Analysis Switching and crosstalk of Soliton in inhomogeneous Dispersion Decreasing Fiber Couplers

A. W. Lima Jr., J. S. de ALMEIDA, W. B. Fraga, J. W. M.Menezes, A. S. B. Sombra and M. G. da Silva

***Abstract*— We present a numerical investigation of the propagation and the switching of fundamental solitons in a two-core nonlinear fiber coupler constructed with dispersion decreasing fiber (DDF). In our simulations are taking into account simulations considering six different profiles, linear, hyperbolic, exponential, logarithm, constant and Gaussian. The transmission characteristics, the critical energy, the compression factor, the crosstalk (Xtalk) and extinction ratio levels (Xratio) of first order solitons were studied for low to high pump energies. . Twin core nonlinear directional couplers that include loss is also examined. The inclusion of loss results in the increase of the critical power of the coupler and broadening of the switched pulses, while the switching characteristics deteriorate. To compensate for this worse behavior, associate to the loss, we investigated the effect of the DDF profiles on the performance of the coupler. We have show that appropriate shaping of the DDF profile is quite effective to recover, almost completely, the original switching behavior associated to the lossless situation.**

***Keywords*— Optics Fiber, nonlinear directional Couplers, dispersion, Solitons.**

I. Introduction

Directional couplers constitute an essential component of lightwave technology. They are use routinely for a multitude of fiber-optic devices that require splitting of an optical field into two coherent but physically separated parts and vice versa (Agrawal) [1]. Optical fiber couplers have been studied for their potential applications to ultrafast all optical switching processing, like optical switch [2]. Jensen showed that varying the input light in the nonlinear coupler could lead to pulse switching between the two cores [3]. He therefore foresaw the possible use of a nonlinear directional coupler as an optical switch. Fiber coupler consists of four-port (two input and two output ports) that are used routinely for a variety of applications related to fiber optics [4-7]. Their function is to split coherently an optical field, incident on one of the input ports, and direct the two parts to the output ports. Since the output is directed in two different directions, such devices are also referred to as directional couplers. Because of evanescent coupling, signals introduced into guide (1) transfer completely to guide (2) in one coupler length Lc (see Figure 1). Higher intensities induce changes in the refractive index and detune the coupler. Coupler is inhibited for input energies above the critical energy $E_C = \lambda/n_2 L_c$, where λ is the pump wavelength and n_2 is the nonlinear refractive index [8-10], L_c is the half-beat-length coupler of length $L_C = \pi/2K$ and K is the linear coupling coefficient between adjacent guides. At the critical energy E_c, 50% of the light emerges from each output port. Above E_c most of the light emerges from port P_1. Previous studies of soliton switching in dual core optical fibers, without loss, have shown excellent switching characteristics, with efficiencies around 96% for a wide range of input energies [11]. In trying to control the switching efficiency, there is a great interest in the study of the crosstalk level (Xtalk) and extinction ratio (Xratio) in directional couplers. In particular the analysis of soliton propagation in nonlinear inhomogeneous waveguides is an important topic with big possibilities of applications. In the following, we will examine the propagation and the switching of fundamental solitons in a two-core nonlinear fiber coupler constructed with dispersion decreasing fiber (DDF). In this paper, we have investigated the effect of using dispersion decreasing fibers on the performance of nonlinear directional couplers (NLDC) with and without loss. Six closely shaped profiles named linear, Gaussian, exponential, hyperbolic, constant and logarithm have been considered. From our study of the dispersion profiles, we introduce light in input and outputting ports of the coupler and find the optimum profile, to recover the original performance of the nonlinear transmission in both cases, to overcome the effect of the intrinsic loss in the device.

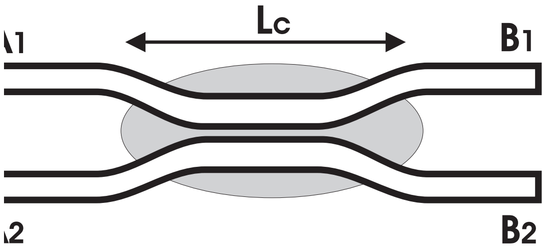

Fig. 1. Schematic illustration of nonlinear directional coupler. The all four ports can accept the initial pulse

A. Theoretical Model

In our studies We will consider ultrashort solitons (picosecond) propagating in the anomalous dispersion regime in an

A. W. Lima Jr. and J. S. de ALMEIDA, Departamento de Engenharia de Teleinformática DETI,Centro de Tecnologia, Universidade Federal do Ceará, Fortaleza, Ceará, Brasil.

W.B.Fraga, J.W.M.Menezes and A. S. B. Sombra¸ Laboratório de Telecomunicações e Ciência e Engenharia dos Materiais LOCEM, Departamento de Física, Universidade Federal do Ceará. Fortaleza, Ceará, Brazil,E-mail: sergio@fisica.ufc.br.

M. G. da Silva¸ Curso de Física, Centro de Ciências Exatas e Tecnológicas, Universidade Estadual Vale do Acaraú, Sobral, Ceará, Brasil, E-mail: marcio@fisica.ufc.br.

nonlinear directional coupler with twin fibers with second-order dispersion coefficient β_2. The propagating of ultrashort solitons through the DFF coupler is described by the nonlinear Schrödinger equation with dispersion decreasing fiber (DFF) with profile $p(\xi)$:

$$j\frac{\partial u_1}{\partial \xi} + \frac{1}{2}p(\xi)\frac{\partial^2 u_1}{\partial \tau^2} + |u_1|^2 u_1 + K u_2 + j\alpha u_1 = 0 \qquad (1)$$

$$j\frac{\partial u_2}{\partial \xi} + \frac{1}{2}p(\xi)\frac{\partial^2 u_2}{\partial \tau^2} + |u_2|^2 u_2 + K u_1 + j\alpha u_2 = 0 \qquad (2)$$

where u_1 and u_2 are the modal field amplitudes in soliton units, $p(\xi)$ is the DFF profile of the GVD, α is the fiber loss. ξ and τ are the normalized length and time in soliton units with $\xi = z/L_D$ and $\tau = t/T_o$. Here $L_D = T_o^2/|\beta_2|$, with pulse width $T_o(T_o = 1.13459ps)$,$|\beta_2| = 20ps2/km$. The varying GVD parameter $p(\xi)$ is a periodic function defined by equation 3 ($|\beta_2| = 20ps^2/km$). In a DDF of certain length, the dispersion is monotonically and smoothly decreased from an initial value to a smaller value at the end of the length according to some specified value. Provided the dispersion variation in the DDF is sufficiently gradual, soliton compression can be an adiabatic process where an input fundamental soliton pulse can be ideally compressed as it propagates, while retaining its soliton character and conserving the energy[10]. Interest in DDF in nonlinear fiber optics has focused on its use to compensate for the detrimental effect of signal attenuation in long distance soliton propagation. In this paper, we compare six simple coefficient of dispersion decreasing profiles, namely linear, Gaussian, exponential, logarithm, hyperbolic and constant. These profiles expressed in terms of the parameters $1/\beta$ (the minimum value of $p(\xi)$) and L(length of the coupler) are:

$$p(\xi) = \frac{1-\beta}{\beta L}\xi + 1, Linear \qquad (3)$$

$$p(\xi) = exp(\frac{-\xi}{L}ln(\beta), Exponential \qquad (4)$$

$$p(\xi) = exp(\frac{-\xi^2}{L^2}ln(\beta), Gaussian \qquad (5)$$

$$p(\xi) = ln(e + \frac{-\xi}{L}(e^(1/\beta) - e), Logarithm \qquad (6)$$

$$p(\xi) = \frac{L}{(\beta-1)\xi + L}, Hyperbolic \qquad (7)$$

$$p(\xi) = \frac{1}{\beta}, Constant \qquad (8)$$

Note that in these normalized profiles the dispersion coefficient p monotonically decreases from 1 to a final value of $1/\beta$, after a length L of the coupler. The dispersion profiles are illustrated in Figure 2.

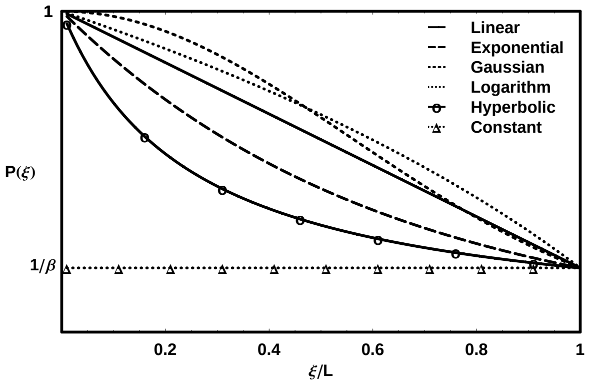

Fig. 2. Illustration of the dispersion profiles considered

B. Numerical procedure

Taking equations 1 or 2 with no coupling, constant profile ($p(\xi) = 1$) and no loss one has the well-known soliton solutions. We have analyzed numerically the first order solitons transmission through the two core nonlinear directional fiber coupler (equations 1-2) with dispersion profiles given by equations 3-8 . The initial pulse at the input ports is given by:

$$u_1(z_p, \tau) = asech(a\tau) \qquad (9)$$

$$u_2(z_p, \tau) = 0 \qquad (10)$$

Where de $z_p = 0$ *or* L_c, depending if the light get in through the port A_1 or B_1, respectively. This system of nonlinearly coupled NLSE's (equations 1-8) was solved numerically using the split-step method with 1024 temporal grid points taking in account the initial conditions given by equations (9-10). We can define the transmission T_i as relation between input energy and initial pulse energy, given by:

$$T_i = \frac{\int_{-\infty}^{\infty} |u_i(L_c - z_p, \tau)|^2 d\tau}{\int_{-\infty}^{\infty} |u_1(z_p, \tau)|^2 d\tau} \qquad (11)$$

Where u_i represent the output ports with i=1,2 and an DFF with length of L_c The crosstalk level of the device was studies considering the input energies (Equations 9 and 10). Xtalk is defined as the ratio of light energy in the unwanted output port by the initial pulse energy in the input port.

$$XTalk = \frac{\int_{-\infty}^{\infty} |u_2(L_c - z_p, \tau)|^2 d\tau}{\int_{-\infty}^{\infty} |u_1(z_p, \tau)|^2 d\tau} \qquad (12)$$

The extinction ratio of an on-off switch is the ratio of the output power in the ´on´ state to the output power in the ´off´ state. This ratio should be as high as possible. For our DFF it is expressed by:

$$XRatio = \frac{\int_{-\infty}^{\infty} |u_1(L_c - z_p, \tau)|^2 d\tau}{\int_{-\infty}^{\infty} |u_2(L_c - z_p, \tau)|^2 d\tau} \qquad (13)$$

Finally, we also define the compression factor C, achieved after propagation of the optical input pulse in the DDF coupler. It is defined as the ratio of initial time width of optical pulse at the input of the coupler τ_o to the time width at the output (transmitted) of the coupler, τ_i.

$$C_i = \frac{\tau_o}{\tau_i} \tag{14}$$

Where $i = 1$ *or* 2 for switching of pulses at port 1 or 2.

II. Results and discussions

We consider the two coupler configurations: the PA_1 coupler configuration that pump energy into port A_1 ($z_p = 0$), in this situation the light travels in forward direction and the PB_1 coupler configuration that pump energy into port (B_1) ($z_p = L_c$) and the light travels in backward direction.

A. PA_1 configuration

The figure 3 shows the soliton transmission characteristics in output channel B_1 for six different profiles without loss. The NLSE equations (equations 1-8) was solved numerically with the input soliton given by equations 9 and 10 with $z_p = 0$. The soliton transmission was obtained (equation 11) for six different couplers constructed with different profiles. In this figure the reference coupler (reference, $\alpha = 0$ and $P(\xi) = 1$) was also included. In this simulation one has $\beta = 2$ for all the six profiles. One concludes that for all the profiles there is a decrease of the critical energy. In figure

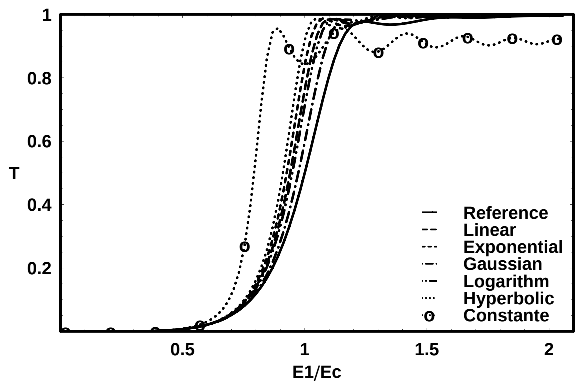

Fig. 3. Switching characteristics of port B_1 as a function of the pump energy into the port A_1 for DDF coupler with $\beta = 2$. The case Reference identifies the reference nonlinear coupler ($p(\xi) = 1$).

4 we compare the critical energy of all DDF couplers with the critical energy of the reference coupler as a function of the parameter β. From that figure, we can conclude that the increase of β(decrease in the profile $p(\xi)$) lead to the decrease of the critical energy. The decrease is stronger for the constant profile and is less pronounced for the Gaussian profile. The sequence of decreasing critical energy is given by Gaussian, logarithm, linear, exponential, hyperbolic and constant. In figure 5 we has the compression factor for channel 1 the DDF coupler with $\beta = 2$. This figure we plot two lines at C=1 and C=2. For the reference coupler we can see that C=1 for energy higher that the critical one, however for the DDF couplers the compression goes to a value around C=2 for high pump power showing a strong shaping effect which result in

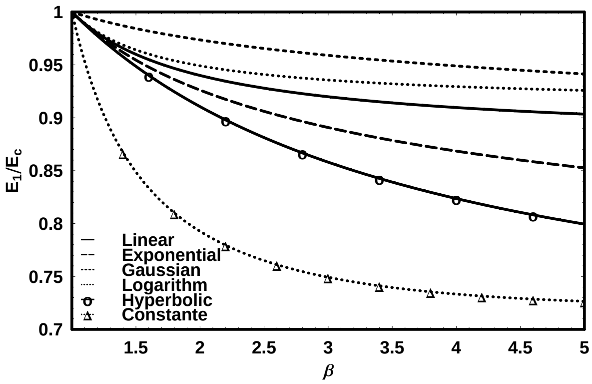

Fig. 4. Critical energy as a function of β for the DDF coupler.

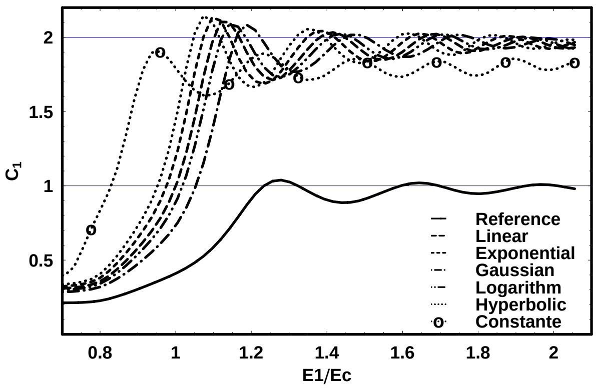

Fig. 5. Compression factor C_1 as a function of the pump energy into the port A_1 for DDF coupler with $\beta = 2$.

compression of the pump pulse.This effect is less pronounced in the constant profile where the compression is around 1.8.

In figure 6 we have the Xtalk level in port B_2 as a function of the input energy for all the six profiles ($\beta = 2$). For the reference coupler one can notice that with the increase in the input energy the Xtalk level is improving. We can observe that only the constant profile has the worse crosstalk result. The other five profiles the Xtalk level is improve A sequence of first minimums in the Xtalk value is constant, hyperbolic, exponential, linear, logarithm, Gaussian and reference.

B. PB_1 configuration

The figure 7 shows the soliton transmission characteristics in output channel A_1 for six different profiles. The NLSE equations was solved numerically with the input soliton with $z_p = L_c$. The soliton transmission was obtained for six different couplers constructed with different profiles. In this simulation one has $\beta = 2$ for all the six profiles. we concludes that for all the profiles there is a decrease of the critical energy better than PA_1 configuration. In figure 8 we compare the critical energy of all DDF couplers with the critical energy of the reference coupler as a function of β. From that figure, we can conclude that the increase of β(increase in the profile $p(\xi)$) lead to the decrease of the critical energy. The decrease is stronger for the constant profile and is less pronounced for the

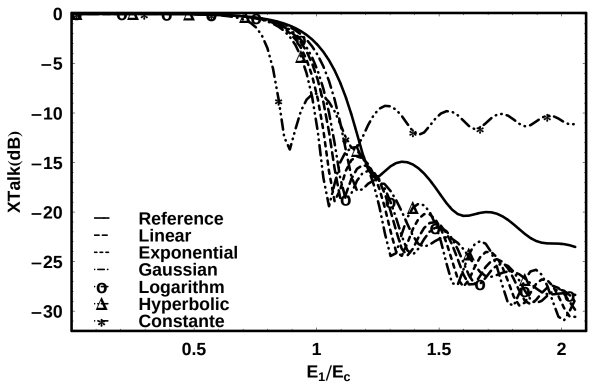

Fig. 6. Xtalk level as a function of the pump energy into the port A_1 for DDF coupler with $\beta = 2$. The case Reference identifies the reference nonlinear coupler $(p(\xi) = 1)$.

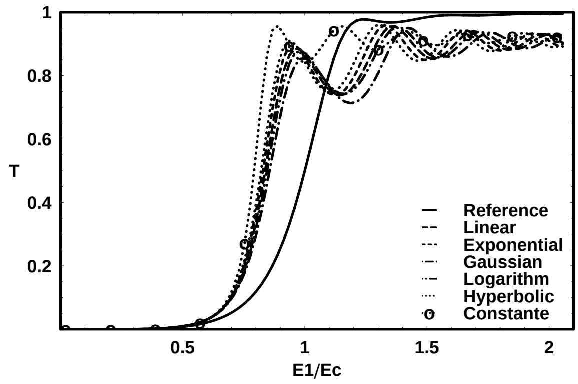

Fig. 7. Switching characteristics of port B_1 as a function of the pump energy into the port A_1 for DDF coupler with $\beta = 2$. The case Reference identifies the reference nonlinear coupler $(p(\xi) = 1)$.

Gaussian profile. The sequence of decreasing critical energy is given by Gaussian, logarithm, linear, exponential, hyperbolic and constant. Now compare with PA_1 configuration we can observe that in all profile that critical energy have decrease more strong. In figure 9 we has the compression factor for

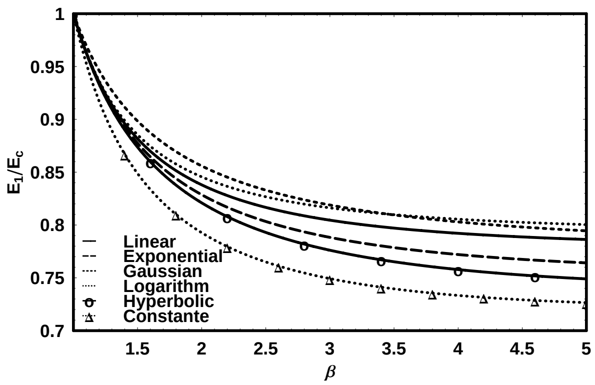

Fig. 8. Critical energy as a function of β for the DDF coupler.

channel 1 the DDF coupler with $\beta = 2$. This figure we plot two lines at C=1 and C=2. For the reference and the most profile coupler we can see that $C_1 = 1$ for energy higher that the critical one. This effect is different only for constant profile where the compression is around 1.8.

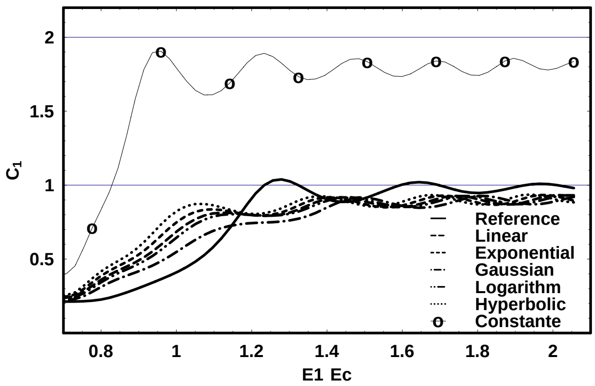

Fig. 9. Compression factor C_1 as a function of the pump energy into the port A_1 for DDF coupler with $\beta = 2$.

In figure 10 we have the Xtalk level in port A_2 as a function of the input energy for all the six profiles $(\beta = 2)$. For the reference coupler one can notice that with the increase in the input energy the Xtalk level is improving. We can observe that all the profile has increase crosstalk level. A sequence of first minimums in the Xtalk value is constant, hyperbolic, exponential, linear, logarithm, Gaussian and reference.

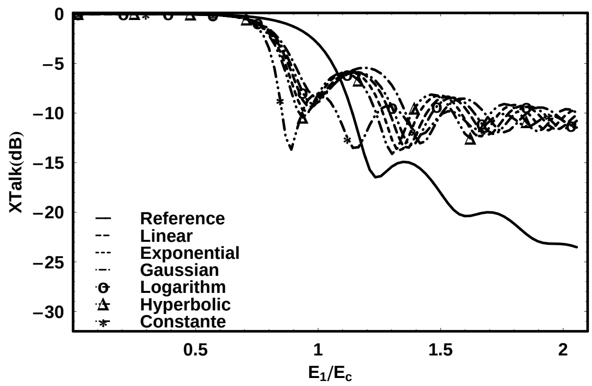

Fig. 10. Xtalk level (in dB) as a function of the pump energy into the port A_1 for DDF coupler with $\beta = 2$. The case Reference identifies the reference nonlinear coupler $(p(\xi) = 1)$.

III. CONCLUSIONS

We present an numerical investigation of the propagation and the switching of fundamental solitons in a two-core nonlinear fiber coupler constructed with dispersion decreasing fiber (DDF).Our simulations studies six different profiles, linear, hyperbolic, exponential, logarithm, constant and Gaussian. The transmission characteristics, the critical energy, the compression factor, crosstalk and extinction ratio of first order solitons were obtained. We can observe some advantages in one and some in other configuration. In the PA_1 configuration we see that all profiles have improve the crosstalk level, except the constant profile. —IN other hand, the PB_1 configuration, all profiles show the smaller value of critical energy and the compression factor around $C_1 \approx 1$. Comparing all profile, we can observe that only the constant profile that show the worse behavior in all configuration. In summary we have shown that the performance of the nonlinear directional coupler constructed with dispersion decreasing fiber is leading the coupler to strong variations in the transmission efficiency, crosstalk, critical energy, compression factor and extinction ratio level as value of β of six different profiles as well as pump energy. The study of soliton switching in DDF nonlinear fiber couplers provides possibilities for achieving, high efficiency in ultrafast all-optical signal processing, especially for optical switches and optical transistors.

ACKNOWLEDGMENTS

We thank CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico), FINEP (Financiadora de Estudos e Projetos) and CAPES (Coordenação de aperfeiçoamento de pessoal de nível superior) for the financial support.

REFERENCE

1 S. Trillo, S. Wabnitz, E. M. Wright, G. I. Stegman, Optics Letters 13, 672-674 (1988).
2 K. Kitayama , S. Wang, Appl. Phys. Lett. 43,17-19(1983)
3 G. D. Peng, A. Ankiewicz, Int. J. Non Opt. Phy. 1,135 (1992).
4 M. G. da Silva, A. F. Teles and A. S. B. Sombra, Journal of Applied Physics 84(4) 1834-1842(1998)
5 G.P. Agrawal , Applications of nonlinear fiber optics, (Academic,San Diego,2002) Chap.2
6 S. M. Jensen, IEEE Journal of Quantum Electronics, Vol. QE-18, páginas: 1580-1583(1982).
7 J.C. Powelson, W Feng, S. Lin, R. J. Feuerstein, D. Tomic, J. Lightwave Technol. 16(11),2020-2027(1998)
8 V. R. Chinni, T. C. Huang, P. K. A. Wai, C. R. Menyuk and G.J. Simonis, J. of Lightwave Tech.,vol. 13, pp. 1530-1535, 1995.
9 K. L. Chen and S. Wang, Appl. Phys. Lett., vol. 44, pp. 166-168, 1984.
10 J. Weber, L. Thylen and S. Wang, IEEE J. Quantum Electron., vol 24, pp. 537-548, 1988.
11 H. A. Haus and N. A. Whitaker Jr., Appl. Phys. Lett., vol 46, pp.1-3, 1985.
12 R. Grimshaw,J. He, B. A. Malomed, Physica Scripta 53,385-390 (1996)
13 F. Kh. Abdullaev, J. G. Caputo, Nikos Flytzanis, Physical Review E, vol 50, 1552-1558(1994)
14 B. A. Malomed, D. F. Parker, N. F. Smyth, Phys. Rev. E 48(2),1418-1425(1993)
15 K.Z. Nóbrega, M. G. da Silva and A.S.B. Sombra, Nonlinear optics 26, 337-351 (2001).
16 P. L. Chu, B. A. Malomed, G. D. Peng, J. Opt. Soc. Am B 10, 1379 (1993).