Optik 152 (2018) 61–68

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Full length article

Evolution of finite-energy Airy pulse interaction with high-power soliton pulse in optical fiber with higher-order effects

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ARTICLE INFO

Article history:
Received 29 July 2017
Received in revised form
18 September 2017
Accepted 28 September 2017

Keywords:
Finite-energy Airy pulse
High-order effects
Shedding soliton
Evolution

ABSTRACT

When a low-power finite-energy Airy pulse (FEAP) and a high-power soliton pulse simultaneously propagate in an optical fiber, we numerically study the evolution of the FEAP affected by higher-order effects, including third-order dispersion (TOD), Raman scattering and self-steepening (SS). It is found that shedding solitons are generated from the FEAP due to the effect of cross-phase modulation (XPM). The TOD only affects the center position of the shedding soliton, but does not change the spectrum structure. The truncation coefficient of a FEAP, TOD and SS can be used to manipulate the Raman-induced frequency shift (RIFS). It is demonstrated that the RIFS is suppressed obviously by both positive TOD, SS and a small truncation coefficient, but the RIFS is enhanced by the negative TOD and a larger truncation coefficient. Further, we comparatively study the simultaneous contributions of TOD, Raman, and SS to the evolution of a FEAP and a Sech pulse, respectively. It is shown that the FEAP generates some static solitons besides the conventional Raman soliton and the whole spectrum is broadened that extended towards to the blue-shifted side besides the conventional red-shifted components. Our results indicate that the FEAP has potential application in supercontinuum generation and broadband sources.

1. Introduction

A nonspreading solution called an Airy wave packet was first found to the potential-free Schrödinger equation within the context of quantum mechanism in 1979 [1]. However, it is difficult to experimentally synthesize Airy optical waves with infinite energy for all practical purposes. Until 2007, Siviloglou and co-workers first experimentally demonstrated the concept of finite-energy Airy beam (FEAB), which is an extended model for the generation of Airy beam [2]. Because the FEAB has some unique characteristics, such as weak diffraction [3,4], self-accelerating [5–7] and self-healing [8], more and more researchers focus on the generation, propagation, control and application of a FEAB in a dispersive medium or free space [9–14]. In addition, these unusual features cause tremendous potential applications of the FEAB in many areas, including plasma channel [15], particle clearing [16], spatiotemporal light bullets [17] and atmospheric communication [18].

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https://doi.org/10.1016/j.ijleo.2017.09.113

For the linear and nonlinear dynamic propagation of a FEAB, many researchers have studied extensively in theory and experiment [19–30]. Because the temporal dispersion term is similar to the spatial diffraction term in the nonlinear Schrödinger equation (NLSE) [31], the finite-energy Airy pulse (FEAP) is introduced. The attributes of the spatial FEAB is directly translated to the corresponding temporal FEAP. Although the FEAB and FEAP have similar mathematical descriptions, there remains an important physical difference between temporal and spatial accelerations. Because the FEAP can be generated by virtue of a cubic spectral phase imposed via either third-order dispersion or a pulse shaper, a great interest in the FEAP propagating in linear and nonlinear regimes is aroused. For example, the versatile three-dimensional linear light bullets is first realized experimentally by Chong and co-worker [19], which consist of the spatial Bessel beam and temporal Airy pulse, and it is found that the linear evolution of an Airy pulse does not depend on the material. Subsequently, many researchers theoretically and numerically investigate the linear and nonlinear dynamics of a FEAP under the condition of the second/third-order dispersion or periodic dispersion modulation with or without the Kerr nonlinearity [32–35]. Furthermore, the effect of pulse chirp on the propagation of a FEAP [36], modulation instability [37], supercontinuum generation [38] and manipulation of Raman-induced frequency shift by a FEAP [39–43] have been studied. Generation of optical soliton, such as induced soliton [44], high order soliton [45], dark soliton [46] and vector soliton [47,48], is an important phenomenon and has potential application when a laser pulse propagates in an optical fiber, thus Fattal et al. have studied the generation of shedding soliton from Airy pulse during nonlinear propagation [49].

It is commonly accepted that the high-order effects, including the third-order dispersion (TOD), Raman scattering and self-steepening (SS) will become important if the pulse width of a laser pulse is close to or <1 ps [31], thus it is necessary to consider the influence of high-order effects on the nonlinear propagation of an ultrashort laser pulse. Recently, Zhang et al. have numerically investigated the influence of higher-order effects on the dynamic propagation of a single FEAP in an optical fiber [50]. When a FEAP and a soliton pulse are interaction with each other, a shedding soliton will be generated and can be manipulated by varying the parameters of the soliton pulse [51,52]. Next, the interactions of the tail-leading and tail-trailing FEAP [53] and the interactions of a FEAP and a dark soliton [54] have been investigated. To the best of our knowledge, the above mentioned previous works have studied the propagation of a single FEAP or a class FEAP with two components. For the pulses with two different components, such as a pulse consists of a FEAP and a soliton pulse, the interactions between pulses are based on a single NLSE, thus the control and distinction between pulses are unclear. In order to solve this problem, we investigate the simultaneous propagation of a low-power FEAP and a high-power soliton pulse in an optical fiber, whose interactions are based on two coupling NLSEs with cross-phase modulation (XPM). In fact, simultaneous propagation of a strong light and a weak light is different from the propagation of a single light, whose propagation characteristics and interaction mechanism will be more complicated.

In this paper, the temporal and spectrum evolution of a FEAP are investigated numerically in the presence of higher-order effects when a low-power FEAP and a high-power soliton pulse simultaneously propagate in an optical fiber. The results may provide a deeper understanding in the interactions between pulses and the interactions between different higher-order effects. This paper is organized as following. In Section 2, we briefly introduce the basic equation that describes the propagation of a low-power FEAP and a high-power soliton pulse. In Section 3, influence of TOD, Raman, and the combined action of Raman together with TOD or SS on the nonlinear propagation of a FEAP are analyzed and discussed in detail. In addition, suppression or enhancement of the Raman-induced frequency shift (RIFS) affected by the truncation coefficient of a FEAP, TOD and SS are analyzed. Conclusions are presented in Section 4.

2. Theoretical model

Propagation of two laser pulses in a nonlinear medium is governed by the two coupled nonlinear Schrödinger equations (NLSEs) [55,56]. The first equation is the NLSE of a high-power soliton pulse, and the second equation is the NLSE of a low-power FEAP whose power is lower than the high-power soliton pulse. For simplicity, the two laser pulses are assumed as the same wavelength, so the two coupled NLSEs without losses are written as

$$\begin{cases} \dfrac{\partial P}{\partial z} + \dfrac{i\beta_2}{2}\dfrac{\partial^2 P}{\partial t^2} - \dfrac{\beta_3}{6}\dfrac{\partial^3 P}{\partial t^3} = i\gamma\left[|P|^2P + (2-f_R)|U|^2P + \dfrac{i}{\omega_0}\dfrac{\partial}{\partial t}\left(|P|^2P\right) - T_R P\dfrac{\partial |P|^2}{\partial t}\right] \\ \dfrac{\partial U}{\partial z} + \dfrac{i\beta_2}{2}\dfrac{\partial^2 U}{\partial t^2} - \dfrac{\beta_3}{6}\dfrac{\partial^3 U}{\partial t^3} = i\gamma\left[|U|^2U + (2-f_R)|P|^2U + \dfrac{i}{\omega_0}\dfrac{\partial}{\partial t}\left(|U|^2U\right) - T_R U\dfrac{\partial |U|^2}{\partial t}\right] \end{cases}, \tag{1}$$

where β_2, β_3 and γ are the group velocity dispersion (GVD), TOD and nonlinear coefficient of the high-power soliton pulse and low-power FEAP, respectively. The parameters f_R is the fractional contribution of the delayed Raman response to nonlinear polarization, which is set as $f_R = 0.18$. The term proportional to $\omega_0^{-1} = s$ is responsible for SS. The term proportional to T_R has its origin in the delayed Raman response, which is responsible for RIFS. For $|U|^2/|P|^2 << 1$, $|U|^2P$ is relatively smaller than $|P|^2P$ and $|U|^2U$ is relatively smaller than $|P|^2U$, so the terms of $|U|^2P$ and $|U|^2U$ in Eq. (1) can be neglected. The initial high-power soliton pulse is written as

$$P(z=0,t) = A_{p0}\,\mathrm{sech}(t), \tag{2}$$