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Femtosecond pulse switching in a fiber coupler with third order dispersion and self-steepening effects

A. Govindaraji [a], A. Mahalingam [b], A. Uthayakumar [a,*]

[a] Department of Physics, Presidency College, Chennai 600005, India
[b] Department of Physics, Anna University, Chennai 600025, India

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ABSTRACT

A numerical study of femtosecond pulse propagation and switching in a dual-core nonlinear directional coupler with the consideration of third order dispersion and self-steepening effects is reported. The Split Step Fourier Method (SSFM) is used to investigate the switching characteristics of nonlinear directional couplers. It is observed that the energy transfer from core to core is not affected by changing the input pulse shapes except super-Gaussian. While the normalized coupling co-efficient and the input peak power dominate the coupling characteristics, the effects of third order dispersion (TOD) and self-steepening (SS) are also reported.

1. Introduction

Fiber couplers or nonlinear directional couplers (NLDC) have been receiving much attention for the past three decades, after the innovative theoretical suggestion of Jensen [1], because of its potential applications to all-optical switching and logic operations for use in ultra-high speed data processing and ultrafast communication systems [2–5]. Jensen and Maier [6] depicted the application of NLDC for all-optical switching by varying the input power of a continuous signal. The usage of the continuous signal resulted in the pulse breakup, distortion and inefficient switching. The advantage of soliton pulses for all-optical switching has been explained by Doran and Wood [7] in nonlinear interferometer. Later, Trillo et al. [8] extended the application of soliton pulses in NLDC and pointed out that the pulse break-up can be evaded when the soliton pulses are used as inputs, due to its particle-like behaviour. Besides, it is revealed [9] that fundamental soliton is the most suitable input among second order soliton and quasi solitons. Presently, the soliton pulses are applied in different optical fiber switching devices such as fiber Bragg gratings [10,11], fiber loop mirrors [12], photonic crystal fiber couplers [13], nonlinear birefringent fibers [14] and many other nonlinear fiber devices [15–17].

Of particular interest is the study of combined influence of higher order perturbative effects. If the input pulse width is too small(<*ps*), we have to include the higher order linear and nonlinear terms in Nonlinear Schrödinger Equation (NLSE) which describes the soliton propagation in optical fibers. Here the pulse propagation in NLDC has been explained by two linearly coupled NLSEs (CNLSE) based on the coupled mode theory. Previously the effect of third order dispersion in nonlinear directional couplers has been carried out in Refs. [18,19] and the influence of Stimulated Raman Scattering (SRS) has been studied in Ref. [20]. The combined effects of SRS and TOD have been described in Ref. [21]. Recently the combined effects of TOD and SS have been addressed in optical fiber [22] and we extend these effects to NLDC. As the larger pulse width may constrain the ultrafast communication, we have taken femtosecond pulses for this work. In this investigation, we study the combined effects of TOD and SS on ultra-short pulse interaction and switching in NLDC.

2. Theoretical framework-coupled nonlinear Schrödinger equations

Since nonlinear directional couplers are having two identical cores that are closely spaced and parallel to each other, the ultra-short pulses inside the NLDC can be expressed mathematically by CHNLSE [23],

$$\frac{\partial A_1}{\partial z} + i\frac{\beta_2}{2}\frac{\partial^2 A_1}{\partial T^2} - \frac{\beta_3}{6}\frac{\partial^3 A_1}{\partial T^3} - iC_0 A_2 + C_1\frac{\partial A_2}{\partial T} = i\gamma\left(|A_1|^2 A_1 + \frac{i}{\omega_0}\frac{\partial}{\partial T}(|A_1|^2 A_1) - T_R A_1 \frac{\partial |A_1|^2}{\partial T}\right) \quad (1)$$

* Corresponding author. Tel.: +91 9445160544.
E-mail address: uthayk@yahoo.com (A. Uthayakumar).

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$$\frac{\partial A_2}{\partial z}+i\frac{\beta_2}{2}\frac{\partial^2 A_2}{\partial T^2}-\frac{\beta_3}{6}\frac{\partial^3 A_2}{\partial T^3}-iC_0A_1+C_1\frac{\partial A_1}{\partial T} = i\gamma\left(|A_2|^2A_2+\frac{i}{\omega_0}\frac{\partial}{\partial T}(|A_2|^2A_2)-T_RA_2\frac{\partial|A_2|^2}{\partial T}\right) \tag{2}$$

where A_1 and A_2 represent the slowly varying envelopes associated with core 1 and core 2 respectively and the nonlinear parameter γ is defined as $\gamma = 2\pi n_2/\lambda A_{\text{eff}}$, where n_2 is the nonlinear refractive index and λ is the optical wavelength. A_{eff} is the effective core area, β_2 and β_3 are the second and third order dispersion co-efficients respectively. The term containing $1/\omega_0$ is related to self-steepening, and that of T_R is responsible for Raman scattering and C_0, C_1 are the linear coupling and intermodal co-efficients respectively. Eqs. (1) and (2) are transferred using standard soliton units [23],

$$\xi=\frac{z}{L_D},\ \tau=\frac{T}{T_0},\ U_1=\frac{A_1}{\sqrt{P_0}},\ U_2=\frac{A_2}{\sqrt{P_0}} \tag{3}$$

where $L_D = T_0^2/|\beta_2|$ is the dispersion length and T_0 is a measure of the input pulse width, P_0 is the input peak power. Then Eqs. (1) and (2) can be written in the following normalized form,

$$\frac{\partial u_1}{\partial \xi}-i\frac{1}{2}\frac{\partial^2 u_1}{\partial \tau^2}-\delta\frac{\partial^3 u_1}{\partial \tau^3}-i\kappa_0u_2+\kappa_1\frac{\partial u_2}{\partial \tau} = i|u_1|^2u_1-s\frac{\partial}{\partial \tau}(|u_1|^2u_1)-i\tau_Ru_1\frac{\partial|u_1|^2}{\partial \tau} \tag{4}$$

$$\frac{\partial u_2}{\partial \xi}-i\frac{1}{2}\frac{\partial^2 u_2}{\partial \tau^2}-\delta\frac{\partial^3 u_2}{\partial \tau^3}-i\kappa_0u_1+\kappa_1\frac{\partial u_1}{\partial \tau} = i|u_2|^2u_2-s\frac{\partial}{\partial \tau}(|u_2|^2u_2)-i\tau_Ru_2\frac{\partial|u_2|^2}{\partial \tau} \tag{5}$$

To remove the order of the soliton N in the above equations, we again put as, $u_1 = NU_1$ and $u_2 = NU_2$, where $N^2 = L_D/L_{NL}$, and $L_{NL} = 1/\gamma P_0$. The terms in the above equations can be written as,

$$\delta=\frac{\beta_3}{6|\beta_2|T_0},\ s=\frac{1}{\omega_0T_0},\ \tau_R=\frac{T_R}{T_0},\ \kappa_0=C_0L_D,\ \kappa_1=\frac{C_1L_D}{T_0} \tag{6}$$

where $\delta, s, \tau_R, \kappa_0, \kappa_1$ are the third order dispersion, self-steepening, Raman, normalized linear coupling and normalized intermodal coefficients respectively. ω_0 is the center frequency and it is defined as, $\omega_0 = 2\pi c/\lambda$, where c is the speed of light in free space. As all three parameters δ, s and τ_R differ inversely with the pulse width, they are negligible for $T_0 > 1ps$, however they become appreciable for femtosecond pulses. As we are particularly interested to study the effects of third order dispersion and self-steepening, we neglect the Raman term by putting $\tau_R = 0$ in the above equations as,

$$\frac{\partial u_1}{\partial \xi}-i\frac{1}{2}\frac{\partial^2 u_1}{\partial \tau^2}-\delta\frac{\partial^3 u_1}{\partial \tau^3}-i\kappa_0u_2+\kappa_1\frac{\partial u_2}{\partial \tau}=i|u_1|^2u_1-s\frac{\partial}{\partial \tau}(|u_1|^2u_1) \tag{7}$$

$$\frac{\partial u_2}{\partial \xi}-i\frac{1}{2}\frac{\partial^2 u_2}{\partial \tau^2}-\delta\frac{\partial^3 u_2}{\partial \tau^3}-i\kappa_0u_1+\kappa_1\frac{\partial u_1}{\partial \tau}=i|u_2|^2u_2-s\frac{\partial}{\partial \tau}(|u_2|^2u_2) \tag{8}$$

3. Numerical results and discussion

In general, the above Eqs. (7) and (8) cannot be solved analytically and so a numerical method is needed to solve them. The most widely used numerical method solving NLSE is the Split Step Fourier Method (SSFM) due to its simplicity, good accuracy and relatively modest computing cost. Here the linear and nonlinear parts are separated and we use the SSFM for the linear section and the difference scheme [24] for the nonlinear section. In this simulation, we have carried out a numerical grid consisting of 1024 points spaced equally from $\tau = -10$ to $\tau = 10$. The initial pulses launched in core 1 and core 2 are given as,

$$u_1(0,\tau)=A\text{sech}(\tau),\ u_2(0,\tau)=0 \tag{9}$$

Now we define the energy transfer co-efficient of ith core as ($i = 1, 2$) [25]

$$T_i=\frac{\int_{-\infty}^{+\infty}|u_i(\xi_L,\tau)|^2d\tau}{\int_{-\infty}^{+\infty}|u_1(0,\tau)|^2d\tau} \tag{10}$$

Converting the soliton units back to the real units of conventional fiber as, $\beta_2 = -20\ \text{ps}^2/\text{km}$, $\beta_3 = 0.108\ \text{ps}^3/\text{km}$, $A_{\text{eff}} = 55$ nm, $n_2 = 2.35\text{x}10^{-20}\ \text{m}^2/\text{W}$ and the wavelength $\lambda = 1.55\mu$ m, we have calculated the TOD and SS co-efficient values. In this work, we have studied the switching characteristics at the half-beat coupling length. The coupling length of the half-beat coupler is defined as [26], $L_C = \pi/2\kappa_0$.

3.1. Combined effects of TOD and SS, varying the normalized coupling co-efficient

In this section, we study the combined influence of TOD and SS by varying the normalized coupling co-efficient. Fig. 1 shows the switching characteristic curves with different values of κ_0.

In all the figures, the dashed lines indicate the transmission curves of core 1 and core 2 with the values of $\delta = 0$, $s = 0$, i.e., in the absence of higher order effects and the solid lines show the transmission curves of core 1 and core 2 with the pulse width $T_0 = 10$fs and $\delta = 0.09$, $s = 0.0822$. Fig. 1(a) depicts the switching characteristics with the conditions of $\kappa_0 = 0.25$, $L_C = 2\pi$. From the figure, one can observe that the threshold power for both dashed line and solid line curves is almost same and lies at $P_{th} = 1.3$ and after the input peak power $P_0 > 1.37$, the switching characteristics have been slightly decreased with the increasing input peak power due to TOD and SS effects. Fig. 1(b) gives the switching characteristic curves with the conditions of $\kappa_0 = 0.5$, $L_C = \pi$. Looking at the figure, it is easily noticed that there are no effects of TOD and SS until the input peak power $P_0 \le 1.742$. The switching threshold power for dashed line curves is $P_{th} = 2.05$ and $P_{th} = 2.17$ for solid line curves respectively. We can clearly observe that the switching characteristics have been decreased further compared with Fig. 1a with the increase in the input peak power. To investigate further, we have plotted Fig. 1(c) and (d) with the conditions of $\kappa_0 = 0.75$, $L_C = 2\pi/3$ and $\kappa_0 = 1$, $L_C = \pi/2$ respectively. In the figures, the effects of TOD and SS do not take place until the input peak powers $P_0 \le 2.121$, $P_0 \le 2.663$ accordingly. From Fig. 1(c), we observe the switching threshold power for dashed line curves is $P_{th} = 2.82$ and $P_{th} = 3.16$ for solid line curves respectively. Likewise from Fig. 1(d), the threshold powers lie at $P_{th} = 3.6$ for dashed line curves and $P_{th} = 4.23$ for solid line curves. In both figures, We can clearly notice that the switching characteristics have been decreased furthermore compared with former figures with the increase in the input peak power and hence we come to know from all the figures that TOD and SS effects tend to a very serious decrease in the transmission curves by increasing the normalized coupling co-efficient, Even though they smoothen the oscillating curves at high input powers.