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Effects of third-order dispersion on soliton switching in fiber nonlinear directional couplers

Yuntuan Fang[a,*], Jun Zhou[b]

[a]Department of Physics, Zhenjiang Watercraft College, Zhenjiang 212003, China
[b]Department of Optical Engineering, Jiangsu University, Zhenjiang 212013, China

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Abstract

The split-step Fourier method is used to study the energy switching characteristics of fiber nonlinear directional couplers with the third-order dispersion. The effects of the third-order dispersion increases with the third-order dispersion coefficient and input power and result in pulse shift and energy decreases. Adding high-order nonlinear can partly overcomes these effects.

Keywords: Nonlinear optics; Optical soliton; Split-step Fourier transformation; Fiber nonlinear directional coupler

Since Jensen first depicted the coupling character of fiber nonlinear directional couplers [1], it arise people's great researching interest [2–7]. The advantage of using solitons for all-optical switching in nonlinear interferometers has been discussed by Doran and Wood [8]. Trillo et al. [9] further pointed out that the switching efficiency double when soliton inputs were used in fiber nonlinear directional couplers, compared with quasi-cw pulses were used. In Trillo's numerical calculation, the propagation of pulses in a nonlinear dual-core fiber directional coupler was described in terms of two linearly coupled nonlinear Schrödinger equations (NLSEs), in which the high-order dispersion and nonlinear effects were ignored. However, if the pulses are too narrow or the high-order dispersion and nonlinear of the material is too large, the NLSEs must include the high-order term. In this paper, we consider the effect of third-order dispersion on soliton switching in fiber nonlinear directional couplers.

The nonlinear-coupled equations including the effect of third-order dispersion for a two-core nonlinear coupler in the soliton units can be expressed as [8,9]

$$\frac{\partial u}{\partial z} = \mathrm{i}\frac{1}{2}\frac{\partial^2 u}{\partial t^2} + \sigma\frac{\partial^3 u}{\partial t^3} + \mathrm{i}|u|^2 u + \mathrm{i}Kv, \tag{1}$$

$$\frac{\partial v}{\partial z} = \mathrm{i}\frac{1}{2}\frac{\partial^2 v}{\partial t^2} + \sigma\frac{\partial^3 v}{\partial t^3} + \mathrm{i}|v|^2 v + \mathrm{i}Ku, \tag{2}$$

where u and v are the slowly varying envelope amplitude of the modal field in the first and second waveguides. $\sigma = \beta_3/6$ and β_3 is the third-order dispersion coefficient. K is the linear coupling coefficient between the two waveguides. In general case, the above equations cannot be solved analytically, so the numerical method is applied. The most and widely used numerical method solving NLSE is the split-step Fourier method (SSFM) because of its simplicity, flexibility, good accuracy, and relatively modest computing cost [10]. The SSFM assumes that the propagation of the optical pulses from z to $z+h$ is carried out in two steps, where h is a small distance. In the first step from z to $z+h/2$, nonlinearlity

*Corresponding author.
E-mail address: fang_yt1965@sina.com (Y. Fang).

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acts alone, while in the second step from $z+h/2$ to $z+h$, only the linearity terms act alone. Hence, (1) can spilt into a linear and a nonlinear part. Mathematically

$$\frac{1}{2}\frac{\partial u}{\partial z} = \mathrm{i}|u|^2 u, \tag{3}$$

$$\frac{1}{2}\frac{\partial u}{\partial z} = \mathrm{i}\frac{1}{2}\frac{\partial^2 u}{\partial t^2} + \sigma\frac{\partial^3 u}{\partial t^3} + \mathrm{i}Kv. \tag{4}$$

In the first step, $|u|^2$ is regarded as invariable. Eq. (3) can be exactly solved and the iterative scheme can be expressed as

$$u(z+h/2, t) = u(z,t)\ \exp(\mathrm{i}u^2 h). \tag{5}$$

Taking the Fourier transformation of (5), we have

$$U(\omega, z+h/2) = F[u(z,t)\ \exp(\mathrm{i}|u|^2 h)], \tag{6}$$

where $U(\omega, z+h/2)$ is the Fourier transformation of $u(z+h/2, t)$. For the second step, we take the Fourier transformation of (10) in the same way and obtain

$$\begin{aligned} U(\omega, z+h) = {} & U(\omega, z+h/2)\exp[\mathrm{i}h/2(-\omega^2 - 2\sigma\omega^3)] \\ & + \mathrm{i}KV(\omega, z+h/2)h. \end{aligned} \tag{7}$$

The same process is simultaneously carried out with Eq. (2). After taking (6) into (7) and carrying out the reversal Fourier transformation, we can implement the numerical analysis on the pulse propagation in the two waveguides.

We suppose that the initial conditions

$$u(z=0,t) = A\ \mathrm{sec}\,h(t), \quad v(z=0,t) = 0. \tag{8}$$

According to [9], the half-beat length of the linear coupler is given by $L = \pi/2K$. Then, using $A_s = 2\sqrt{K}$ to obtain those values for which the peak input power equals the cw switching power. In order to verify our program, we give $K = 1$ and $A = 1$ for Eq. (8), and consider the case without third-order dispersion ($\sigma = 0$) in Eqs. (1) and (2). Fig. 1 shows the result, which is consistent with [9]. Next, we study the energy switching characteristics that can be achieved (by the method of [9]) by using our solitonlike input pulses with different σ, for the case of $K = 1/4$ and $L = 2\pi$. In this case, the cw switching power $P_s = {A_s}^2 = 1$. The numerical results are shown in Fig. 2. As can been seen, the transmissions have same steep curves in the range of $1 < P < 1.5$ for all values of σ. Then $P = 1$ becomes the threshold power of the switching. It is clear that the third-order dispersion with small σ hardly influence the averaged transmission value, especially for the range of $P < 1.5$. Then the switching function still takes effect. However, when the value of σ increases, the averaged transmission value quickly decreases with the value of P increasing in the range of $P > 1.5$. To the worst, the averaged transmission at $P = 3$ is even less than 0.5, which basically disable the switching function. Fig. 3 shows the final wave shapes through the directional couplers on the conditions of $P = 1$, 1.5 and 3, corresponding to $\sigma = 0$, 0.1, 0.14 and 0.18. For the case of $P = 1$ and 1.5, whatever the values of σ are, the position or intensity of the pulse in two fibers changes little. But when $P = 3$, with the value of σ increasing, not only the pulse intensity for u decreases, but also the position of the pulse for u results in shift in the right direction, which means that a time delay occurs when the u pulse goes through coupler. In order to solve the question that the switching function of directional couplers is disabled in the cases of the large σ and P, we try to use fibers adulterated by high nonlinear material. On the condition of large input power, the fibers will result in high-order nonlinear, thus the Eqs. (1) and (2) must include high-order nonlinear term, which can be rewritten by

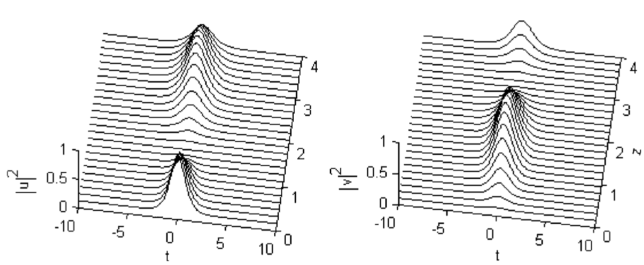

Fig. 1. Evolution of pulses in the fiber nonlinear directional coupler for soliton like input with $A^2 = 1$ and $K = 1$.

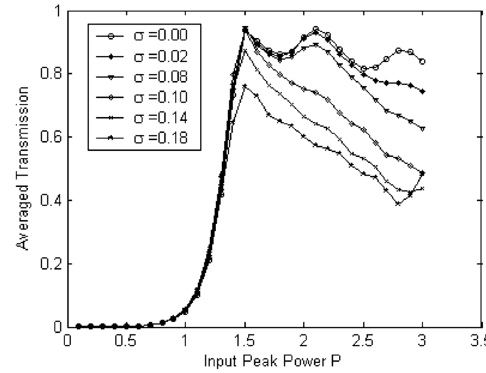

Fig. 2. Averaged transmission versus input peak power $P = A^2$ for different values of σ.

$$\frac{\partial u}{\partial z} = \mathrm{i}\frac{1}{2}\frac{\partial^2 u}{\partial t^2} + \sigma\frac{\partial^3 u}{\partial t^3} + \mathrm{i}(1 - e|u|^2)|u|^2 u + \mathrm{i}Kv, \tag{9}$$

$$\frac{\partial v}{\partial z} = \mathrm{i}\frac{1}{2}\frac{\partial^2 v}{\partial t^2} + \sigma\frac{\partial^3 v}{\partial t^3} + \mathrm{i}(1 - e|v|^2)|v|^2 v + \mathrm{i}Ku, \tag{10}$$

where e is the fifth-order nonlinear coefficient. These equations are called as the third–fifth order NLSE's [11]. SSFM method can be also used to solve Eqs. (9) and (10) and study the energy switching characteristics. Fig. 4 shows the result for different values of e and σ. From Fig. 4, we find that the averaged transmission hardly decreases after $P > 1.5$ in spite of $\sigma = 0.18$, which is attributed to that the fifth order nonlinear term partly overcomes the third-order dispersion. Fig. 5 depicts the