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Bidirectional all-optical switches based on highly nonlinear optical fibers

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Abstract – All-optical switches have become one of the research focuses of nonlinear optics due to their fast switching speed. They have been applied in such fields as ultrafast optics, all-optical communication and all-optical networks. In this paper, based on symbolic computation, bidirectional all-optical switches are presented using analytic two-soliton solutions. Various types of soliton interactions are analyzed through choosing the different parameters of high-order dispersion and nonlinearity. Results indicate that bidirectional all-optical switches can be effectively achieved using highly nonlinear optical fibers.

Introduction. – With the development of optical communications, optical switches used in those systems have been studied theoretically and experimentally [1–5]. They have broken through the bottleneck problem of controlling optical signal by reducing the switching time, and improving the transmission velocity [6]. On account of the advantages of solitons, which can preserve their velocity and energy when they interact with each other, the study of soliton has attracted much attention in the literature [7–14]. In the passively mode-locked fiber lasers, the soliton formation and evolution without wave breaking have been studied [15–18]. In addition, they have been proposed for the research on all-optical switches [19].

Some researches have been presented using soliton interaction to design all-optical switches [20–23]. Considering the possibility of combination between second-order coupling coefficient dispersion and intermodal dispersion, the gain of the bar channel has been found to possess the switching property on dark soliton switches in the nonlinear directional coupler [22]. Besides, through changing parameters of soliton solutions, all-optical switches' properties can be achieved in the asymmetric fiber couplers [23]. The all-optical logic gate has been analyzed based on the changes of the soliton self-frequency by soliton interactions [24]. Moreover, an all-optical switch has been studied numerically in an active nonlinear directional coupler [25].

To our knowledge, numerous researches have been carried out on the interactions of two solitons [26–29]. Recently, ref. [30] has proposed that the interaction of two solitons can lead to discrete equilibrium distances. However, all-optical switches have not been discussed based on the amplitude shift with soliton interactions, which is a great character of solitons to design the all-optical switches. In this paper, we will study the inelastic interactions between solitons in optical fibers, which can be described by the following fifth-order nonlinear Schrödinger (NLS) equation [31]:

$$\begin{aligned}&i\Psi_x+\frac{1}{2}\Psi_{tt}+|\Psi|^2\Psi-i\alpha(\Psi_{ttt}+6|\Psi|^2\Psi_t)+\gamma(\Psi_{tttt}\\&+6\Psi^*\Psi_t^2+4\Psi|\Psi_t|^2+8|\Psi|^2\Psi_{tt}+2\Psi^2\Psi_{tt}^*+6|\Psi|^4\Psi)\\&-i\delta(\Psi_{ttttt}+10|\Psi|^2\Psi_{ttt}+30|\Psi|^4\Psi_t+10\Psi\Psi_t\Psi_{tt}^*\\&+10\Psi\Psi_t^*\Psi_{tt}+20\Psi^*\Psi_t\Psi_{tt}+10\Psi_t^2\Psi_t^*)=0.\end{aligned}\qquad(1)$$

Here, $\Psi(x,t)$ is a complex function which represents the amplitude of the pulse envelop. x and t are the propagation and transverse variable, respectively. The asterisk denotes the complex conjugate. And the physical parameters α, γ and δ correspond to the third-order, fourth-order and fifth-order coefficient.

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Equation (1), when $\alpha=\gamma=\delta=0$, becomes the standard NLS equation, and its integrability has been investigated [31]. The Lax pair and infinitely-many conservation laws have been derived, and the elastic interactions have been presented [32]. However, the all-optical switching phenomenon has not been observed before. In this paper, interactions between solitons have been investigated, and all-optical switches have been realized.

This paper is organized as follows: In the second section analytic two-soliton solutions are derived. Then in the third section bidirectional all-optical switches based on highly nonlinear optical fibers are presented and discussed. Finally in the last section we make the summary of our discussions.

Analytic two-soliton solutions. – Soliton solutions for eq. (1) have been derived by Lax pair and Darboux transformation [31]. In the following, two-soliton solutions for eq. (1) through Hirota's bilinear method will be employed [32–34]. In order to transform eq. (1) into the Hirota bilinear form, the transformation $\Psi=\frac{g(x,t)}{f(x,t}$ is made firstly, and the auxiliary functions $h(x,t)$ and $s(x,t)$ are used. $g(x,t)$, $h(x,t)$ and $s(x,t)$ are complex differentiable functions, and $f(x,t)$ is a real one. According to Hirota's bilinear method, the bilinear representation of eq. (1) can be obtained as

$$\begin{aligned}&\Big(iD_x+\frac{1}{2}D_t^2-i\alpha D_t^3+\gamma D_t^4-i\delta D_t^5\Big)g\cdot f\\&-5i\delta hg_t^*-3\gamma hg^*=5i\delta g^*s, &(2)\\&2D_tg\cdot g_{tt}+hf_t=sf, &(3)\\&D_t^2g\cdot g=hf, &(4)\\&D_t^2f\cdot f=2|g|^2. &(5)\end{aligned}$$

The Hitota bilinear operators D_x^p and D_x^q are definned by [35]

$$D_x^pD_t^qg(x,t)\cdot f(x,t)=\Big(\frac{\partial}{\partial x}-\frac{\partial}{\partial x'}\Big)^p\Big(\frac{\partial}{\partial t}-\frac{\partial}{\partial t'}\Big)^q g(x,t)f(x',t')\Big|_{x'=x,t'=t}. \quad (6)$$

With Hirota's bilinear method, eq. (2) can be solved by the following power series expansions for $g(z,t)$, $f(z,t)$, $h(z,t)$ and $s(z,t)$:

$$\begin{aligned}g(x,t)&=\varepsilon g_1(x,t)+\varepsilon^3g_3(x,t)+\varepsilon^5g_5(x,t)+\cdots, &(7)\\f(x,t)&=1+\varepsilon^2f_2(x,t)+\varepsilon^4f_4(x,t)+\cdots, &(8)\\h(x,t)&=h_0+\varepsilon^2h_2(x,t)+\varepsilon^4h_4(x,t)+\cdots, &(9)\\s(x,t)&=s_0+\varepsilon^2s_2(x,t)+\varepsilon^4s_4(x,t)+\cdots, &(10)\end{aligned}$$

where ε is a formal expression parameter, $g_m(x,t)$ ($m=1,3,5,\cdots$), $h_n(x,t)$, $s_n(x,t)$ ($n=0,2,4,\cdots$) are complex functions and $f_l(x,t)$ ($l=2,4,6,\cdots$) are the real ones. To obtain two-soliton solutions for eq. (1), we truncate expression (4), and set $g=\varepsilon g_1+\varepsilon^3g_3, f=1+\varepsilon^2f_2+\varepsilon^4f_4, h=h_0+\varepsilon^2h_2$ and $s=s_0+\varepsilon^2s_2$. Analytic two-soliton solutions for eq. (2) can be written as

$$\Psi=\frac{g_1+g_3}{1+f_2+f_4}, \quad (11)$$

where

$$\begin{aligned}\theta_1&=p_1x+\Big(\frac{i}{2}p_1^2+\alpha p_1^3+i\gamma p_1^4+\delta p_1^5\Big)t+\eta_1,\\\theta_2&=p_2x+\Big(\frac{i}{2}p_2^2+\alpha p_2^3+i\gamma p_2^4+\delta p_2^5\Big)t+\eta_2,\\s_0&=h_0=0,\quad s_2=-2(p_1-p_2)^2(p_1+p_2)e^{\theta_1+\theta_2},\\h_2&=2(p_1-p_2)^2e^{\theta_1+\theta_2},\quad g_1=e^{\theta_1}+e^{\theta_2},\\g_3&=\frac{(p_1-p_2)^2}{(p_1+p_2^*)^2}e^{\theta_1+\theta_2+\theta_1^*}+\frac{(p_1-p_2)^2}{(p_1+p_2^*)^2}e^{\theta_1+\theta_2+\theta_2^*},\\f_2&=\frac{1}{(p_1+p_1^*)^2}e^{\theta_1+\theta_1^*}+\frac{1}{(p_1+p_2^*)^2}e^{\theta_1+\theta_2^*}\\&\quad+\frac{1}{(p_2+p_1^*)^2}e^{\theta_2+\theta_1^*}+\frac{1}{(p_2+p_2^*)^2}e^{\theta_2+\theta_2^*},\\f_4&=\frac{(p_1-p_2)^2(p_1^*-p_2^*)^2e^{\theta_1+\theta_2+\theta_1^*+\theta_1^*}}{(p_1+p_1^*)^2(p_2+p_1^*)^2(p_1+p_2^*)^2(p_2+p_2^*)^2}.\end{aligned}$$

Here, p_1, p_2, η_1 and η_2 are complex constants.

Discussion. – For analytic two-soliton solution (11), we can choose the corresponding parameters to study the interactions between solitons. As shown in fig. 1(a), $\eta_1=1+2i$, $\eta_2=2+2i$, $\rho_1=0.84-1.3i$, $\rho_2=1.4-0.91i$, $\alpha=-1.6$, $\gamma=0.016$ and $\delta=0.25$. The interactions between solitons are inelastic, which can be used in the design of all-optical switches. Besides, through changing the

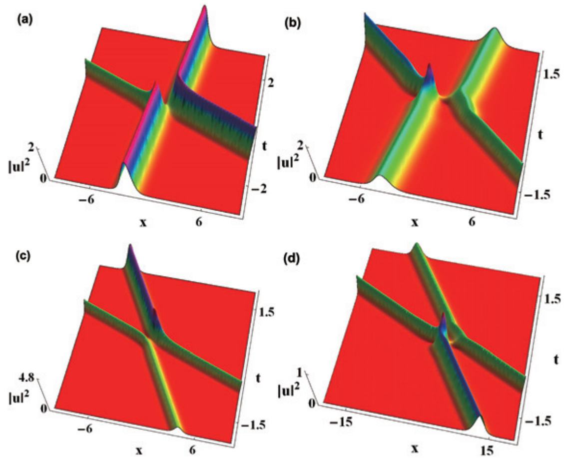

Fig. 1: (Colour online) Inelastic interactions between solitons in highly nonlinear optical fibers. The parameters are $\eta_1=1+2i$ and $\eta_2=2+2i$ with (a) $\rho_1=0.84-1.3i$, $\rho_2=1.4-0.91i$, $\alpha=-1.6$, $\gamma=0.016$, and $\delta=0.25$; (b) $\rho_1=1.1-0.78i$, $\rho_2=0.94-0.46i$, $\alpha=-9.1$, $\gamma=0.89$, and $\delta=0.48$; (c) $\rho_1=-1.8-0.78i$, $\rho_2=-1.1-1.3i$, $\alpha=-5$, $\gamma=1.7$, and $\delta=0.66$; (d) $\rho_1=0.81+1.6i$, $\rho_2=0.61+1.6i$, $\alpha=5$, $\gamma=1$, and $\delta=1.9$.

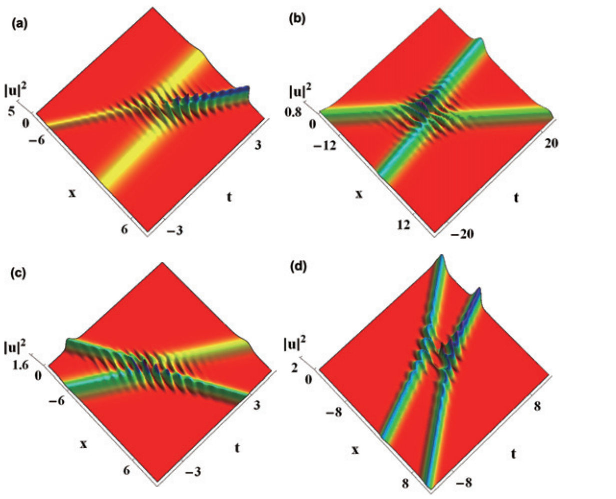

Fig. 2: (Colour online) Inelastic interactions between solitons in highly nonlinear optical fibers with periodic oscillation. The parameters are $\eta_1 = 1 + 2i$ and $\eta_2 = 2 + 2i$ with (a) $\rho_1 = -1.85 - 0.75i$, $\rho_2 = -0.94 - 0.22i$, $\alpha = -1.3$, $\gamma = 0.67$, and $\delta = 0.92$; (b) $\rho_1 = 0.5 + 0.28i$, $\rho_2 = 0.63 - 0.34i$, $\alpha = -5.5$, $\gamma = 0.73$, and $\delta = 1.1$; (c) $\rho_1 = -0.91 - 0.59i$, $\rho_2 = -0.88 + 0.59i$, $\alpha = 5.2$, $\gamma = 0.36$, and $\delta = 0.7$; (d) $\rho_1 = -1.25 - 0.59i$, $\rho_2 = -1.1 - 0.51i$, $\alpha = 1.9$, $\gamma = 0.69$, and $\delta = 1.3$.

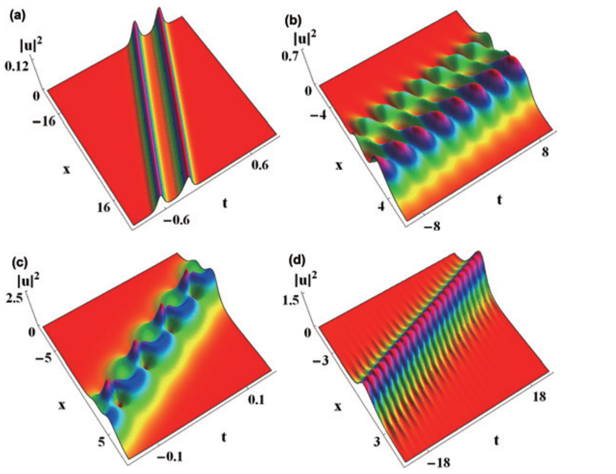

Fig. 3: (Colour online) Parallel transmission between solitons in highly nonlinear optical fibers. The parameters are $\eta_1 = 1 + 2i$ and $\eta_2 = 2 + 2i$ with (a) $\rho_1 = -0.35 + 1.3i$, $\rho_2 = -0.28 + 1.3i$, $\alpha = -5.8$, $\gamma = 3.3$, $\delta = -0.13$; (b) $\rho_1 = -1.1 - 0.28i$, $\rho_2 = -0.72 + 0.84i$, $\alpha = -0.78$, $\gamma = 0.2$, $\delta = 0.52$; (c) $\rho_1 = -0.59 + i$, $\rho_2 = 1.4 + 1.4i$, $\alpha = -7$, $\gamma = 2$, $\delta = 0.2$; (d) $\rho_1 = 0.16 - 0.14i$, $\rho_2 = 1.1 - 0.72i$, $\alpha = -0.78$, $\gamma = 1.8$, $\delta = 1.3$.

dispersion and nonlinearity effects, we can adjust the amplitude of solitons after interactions in fig. 1(b). Further, the position of the modulated pulse and signal pulse can be exchanged with each other, and the all optical switching function can be achieved in figs. 1(c) and 1(d). Thus, we can realize the bidirectional all-optical switches based on highly nonlinear optical fibers.

In fig. 1, there is no modulation, and the solitons can achieve stable transmission in the interaction process. Changing the relative phase of solitons, there will be a periodic interaction between adjacent solitons in fig. 2. The oscillation period is related to the amplitude and relative phase of solitons. In addition, solitons can be propagated in parallel in fig. 3. Changing the spacing of solitons, we can adjust the soliton interactions, and the case of inelastic interactions also happen. In fig. 3(a), solitons do not interact with each other when the distance between adjacent solitons is large. With the decrease of soliton spacing, the two solitons are almost merged into one soliton during the transmission process. This method can effectively enhance the soliton energy, and amplify the soliton amplitude.

Conclusions. – In this paper, bidirectional all-optical switches have been realized through analysing the analytic two-soliton solutions theoretically. In-phase, out-of-phase and parallel transmissions have been presented when we have adjusted the high-order dispersion and nonlinearity of highly nonlinear optical fibers. The interactions of solitons have been analyzed, and the method to control the soliton energy and amplitude has been suggested. Results are helpful to design the optical logic devices in ultrafast optics.

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