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Soliton manipulation using Airy pulses

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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,

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$Z=z/L_d$ 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.

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

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

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.

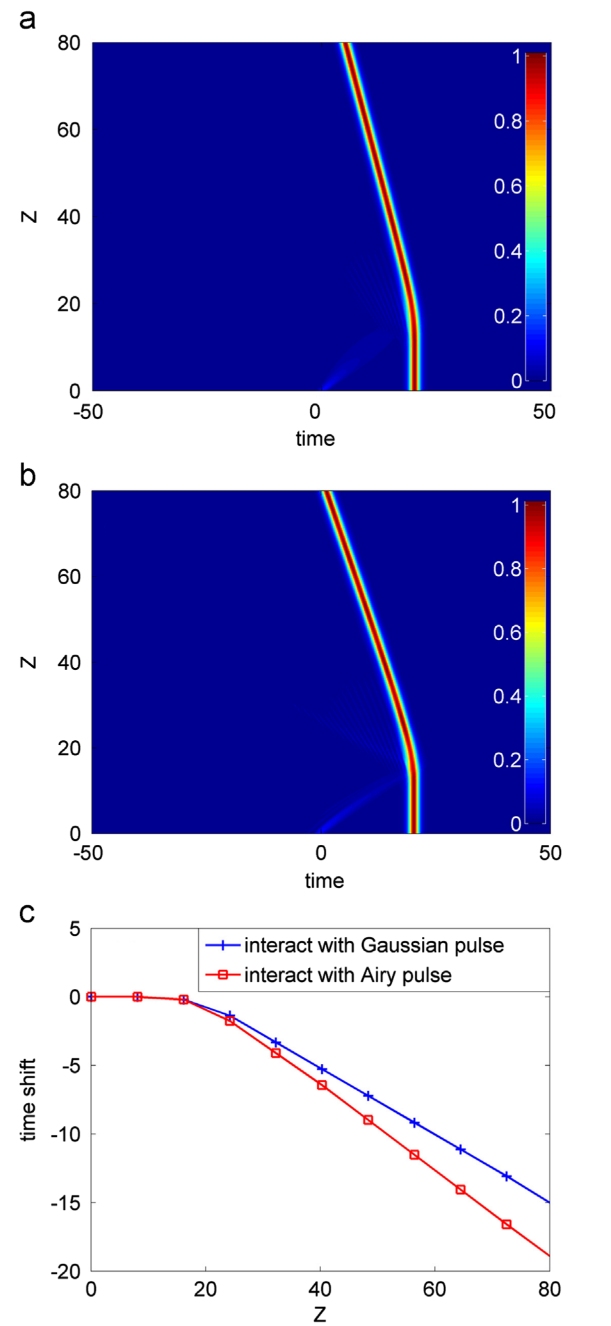

Fig. 1. Evolution of CP and SP: (a) Propagation of weak Gaussian pulse and soliton. (b) Propagation of weak Airy pulse and soliton. (c) Time shift of soliton.

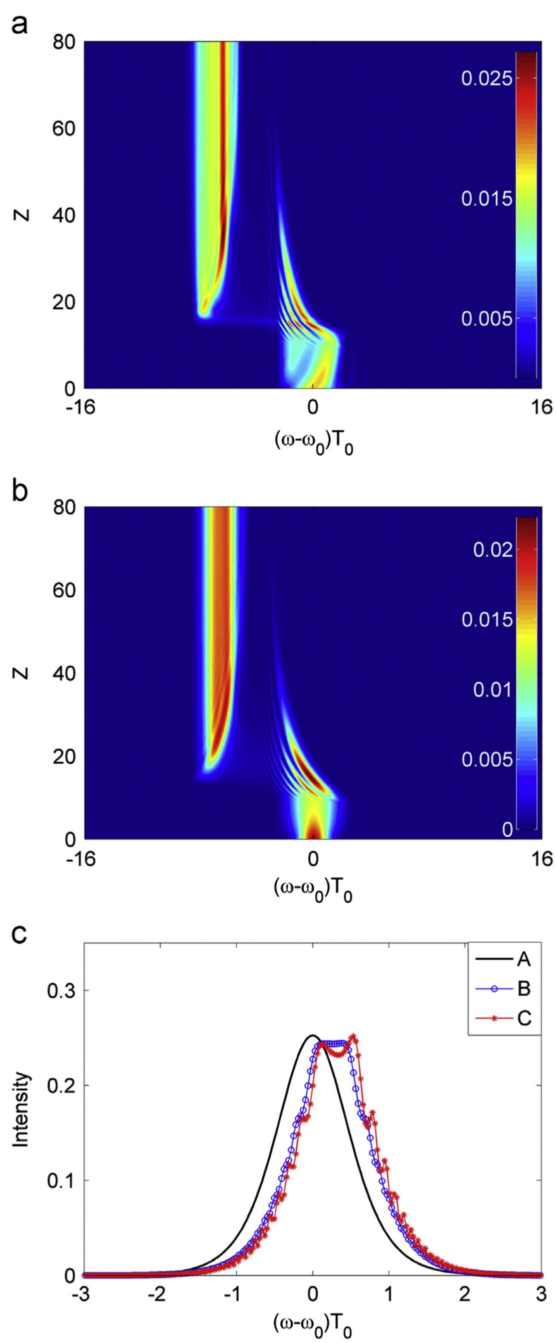

Fig. 2. (a) frequency shift of Airy pulse; (b) frequency shift of Gaussian pulse; (c) frequency shift of soliton: (A) original spectra of soliton; (B) after collision with Gaussian pulse; (C) after collision with Airy pulse.

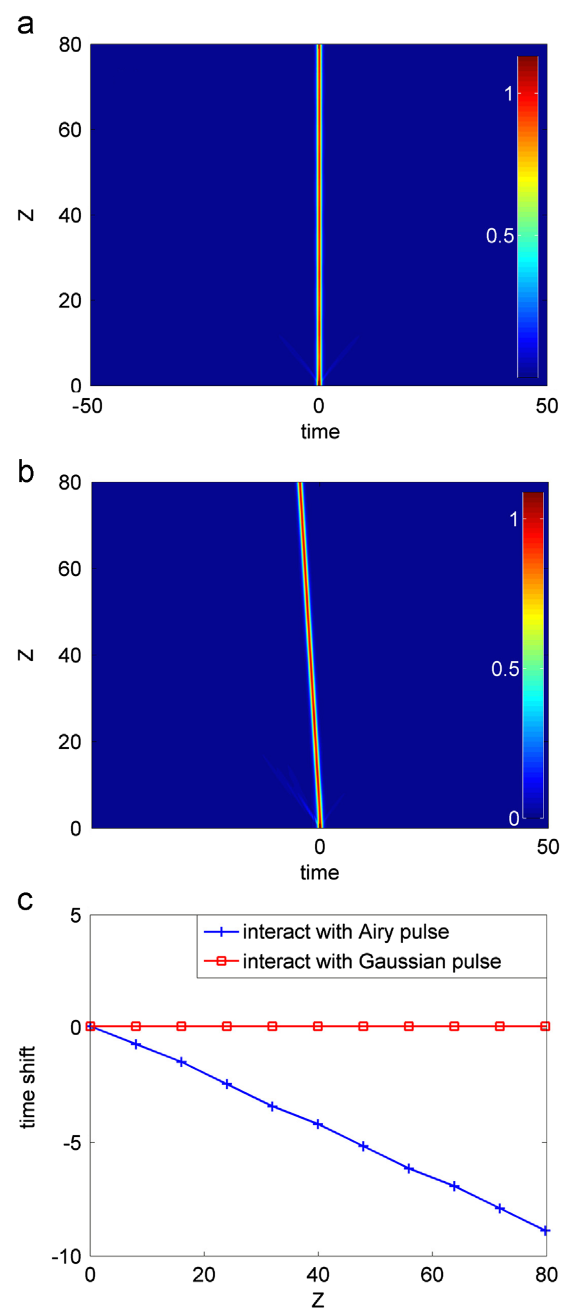

Fig. 3. (a) Evolution of Gaussian pulse and soliton. (b) Evolution of Airy pulse and soliton. (c) Time shift of soliton.

The output spectra of CP and SP are both affected by the reflection process. The soliton frequency is shifted toward the blue, and the central frequency of the CP has a large frequency shift to red. We can see from Fig. 2(c), the frequency shift of the SP is larger when it co-propagates with Airy pulse than with the Gaussian pulse. The CP and SP are both experienced larger shift in the case of Airy–soliton interaction.

The results shown in Fig. 3(a) and (b) correspond to another case that the group velocity for control and signal pulses is assumed to be the same. In this case the carrier frequency of CP is about 1.65 PHz. They are launched without initial time delay so that they overlap initially and continue to do so during their passage through the fiber. While the control pulse is Gaussian pulse, the CP splits into two pulses which are symmetric with respect to the SP. These two pulses influence the SP the same. The soliton keep its straight direction through propagation as shown in Fig. 3(a). If the control pulse is Airy pulse, because of the asymmetric of the energy, the main lobe of the Airy pulse splits, but they are no longer symmetric with respect to the soliton. The soliton resist the most energy of Airy pulse to pass through it and the soliton shifts to the leading side of Airy pulse. Fig. 3(b) shows the evolution of Airy pulse interaction with soliton with no initial time delay. The time shifts of solitons are contrasted in Fig. 3(c). It is clearly that the soliton shift at the beginning when it interacts with Airy pulse, but there is no time shift of soliton in the case of Gaussian–soliton interaction. They behave differently.

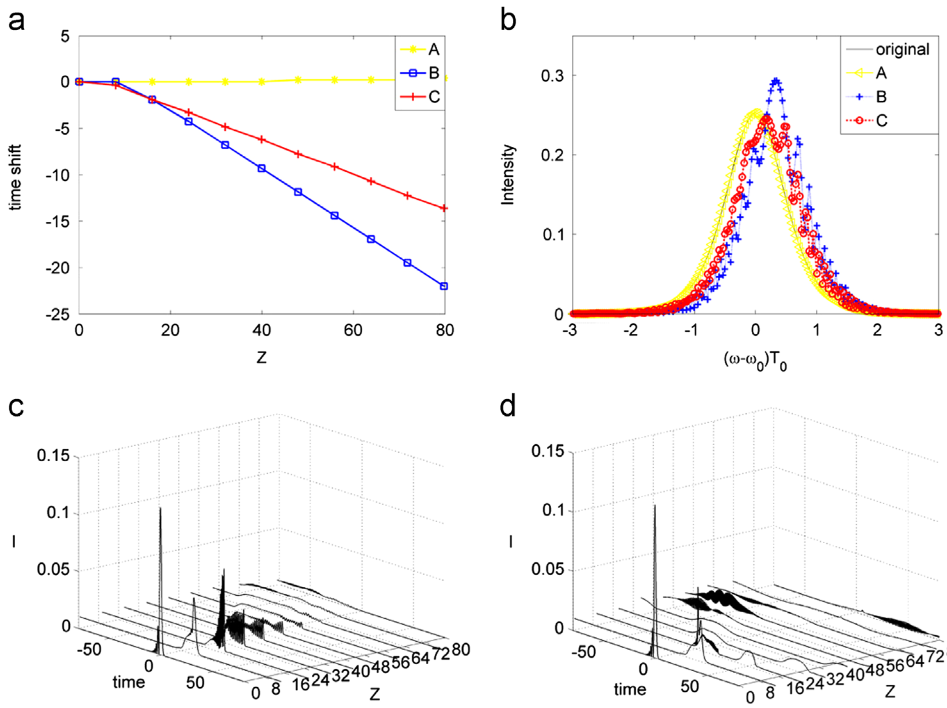

Fig. 4. (a) Time shift of soliton (b) frequency shift of soliton (A) CP and SP at same carrier frequency; (B) $\omega_S = 0.6$ PHz and $\omega_C = 1.8$ PHz; (C) $\omega_S = 0.6$ PHz and $\omega_C = 2$ PHz(c) propagation of Airy pulse at 1.8 PHz; (c) propagation of Airy pulse at 2 PHz.

The frequency gap of the CP and SP influences the time and the frequency shift of the soliton (Fig. 4). The yellow line A plot the time and the frequency shift of the soliton when CP and SP at same carrier frequency as the CP prior to SP about $10t_0$. The time and the frequency shifts of the soliton are very small, like the results in [20]. If the carrier frequency gap of the CP and SP increased, the group velocity, the GVD and nonlinearity coefficients are changed. The red line C plot the time and the frequency shift of the soliton when the carrier frequency of soliton fixed and the carrier frequency of Airy pulse increase to 2 PHz. The velocity of CP is slower than SP and the group velocity mismatch gets larger. Unlike the Airy pulse reflect from the soliton as seen in Fig. 4(c), the Airy pulse splits (Fig. 4(d)). They are no longer locked after they meet each other and the interaction length decreased. This reduces the XPM interaction of the two pulses. The time and frequency shifts of the soliton are smaller than the case which the carrier frequency of CP is 1.8 PHz but much larger than the case of CP and SP at same carrier frequency.

We next track the characteristics change of SP. Solitons experience time position change during the collision and permanent frequency changes which map to time position alterations by group velocity dispersion [20]. Fig. 5(a) shows the time shift of soliton with different truncation coefficient. If the truncation coefficient is small ($a \ll 1$), the CP displays all characteristics like the ideal Airy pulse [14]. With same peak intensity, it needs larger energy than Gaussian pulse to generate the Airy pulse with very small truncation coefficient. Because of its larger total energy, the peak intensity of Airy is higher when it interacts with soliton. So the Airy pulse with small truncation coefficient affects the soliton more, and more power of the Airy pulse pass through the soliton. If the truncation coefficient gets larger than 0.2 ($a > 0.2$), the Airy tail decays rapidly and the total energy of Airy pulse is lower than the Gaussian pulse of the same peak intensity, but most of the energy of Airy pulse are concentrated in the main lobe and it freely

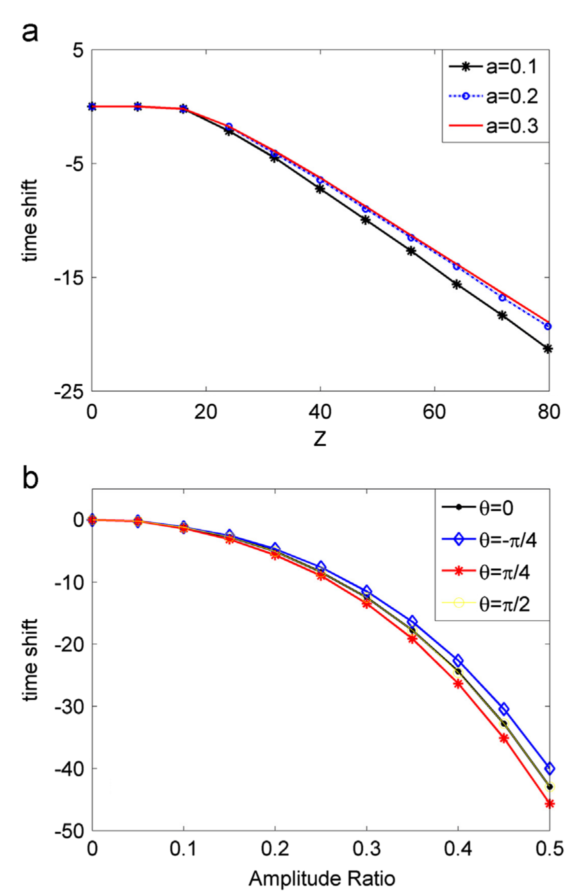

Fig. 5. (a) Soliton time shifts for different truncation coefficient; (b) soliton time shifts with respect to Airy's initial amplitude for different initial relative phase.

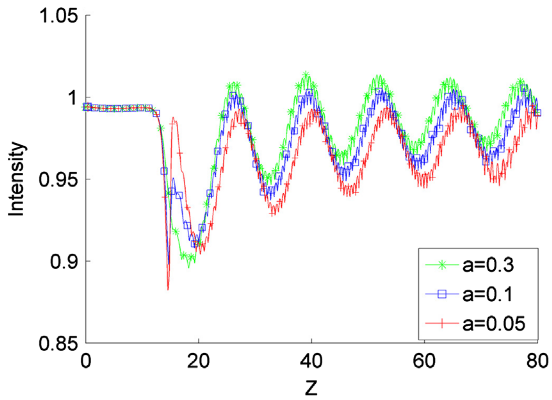

Fig. 6. Soliton intensity oscillations for different truncation coefficient.

accelerates to the soliton. When it reaches the soliton, the peak intensity of Airy is also higher than Gaussian pulse and affects the soliton more. In this case, it enables manipulating a strong soliton by a lower energy Airy pulse.

We plot the soliton time shift for different Airy pulse's amplitude ratio and relative phase between Airy and soliton (Fig. 5(b). The stronger intensity of Airy induces the larger time shift of soliton. But the time shift of soliton is weakly depend on the relative phase. The time shift of solitons can be modulated by parameters of Airy pulse.

The soliton peak power behavior is analyzed along the propagation range (Fig. 6). The intensity of the soliton experiences oscillation after collision with Airy pulse. These oscillations are dependent on the colliding Airy pulse truncation coefficient. In the absence of the Raman Effect, the oscillation of soliton intensity can then be understood as an energy transfer between the pulses during collision. The largest energy transfer between the pulses is at the primary collision point where the interaction is most strong. As the CP is reflected by strong SP, both pulses thus drift apart with larger group velocities than before. With continuous interaction with the Airy pulse, the intensity of the SP still oscillates but its amplitude slowly decreases. Like the time position changes which analyzed above, the soliton peak power behavior is influenced by Airy pulse's parameters.

4. Conclusion

We investigate the interaction between an Airy pulse and a soliton pulse at different center frequencies. The results reveal that the Airy pulse is better than Gaussian pulse to control the soliton. The Airy pulse can maintain its shape and accelerate to soliton. With the same peak power, the Airy pulse shifts the time position of soliton pulse more than Gaussian pulse do. If the truncation coefficient $a > 0.2$, the total energy of Airy pulse is lower than Gaussian pulse with same peak intensity. In this condition, the Airy CP still affects the soliton more than Gaussian CP. This implies we can use a weak Airy control pulse to control the properties of a strong signal soliton pulse. If Airy pulse and soliton propagate with no initial time delay, they interact at the beginning and the soliton get time position shift. The soliton experienced time position and intensity changes as we change the Airy's parameter. The different influence of Airy's amplitude ratio, the truncation coefficient and the relative phase are discussed.

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