Optics Communications 316 (2014) 127–131

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Soliton manipulation using Airy pulses

Wangyang Cai [a,b,c,*], Matthew S. Mills [b], Demetrios N. Christodoulides [b], Shuangchun Wen [a]

[a] Key Laboratory for Micro/Nano Opto-Electronic Devices of Ministry of Education, College of Information Science and Engineering, Hunan University, Changsha 410082, China

[b] CREOL/The College of Optics & Photonics, University of Central Florida, 4000 Central Florida Boulevard, Orlando, FL 32816-2700, USA

[c] School of Computer and Communication Engineering, Changsha University of Science and Technology, Changsha 410004, China

ARTICLE INFO

Article history:
Received 17 August 2013
Received in revised form
28 November 2013
Accepted 30 November 2013
Available online 11 December 2013

Keywords:
Soliton
Airy pulse
Nonlinear optics

ABSTRACT

We show that a weak Airy pulse can be used to manipulate the dynamics of an optical soliton when propagating at a different wavelength. Our results indicate that an Airy wave packet is considerably more effective in controlling the arrival time of a soliton than a corresponding Gaussian pulse. The nature of these interactions is systematically explored as a function of the initial parameters used and is illustrated using pertinent examples.

1. Introduction

Controlling light by light using nonlinear interactions has always been an active area of research, and over the years, several directions have been pursued to meet this goal [1–3]. One of the most promising avenues is to make use of cubic nonlinearities in optical fibers where two co-propagating pulses are known to interact via cross-phase modulation (XPM) [4]. Many different approaches exist to exploit this effect for an all-optical control of optical light pulses [5]. All-optical switching based on XPM has been discussed in [6]. The logic gates based on XPM in the highly nonlinear fiber have been reported [7,8]. Intermittent injection of cw light pulses is used for timing solitons [9]. The evolution of the signal spectrum and the temporal location of the signal pulse can be controlled by choosing an appropriate pulse width, initial delay, amplitude, and walk-off between signal and pump pulses [10,11]. In each of these methods, the ability to command a weak signal pulse requires the use of a stronger control pulse. To this end, dispersive wave packets which allow for the manipulation of solitons at the optical event horizon have been proposed [12]. A dispersive wave packet and a fundamental soliton experience a strong light-light interaction at the group-velocity horizon in an optical fiber. However when such a wave packet approaches a high power soliton by group velocity dispersion, the peak intensity of the dispersive wave decreases. Naturally, we can utilize a beam that is resilient to the effects of dispersion, such as an Airy pulse [13–16]. Because of its non-dispersive characteristic, the intensity of Airy pulse is larger than dispersive wave when they reach the signal pulse. This would increase the interaction between the two wave fronts. So far, these self-accelerating pulses (beams) have been investigated in linear and nonlinear region [17–19]. Airy–soliton interactions at the same center wavelength in Kerr media have been studied [20], but further analysis at different wavelengths is lacking.

In this paper, we explore Airy–soliton pulse interactions with different center wavelengths. We show that an Airy pulse cannot pass over the soliton at the optical event horizon and will experience a large frequency/time shift. When compared with a Gaussian pulse of equivalent power, we conclude that the Airy pulse induces a greater nonlinear interaction resulting from the extended amount of XPM. This provides the potential to control the properties of a strong soliton with another weaker pulse.

2. Model

To begin, we consider two differently colored light pulses propagating in a single-mode fiber. If fiber losses are neglected for simplicity, the slowly varying envelopes for the signal ψ_S, and control pulse ψ_C, obey a coupled nonlinear Schrödinger equation [4]:

$$\begin{aligned}&\frac{\partial\psi_S}{\partial Z}+\frac{i}{2}\beta''_S\frac{\partial^2\psi_S}{\partial T^2}=i\gamma_S[|\psi_S|^2+2|\psi_C|^2]\psi_S\\&\frac{\partial\psi_C}{\partial Z}+\frac{i}{2}\beta''_C\frac{\partial^2\psi_C}{\partial T^2}-d\frac{\partial\psi_C}{\partial T}=i\gamma_C[|\psi_C|^2+2|\psi_S|^2]\psi_C\end{aligned} \tag{1}$$

The model given in Eq. (1) includes cross- and self- phase modulation, group velocity dispersion, and pulse walk-off. Here,

* Corresponding author. Tel.: +86 13787046086.
E-mail address: cwy@hnu.edu.cn (W. Cai).

0030-4018/$ - see front matter
http://dx.doi.org/10.1016/j.optcom.2013.11.057

$Z=z/L_d$ is the propagation coordinate normalized to the dispersion length, $L_d=t_0^2/|\beta''_S|$, $T=(t-Z/v_{gs})t_0^{-1}$ is the normalized temporal coordinate, $d=v_{gs}^{-1}-v_{gc}^{-1}$ is a measure of group-velocity mismatch, β''_S and β''_C are the GVD coefficients of the signal and control pulse respectively, and $\gamma_S=n_2\omega_S/cA_{eff}$ and $\gamma_C=n_2\omega_C/cA_{eff}$ are the normalized Kerr coefficients with effective area A_{eff} and coefficient n_2.

For our initial profiles, we simultaneously launch both a fundamental soliton signal pulse (SP) and an Airy control pulse (CP). Then we compare the results with the case of utilizing Gaussian pulse as CP.

$$\psi_S(T,Z=0)=\mathrm{sech}(T-T_S) \quad (2)$$

$$\psi_C(T,Z=0)=rAi(T-T_C)\exp(\alpha(T-T_C))\exp(i\theta) \quad (3)$$

where r is the amplitude ratio of the control to signal pulse, T_S and T_C are the signal/control time delays, α is a truncation coefficient and θ is the relative phase of the control pulse. For our simulations, we model a fluoride glass fiber propagating $t_0=21$ fs wave packets at signal and control pulse frequencies of $\omega_S=0.6$ PHz and $\omega_C=1.8$ PHz [12]; these particular frequency values ensure that the control pulse is normally dispersive while the signal remains in the anomalous regime. The amplitude of the CP is significantly lower than that of the SP. For this material, the signal's pertinent coefficients are $\beta''_S(\omega_S)=-0.229\ \mathrm{fs}^2/\mu m$ and $\tilde{\gamma}_S=0.1\ \mathrm{W}^{-1}/m$ ($\gamma_S=1/2(cn_0\varepsilon_0\tilde{\gamma}_S)$) while the coefficients of CP are $\beta''_C(\omega_C)=0.08\ \mathrm{fs}^2/\mu m$ and $\tilde{\gamma}_C=0.3\ \mathrm{W}^{-1}\mathrm{m}^{-1}$. We note that the time separation between the Airy and soliton wavefronts are chosen to be at least $6t_0$ in order to ensure no initial overlap between the two pulses.

3. Results

We consider the case that the CP slowly passes the signal soliton (SP) with carrier frequencies ω_C and ω_S, respectively. The SP propagates in anomalous dispersion regime that the optical fiber can support the fundamental soliton. The SP and CP launch with no initial overlap. The CP propagates in normal dispersion regime, that the dispersive pulse can approach the soliton by group-velocity dispersion. We choice the Gaussian pulse as the represent of the dispersive wave packet. The pulse widths are the same and are normalized to 1. Fig. 1 show the temporal evolutions for the two cases of the Gaussian pulse (CP) interaction with the signal soliton (the left column) and the Airy pulse (CP) interaction with the signal soliton (the right column). The pertinent coefficients of SP and CP are normalized to the value of the signal one. The normalized nonlinearities are $\gamma_S=1$, $\gamma_C=3$, and the normalized GVD parameters are $\beta''_S=-1$, $\beta''_C=0.35$. The amplitude of CP is lower than SP, that the amplitude ratio r is 0.36. The control pulse is injected prior to the soliton into the fiber with a delay of $20t_0$. The group velocity of the CP is slightly smaller than the group velocity of soliton, the walk-off d is -1.

Fig. 1(a) shows the propagation of Gaussian pulse and the fundamental soliton in the reference frame moving with the soliton. The Gaussian pulse approaches the soliton because of group-velocity dispersion. When the two pulses begin to overlap, XPM builds up. XPM induces frequency shift of their central frequencies [12,21] and preventing the pulses from crossing each other. The soliton behave as an impenetrable barrier. The weak CP is reflected at the leading edge of the strong soliton.

In the case of Airy–soliton interaction, as shown in Fig. 1(b), the evolution of pulses is similar like the case of Gaussian–soliton interaction. The peak intensity of Airy pulse is the same as Gaussian pulse. The truncation coefficient α of Airy pulse is 0.25, that the total energy of Airy pulse is lower than Gaussian. The Airy pulse reaches the soliton and then reflects. But because of the dispersion-free and acceleration characters of the Airy pulse, it expands slower than Gaussian pulse [13] and most of its power is concentrated in the main lobe. The Airy pulse maintains its shape and accelerates to soliton. When the control pulse reaches the soliton, the peak power of the Airy pulse is higher than Gaussian pulse. Because the XPM term in Eq. (1) is related to the intensity of control pulse, so the interaction between Airy pulse and soliton is stronger than Gaussian pulse co-propagate with soliton. The most of the intensity of Airy pulse is reflected, and it affects the soliton pulse strongly. The time shift of soliton interact with Airy is larger than soliton interact with Gaussian, which is shown in Fig. 1(c). This enabling switching of a strong soliton pulse with a lower energy CP.

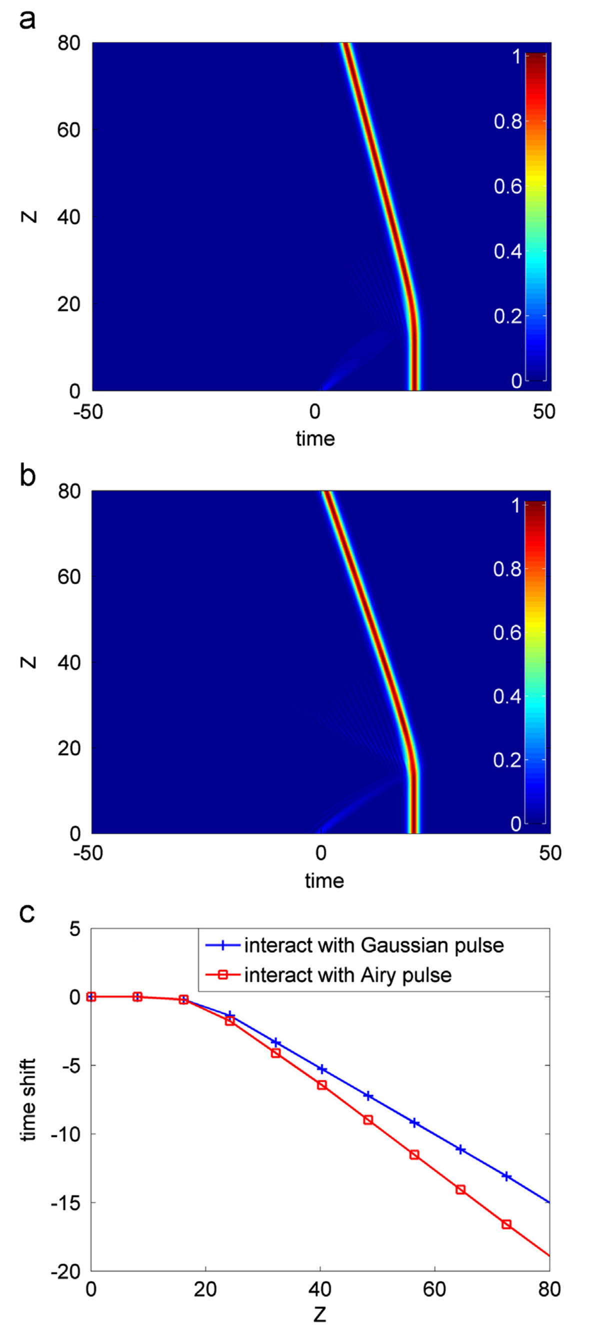

Fig. 1. Evolution of CP and SP: (a) Propagation of weak Gaussian pulse and soliton. (b) Propagation of weak Airy pulse and soliton. (c) Time shift of soliton.