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Optical wave breaking and soliton trains generation due to cross-phase modulation in an optical fiber with quintic nonlinearity

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ABSTRACT

Based on the extended coupled nonlinear Schrödinger equations in an optical fiber with quintic nonlinearity (QN), the approximate analytical frequency chirps and the critical distances for the cross-phase modulation induced optical wave breaking (OWB) are discussed for the initial Gaussian optical pulses. Evolutions of the frequency chirps, shapes and spectra of pulses are numerically calculated in the normal dispersion regime. It is shown that, the approximate analytical frequency chirps accords well with the numerical ones at the initial evolution stages of the pulses. And the calculated approximate critical OWB distances accord well with the numerical ones only for the traditional OWB. In addition, for the positive QN and the negative one but with small absolute values, the traditional OWB can be observed. While for the negative QN with large absolute values, non-traditional OWB may occur. Namely, soliton pulse trains may develop during the pulse propagation.

1. Introductions

It is well-known that, when propagating inside an optical fiber, optical pulses may experience rich time- and frequency-domain evolutions due to the combined effects of the group-velocity dispersion (GVD), self-phase modulation (SPM), cross-phase modulation (XPM), self-steepening, intra-pulse Raman scattering, and etc. As time goes on, more and more interesting and important nonlinear optical propagating phenomena in an optical fiber have been revealed. Typically, these phenomena include modulation instability [1,2], optical wave breaking (OWB) [3–9], various bright, dark, or gray solitons and soliton pairs [10], self similaritons [11], optical rogue waves [12], optical shocks [13], and so on. Owing to their beneficial or detrimental effects on various engineering applications such as optical switching, supercontinuum generation, optical soliton communications, high power and high quality ultra-short pulse fiber lasers, pulse compression, high-repetition-rate pulse train generation, frequency conversion, and so on, they have attracted intensive interests and been extensively studied.

OWB is an important nonlinear optical phenomenon which is usually thought to cause oscillation structures in the wings of the pulse and correspondingly in the sidelobes of the pulse spectrum when the pulse propagates in an optical fiber. People generally think it occurs in the normal dispersion regime of an optical fiber. However, owing to the fact that, the developed nonmonotonic frequency chirps may cause overtaking of different pulse components and then break the initial quasi-continuous optical wave or high-order bright (dark) solitons into ultra-short pulse trains or multiple peak (dip) structures, this phenomenon is also factually closely related to modulation instability or breaking of high-order solitons. We all know that modulation instability and high-order bright solitons generally occur in the anomalous dispersion regime. That is to say, generally speaking, OWB can also occur in the anomalous dispersion regime. Moreover, the generated oscillation structures can also appear near the pulse center. Owing to its considerable detrimental influence on some practical applications such as high efficiency pulse compression, generation of high quality cleaning pulses in fiber lasers, generation of similaritons in fiber amplifiers, and so on, it has been extensively studied analytically [7–9], numerically [7,9], and experimentally [13,14]. Up to now, due to the mathematical difficulty in accurate analytical procedure of the initial value problem in nonlinear partial differential equation, its

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analytical approach is usually approximate. In this work, we will pay attention to both the numerical and analytical approaches of OWB. Being different from the previous investigations [5,6], we will take into account both QN and XPM effects.

2. Theoretical analysis

In case of quintic nonlinearity, the slowly varying envelopes ψ_j (j = 1, 2) of the two optical pulses with the same polarization but different carrier frequencies propagating in an optical fiber should satisfy the following coupled extended nonlinear Schrödinger equations [15]

$$\begin{cases} \dfrac{\partial \psi_1}{\partial z} = -\dfrac{i}{2}\beta_2 \dfrac{\partial^2 \psi_1}{\partial T^2} + i\gamma_1 \left(|\psi_1|^2 + 2|\psi_2|^2 \right) \psi_1 + i\gamma_2 \left(|\psi_1|^4 + 3|\psi_2|^4 + 6|\psi_1|^2 |\psi_2|^2 \right) \psi_1 = 0 \\ \dfrac{\partial \psi_2}{\partial z} = -\dfrac{i}{2}\beta_2 \dfrac{\partial^2 \psi_2}{\partial T^2} + i\gamma_1 \left(|\psi_2|^2 + 2|\psi_1|^2 \right) \psi_2 + i\gamma_2 \left(|\psi_2|^4 + 3|\psi_1|^4 + 6|\psi_1|^2 |\psi_2|^2 \right) \psi_2 = 0 \end{cases} \tag{1}$$

where β_2, γ_1, γ_2, z, and T are the second-order group velocity dispersion (GVD) coefficient, cubic nonlinear coefficient, quintic nonlinear coefficient, propagating distance, and the retarded time, respectively. The last two terms on the right-handed sides of Eq. (1) stand for SPM and XPM, respectively.

For the initial Gaussian pulses of the forms

$$\psi_j(0, T) = A_{j0} \exp\left(-T^2/2T_0^2\right) \tag{2}$$

where A_{j0} and T_0 are, respectively, the input peak amplitudes of the pulses and the pulse durations. For OWB is closely related to the developing frequency chirp, we will first discuss it. For the case of no nonlinearities, GVD induced chirps can be deduced as the following forms

$$\omega_{cgj}(z, T) = \frac{\beta_2 z/T_0^2}{1 + \left(\beta_2 z/T_0^2\right)^2} \frac{T}{T_0^2} \tag{3}$$

Taking the lowest order in z, Eq. (1) becomes the following forms

$$\omega_{cgj}(z, T) \cong \frac{\beta_2 z}{T_0^2} \frac{T}{T_0^2} \tag{4}$$

For the dispersionless (β_2 = 0) case, one can realize that the solutions of Eq. (1) satisfy the forms $\psi_j(z, T) = \psi_j(0, T) \exp\left[i\phi_j(z, T)\right]$ (j = 1, 2), where ϕ_j are SPM and XPM induced nonlinear phase shifts at the distance z and can be deduced as

$$\phi_j(z, T) = z \begin{Bmatrix} \gamma_1 \left[|\psi_j(0, T)|^2 + 2|\psi_{3-j}(0, T)|^2 \right] \\ +\gamma_2 \left[|\psi_j(0, T)|^4 + 3|\psi_{3-j}(0, T)|^4 + 6|\psi_j(0, T)|^2 |\psi_{3-j}(0, T)|^2 \right] \end{Bmatrix} \tag{5}$$

Then the frequency chirps induced by SPM and XPM at the distance z can be deduced as

$$\omega_{cNj}(z, T) = -z \begin{Bmatrix} \gamma_1 \left[\dfrac{\partial}{\partial T} |\psi_j(0, T)|^2 + 2\dfrac{\partial}{\partial T} |\psi_{3-j}(0, T)|^2 \right] \\ +\gamma_2 \begin{bmatrix} \dfrac{\partial}{\partial T} |\psi_j(0, T)|^4 + 3\dfrac{\partial}{\partial T} |\psi_{3-j}(0, T)|^4 \\ +6|\psi_{3-j}(0, T)|^2 \dfrac{\partial}{\partial T} |\psi_j(0, T)|^2 \\ +6|\psi_j(0, T)|^2 \dfrac{\partial}{\partial T} |\psi_{3-j}(0, T)|^2 \end{bmatrix} \end{Bmatrix} \tag{6}$$

Substituting Eq. (2) into Eqs. (5) and (6), one can, respectively, obtain the nonlinear phase shifts and chirps of Gaussian pulses at the distance z as

$$\phi_{Nj}(z, T) = \left[z \exp\left(-\frac{T^2}{T_0^2}\right) \right] \begin{bmatrix} \gamma_1 \left(A_{j0}^2 + 2A_{3-j0}^2 \right) \\ +\gamma_2 \left(A_{j0}^4 + 3A_{3-j0}^4 + 6A_{j0}^2 A_{3-j0}^2 \right) \exp\left(-\dfrac{T^2}{T_0^2}\right) \end{bmatrix} \tag{7}$$

$$\omega_{cNj}(z, T) = \frac{2Tz}{T_0^2} \left[\exp\left(-\frac{T^2}{T_0^2}\right) \right] \begin{bmatrix} \gamma_1 \left(A_{j0}^2 + 2A_{3-j0}^2 \right) \\ +2\gamma_2 \left(A_{j0}^4 + 3A_{3-j0}^4 + 6A_{j0}^2 A_{3-j0}^2 \right) \exp\left(-\dfrac{T^2}{T_0^2}\right) \end{bmatrix} \tag{8}$$

For simplicity, we assume $A_{20}^2 = A_{10}^2 = A_0^2$ in the following discussion and then Eq. (8) changes as

$$\omega_{cNj}(z, T) = \frac{2TA_0^2 z}{T_0^2} \left[3\gamma_1 + 20\gamma_2 A_0^2 \exp\left(-\frac{T^2}{T_0^2}\right) \right] \exp\left(-\frac{T^2}{T_0^2}\right) \tag{9}$$