We find that the change of gain coefficient g_0 of DDF can impact directly on the linear chirp of the self-similar pulses. We compare the case when g_0 remain constant with the case when g_0 is changed. The simulation result shows that the change of g_0 can bring the chirp changing accordingly, and the smaller g_0 can generate better high-quality femto-second pulses than the higher g_0 after pulses compression, which is possible to generate a train of ultra-short pulses at a high repetition rate for optical communication system.

2. Theoretical model

The propagation of optical pulses in a ND-DDF is modeled by a NLS equation of the form [1]

$$i\frac{\partial A}{\partial z} - \frac{\beta_2}{2}D(z)\frac{\partial^2 A}{\partial T^2} + \gamma\left|A\right|^2 A = 0 \tag{1}$$

where $A(z, T)$ is the slowly varying amplitude of the pulse envelope and T is measured in a frame of reference moving with the pulse at the group velocity vg ($T = t - z/\text{vg}$), $D(z)$ represents the variation in the GVD due to dispersion tapering and is normalized such that $D(0) = 1$. β_2 and γ are the GVD value at $z = 0$ and the nonlinearity coefficient, respectively. Here we use hyperbolic dispersion tapering in a passive fiber so that the propagating pulse obtains

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the equivalent (noise-free) gain necessary for parabolic pulse generation, it means $D(z) = \left(1/(1+g_0 z)\right)$. Here g_0 is a constant gain coefficient.

It has been proved than the solutions of Eq. (1) is a self-similar asymptotic solution, characterized by a parabolic intensity profile with constant linear chirp

$$\delta\omega(T) = -\frac{\partial\varphi}{\partial T} = \frac{g_0}{3\beta_2}T, \quad \left(\left|T\right| \le \tau(z)\right) \tag{2}$$

Importantly, the theory predicts that in the parabolic region, the chirp characteristic of the pulse is determined only by the DDF parameters.

3. Influences of gain coefficient on self-similar pulses interaction

It is well-known that the spectrum phase changed induced by group-velocity dispersion (GVD) and the spectrum broadened induced by self-phase modulation (SPM) is caused by the relationship between the phase and time. The instantaneous changed phase means that the center pulse frequency is different from the edge frequency, the relationship between the difference and the time is defined as chirp, as Eq. (2) gave out. Here we first study the influences of the gain coefficient of the DDF on self-similar pulses propagation.

3.1. The chirp characteristic when g_0 remain constant

We launch a pair of Gaussian pulses with the center wavelength $\lambda_0 = 1550$ nm, separated by a time-delay $\Delta T = 5$ ps and the initial phases difference $\theta = \pi$ into ND-DDF. Each pulse has pulse energy of 45 pJ and the full width at half maximum TFWHM of 1.0 ps, resulted in the half-width $T_0 = T_{FWHM}/(2\sqrt{\ln 2}) = 0.6$ ps. The parameters of ND-DDF are as follows: $\beta_2 = 1.35\ \text{ps}^2\ \text{km}^{-1}$, $\gamma = 3.6\ \text{W}^{-1}\ \text{km}^{-1}$ and g_0 is considered to have a constant value of $0.022\ \text{m}^{-1}$. These conditions lead to dispersion length $L_D = T_0^2/\left|\beta_2\right| = 267.2$ m and nonlinearity length $L_{NL} = 1/(\gamma P_0) = 6.6$ m, yielding the order $N = \sqrt{L_D/L_{NL}} \approx 6$, which means when the fiber length L is equal to L_D, dispersion and nonlinearity act together as the pulses propagates along the fiber.

The pulses evolution in the ND-DDF within $z = L_D$ is showed in Fig. 1(a), and the chirp evolution in three-dimension is plotted in Fig. 1(b), as well as the chirp evolution in two-dimension shown in Fig. 1(c).

As seen from Fig. 1(a), an oscillation happens inside the overlap region at the length of L_D, and the interaction effect will be stronger as the fiber length increasing, resulted in a train of asymptotic dark solitons [9]. This phenomenon can be explained from the point of view of chirp. As the interacting of self-similar pulses propagation is under the combined effects of group-velocity dispersion (GVD) and self-phase modulation (SPM), the composite of GVD-induced chirp and SPM-induced chirp is linear with time in the center part of each pulse, while the frequency difference between the overlapping falling and raising edges of the pulses inducing a beating in the resultant signal, resulting in the strong oscillation of the interaction pulses. As shown in Fig. 1(b), the chirp of the self-similar pulses outside the overlap region remains linear, but presents complex nonlinear characteristics in the overlap region, with the nonlinear area broadening as the propagation distance increases.

The chirp evolution trend can be studied more clearly in two-dimension figure. From Fig. 1(c), the chirp of the single self-similar pulse is linear in the center, which follows Eq. (2), and the range of the linear part broadens accordingly with the pulse temporal width broadening. This high linear chirp can provide enough linear range to symmetrically broaden pulses, resulting in the perfect self-similar pulses without the edge oscillation outside the overlap area.

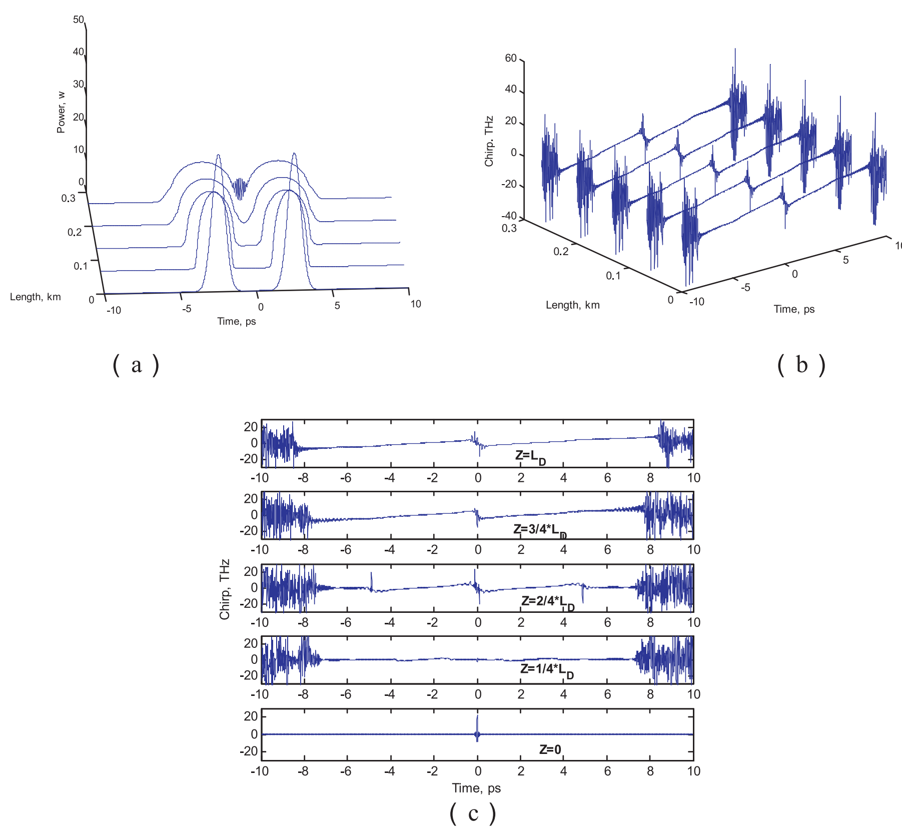

Fig. 1. Waveform evolution (a), chirp evolution in three-dimension (b) and chirp evolution in two-dimension (c) of self-similar pulses in DDF.