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Role of third-order dispersion in chirped Airy pulse propagation in single-mode fibers

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ABSTRACT

The dynamic propagation of the initial chirped Airy pulse in single-mode fibers is studied numerically, special attention being paid to the role of the third-order dispersion (TOD). It is shown that for the positive TOD, the Airy pulse experiences inversion irrespective of the sign of initial chirp. The role of TOD in the dynamic propagation of the initial chirped Airy pulse depends on the combined sign of the group-velocity dispersion (GVD) and the initial chirp. If the GVD and chirp have the opposite signs, the chirped Airy pulse compresses first and passes through a breakdown area, then reconstructs a new Airy pattern with opposite acceleration, with the breakdown area becoming small and the main peak of the new Airy pattern becoming asymmetric with an oscillatory structure due to the positive TOD. If the GVD and chirp have the same signs, the finite-energy Airy pulse compresses to a focal point and then inverses its acceleration, in the case of positive TOD, the distance to the focal point becoming smaller. At zero-dispersion point, the finite-energy Airy pulse inverses to the opposite acceleration at a focal point, with the tight-focusing effect being reduced by initial chirp. Under the effect of negative TOD, the initial chirped Airy pulse disperses and the lobes split. In addition, in the anomalous dispersion region, for strong nonlinearity, the initial chirped Airy pulse splits and enters a soliton shedding regime.

1. Introduction

In 1979, Berry and Balazs first found a non-spreading Airy wave packet solution to the Schrödinger's equation for a free particle within the context of quantum mechanics [1]. However, such an Airy wave packet contains infinite energy, and thus cannot be realized experimentally. In 2007, Siviloglou and Christodoulides made a great breakthrough, extending the model by using the analogy between the optical paraxial wave equation and the potential-free Schrödinger equation. They first introduced the concept of finite-energy Airy beams (FEAB) [2], and then performed the first experiment [3]. The truncated Airy beam is experimentally easy to create, by applying a cubic phase mask across a Gaussian beam in the Fourier plane [3]. Since then, the FEAB has been studied extensively. Though the FEAB is exponentially truncated, they still keep its key characteristics such as self-accelerating, weak diffraction, and self-healing [4–6]. These unique features led the spatial FEAB to particular applications such as laser filamentation [7,8], optically mediated particle clearing [9,10], generating self-bending electron beams [11], and nonlinear optics [12–16]. In addition to spatial Airy beam, the temporal Airy pulse which propagates with its acceleration resulting from a varying group velocity was introduced [17,18]. The FEAP can be translated from spatial FEAB as their analogy between "dispersion in time" and "diffraction in space", and can be obtained through imparting a cubic spectral phase onto an incident pulse by either pulse shaping technique [19] or propagation in cubic dispersive media (at the zero-dispersion wavelength) [20]. The FEAP has various applications, including light bullets generation [20,21], supercontinuum generation [22], soliton manipulation [23], and soliton self-frequency shift [24,25] etc. In addition, the modulational instability [26], the propagation in non-instantaneous cubic medium [27], the Raman effects [28], soliton emitting [29,30], and supercontinuum generation [31], were conducted for FEAPs.

Recently, the dynamic of FEAP propagation under the action of second and third-order dispersion (TOD) has been investigated [32–35].

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The dispersion terms not only impact the shape and time width of propagated pulse [36,37], and also be demonstrated that the presence of cubic dispersion can increase the "depth of penetration" of the Airy wave packet [24]. With large value of positive TOD whether in the normal or anomalous dispersion region, the FEAP propagation experiences an acceleration reversal [33,34]. If the FEAP launched into a single mode fiber (SMF) close its zero-dispersion point in the presence of a strong positive TOD, the pulse dynamics is governed by the TOD. The Airy pulse reaches focal point, then undergoes an inversion, and finally propagates with an opposite acceleration. At the focal point, the pulse is concentrated in a very narrow and intense light spot [33]. The FEAP propagation in media exhibiting Kerr nonlinearity, group velocity dispersion (GVD), TOD [34] and higher order effects [33] are analyzed. With the presence of TOD, the airy pulses can evolve into solitons in abnormal dispersion region [34]. During the nonlinear propagation of a FEAP, TOD and self-steepening (SS) effects slow down the Raman-induced frequency shift [38].

For pulses emitted from laser sources are often chirped and the chirp can also be imposed externally. The chirped pulse is particularly useful in pulse compression or amplification [39,40], supercontinuum generation [41] and filamentation [42]. More recently, the effect of initial frequency chirp has been considered on Airy pulse propagation [43,44]. The sign of chirp parameter C plays a critical role in FEAP propagation considering the action of GVD. Whether the chirped Airy pulse experiences an acceleration reversal depends on the combined sign of the second-order dispersion and chirp [43]. The compression mechanism of femtosecond chirped FEAP is also analyzed in a silicon-on-insulator (SOI) waveguide under fourth-order dispersion (FOD) [44]. In this paper, we study the femtosecond initial chirped Airy pulses propagation dynamics under the action of TOD in both normal and anomalous dispersion region of optical fibers, trying to reveal the different phenomena resulted from the TOD.

2. Theoretical model

The evolution of light pulses in single-mode fiber is governed by the nonlinear Schrödinger equation (NLSE). To simplify the model and broaden the applicability of the results, we normalize the NLSE by introducing two dimensionless variables: the temporal coordinate T is normalized to the incident pulse width T_0, propagation distance Z is measured in units of the dispersion length $L_D = T_0^2/|\beta_2|$, where β_2 is the GVD parameter. And then we can write the NLSE in the normalized form [45]

$$i\frac{\partial U}{\partial Z} - \frac{1}{2}s\frac{\partial^2 U}{\partial T^2} - i\frac{1}{6}\delta_3\frac{\partial^3 U}{\partial T^3} + N^2|U|^2U = 0 \tag{1}$$

where the amplitude U is normalized to $\sqrt{P_0}$, where P_0 is the peak power of the incident pulse. The coefficient s governs the effect of group-velocity dispersion (GVD), with $s = +1 (s = -1)$ denoting normal (anomalous) GVD. The coefficient $\delta_3 = \beta_3/|\beta_2| T_0$ governs the effect of TOD, where β_3 is the TOD parameter. The coefficient $N = \sqrt{\gamma P_0 T_0^2/|\beta_2|}$ represents the strength of the Kerr nonlinearity, where γ is the nonlinear parameter.

The input Airy pulse profile is defined as:

$$A(T, Z = 0) = Ai(T)\exp(aT)\exp\left(-iCT^2\right) \tag{2}$$

where $0 < a < 1$ $0 \ll$ a $\ll 1$ is the decay factor. The airy pulse with a multi-peak structure, the width of the main lobe of the Airy pulse T_0 is usually used as a temporal scale [21,43].

3. Numerical results

3.1. Propagation of chirped Airy pulse at zero-dispersion point

If the pulse wavelength nearly coincides with the zero-dispersion wavelength of fiber or the ultrashort pulse with the width in the femtosecond range, it is necessary to include the δ_3 term in Eq. (1) for TOD effect play a significant role. We model pulse propagation using the split step Fourier method algorithm which is based on numerical solutions of the Eq. (1). This numerical method is chosen due to its high efficiency in simulating one-dimensional pulse propagation [43].

When the propagation dynamics is dominated by the positive TOD term ($\delta_3 > 0$) in Eq. (1), the initial unchirped FEAP reaches a focal point, then undergoes inversion, and propagates with an acceleration that is opposite in sign (Fig. 1(b)). Pass through the focal point, the propagation dynamics is similar to that of Gaussian pulses in fibers with TOD [42,43]. For FEAP imposed chirp with opposite sign, such as $C = -0.5$ and $C = 0.5$ shown in Fig. 1(a) and (c), the initial chirped FEAP first undergoes slight compression and then inverses to the opposite acceleration at the focal point like the dynamics of unchirped FEAP as seen in Fig. 1(b), with the distance to the focal point being reduced. Increasing the value of the initial chirp, the intensity of the pulse decreases, shown in Fig. 1(d). In addition, the maximum normalized intensity I_{max} of initial unchirped Airy pulse reaches the largest value at about $Z = 2$, as seen in Fig. 1(e). At this point, the intensity of the Airy pulse is compressed to the largest value and then the pulse begins to inverse. For initial chirped FEAPs, the tight-focusing effect is reduced by initial chirp. Increasing the distance, I_{max} tends to increase and then decrease with slight frequency oscillation, as seen in Fig. 1(e). With increase of the initial chirp parameter, the distance to the focal point decreases (Fig. 1(e)). When the propagation dynamics is dominated by the negative TOD, the lobes of the initial chirped FEAP split and the main lobe construct a new Airy pattern with the same acceleration irrespective of the sign of initial chirp.

3.2. Propagation of chirped Airy pulse in the normal dispersion region

If the action of second- and third-order dispersion terms have comparable strengths, the focal point extends to a finite area where the initial unchirped FEAP experiences an acceleration reversal [42], as seen in Fig. 2(j). For initial chirped Airy pulse, both the initial chirp parameter and the TOD affect its propagation.

Fig. 2 displays the temporal dynamics of the FEAPs with initial chirp for different values of TOD in normal dispersion regime. In the case of GVD parameter s and chirp C have the opposite signs ($sC < 0$), the chirped Airy pulse first undergoes slight compression and then its Airy pattern breaks down. After passing through a breakdown area, the pulses reconstruct a new Airy pattern with opposite acceleration [42]. Fig. 2(c) displays the temporal evolution of negatively chirped Airy pulse in absence of TOD effects. When the initial FEAP imposed a negative chirp ($C < 0$), such as $C = -0.5$ shown in Fig. 2(a)–(e), under the action of different TOD, the dynamics of the FEAPs are different. In the case of positive TOD, such as shown in Fig. 2(d) and (e), the temporal dynamics of negatively chirped Airy pulse is similar to that in the absence of TOD (Fig. 2(c)). The negatively chirped FEAP undergoes inversion and reconstructs a new Airy pattern. With increasing the value of TOD parameter δ_3, the main peak of the new Airy pattern converges, the breakdown area becomes smaller and width of the lobes narrow. But in the presence of negative TOD, such as shown in Fig. 2(a) and (b), the temporal dynamics of negatively chirped Airy pulse maintains its shape and do not inverse its acceleration. Compared with the initial unchirped Airy pulse [Fig. 2(f)], the lobes of initial negative chirped FEAP diverges.

If the FEAP imposed a positive chirp ($C > 0$), such as $C = 0.5$, the GVD parameter s and chirp C have the same signs ($sC > 0$). The Airy pulse always disperse during the propagation in the absence of TOD, as seen in Fig. 1(m). In the case of negative TOD, the contribution of negative TOD disperses the FEAP [Figs. 2(k) and (l)]. If the TOD is positive, though $sC > 0$, the pulse pattern breaks up and reconstruct a new Airy pattern with opposite acceleration, as seen in Fig. 2(n) and (o).

Fig. 3 shows the intensity distribution of different chirped FEAPs at propagation distance $Z = 6$ of different TOD parameter δ_3. As shown in