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Influence of Parameters of Optical Fibers on Optical Soliton Interactions

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The interaction between optical solitons is of great significance for studying interaction between light and matter and development of all-optical devices, and is conducive to the design of integrated optical path. Optical soliton interactions for the nonlinear Schrödinger equation are investigated to improve the communication quality and system integration. Solutions of the equation are derived and used to analyze the interaction of two solitons. Some suggestions are put forward to weaken their interactions.

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Optical soliton communication systems can be used to integrate multi-channel soliton transmission.[1–3] In the high speed communication systems, communication capacity and transmission speed are enhanced by reducing distance between neighbor optical solitons, and it cause some interaction problems in the process of optical soliton propagation.[4–6] Especially, when multi-channel signals are transmitted in the same optical fiber simultaneously, they will cause mutual interference and severely affect the communication system.[7–9] Based on observation, interaction between optical solitons may induce soliton distortion and bit error rate increase, which has serious implications for transmitting quality of a communication system. Therefore, with increasing communication capacity and extensively used multiplexing technology, research on their interaction is of necessity so as to ensure that the reliability and effectiveness of the optical communication system are not reduced.[10–12]

Researchers have found that, when there exist over two optical solitons in an optical fiber, optical solitons will interact with each other.[13–16] Optical solitons attract or repel mutually in interaction like matter particles.[17–19] Under appropriate initial conditions, a series of interesting phenomena are produced through these complex interactions, which are divided into coherent and non-coherent interactions.[20–24] The condition of coherent interaction is that optical fibers can respond to interference generated by crossed lasers, while noncoherent interaction occurs when relative phase change between optical solitons is faster than the medium response.[25–29] Taking the bright optical soliton as an example, when the coherent interaction occurs, attraction or repulsion will occur between bright optical solitons depending on their relative phase. However, when the incoherent interaction occurs, optical solitons are mainly repulsive.[30–32] For local nonlinear dark solitons, the interaction is primarily repulsive. In addition to the two interactions mentioned above, cyclical integration and separation will occur when two optical solitons with the same amplitude get close enough.[33–35]

In this study, elastic interaction between optical solitons is utilized to overcome the mutual interference in the soliton transmission. For an optical fiber in the actual environment, due to the influence of the surrounding environment, the soliton transmission is simulated by the nonlinear Schrödinger (NLS) equation with variable coefficients as follows:[36,37]

$$iu_x + \gamma_2(x)(u_{\rm tt} + 2u|u|^2) - i\gamma_3(x)(u_{\rm ttt} + 6u_t|u|^2) = 0. \tag{1}$$

Here, $\gamma_2(x)$ and $\gamma_3(x)$ are related to the second-order and third-order parameters for the dispersion and nonlinearity. For Eq. (1), the influences of parameters of optical fibers on optical soliton interactions have not been reported before. Here, we will mainly investigate the optical soliton interactions based on the parameters of optical fibers.

In this Letter, solutions of system (1) are presented. Influences of parameters of optical fibers on optical soliton interactions are discussed. Finally, the conclusions are given.

Two Soliton Solutions of System (1). First, we assume u as

$$u = P/Q, \tag{2}$$

where P and Q are complex and real functions, respectively. The bilinear equations of system (1) are

$$\left[iD_x + \gamma_2(x)D_t^2 - i\gamma_3(x)D_t^3\right]P \cdot Q = 0, \tag{3}$$

$$D_t^2 Q \cdot Q = 2|P|^2, \tag{4}$$

where D is the Hirota operator.[36] We assume

$$P = \varsigma P_1 + \varsigma^3 P_3, Q = 1 + \varsigma^2 Q_2 + \varsigma^4 Q_4, \tag{5}$$

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and take P_1 as

$$\begin{aligned} P_1 &= e^{\mu_1} + e^{\mu_2}, \\ \mu_j &= \rho_j(x) + \chi_j t + \kappa_j \\ &= \rho_j(x) + (a_j + ib_j)t + \kappa_j, \quad (j = 1, 2). \end{aligned} \tag{6}$$

Here, a_j and b_j are related to the wave numbers, and κ_j are free parameters. We can obtain

$$\rho_j(x) = \int \left[\gamma_3(x)\chi_j^3 + i\gamma_2(x)\chi_j^2\right] dx. \tag{7}$$

Then, we can derive

$$\begin{aligned} Q_2 &= A_{11}e^{\mu_1+\mu_1^*} + A_{12}e^{\mu_2+\mu_1^*} + A_{13}e^{\mu_1+\mu_2^*} \\ &\quad + A_{14}e^{\mu_2+\mu_2^*}, \\ P_3 &= A_{21}e^{\mu_1+\mu_2+\mu_1^*} + A_{22}e^{\mu_1+\mu_2+\mu_2^*}, \\ Q_4 &= A_{31}e^{\mu_1+\mu_2+\mu_1^*+\mu_2^*}, \end{aligned}$$

with

$$\begin{aligned} &A_{11} = \frac{1}{4a_1^2}, \quad A_{12} = \frac{1}{(\chi_1^* + \chi_2)^2}, \quad A_{13} = \frac{1}{(\chi_2^* + \chi_1)^2}, \\ &A_{14} = \frac{1}{4a_2^2}, \quad A_{21} = \frac{(\chi_2 - \chi_1)^2}{4a_1^2(\chi_1^* + \chi_2)^2}, \\ &A_{22} = \frac{(\chi_2 - \chi_1)^2}{4a_2^2(\chi_2^* + \chi_1)^2}, \\ &A_{31} = \frac{(\chi_1 - \chi_2)^2(\chi_1^* - \chi_2^*)^2}{16a_1^2a_2^2(\chi_1^* + \chi_2)^2(\chi_2^* + \chi_1)^2}. \end{aligned}$$

Thus, we assume $\varsigma = 1$, and the solution to system (1) is

$$u = P/Q = (P_1 + P_3)/(1 + Q_2 + Q_4). \tag{8}$$

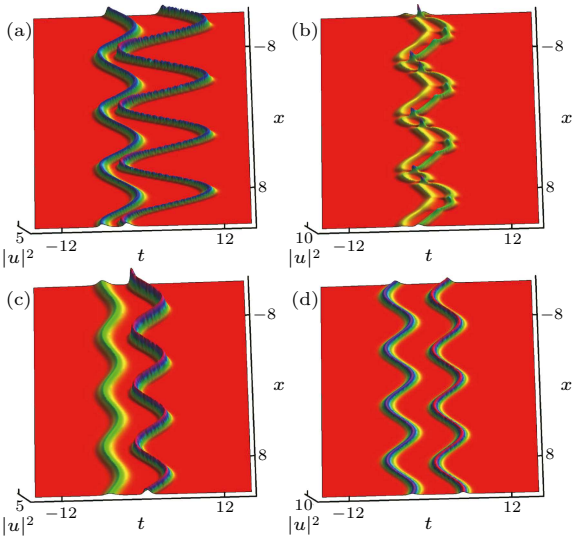

Fig. 1. Propagation characteristics of interactions between optical solitons for $\gamma_2(x) = \sin(x)$, $\gamma_3(x) = \cos(x)$, $\kappa_1 = 2$, $\kappa_2 = 3$ with (a) $a_1 = 1.5$, $b_1 = 1.1$, $a_2 = -1.5$, $b_2 = 1.6$, (b) $a_1 = -1.2$, $b_1 = 0.9$, $a_2 = -1.7$, $b_2 = 1.1$, (c) $a_1 = -1.9$, $b_1 = 0.89$, $a_2 = 1.1$, $b_2 = 0.47$, (d) $a_1 = -1.7$, $b_1 = -0.7$, $a_2 = 1.5$, $b_2 = -0.38$.

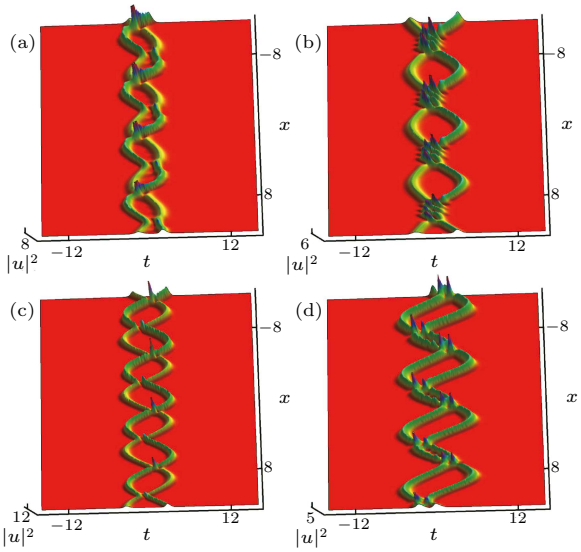

Fig. 2. Propagation characteristics of interactions between optical solitons for $\gamma_2(x)$ and $\gamma_3(x)$, with κ_1 and κ_2 having the same values as them in Fig. 1 but (a) $a_1 = 1.38$, $b_1 = 0.66$, $a_2 = 1.9$, $b_2 = -0.88$, (b) $a_1 = 1.3$, $b_1 = 0.7$, $a_2 = -1.7$, $b_2 = -1.1$, (c) $a_1 = -1.9$, $b_1 = 1.3$, $a_2 = -2.5$, $b_2 = -1.5$, (d) $a_1 = 1.5$, $b_1 = -1.2$, $a_2 = -1.5$, $b_2 = 1.28$.

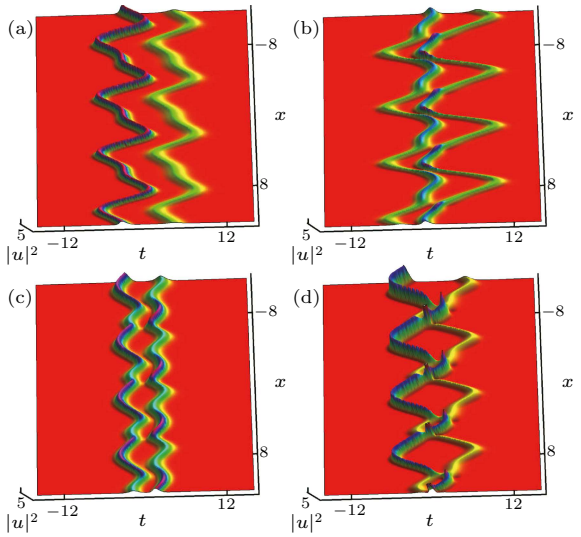

Fig. 3. Propagation characteristics of interactions between optical solitons for $\gamma_2(x) = \cos(2x)$, $\gamma_3(x) = \cos(x)$, $\kappa_1 = 2$, $\kappa_2 = 3$ with (a) $a_1 = -0.8$, $b_1 = -1$, $a_2 = 1.5$, $b_2 = -1.3$, (b) $a_1 = -1.2$, $b_1 = 0.94$, $a_2 = -0.84$, $b_2 = 1.5$, (c) $a_1 = -1.5$, $b_1 = 0.19$, $a_2 = -1.1$, $b_2 = 0.8$, (d) $a_1 = -1$, $b_1 = 1.1$, $a_2 = 2$, $b_2 = 0.52$.

Discussion. According to solution (8), the interactions between optical solitons can be obtained in Fig. 1. The values of b_1 and b_2 determine the phase of optical solitons. The values of b_1 and b_2 are positive in Figs. 1(a)–1(c), they have the same incident phase. Different values of a_1 and a_2 lead to different interaction characteristics. In Figs. 1(a) and 1(c), there is a large difference between the values of a_1 and a_2. The distance between the two optical solitons is large, there is no interaction, and they do not affect each other during the transmission. In Fig. 1(b), there is little difference between the values of a_1 and a_2, their interaction is obvious, and it shows the periodic os-

cillation. In Fig. 1(d), both b_1 and b_2 have negative values, and the difference between a_1 and a_2 is large, the distance between two optical solitons is large, and they can transmit without affecting each other. Different from Fig. 1, two optical solitons transmit in different directions when the signs of the values of b_1 and b_2 are opposite in Fig. 2. By adjusting the values of a_1, a_2, b_1 and b_2, we can effectively control the soliton interaction, and make them interact strongly or weakly.

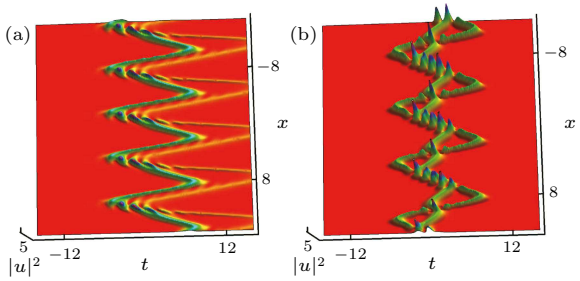

Fig. 4. Propagation characteristics of interactions between optical solitons for $\gamma_2(x)$ and $\gamma_3(x)$, with κ_1 and κ_2 having the same values as them in Fig. 3 but (a) $a_1 = -0.84$, $b_1 = -1.4$, $a_2 = -0.38$, $b_2 = 1.8$, (b) $a_1 = -1.2$, $b_1 = 0.98$, $a_2 = -1.3$, $b_2 = -1.5$.

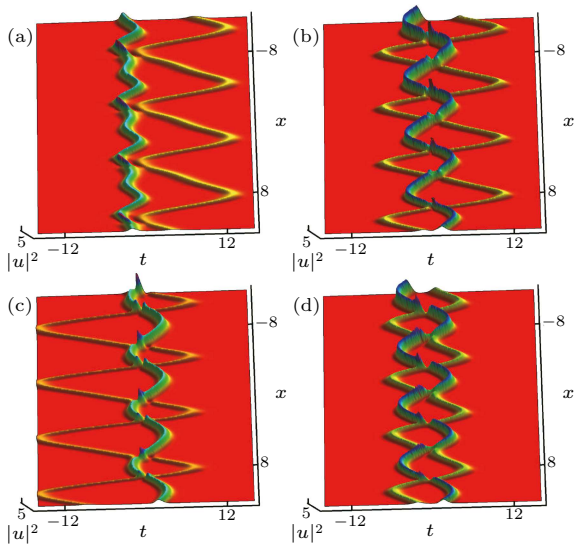

Fig. 5. Propagation characteristics of interactions between optical solitons for $\gamma_2(x)$ and $\gamma_3(x)$, with κ_1 and κ_2 having the same values as them in Fig. 3 but (a) $a_1 = 1.4$, $b_1 = -0.98$, $a_2 = -0.75$, $b_2 = -1.5$, (b) $a_1 = -1.9$, $b_1 = 0.47$, $a_2 = -1$, $b_2 = -1.7$, (c) $a_1 = -1.5$, $b_1 = 0.14$, $a_2 = 0.7$, $b_2 = -1.9$, (d) $a_1 = 1.1$, $b_1 = -1.3$, $a_2 = 1.8$, $b_2 = -0.1$.

For Fig. 3, we assume $\gamma_2(x) = \cos(2x)$, showing different transmission characteristics from Fig. 1. At the same distance, the interaction between optical solitons is stronger. In the transmission process, they will have a certain impact on each other. In Fig. 4, due to the anisotropic interaction of optical solitons, their interaction is more intense. There is periodic oscillation between optical solitons. By adjusting the values of a_1, a_2, b_1 and b_2, we can also adjust the spacing between optical solitons to control the interaction between optical solitons in Fig. 5. Their interaction makes them form a bound state and transmit periodically all the time.

In summary, solution (8) for system (1) has been presented. Influences of the free parameters a_1, a_2, b_1 and b_2 of solution (8) on optical soliton interactions have been discussed. Different dispersion effects have led to different interaction characteristics shown in Figs. 1–5. The values of b_1 and b_2 have determined the phase of optical solitons. The values of a_1 and a_2 have an effect on the amplitude and spacing of optical solitons. By adjusting the values of those parameters, the interaction of optical solitons have been effectively controlled. Those results are helpful to weaken interactions of optical solitons and to reduce communication qualities of the system.

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