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Femtosecond second-order solitons in optical fiber transmission

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Abstract

A propagation of the femtosecond second-order solitons in an optical fiber is studied. We show that a generalized nonlinear Schrödinger equation well describes the propagation of the second-order soliton even containing only a few optical cycles. The propagations of a 50 fs and a 10 fs second-order soliton in an optical fiber are numerically simulated. It is found that, for the case of 10 fs second-order soliton, the soliton decay is dominated by the third-order dispersion, in contrast to the case of 50 fs second-order solitons, where the soliton decay is dominated by the delayed Raman response. It is also found that the exact delayed Raman response form must be used for the propagation of the 50 fs or less than 50 fs second-order soliton.

Keywords: Ultrashort optical pulse; Optical pulse propagation; Femtosecond second-order soliton; Nonlinear effects; Nonlinear Schrödinger equation

1. Introduction

The higher-order dispersive and nonlinear effects of ultrashort optical pulses are currently investigated by theory and experiment [1–8]. The positive third-order dispersion effect, distort the pulse shape with an oscillatory structure near the trailing edge [2,3]. The delayed Raman response effect causes a continuous downshift of the optical frequency of the pulse propagating along the optical fiber, known as the soliton self-frequency shift [4,5]. The effect of the self-steeping term leads to an optical shock on the trailing edge of the pulse [6–8]. On the other hand, the effects of third-order dispersion, delayed Raman response, and self-steeping term on the propagation of second-order solitons in a single-mode fiber will lead to the soliton decay [9–15]. When the third-order dispersion parameter exceeds a threshold values, the third-order dispersion effect is going to lead to the soliton decay of higher-order solitons [10–12]. The delayed Raman response effect leads to breakup of higher-order solitons into their constituents, the main peak shifts toward the trailing side [13,14]. The shift is due to a decrease in the group velocity occurring as a result of the red shift of soliton spectral peak. Even relatively small delay Raman response effect still leads to the decay of higher-order solitons. The self-steeping effect will break the degeneracy of higher-order solitons and causes the propagating speed of the solitons being different [15].

In the paper, we will research a propagation of the femtosecond second-order solitons in optical fiber. It is shown that a generalized nonlinear Schrödinger equation well describes the propagation of the second-order soliton of pulsewidth down to 10 fs. We numerically

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investigate that the 50 and 10 fs second-order solitons of propagation in an optical fiber. We find that, for the case of 10 fs second-order soliton, the soliton decay is dominated by the third dispersion and the delayed Raman response has the least effect, in contrast to the case of 50 fs second-order soliton, where the soliton decay is dominated by the delayed Raman response. We also find that the approximation which assumes the Raman gain is linear in frequency is no longer suitable for the propagation of a 50 fs or less than 50 fs second-order soliton pulses. The method overestimates the soliton decay. Therefore, it is necessary to use the exact delayed Raman response form when the propagation of a 50 fs or less than 50 fs second-order soliton pulse is considered.

2. Theory model

We now consider the influence of third-order dispersion, delayed Raman response, and self-steeping on the propagation of the second-order soliton in a single-mode fiber. An accurate wave equation is used to describe the propagation [16]:

$$\begin{aligned}\frac{\partial A}{\partial z} = &\left(-\beta_1\frac{\partial A}{\partial t} - \frac{\mathrm{i}\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} + \frac{\mathrm{i}\beta_4}{24}\frac{\partial^4 A}{\partial t^4}\right) \\ &+ \mathrm{i}\gamma\left(NA + \mathrm{i}\alpha_1\frac{\partial}{\partial t}NA\right) \\ &- \mathrm{i}\gamma\,\alpha_2\frac{\partial^2 NA}{\partial t^2} - \frac{\mathrm{i}\gamma\,\beta_2 A}{\beta_0}\left[(1-\alpha)\left|\frac{\partial A(z,t)}{\partial t}\right|^2\right. \\ &\left.+\alpha\int_{-\infty}^{t}\mathrm{d}t' f(t-t')\left|\frac{\partial A(z,t')}{\partial t}\right|^2\right] \\ &- \frac{\mathrm{i}\gamma\,\beta_2}{\beta_0}\frac{\partial N}{\partial t}\frac{\partial A}{\partial t} - \frac{\mathrm{i}}{2\beta_0}\gamma^2 N^2 A, \end{aligned} \quad (1)$$

where $A(z,t)$ is the field envelope, $\gamma = n_2\omega_0/cA_{\mathrm{eff}}$, n_2 is the Kerr coefficient, A_{eff} is effective fiber cross section, $\alpha_1 = 2/\omega_0 - \beta_1/\beta_0 \approx 1/\omega_0$, $\alpha_2 = 1/\omega_0^2 - 2\beta_1/\beta_0\omega_0 + \beta_1^2/\beta_0^2 - \beta_2/2\beta_0 \approx -\beta_2/2\beta_0$, ω_0 is the angular frequency of the carrier wave, β_0 is the propagation constant β at ω_0, and β_1 is the reciprocal group velocity. β_2, β_3, and β_4 are the second-, third-, and fourth-order dispersions, respectively.

The delayed response $N(z,t)$ is described by Chen et al. [17]

$$N(z,t) = (1-\alpha)\left|A(z,t)\right|^2 + \alpha\int_{-\infty}^{t}\mathrm{d}t' f(t-t')\left|A(z,t')\right|^2. \quad (2)$$

On the right-hand side of Eq. (2), the first term represents Kerr nonresonant virtual electronic transitions in the order of about 1 fs or less [18], the second term represents delayed Raman response, $f(t)$ is the delayed response function, and $\alpha = 0.18$ parameterizes the relative strengths of Kerr and Raman interactions. In this paper, $f(t)$ is obtained by modeling the Raman gain by 27 Lorentzian lines, centered on the different optical phonon frequencies and

$$f(t) = \sum^{27}\frac{\tau_{1\mathrm{i}}^2 + \tau_{2\mathrm{i}}^2}{\tau_{1\mathrm{i}}\tau_{2\mathrm{i}}^2}\exp(-t/\tau_{2\mathrm{i}})\sin(t/\tau_{1\mathrm{i}}), \quad (3)$$

where the parameters are determined by fitting the imaginary parts of its spectrum to actual Raman gain of fused silica. The fitted Raman gain spectrum is plotted in Fig. 1.

In dimensionless soliton units, Eq. (1) can be rewritten to

$$\begin{aligned}\frac{\partial}{\partial\xi}u = &\frac{\mathrm{i}}{2}\frac{\partial^2 u}{\partial\tau^2} + \beta\frac{\partial^3 u}{\partial\tau^3} + \frac{\mathrm{i}\beta_4}{24|\beta_2|T_0^2}\frac{\partial^4 u}{\partial\tau^4} \\ &+ \mathrm{i}\overline{N}u - \frac{1}{\omega_0 T_0}\frac{\partial}{\partial\tau}\overline{N}u \\ &- \frac{\mathrm{i}\beta_2}{\beta_0 T_0^2}\left\{\frac{1}{2}\frac{\partial^2\overline{N}u}{\partial\tau^2} + \left[(1-\alpha)\left|\frac{\partial u}{\partial\tau}\right|^2\right.\right. \\ &\left.\left.+\alpha\int_{-\infty}^{\tau}\mathrm{d}\tau' f(\tau-\tau')\left|\frac{\partial u}{\partial\tau}\right|^2\right] + \frac{\partial\overline{N}}{\partial\tau}\frac{\partial u}{\partial\tau} + \frac{1}{2}\overline{N}^2 u\right\}, \end{aligned} \quad (4)$$

where $\xi = z/L_{\mathrm{D}}$, $\tau = t - \beta_1 z/T_0$, $u = N_P A/\sqrt{P_0}$, $\beta \equiv \beta_3/6|\beta_2|T_0$, $L_{\mathrm{D}} - T_0^2/|\beta_2|$ is dispersion length, and $\overline{N} = N_{\mathrm{P}}^2 N/P_0$. The parameter $N_{\mathrm{P}} = [\gamma P_0 T_0^2/|\beta_2|]^{1/2}$, $N_{\mathrm{P}} = 1$ for the fundamental soliton, $T_0 = T_{\mathrm{w}}/1.763$, T_{w} is the pulse full-width at the half-maximum, and P_0 is peak power of the incident pulse.

When these higher nonlinear terms are negligible, Eq. (4) reduces to

$$\begin{aligned}\frac{\partial}{\partial\xi}u = &\frac{\mathrm{i}}{2}\frac{\partial^2 u}{\partial\tau^2} + \beta\frac{\partial^3 u}{\partial\tau^3} \\ &+ \frac{\mathrm{i}\beta_4}{24|\beta_2|T_0^2}\frac{\partial^4 u}{\partial\tau^4} + \mathrm{i}\overline{N}u - \frac{1}{\omega_0 T_0}\frac{\partial}{\partial\tau}\overline{N}u. \end{aligned} \quad (5)$$

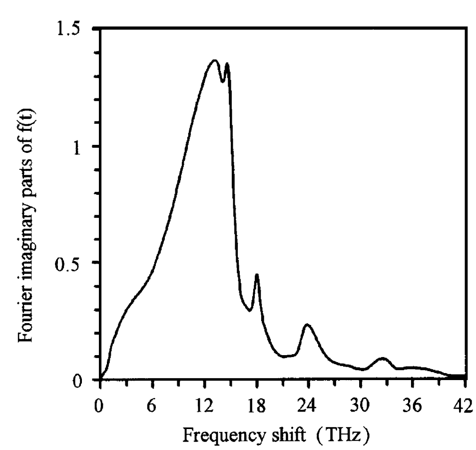

Fig. 1. The imaginary part of the spectrum of delayed Raman response function fitted by 27 Lorentzian lines.