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Dark soliton switching in nonlinear fiber couplers with gain

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ABSTRACT

In this paper, we present a study of numerical simulations for all-optical dark soliton switching in nonlinear directional couplers with gain additions in two waveguides whilst considering intermodal dispersion and its higher-order effects. The effects of possible combinations of gain addition in the bar channel as well as in the cross channel of the nonlinear couplers are theoretically presented. In addition, the consequence of second-order coupling coefficient dispersion based on coupled mode theory for dark soliton switching is numerically depicted.

1. Introduction

Lightwave communication systems based on solitons are expected to be available worldwide as they offer a dedicated balance between the group velocity dispersion and self-phase modulation, the two effects that severely affect the performance of non-soliton communication systems. Many functions like transmission, routing, and switching must cooperate to function the lightwave communications properly. Nonlinear Directional Coupler (NLDC) made of two single mode fibers is one of the functional devices which is mostly used as an all-optical switching device [1–5]. There are two operating modes in the nonlinear couplers. At low optical power, light couples linearly between the two waveguides. But the NLDC tends to be mismatched at higher optical powers, due to the dependence of the refractive index on the intensity of the light. This negative behavior becomes a problem when the NLDC switches each point of the pulse with respect to its own intensity leading to a severe pulse break-up, when the pulse peak emerges from one waveguide while low-power wings emerge from the other. However, bright (temporal) soliton pulses have been proved to overcome the pulse break-up due to its particle-like behavior [2].

Despite having the problem that dark solitons require a constant input power to maintain the background wave whereas bright solitons only require a transient power, dark solitons remain a subject of continuing interest, since they are more stable in the presence of noise and propagate more slowly in the presence of fiber loss compared with bright solitons in the lightwave communication systems [6]. They are also relatively less affected by many other factors that have an impact on the use of bright solitons. For instance, dark solitons show a time jitter which is $\sqrt{2}$ times lower than that of bright solitons while propagating in ultra-long amplified fiber links [7]. These inherent properties make the dark solitons as a potential source in optical communication systems. Dark solitons propagate in normal dispersion regime or self-defocusing nonlinearity of the fiber couplers and hence all-optical switching devices using dark solitons have been studied extensively in the nonlinear couplers [8–10] and other types of fiber couplers including those made of chalcogenide glasses [11] (Fig. 1).

The common problem of the fiber coupler is the linear loss of the material from which it is fabricated. As a lossless coupler is an idealized condition, in practice, this loss leads to the degradation of the switching characteristics of the nonlinear couplers [12] along with increasing switching power that can be of the order of kW or even higher power [5]. In this paper, we try to overcome the detrimental effect of loss by introducing gain additions on dark soliton transmission in the fiber couplers. We achieve the gains in the nonlinear couplers by adding the amplifiers and we can also vary the gains by pumping the amplifiers.

2. Theory

Dark soliton pulses propagating inside the nonlinear couplers are explained by a pair of coupled nonlinear Schrödinger equations (CNLSE). Such equations taking into account of linear gain [13–16] in the two cores with the consideration of intermodal dispersion [17] and second-order coupling coefficient dispersion in soliton units can be written as

$$\frac{\partial u_1}{\partial \xi} = -\frac{i}{2}\frac{\partial^2 u_1}{\partial \tau^2} + i|u_1|^2 u_1 + i\kappa_0 u_2 - \kappa_1 \frac{\partial u_2}{\partial \tau} + i\kappa_2 \frac{\partial^2 u_2}{\partial \tau^2} + g_1 u_1 \tag{1}$$

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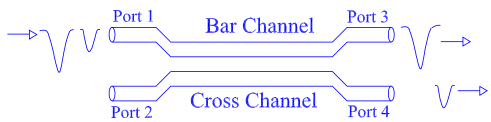

Fig. 1. Schematic diagram of dark soliton switching in nonlinear fiber couplers.

$$\frac{\partial u_2}{\partial \xi} = -\frac{i}{2}\frac{\partial^2 u_2}{\partial \tau^2} + i|u_2|^2 u_2 + i\kappa_0 u_1 - \kappa_1 \frac{\partial u_1}{\partial \tau} + i\kappa_2 \frac{\partial^2 u_1}{\partial \tau^2} + g_2 u_2 \quad (2)$$

where u_1 and u_2 are the normalized magnitude of the input pulses in the bar channel and the cross channel of the NLDC respectively. ξ and τ are respectively the normalized length and the time with $\xi = z/L_D$, $\tau = T/T_0$. Here, $L_D = T_0^2/|\beta_2|$ is the dispersion length, T_0 is the pulse width and β_2 is the group velocity dispersion ($\beta_2 < 0$). g_1 is the gain added in the bar channel and g_2 is the gain added in the cross channel of the nonlinear coupler. The coupling length of fiber coupler is taken as $L_C = \pi/2\kappa_0$ [18]. κ_0, κ_1, and κ_2 are the normalized coupling coefficient, intermodal dispersion and second-order coupling coefficient dispersion respectively. The effect of intermodal dispersion which causes the splitting in optical pulses as in the case of bright solitons has previously been addressed on the dark soliton switching in Ref. [9] along with the usual higher-order effects. It is shown that the intermodal dispersion and the higher-order effects such as third-order dispersion, self-steepening and stimulated Raman scattering do not have any influence on the dark soliton switching. But the second-order coupling coefficient dispersion has not yet been taken into account for the dark soliton switching. In this work, we are particularly interested to study the effects of the normalized coupling coefficient and the second-order coupling coefficient dispersion along with the linear gains.

3. Numerical results and discussion

As the above Eqs. (1) and (2) cannot be solved analytically, they have been solved numerically by Asymmetric Split Step Fourier Method (ASSFM) [19] due to its simplicity as well as good accuracy. The initial conditions are taken such that dark soliton pulse is launched in the bar channel of the waveguide with no pulse in the cross channel in the NLDC as follows:

$$u_1(0,\tau) = \sqrt{P_0}\tanh(\sqrt{P_0}\tau), \quad u_2(0,\tau) = 0 \quad (3)$$

where P_0 represents the input peak power. Now we define the energy transfer coefficient of jth waveguide as [20]

$$T_j = \frac{\int_{-\infty}^{+\infty} |u_j(\xi_L,\tau)|^2\, d\tau}{\int_{-\infty}^{+\infty} |u_1(0,\tau)|^2\, d\tau} \quad (4)$$

In this work, the dark soliton switching characteristics have been studied at half-beat coupling length which is defined as $L_C = \pi/2$ with $\kappa_0 = 1$. Firstly, to check the stability and evolution of fundamental dark soliton inside the NLDC, time domain evolution profiles have been plotted in Fig. 2 with the values of $P_0 = 1$ and $\kappa_1 = \kappa_2 = g_1 = g_2 = 0$. From the above figures, one can notice that dark soliton propagates back and forth between the bar and cross channels of the coupler to the expected length of $\pi/2$ as in the case of bright solitons and they have been preserved inside the couplers. We give the detailed study of every individual effect in the following subsections.

3.1. Effect of gain additions

3.1.1. Case (i)

Fig. 3 shows the switching characteristic curves of normalized input peak power against transmission of the bar channel for different values of gain added in the bar channel (active core) and keeping the gain of the cross channel as zero (passive core).

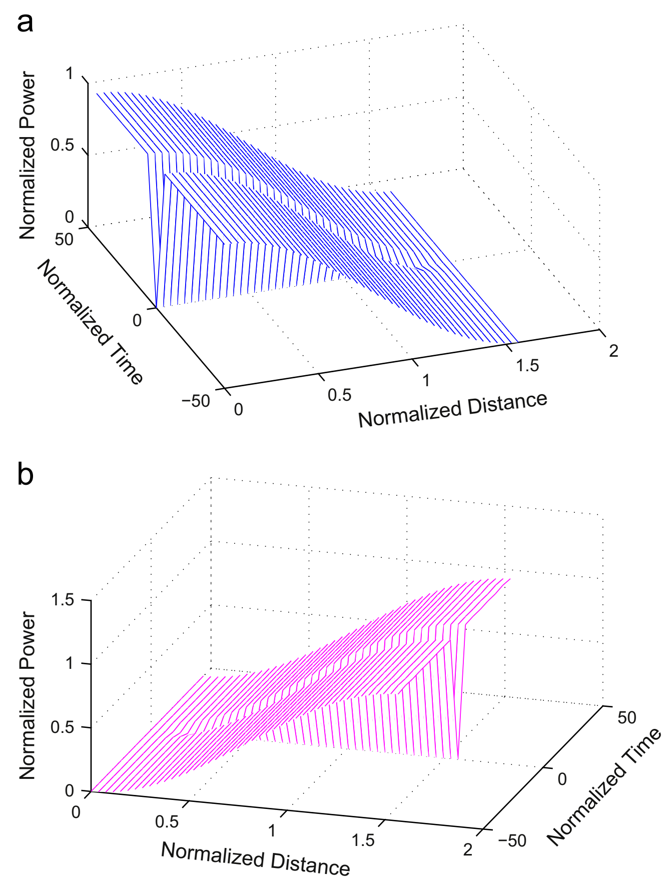

Fig. 2. Time domain evolution of dark soliton. Dark soliton inside (a) bar channel and (b) cross channel.

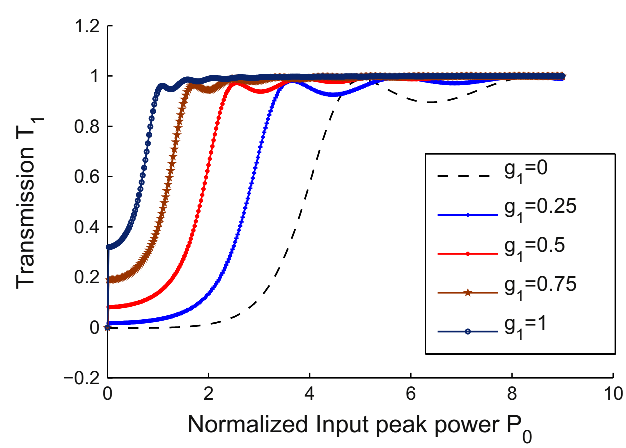

Fig. 3. Plot of transmission in bar channel versus normalized input power for different values of g_1 with $g_2 = 0$.

From Fig. 3, we can notice that by increasing the gain in the bar channel of the coupler, switching steepness has been increased with same output transmission value. Another notable influence with the increasing gain in the bar channel is the decrease of switching threshold power which is a desirable effect and particularly the switching threshold power is reduced by about a factor of 4 for the gain $g_1 = 1$. Hence, by increasing the gain of bar channel, excellent switching characteristics can be achieved.