RP Current Trends in Engineering and Technology
Vol. 1, No. 5 (November 2022) pp. 87–90
e-ISSN: 2583-5491

Cite this article: V.P. Singh, $\chi^{(3)}$ nonlinearity and soliton switching in a periodically modulated dispersion fiber coupler, *RP Cur. Tr. Eng. Tech.* **1** (2022) 87–90.

Original Research Article

$\chi^{(3)}$ - nonlinearity and soliton switching in a periodically modulated dispersion fiber coupler

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ARTICLE HISTORY
Received: 10 Sept. 2022
Revised: 6 Nov. 2022
Accepted: 7 Nov. 2022
Published online: 8 Nov. 2022

KEYWORDS
Soliton; modulated dispersion; fiber coupler; cubic nonlinearity.

ABSTRACT
Using a regularly modulated dispersion fibre coupler with cubic quintic nonlinearity and coupling constant dispersion, we conducted a thorough examination into soliton switching. The results are presented in this paper. Comprehensive research has been done on the effects of coupling coefficient dispersion, quintic nonlinearity, and periodically modulated dispersion on switching dynamics. In the setting of quintic nonlinearity and periodically modulated dispersion, the expressions for transmission coefficient, cross talk, and extinction ratio have been developed and analysed. It has been discovered that, except from low values, quintic nonlinearity negatively affects soliton switching. Numerical analysis has confirmed our analytic findings.

1. Introduction

Due to their technological applications to numerous optical instrumentations, including power splitting, wavelength division multiplexing-demultiplexing, polarisation splitting, fibre optic sensing, and others, nonlinear directional couplers have been the focus of research for more than two decades. While many theoretical and experimental studies have been conducted over the course of this lengthy time, several gadgets have also been made using these technologies and put to use in the commercial sector.

Soliton switching in nonlinear directional couplers (NLDC) has been thoroughly researched and reported on among the many uses. Research on soliton switching behaviour on NLDC in Kerr media and later in non-Kerr media was sparked by Jenson's groundbreaking works [1]. NLDC is now viewed as one of the fundamental components of an all-optical communication system and signal processing.

Two forms of pulse switching are possible in NLDC. One type of switching is power controlled, in which the output depends on the input power in a single channel. The first example of such power-dependent switching was found in multiple quantum wells made of GaAs and AlGaAs (MQW). The switching dynamics of the other switching type, known as phase controlled switching, are controlled by the phase difference between a weak and a strong input signal. This switching type may be thought of as an appealing substitute for power controlled switching. The soliton production is also conceivable for more realistic cases that contain two orthogonal polarizations in the coupler cores, even though most NLDC investigations treat each core as a monomode waveguide.

Without a thorough exploration of soliton interactions as well as stability analysis, which draws many scholars, the study of soliton switching could not take on its final form. Remember that NLDC is made up of single mode fibres that are truly bimodal in nature and may support two eigen modes, namely symmetrical mode and anti-symmetrical mode. As a result, there is intermodal dispersion (IMD). The switching dynamics of NLDC can be dramatically altered by the IMD between these two eigen modes [2]. This IMD can be represented mathematically by coupling constant dispersion in linked NLSE. Both numerically [3] and semi-analytically [4] soliton switching with coupling constant dispersion has been explored. In practise, an NLDC's component fibres may exhibit random fluctuation along their transverse dimension, which results in birefringence and, as a result, a periodically modulated dispersion (PMD). Additionally, this transverse fluctuation has the power to modify the overall switching dynamics by affecting the nonlinear dispersion along the length of the fibre.

Both analytical and numerical studies have been done on the performance of NLDC fibre couplers with periodically regulated dispersion [5-7]. To the best of our knowledge, no work has been reported on the combined effect of these two, which promise more intriguing switching dynamics, despite the fact that NLDC has been explored in the context of IMD and periodically modulated dispersion. Additionally, higher order nonlinearity enters the picture when studying NLDC with a high intensity radiation such as a laser, making Kerr nonlinearity insufficient to explain the system. Soliton switching in a periodically modulated dispersion fibre coupler with cubic quintic nonlinearity and coupling constant dispersion has been the subject of a thorough analysis, the findings of which are presented in this paper. The structure of this article is as follows. We mathematically described the system in part 2. The findings and discussion are presented in Section 3. In section 4, a concluding statement has been provided.

2. Mathematical formulation

We take into account the propagation of brief pulses through a dual core NLDC with cubic quintic nonlinearity. Dispersion fibre that is periodically modulated is used to make the coupler (PMDF). Linear coupling is produced by the evanescent-field coupling between the cores, whereas nonlinear coupling is produced by cross phase modulation (XPM). The last one can be disregarded because there is only a minimal amount of overlap between the elemental modes corresponding to each core. The following pair of coupled nonlinear Schrödinger equations (CNLSE), where the coupling is mediated by a linear coupling term, can be used to represent this system mathematically [4, 5].

$$i\left(\frac{\partial u}{\partial \xi}+\delta\frac{\partial v}{\partial t}\right)+\frac{P(\xi)}{2}\frac{\partial^2 u}{\partial t^2}+|u|^2 u+s|u|^4 u=-k_0 v \quad (1)$$

$$i\left(\frac{\partial v}{\partial \xi}+\delta\frac{\partial u}{\partial t}\right)+\frac{P(\xi)}{2}\frac{\partial^2 v}{\partial t^2}+|v|^2 v+s|v|^4 v=-k_0 u \quad (2)$$

$$P(\xi)=|\beta_2|(1+A\cos\omega\xi), \quad (3)$$

where, u , v are the normalized slowly varying envelope amplitude in the input core (core- 1) and its neighbouring core (core-2) respectively, ξ is the normalized distance along the fiber length, t is the normalized time, δ is the first order coupling constant dispersion coefficient, s is the coefficient of quintic nonlinearity which takes '-ve' sign in our present discussion as we are interested in anomalous dispersion regime only, k_0 is the normalized zeroth order coupling coefficient which is the measure of the strength of interaction between the fiber cores. k_0 depends on fiber characteristics, separation between the cores and operational frequency. $P(\xi)$is the group velocity dispersion profile and ω is the frequency of modulation in the PMDF.

We use the variational analysis method to solve the aforementioned CNLSE in order to investigate the switching dynamics. The system's Lagrangian density is given by

$$L=\frac{i}{2}\left(u\frac{\partial u^*}{\partial \xi}-u^*\frac{\partial u}{\partial \xi}\right)+\frac{P(\xi)}{2}\left|\frac{\partial u}{\partial t}\right|^2-\frac{1}{2}|u|^4-\frac{\gamma}{3}|u|^6$$
$$+\frac{i}{2}\left(v\frac{\partial v^*}{\partial \xi}-v^*\frac{\partial v}{\partial \xi}\right)+\frac{P(\xi)}{2}\left|\frac{\partial v}{\partial t}\right|^2-\frac{1}{2}|v|^4-\frac{\gamma}{3}|v|^6$$
$$+\frac{i\delta}{2}\left(v\frac{\partial u^*}{\partial t}-v^*\frac{\partial u}{\partial t}+u\frac{\partial v^*}{\partial t}-u^*\frac{\partial v}{\partial t}\right)-k_0(u^*v+uv^*) \quad (4)$$

Assumed are the following Ansatz that, in cores 1 and 2, corresponds to the bright soliton solution.

$$u(t,\xi)=A(\xi)\cos(\theta(\xi))\sec h\left(\frac{t-\tau(\xi)}{a(\xi)}\right)$$
$$\times\exp[-in(\xi)(t-\tau)+ib(\xi)(t-\xi)^2+i\phi(\xi)] \quad (5)$$

$$v(t,\xi)=A(\xi)\sin(\theta(\xi))\sec h\left(\frac{t-\tau(\xi)}{a(\xi)}\right)$$
$$\times\exp[-in(\xi)(t-\tau)+ib(\xi)(t-\xi)^2-i\phi(\xi)], \quad (6)$$

where, $A(\xi)$ is the amplitude of the pulse envelope, $\theta(\xi)$ is the coupling angle, $\tau(\xi)$ is the position of the pulse centre, $a(\xi)$ is the pulse width, $b(\xi)$ represents chirp and $\varphi(\xi)$is the relative phase difference between the pulses. The averaged Lagrangian L_{av} of the system is obtained by following formula:

$$L_{av}=\int_{-\infty}^{\infty} L dt. \quad (7)$$

Substituting Eqs. (5) and (6) in (4), we get

$$L_{av}=ia\left(A\frac{\partial A^*}{\partial \xi}-A^*\frac{\partial A}{\partial \xi}\right)+2|A|^2 an\frac{d\tau}{d\xi}$$
$$+\frac{\pi^2}{6}|A|^2 a^3\frac{db}{d\xi}+2|A|^2 a\cos(2\theta)\frac{d\phi}{d\xi}$$
$$+\frac{|A|^2 P}{3a}+|A|^2 an^2P+\frac{\pi^2}{3}|A|^2 a^3b^2P-\frac{2}{3}|A|^4 a(\sin^4\theta+\cos^4\theta)$$
$$-\frac{16\gamma}{45}|A|^6(\sin^6\theta+\cos^6\theta)-2|A|^2 a(n\delta+k_0)\sin(2\theta)\cos(2\phi) \quad (8)$$

Variations of the average Lagrangian with respect to different parameters that characterize the system give rise to the following set of evolution equations.

$$\frac{d(2|A|^2 a)}{d\xi}=0 \quad (9a)$$

$$\frac{dn}{d\xi}=0 \quad (9b)$$

$$\frac{d\tau}{d\xi}=\delta\sin(2\theta)\cos(2\phi)-nP \quad (9c)$$

$$\frac{da}{d\xi}=2abP \quad (9d)$$

$$\frac{d\theta}{d\xi}=-(n\delta+k_0)\sin(2\phi) \quad (9e)$$

$$\frac{d\phi}{d\xi}=-(n\delta+k_0)\cot(2\theta)\cos(2\phi)+\left(\frac{E_0}{6a}+s\frac{E_0^2}{15a^2}\right)\cos(2\theta) \quad (9f)$$

$$\frac{db}{d\xi}=\frac{2P}{\pi^2a^4}-2b^2P-\frac{E_0}{\pi^2a^3}(\sin^4\theta+\cos^4\theta)$$
$$-\frac{8E_0^2 s}{15\pi^2a^4}(\sin^6\theta+\cos^6\theta). \quad (9g)$$

Eq. (9a) can be written as: $2|A|^2 a = E_0$ (constant). E_0 may be identified as the input soliton energy. The evolution of the pulse as well as soliton switching in the coupler are then thoroughly analysed using the aforementioned equations. The fractional energy at the output end of the cores is a crucial component of the switching function in NLDC.

One can determine the fractional energy at the output end of core 1 by using Eqs. (5) and (6) as follows:

$$E_{1f}\,\frac{\int_{-\infty}^{\infty}|u|^2\,d\tau}{\int_{-\infty}^{\infty}|u|^2\,d\tau+\int_{-\infty}^{\infty}|v|^2\,d\tau}=\cos^2\theta\,. \qquad (10)$$

3. Results and discussion

It will be helpful to highlight the properties of the 1st order coupling constant dispersion coefficient (δ) before analysing the switching characteristics. The value of δ can be calculated by the method employed by Ramos et al. [3]. Here, we redraw the variation characteristic of δ with pulse width in Figure 1, which is more informative as we take k_0 as a parameter.

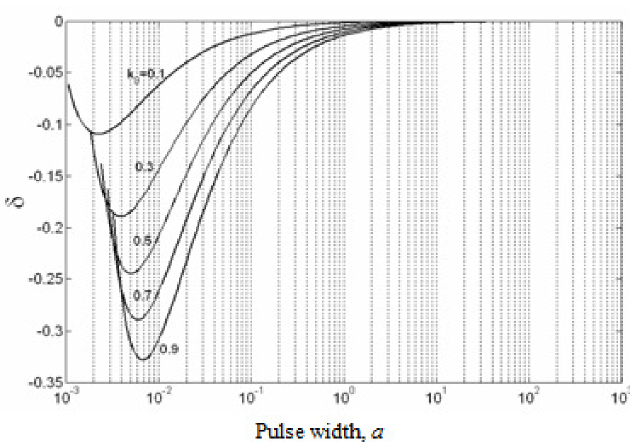

Figure 1. Variation of first order coupling coefficient dispersion coefficient δ with pulse width taking k_0 as a parameter.

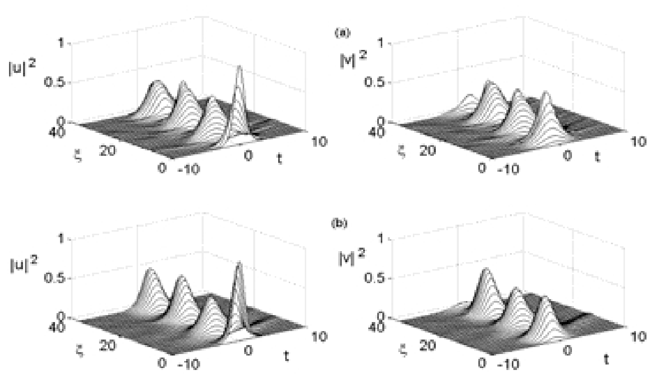

Figure 2. Evolution of u and v along the propagation length of the NLDC. $k_0 = 0.3$, $\delta = -0.1456$, $s = -0.01$. (a) with PMD effect, (b) without PMD effect.

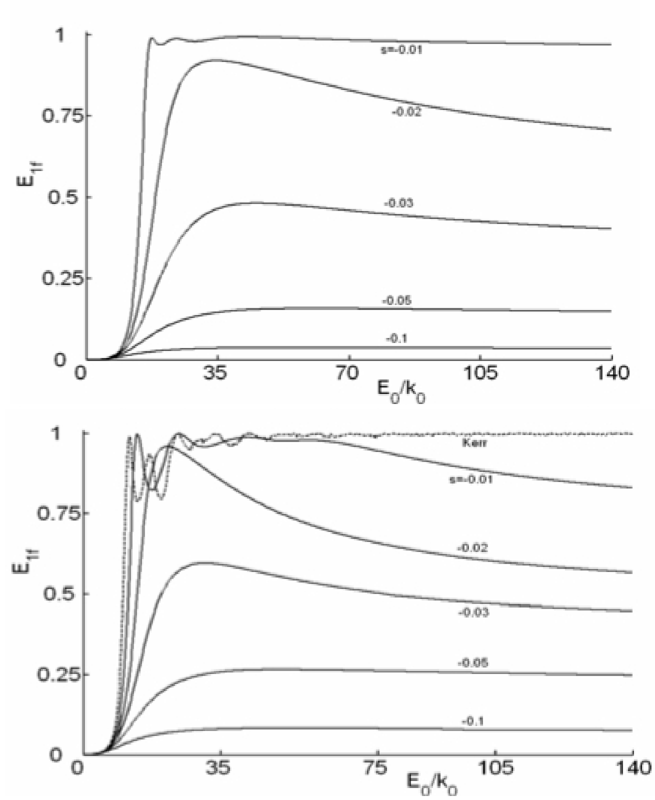

Figure 3. Variation of the fractional energy at the output end of core 1 (i.e. E_{1f}) with input soliton energy normalized by k_0. $k_0 = 0.3$, $\delta = -0.1656$, $s = -0.01$. Left panel with PMD effect, Right panel without PMD.

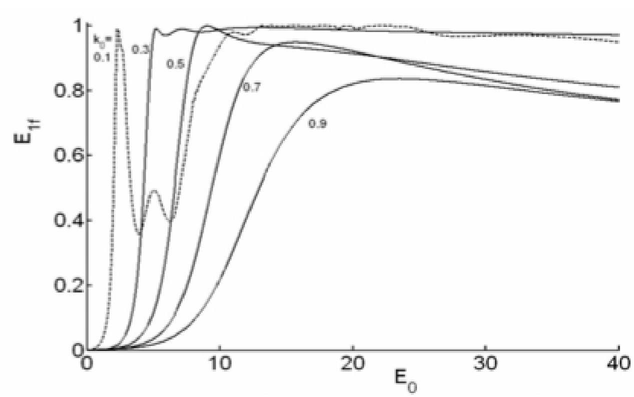

Figure 4. Variation of E_{1f} with input soliton energy E_0.

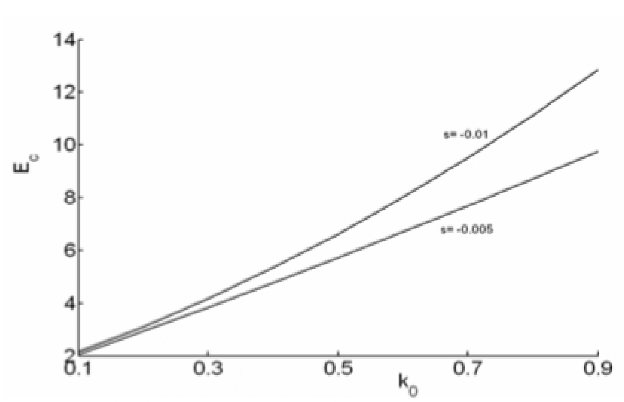

Figure 5. Variation of critical energy E_c with k_0 in presence of PMD.

Figure 1 demonstrates that although δ becomes the same for all values of k_0 at comparably larger pulse widths (~ 1 ps), k_0 has a considerable impact on δ for smaller pulse widths. For more research, we gather the values of δ from Figure 1. Eqs. (5) and (6) have been solved using direct numerical technique employing split step Fourier transformation in order to depict the switching profile in the NLDC. Figure 2's upper panel depicts the pulse propagation profile in cores 1 and 2 whereas the lower panel depicts the same minus the PMD impact. Here, seven half beats of the coupler's length of propagation are covered. Figure clearly shows that the PMD effect reduces the pulse intensity in either core. The fractional energy at the output end of core 1 depends on input soliton energy E_0 , δ , k_0 and PMD effect.

To recognize a comparison study, Figure 3a depicts the evolution of E1f with normalised input soliton energy when the PMD effect is present, while Figure 3b shows the same evolution without the PMD effect. The quintic nonlinearity has a relatively negative impact on switching characteristics, as seen by both figures. Of course, for $s = -0.01$, we observe a very distinct switching in both the PMD- and non-PMD-cases. We now investigate how coupling coefficient affects switching. Figure 4 describes the variation of E_{1f} with normalized input soliton energy considering k_0 as a parameter.

Figure shows that the critical energy for switching E_c grows as k_0 increases. Figure 5 illustrates this for various quintic nonlinearity values.

4. Conclusions

The soliton switching in an NLDC with cubic quintic nonlinearity and coupling constant dispersion, which results from the intermodal dispersion between symmetric and antisymmetric modes of the coupler, is discussed in this study. Comprehensive research has been done on the effects of coupling coefficient dispersion, quintic nonlinearity, and periodically modulated dispersion on switching dynamics. In the setting of quintic nonlinearity and periodically modulated dispersion, the expressions for transmission coefficient, cross talk, and extinction ratio have been developed and analysed. It has been discovered that, except from low values, quintic nonlinearity negatively affects soliton switching. Numerical analysis has confirmed our analytic findings.

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