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Dynamic propagation of symmetric Airy pulses with initial chirps in an optical fiber

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ABSTRACT

We analytically and numerically investigate the propagation dynamics of initially chirped symmetric Airy pulses in an optical fiber. The results show that the positive chirps act to promote the interference in generating a focal point on the propagation axis, while the negative chirps tend to suppress the focusing effect, as compared to conventional unchirped symmetric Airy pulses. The numerical results demonstrate that the linear propagation of chirped symmetric Airy pulses depend considerably on the chirp parameter and the primary lobe position. In the anomalous dispersion region, positively chirped symmetric Airy pulses first undergo an initial compression, and reach a foci due to the opposite acceleration, and then experience a lossy inversion transformation, and come to the opposite facing focal position. The impact of truncation coefficient and Kerr nonlinearity on the chirped symmetric Airy pulses propagation is also disclosed separately.

1. Introduction

The Airy wave packet was first found as a solution to the Schrödinger equation for a free particle in 1979 [1]. Since the first experimental observation of accelerating finite energy Airy beams equipped with unique characteristics, such as self-acceleration, quasi-diffraction free, and self-reconstruction [2–4], great attention has been devoted to the propagation, manipulation, generation, and application in a dispersive or in free space [5–8]. Spatially truncated Airy beams have been applied in creating curved plasma channels [9,10], particle clearing [11], optical micromanipulation [12], and are capable of recovering from spatial obscurations due to their energy redistribution mechanism [4]. Airy beams are also useful for imaging in scattering media [13], all optical routing [14], and light bullets generation [15–17].

As the temporal dispersive equation and the spatial diffraction equation are isomorphic [18], attributes of spatial Airy beams are directly translated to the corresponding temporal Airy pulses. In spite of similar mathematical descriptions of Airy pulses and Airy beams, there remains an important physical difference between temporal and spatial accelerations. That is, an accelerating beam bends its trajectory in space, whereas only the acceleration of Airy pulse corresponds to a change in the velocity of the intensity peak of the pulse that manifests as self-acceleration or self-deceleration depending on its tails behind or in front of the main peak [19,20]. Airy pulses, whose temporal field envelope is described by an Airy function, can be formed by virtue of a cubic spectral phase imposed via either third-order dispersion or a pulse shaper. Extensive theoretical and numerical studies have been performed on the study of linear and nonlinear dynamics of Airy pulses under second- and/or third-order dispersion with or without the presence of Kerr nonlinearity [21–24]. The experimental and numerical investigations on supercontinuum generation have been carried out by using a femtosecond Airy pulse in photonic crystal fiber [25]. The propagation of decelerating Airy pulses in non-instantaneous cubic medium is investigated both theoretically and numerically [26]. Furthermore, periodic dispersion modulation [27], initial quadratic phase modulation [28] and the interaction with solitons [29] have also been investigated.

In practice, the laser system based on the chirped pulse amplification technology involves chirp in pulse generation, propagation and amplification. Consequently, the pulses emitted from laser sources are often chirped. Frequency chirp can also be imposed externally and is expected to engineer the laser pulse propagation. It is demonstrated that the frequency chirp can influence laser self-focusing significantly [30,31]. Initial frequency chirp have also been used to control supercontinuum generation [32], filamentation [33,34] and pulse compression [35]. The electron density and energy deposition in the filament channel can be tuned by changing input chirp of laser pulse [36]. More

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recently, Janus waves are introduced in the case of accelerating ring-Airy beams, which achieve the appearance of two focal regions after the action of a focusing lens [37]. Dual autofocusing properties of chirped circular Airy beams with a quadratic phase are investigated analytically and numerically [38]. Meanwhile, Zhang et al. investigated the effect of initial frequency chirp on Airy pulse propagation in an optical fiber, and found that it travels with an opposite acceleration after an initial compression phase if both group-velocity dispersion and chirp have the opposite signs [39]. And the dynamics of a chirped Airy pulse in a fiber under the action of third-order dispersion also have been investigated [40].

Inspired by these pioneers researches, in this paper, we are devoted to the study of propagation properties of symmetric Airy pulses imposed an initial frequency chirp, and disclosed the novel characteristics of multi-collisions generation. The paper is structured as follows. In Section 2, we briefly introduce the theoretical model and the analytical results. In Section 3, we discuss the impact of the chirp parameter, the primary lobe position and nonlinear coefficient for the occurrence of collisions in numerically. Section 4 summarizes the results of the work.

2. Theoretical model and analysis

The propagation of optical pulses in an optical fiber can be described by the well-known nonlinear Schrödinger equation (NLSE). To simplify the model and broaden the applicability of the results, we normalize all the variables including the light field that is normalized so that its peak input value is unity. The coordinate are normalized as follows: temporal coordinate T is normalized to incident pulse width T_0, propagation distance Z is measured in units of the dispersion length, where β_2 is the group velocity dispersion (GVD) parameter $L_D = T_0^2/|\beta_2|$. The normalized NLSE then takes the form as [18]

$$i\frac{\partial U}{\partial Z} - \frac{sgn(\beta_2)}{2}\frac{\partial^2 U}{\partial T^2} + N^2|U|^2U = 0. \tag{1}$$

Here the parameter $N = \sqrt{\gamma T_0^2 P_0/|\beta_2|}$, represents the strength of Kerr nonlinearity, where P_0 and γ are the input peak power and the nonlinear coefficient respectively. The width of the main lobe of Airy pulse is usually used as a temporal scale.

The linear propagation of Airy pulse is studied by setting N=0 in Eq. (1). $U(Z,T)$ satisfies the following liner partial differential equation as

$$i\frac{\partial U}{\partial Z} - \frac{1}{2}\frac{\partial^2 U}{\partial T^2} = 0. \tag{2}$$

By the means of the Fourier Transform method, the general solution of Eq. (2) is given as

$$U(Z,T) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\widetilde{U}(0,\omega)\exp\left(i\frac{\omega^2 Z}{2}\right)\exp(-i\omega T)d\omega. \tag{3}$$

where $\widetilde{U}(0,\omega)$ is the Fourier transform of the incident field at $Z = 0$ and is obtained by using

$$\widetilde{U}(0,\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty}U(0,T)\exp(i\omega T)dT. \tag{4}$$

In this paper, the symmetric Airy pulses with an initial chirp is taken into consideration:

$$U(Z=0,T) = [\Phi(T_B+T) + \Phi(T_B-T)]\exp(-iCT^2). \tag{5}$$

where $\Phi(Z=0,T) = Ai(T)\exp(aT)$ represents finite energy Airy pulse [2]. a is the truncated coefficient, $T_B > 0$ is the primary lobe position and C represents the initial chirps.

Substituting Eq. (5) into (3), the evolution of symmetric Airy pulses can be approximately described by:

$$\begin{aligned}|U(Z,T)| = \Bigg|&\frac{1}{\sqrt{1-2CZ}}Ai\left(\frac{T_B+T-2CT_BZ}{1-2CZ} - \frac{Z^2}{4(1-2CZ)^2} + \frac{iaZ}{1-2CZ}\right)\\ &\times exp\left(\frac{a(T_B+T-2CT_BZ)}{1-2CZ} - \frac{aZ^2}{2(1-2CZ)^2}\right)\\ &+\frac{1}{\sqrt{1-2CZ}}Ai\left(\frac{T_B-T-2CT_BZ}{1-2CZ} - \frac{Z^2}{4(1-2CZ)^2} + \frac{iaZ}{1-2CZ}\right)\times exp\left(\frac{a(T_B-T-2CT_BZ)}{1-2CZ} - \frac{aZ^2}{2(1-2CZ)^2}\right)\Bigg|.\end{aligned} \tag{6}$$

where the condition of $1-2CZ$ is unequal to 0.

As expected the resulting amplitude distribution is the result of the interference of the two waves. From Eq. (6), under the condition of $(1-2CZ \neq 0)$, it is easy to be deduced that the symmetric parabolic trajectories of chirped symmetric Airy pulses follows the modified path

$$\begin{aligned}T_1 &= T_B - \frac{Z^2}{4(1-2CZ)} - 2CT_BZ,\\ T_2 &= -T_B + \frac{Z^2}{4(1-2CZ)} + 2CT_BZ.\end{aligned} \tag{7}$$

Based on Eq. (7), we further arrived at two special positions on propagation axis by setting $T_1 = T_2 = 0$ as follows

$$Z_1 = \frac{2\sqrt{T_B}}{1+4C\sqrt{T_B}}, \quad Z_2 = \frac{2\sqrt{T_B}}{-1+4C\sqrt{T_B}}. \tag{8}$$

Eqs. (6)–(8) will be able to apply for estimating some dynamical features of chirped symmetric Airy pulses. In fact, when compared to numerical solution latter, we easily deduce that the parameter Z_1 approximately corresponds to the first focus position, while the parameter Z_2 just corresponds to the second focus position for the chirped symmetric Airy pulses on linear propagation. When the chirp parameter equals to zero, the initial focus position $Z_0 = 2\sqrt{T_B}$. When $C\sqrt{T_B} < -1/4$, no foci can be obtained as $Z_1 < 0$; when $C\sqrt{T_B} > 1/4$, two focus will be presented since $Z_2 > 0$; when $-1/4 < C\sqrt{T_B} < 1/4$, only one fucus point can be reached since $Z_1 > 0$, $Z_2 < 0$. From the result of Ref. [37] and our analysis, as long as $Z_0 \neq 0$, we may obtain the relationship among these fucus positions as follows

$$\frac{1}{Z_0} + \frac{1}{Z_2} = -\frac{1}{Z_0} + \frac{1}{Z_1} = 2C. \tag{9}$$

Here, the parameter $C_{cr} = 1/(4\sqrt{T_B})$ is defined as a critical chirp value. According to the sign of the chirp parameter C, from Eq. (8), we can directly arrive at some interesting conclusions as follows: When $C = 0$, it present the evolution of unchirped symmetric Airy pulse, there exists the real focus position at $Z_0 = 2\sqrt{T_B}$ and the virtual collision point lies on the opposite side (at $-Z_0$). When $C > 0$, the real focus point always occurs since Z_1 is positive value whatever the magnitude of the chirp parameter C. The second foci will occur only if $C > C_{cr} = 1/(4\sqrt{T_B})$, while it is entirely suppressed since $Z_2 < 0$ if $0 < C < C_{cr}$. Moreover, one notes that both the focus positions Z_1 and Z_2 monotonously decrease with the increase of parameter C, implying that the large chirps may lead to the enhanced focusing effect. When the parameter T_B increases, the first focus position Z_1 monotonously increases while the second focus position Z_2 monotonously decreases. Therefore, the length between the two foci is accordingly decreased. When $C < 0$, the striking feature is that the chirped symmetric Airy pulses will not exhibit the second focusing effect since Z_2 is always negative value whatever the magnitude of the chirp parameter C. However, there may exist the first foci if $-C_{cr} < C < 0$. Therefore, the focusing effect will be completely suppressed since $Z_1 < 0$ if $C < -C_{cr}$.

Fig. 1 shows the unchirped (left column) and positively chirped