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Stable transmission characteristics of double-hump solitons for the coupled Manakov equations in fiber lasers

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Stable transmission characteristics of double-hump solitons for the coupled Manakov equations in fiber lasers

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Abstract The fiber laser has become an ideal ultrashort pulse source because of its cheap structure, high integration, convenient and controllable output direction, which greatly promotes the development and application of ultrafast optics. This paper mainly focuses on the control and amplification of double-hump solitons in fiber lasers theoretically. The bilinear forms and soliton solu-

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tions of the coupled Manakov equations are presented, and the transmission of double-hump solitons is discussed. The factors affecting the stable transmission of double-hump solitons are analyzed. The relevant conclusions have important guiding significance for understanding the generation of stable double-hump solitons in fiber lasers.

Keywords Double-hump solitons · soliton solution · coupled Manakov equations · fiber laser

1 Introduction

Optical soliton is one of the most studied form of solitons [1]. It not only can be conformed to the characteristics predicted by soliton theory [2–4], but also can be used as an optical information carrier for communication systems [5–7]. Up to now, optical fiber communication is one of the largest potential applications of optical solitons [8]. Optical fiber is the best carrier for transmitting optical signals, because it can confine the optical field to a plane perpendicular to the axis of the fiber core [9,10].

In communications, the transformation content is achieved by expanding the range of carrier frequency in the form of bandwidth. In a linear optical fiber communication system, dispersion and nonlinear effects are highly destructive to the high-bit and long-distance transmission of the communication system. However, in the soliton optical fiber communication system, it is through the use of these two effects to solve these two problems at the same time [11]. The advantage of optical soliton communication is all-optical communication, and the signal does not need to be transferred to the electrical field for processing. Apart from being used in the communications field, optical solitons can also be used to construct optical switches. The advantage of optical soliton communication is that it does not change its shape when it interacts with other pulses [12,13].

An excellent system for generating and observing solitons is the fiber laser [1]. In optical fibers, dispersion and nonlinearity play a key role in the properties of soliton fiber lasers [14]. Nonlinearity here specifically refers to the Kerr effect, that is, the refractive index of optical fibers has the nonlinear relationship with the pulse propagation intensity, and the phase of the pulse will also change with time [15,16]. Also, the optical fiber refractive index is caused by the third-order nonlinear susceptibility. Dispersion here refers to group velocity dispersion (GVD), that is, the refractive index is related to the wavelength, which causes the pulse to broaden in the time domain [17,18].

In this paper, the effects of dispersion and nonlinearity on double-hump solitons will be investigated analytically. Double-hump soliton transmission in fiber lasers is expressed as the variable coefficient coupled Manakov equa-

tions [19],

$$iu_x + \beta_2(x)u_{tt} + 2\gamma(x)\Big(|u|^2 + |v|^2\Big)u = 0,$$
$$iv_x + \beta_2(x)v_{tt} + 2\gamma(x)\Big(|v|^2 + |u|^2\Big)v = 0. \tag{1}$$

Here, u and v represent the pulse intensity, which are related to x and t. $\beta_2(x)$ is the coeffiecient of GVD, and $\gamma(x)$ represents the nonlinearity. For Eq. (1), interactions between solitons have been studied [19–21]. However, the stable transmission characteristics of double-hump solitons in fiber lasers have not been reported before, which plays a key role in signal transmission and amplification in communication systems.

The generation and amplification of double-hump solitons will be investigated in the fiber lasers theoretically. The double-hump soliton solutions will be obtained in the coupled Manakov equations, which can model the double-hump soliton transmission in the fiber lasers in section 2. We will analyze the factors affecting the stable transmission of double-hump solitons in section 3. Results of this paper will be summarized at last.

2 Double-hump soliton solutions

At first, we will get the analytic double-hump soliton solutions with the Hirota method. We assume the rational transformation [22],

$$u = p/h, \quad v = q/h. \tag{2}$$

Here, p, q and h are all functions related to x and t. We substitute transformation (2) into Eq. (1), and extract the coefficients of the same power of h, Eq. (1) can be divided into the following bilinear forms,

$$iD_x p \cdot h + \beta(x)D_t^2 p \cdot h = 0,$$
$$iD_x q \cdot h + \beta(x)D_t^2 q \cdot h = 0,$$
$$\beta_2(x)D_t^2 h \cdot h = 2\gamma(x)\Big(|p|^2 + |q|^2\Big). \tag{3}$$

Here, D_x and D_t are defined as the Hirota operators [22].

Then, to obtain the double-hump soliton solution, we can assume

$$p = \varepsilon p_1 + \varepsilon^3 p_3, \quad q = \varepsilon q_1 + \varepsilon^3 q_3, \quad h = 1 + \varepsilon^2 h_2 + \varepsilon^4 h_4, \tag{4}$$

where

$$p_1 = \alpha_1 e^{\delta_1}, \quad q_1 = \alpha_2 e^{\delta_2}, \quad p_3 = \alpha_3 e^{\delta_1+\delta_2+\delta_2^*},$$
$$q_3 = \alpha_4 e^{\delta_2+\delta_1+\delta_1^*}, \quad h_2 = \alpha_5 e^{\delta_1+\delta_1^*} + \alpha_6 e^{\delta_2+\delta_2^*}, \quad h_4 = \alpha_7 e^{\delta_1+\delta_2+\delta_2^*+\delta_2^*}$$

with

$$\delta_j(x,t) = \eta_j(x) + \sigma_j t \quad (j = 1, 2),$$

and the asterisk represent the complex conjugate. We substitute expressions (4) into Eq. (3), and can obtain that

$$\gamma(x) = \beta_2(x), \quad \eta_j(x) = i\sigma_j^2 \int \beta_2(x)dx,$$

$$\alpha_3 = \frac{\alpha_1|\alpha_2|^2(\sigma_1 - \sigma_2)}{(\sigma_1 + \sigma_2^*)(\sigma_2 + \sigma_2^*)^2}, \quad \alpha_4 = \frac{\alpha_2|\alpha_1|^2(\sigma_2 - \sigma_1)}{(\sigma_2 + \sigma_1^*)(\sigma_1 + \sigma_1^*)^2},$$

$$\alpha_5 = \frac{|\alpha_1|^2}{(\sigma_1 + \sigma_1^*)^2}, \quad \alpha_6 = \frac{|\alpha_2|^2}{(\sigma_2 + \sigma_2^*)^2}, \quad \alpha_7 = \frac{|\alpha_1|^2|\alpha_2|^2|\sigma_1 - \sigma_2|^2}{(\sigma_1 + \sigma_1^*)^2(\sigma_2 + \sigma_2^*)^2|\sigma_2 + \sigma_1^*|^2}.$$

Finally, we make ε equal to 1, and double-hump soliton solutions can present as

$$\begin{aligned}
q_1 &= \frac{p_1 + p_3}{1 + h_2 + h_4} = \frac{\alpha_1 e^{\delta_1} + \alpha_3 e^{\delta_1 + \delta_2 + \delta_2^*}}{1 + \alpha_5 e^{\delta_1 + \delta_1^*} + \alpha_6 e^{\delta_2 + \delta_2^*} + \alpha_7 e^{\delta_1 + \delta_2 + \delta_2 + \delta_2^*}}, \\
q_2 &= \frac{q_1 + q_3}{1 + h_2 + h_4} = \frac{\alpha_2 e^{\delta_2} + \alpha_4 e^{\delta_2 + \delta_1 + \delta_1^*}}{1 + \alpha_5 e^{\delta_1 + \delta_1^*} + \alpha_6 e^{\delta_2 + \delta_2^*} + \alpha_7 e^{\delta_1 + \delta_2 + \delta_2 + \delta_2^*}}.
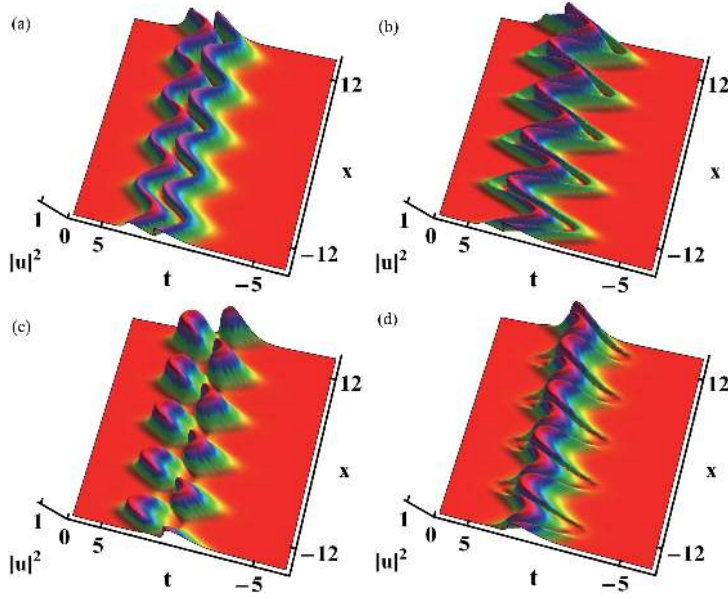\end{aligned} \quad (5)$$

3 Discussion

Fig. 1 Analysis of double-hump soliton transmission characteristics. The values of parameters in solutions (5) are: $\gamma(x) = sin(x)$, $\alpha_1 = 1 + i$, $\alpha_2 = 1 + i$ with (a) $\sigma_1 = 1 + 0.34i$, $\sigma_2 = 2 + 0.44i$; (b) $\sigma_1 = 1 + 0.81i$, $\sigma_2 = 2 + 1.2i$; (c) $\sigma_1 = 1 - 0.5i$, $\sigma_2 = 2 + 0.28i$; (d) $\sigma_1 = 1 + 0.38i$, $\sigma_2 = 2 + 1.4i$.

For double-hump soliton solutions (5), we can choose different parameters to analyze the transmission characteristics of double-hump solitons. At first, we assume that $\gamma(x) = \beta_2(x) = sin(x)$, $\alpha_1 = 1+i$, $\alpha_2 = 1+i$, $\sigma_1 = 1+0.34i$ and $\sigma_2 = 2+0.44i$ in Fig. 1(a), and can observe double-hump solitons are generated. They show periodic transmission, and the spacing and speed between the two pulses remain unchanged during the transmission. The two pulses feel like forming a bound state, and the double-hump solitons also have particle properties. Changing the values of σ_1 and σ_2, the waveform of the pulse has changed, and the peak power of pulses is generated alternately in Fig. 1(b). However, the two pulses do not affect each other in the transmission process, and also show the periodic transmission of double-hump solitons. Pulses can be transformed into other local waves and appear alternately in Figs. 1(c) and 1(d). No matter how their forms change, they do not affect each other and can maintain their independent characteristics. This is mainly due to the dispersion of the optical fiber is the sinusoidal profile in fiber lasers.
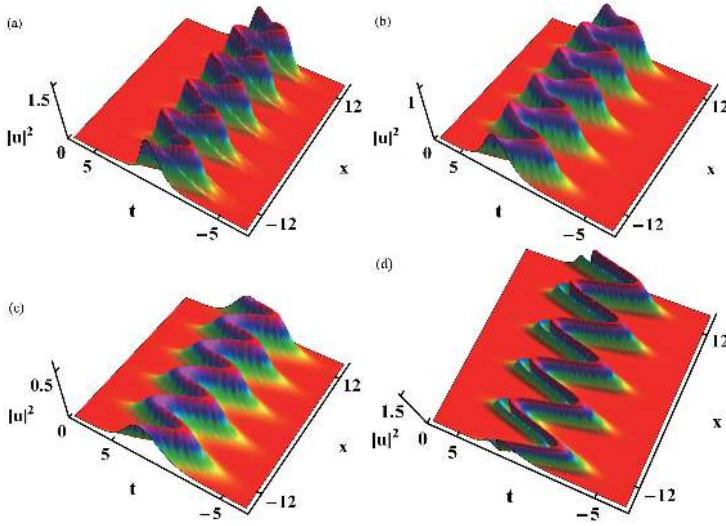

Fig. 2 Analysis of double-hump soliton transmission characteristics. The values of parameters in solutions (5) are: $\gamma(x) = sin(x)$, $\alpha_1 = 1+i$, $\alpha_2 = 1+i$ with (a) $\sigma_1 = -1.1+i$, $\sigma_2 = -1.3+2i$; (b) $\sigma_1 = 0.9+i$, $\sigma_2 = 0.6+2i$; (c) $\sigma_1 = -0.6+i$, $\sigma_2 = 0.5+2i$; (d) $\sigma_1 = -1+i$, $\sigma_2 = 4+i$.

In Fig. 1, we mainly change the imaginary parts of σ_1 and σ_2 to realize different types of soliton transmission. Next, we will discuss how to change the real parts of σ_1 and σ_2 to realize the periodic transmission of double-hump solitons. In Fig. 2(a), $\sigma_1 = 1+0.34i$ and $\sigma_2 = 2+0.44i$, double-hump solitons exhibit periodic transmission, and have two obvious peaks. We reduce the values of the corresponding real parts of σ_1 and σ_2 in Fig. 2(b), and the peak of double-hump solitons are weakened.

If we continue to reduce the value of the real part of σ_1 and σ_2, the strength of the double-hump soliton basically does not change in the transmission process in Fig. 2(c), which is similar to the traditional single soliton. If we set the value of the imaginary part to be equal, but the value of the real part is not equal, the double-hump soliton can realize non-interaction transmission. In the transmission process, the soliton strengths are not equal, but they do not affect each other in Fig. 2(d). Due to the same variation period, the soliton velocities are equal.
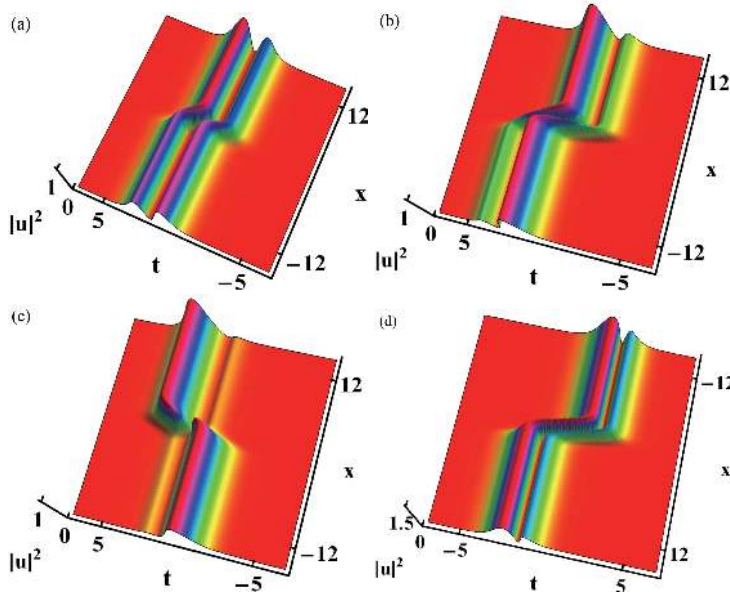

Fig. 3 Analysis of double-hump soliton transmission characteristics. The values of parameters in solutions (5) are: $\gamma(x) = -exp(-x^2)$, $\alpha_1 = 1+i$, $\alpha_2 = 1+i$ with (a) $\sigma_1 = 1+0.34i$, $\sigma_2 = 2+0.44i$; (b) $\sigma_1 = 1+0.81i$, $\sigma_2 = 2+1.2i$; (c) $\sigma_1 = 1-0.5i$, $\sigma_2 = 2+0.28i$; (d) $\sigma_1 = -1+i$, $\sigma_2 = 4+i$.

Compared with Fig. 1, we assume the GVD function $\beta_2(x)$ is the Gaussian profile, that is $\beta_2(x) = \gamma(x) = -exp(-x^2)$, double-hump solitons exhibit stable transmission. The same spacing is always maintained during transmission without interaction in Fig. 3(a). By changing the values of σ_1 and σ_2, some interaction transmission of double-hump solitons can be realized in Figs. 3(b)-3(d). The pulse intensities exchange with each other in Figs. 3(b) and 3(c). However, when $\sigma_1 = -1+i$ and $\sigma_2 = 4+i$, the pulse maintains its original strength during the transmission in Fig. 3(d), which is beneficial to improve the communication capacity of the system by reducing the pulse spacing.

When the GVD function $\beta_2(x)$ is the constant, such as $\beta_2(x) = \gamma(x) = -5$, double-hump solitons exhibit excellent transmission characteristics when $\sigma_1 = 1$ and $\sigma_2 = 2$ in Fig. 4(a). Double-hump soliton transmission is stable, and
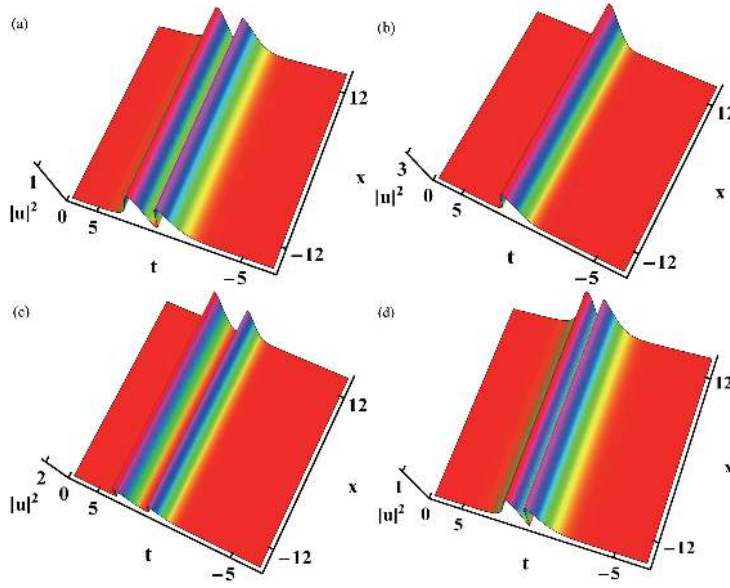
Fig. 4 Analysis of double-hump soliton transmission characteristics. The values of parameters in solutions (5) are: $\gamma(x) = -5$, $\alpha_1 = 1 + i$, $\alpha_2 = 1 + i$ with (a) $\sigma_1 = 1$, $\sigma_2 = 2$; (b) $\sigma_1 = 2$, $\sigma_2 = 1$; (c) $\sigma_1 = 1.9$, $\sigma_2 = 2$; (d) $\sigma_1 = 1$, $\sigma_2 = 4$.

there is no timing jitter. When $\sigma_1 = 2$ and $\sigma_2 = 1$, double-hump solitons merge into traditional solitons in Fig. 4(b). The strength of the soliton increases, and other properties remain unchanged. We can also change the soliton spacing by increasing or decreasing the values of σ_1 and σ_2 in Figs. 4(c) and 4(d). No matter how small their spacing is, double-hump solitons can achieve the stable transmission. Those results are beneficial to the generation of double-hump solitons in fiber lasers. Furthermore, it is conducive to amplify the pulses in the fiber lasers.

4 Conclusion

The generation and transmission of stable double-hump solitons have been studied. Double-hump soliton solutions of the variable coefficient coupled Manakov equations have been obtained with the help of the Hirota method. When the GVD function is the sinusoidal function, the double-hump soliton has shown the periodic transmission. The corresponding transmission is related to the values of σ_1 and σ_2. The imaginary parts of them have affected the waveform and spacing of double-hump solitons. The real parts of them have affected the double-hump soliton strength. When the GVD function is the Gaussian function, the double-hump soliton has presented the stable transmission. Through adjusting the corresponding parameters, the purpose of soliton energy exchange has been realized. Finally, when the GVD function is con-

stant, the stable double-hump soliton has been generated, and the soliton amplification has been demonstrated. Results in this paper is of great significance for the generation and amplification of double-hump solitons in fiber lasers.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest concerning the publication of this manuscript.

Ethical approval The authors declare that they have adhered to the ethical standards of research execution.

Availability of data and material The authors declare that all data generated or analysed during this study are included in this article.

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