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Full Length Research Paper

Numerical simulation of nonlinear pulses propagation in a nonlinear optical directional coupler

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The concept of non-linear pulse is a symptom of such physical phenomenon inherently non linear, and its history is intimately linked to the development of theories of equations of nonlinear waves. As such, we now know that the non-linear pulses occur naturally in most nonlinear systems. This paper is devoted to modeling the evolution of nonlinear pulse during its propagation in a nonlinear directional coupler (NLDC) in terms of intermodal dispersion (IMD) in order to show the impact of these phenomena on the propagation in the (NLDC). In this case modeling the propagation in a nonlinear medium is governed by a system of coupled nonlinear Schrödinger equations (CNLSE). This is a mathematical model using to describe the (NDLC). The study is focused on the propagation of fundamental solitary pulses.

Key words: Nonlinear optic, dispersive medium, nonlinear medium, modeling, temporal widening, optical coupler, nonlinear pulses, nonlinear fiber, coupled nonlinear Schrödinger equation (CNLSE), intermodal dispersion (IMD).

INTRODUCTION

This Communication is now an essential value to human progress. The number of system users canceled and the amount of information conveyed is increasing (Stéphane, 2002). The invention and development of amplifiers /regenerator's erbium-doped fiber (Agrawal, 1989), and optical directional couplers then came the revolution in telecommunications fiber.

This new all-optical technology, which combines the principle of Issue stimulated in erbium with the guiding properties of the fiber, allows, without the conversion steps optical-electronic and electronic-optical increase rates of transmission (Chiang, 1995). The fiber can be an optical amplifier, an optical switch converter wavelength, solitons in a source, a compressor noise, a filter, an optical memory...etc.

The directional couplers optical fibers are widely used in modern optical communications systems (Sorin, 2002). Bandwidth in the directional coupler is usually limited by intermodal dispersion (IMD) rather than the velocity dispersion group in the fibers (or guides) that form the coupler (Thibaut, 1999; Chang and Weiner, 1994; Chiang, 1997; Chiang, 1995). Nonlinear effects in directional couplers were studied starting in 1982. Fiber couplers, also known as directional couplers, constitute an essential component of light wave technology. They are used 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). Although most applications of fiber couplers only use their linear characteristics, nonlinear effects have been studied since 1982 and can lead to all-optical switching among other applications (Jenson, 1982; Friberg et al., 1987).

The transfer of optical power between the modes of the two cores of the coupler is explained as evanescent field-coupling between the modes of the individual cores of the coupler. The mechanism is characterized by a parameter known as the coupling coefficient. In general, the coup-ing coefficient is wavelength-dependent (dispersive). As far as the intermodal dispersion (IMD) is concerned, it is a phenomenon that arises from the coupling of the propagating fields inside the two cores.

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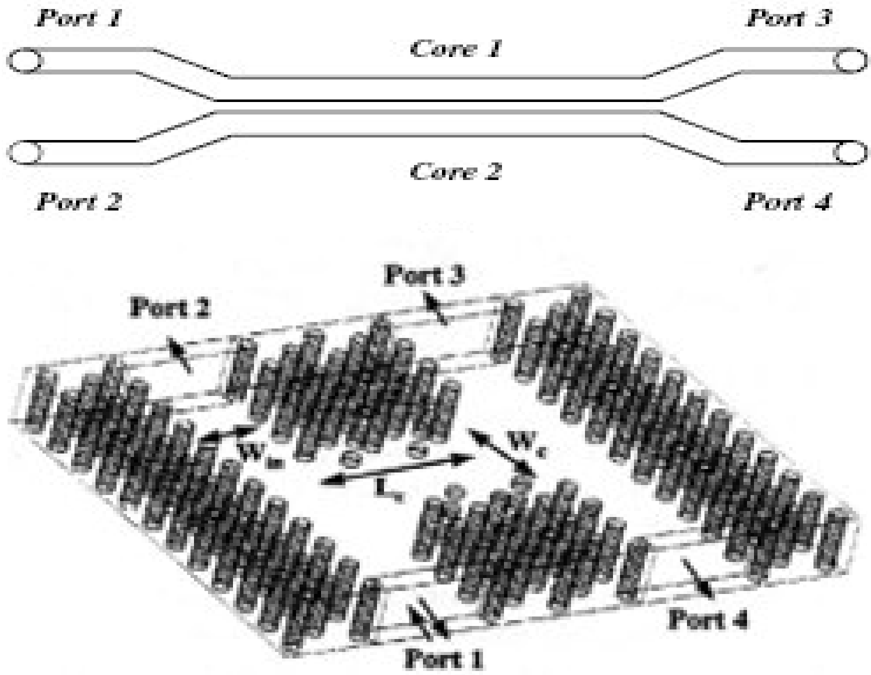

Figure 1. The nonlinear directional coupler (NLDC).

According to the normal-mode theory, on the one hand, the IMD arises from the group-delay deference between the two super modes of the composite fiber. On the other hand, according to the coupled-mode theory, the IMD has to do with the frequency dependency of the coupling coefficient.

As far as previous works are concerned, the coupling coefficient in all approaches (Romagnoli et al., 1992; Chu et al., 1992; Akhmediev and Ankiewicz, 1993; Chu et al., 1995) is considered as a constant with respect to frequency: it is a parameter which depends on the geometry of the wave guides of the coupler and the proximity of the two fibers but is independent of the bandwidth coefficients of the pulse that is being transmitted in the device.

In the present work, a numerical approach of a set of generalized equations is presented. In Section 2 the mathematical model that represents the physical problem is discussed, the existing models are compared. The main focus is the evanescent-field NLDC, thus the coupled-mode theory is chosen as the underlying model.

In Section 3 the split-step Fourier method is employed that solves the exact partial differential equations that represent the model (the CNLSE). Several simulations are executed aiming to determine the way intermodal dispersion influences. A coupler with specific (normalized) constant parameters is considered and only the IMD coefficient is left unbound to vary. Finally the main conclusion is summarized.

THE STUDY OF PROPAGATION IN A DIRECTIONAL COUPLER

The directional coupler is a device consisting of two parallel single mode optical fiber which are passive components used in modern optical communication systems. Figure 1 reveals that fiber couplers are four port devices: they have two input and two output ports. In the frame work of the light wave technology, their operation is based on splitting coherently an optical field incident on one of the input ports and directing the two parts to the output ports.

Since the output is directed in one of the two different directions, such devices are known as directional fiber couplers or simply directional couplers. Their full name nonlinear directional couplers (NLDC) are due to the fact that they exhibit nonlinear phenomena of Kerr type (Wang et al., 2006)

The optical fiber is a very thin transparent thread which owns driving light and transmissions used in land and ocean data. Cylindrical, it is composed of a core of refractive index n1 of a diameter, surrounded by a cladding of index n2, all wrapped in a plastic coating (Figure 2) (Agrawal, 1989).

Modeling the propagation of a pulse in a directional coupler

Propagation in a directional coupler is modeled by the

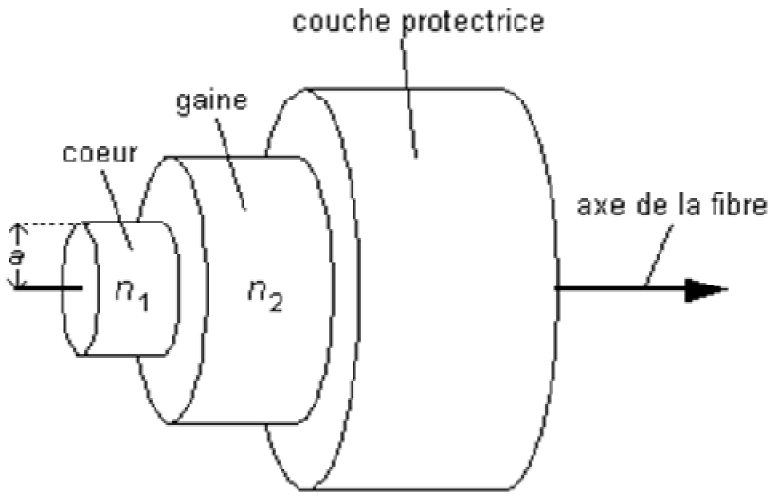

Figure 2. The anatomic description of optical fiber.

equation system of coupled nonlinear (Agrawal, 2001) Schrödinger NLSE: it is a model that describes the propagation of the pulse inside the evanescent field coupling to a system of coupled equations of nonlinear Schrödinger (CNLSE) (Wang et al., 2006).

$$i\frac{\partial A_1}{\partial z}+\beta_{01}A_1+i\beta_{11}\frac{\partial A_1}{\partial t}-\frac{\beta_{21}}{2}\frac{\partial^2 A_1}{\partial t^2}+\left(C_{11}|A_1|^2+C_{12}|A_2|^2\right)A_1$$
$$+k_{01}A_2+ik_{11}\frac{\partial A_2}{\partial T}-\frac{k_{21}}{2}\frac{\partial^2 A_2}{\partial t^2}=0 \qquad (1)$$

$$i\frac{\partial A_2}{\partial z}+\beta_{02}A_2+i\beta_{12}\frac{\partial A_2}{\partial t}-\frac{\beta_{22}}{2}\frac{\partial^2 A_2}{\partial t^2}+\left(C_{21}|A_1|^2+C_{22}|A_2|^2\right)A_2$$
$$+k_{02}A_1+ik_{12}\frac{\partial A_2}{\partial T}-\frac{k_{22}}{2}\frac{\partial^2 A_1}{\partial t^2}=0 \qquad (2)$$

$\beta_{0n},\beta_{1n},\beta_{2n}$ k_{0n},k_{1n},k_{2n}

:

and the coefficients of development of Tylor

$$k_n(\omega)=k_{0n}+(\omega-\omega_0)k_{1n}+\frac{1}{2}(\omega-\omega_0)^2k_{2n}+\cdots,$$

$$\beta_n(\omega)=\beta_{0n}+(\omega-\omega_0)\beta_{1n}+\frac{1}{2}(\omega-\omega_0)^2\beta_{2n}+\ldots,$$

$n=1,2$ and $\beta_{jn}=\left(\frac{d^j\beta_n}{d\omega^j}\right)_{\omega=\omega_0}$

$n=1,2$ and $k_{jn}=\left(\frac{d^jk_n}{d\omega^j}\right)_{\omega=\omega_0}$

The frequency carrier.

$\beta\,\omega_0$ the wave number calculated at $\omega = \omega_0$.

β_{1n} the inverse group velocity.

β_{2n} the group velocity dispersion.

k_{0n} The linear coupling coefficient.

k_{1n} The coefficient of dispersion Intermodal.

k_{21n} Higher order term.

$C_{11},C_{12},C_{21},C_{22}$ SiO_2 : Are the Kerr coefficients that Usually (for single-mode fibers) acquire the following values (Agrawal, 2001)

$$C_{11}=C_{22}=\frac{\eta_2\omega_0}{cA_{eff}}=C_{SPM}$$

: ((SPM) accounts for Self _ phase modulation)

A_{eff} : (effective surface area of the mode) is an additional phase term depending on the refractive index of non-linear and the power injected into the guide This term will result in a self phase modulation and a spreading of the optical pulse.

$C_{12} = C_{21} = C_{XPM}$: ((XPM) accounts for cross phase modulation).

Usually the terms including C_{12}, C_{21} are omitted, since these coefficients are associated with an overlap integral leading to extremely weak XPM.

Adopting the transformations

$$A_n = U_n \exp\left(i\frac{\beta_{01}+\beta_{02}}{2} z \right), n = 1,2, \tag{3}$$

$$T = t - \frac{\beta_{11} + \beta_{12}}{2} z , \tag{4}$$

$$i\frac{\partial U_1}{\partial z} + \frac{\delta\beta_0}{2} U_1 + i\frac{\delta\beta_1}{2}\frac{\partial U_1}{\partial T} - \frac{\beta_{21}}{2}\frac{\partial^2 U_1}{\partial T^2} + \left(C_{SPM}|U_1|^2 + C_{XPM}|U_2|^2\right)U_1 + k_{01}U_2 + ik_{11}\frac{\partial U_2}{\partial T} - \frac{k_{21}}{2}\frac{\partial^2 U_2}{\partial T^2} = 0 \tag{5}$$

$$\delta\beta_0 = \beta_{01} - \beta_{02} \tag{6}$$

: phase velocity mismatch between the two propagating pulses.

$\delta\beta_1 = \beta_{11} - \beta_{12}$: Velocity mismatch between the two propagating pulses.

When the two pulses coincide in wavelength these two terms vanish from the equations, as long as the two fibers have the same material and geometrical characteristics.

By applying the following transformations on (5) and (6)

$$\tau = \frac{T}{T_0}, \quad \xi = \frac{z}{Z_0}, \quad u_i = \frac{U_i}{U_0}, \tag{7}$$

$$NL_{SPM} = U_0^2 Z_0 C_{SPM}, \; NL_{XPM} = U_0^2 Z_0 C_{XPM}, \tag{8}$$

The coupled-mode equations in normalized form are obtained. The quantities, are the reference time, distance and amplitude, respectively, that are chosen at will.

Usually to coincide with the initial temporal width of the pulse, U_0 with its initial amplitude and Z_0 with the dispersion length.

Hence the system of equations (5) and (6) under the transformations equations (7), (8) becomes

$$i\frac{\partial u_1}{\partial \xi} + \Delta\beta_0 u_1 + i\Delta\beta_1\frac{\partial u_1}{\partial \tau} + \frac{D_1}{2}\frac{\partial^2 u_1}{\partial \tau^2} + \left(NL_{SPM}|u_1|^2 + NL_{XPM}|u_2|^2\right)u_1 + K_{01}u_2 + iK_{11}\frac{\partial u_2}{\partial \tau} + \frac{K_{21}}{2}\frac{\partial^2 u_2}{\partial \tau^2} = 0 \tag{9}$$

$$i\frac{\partial u_2}{\partial \xi} - \Delta\beta_0 u_2 - i\Delta\beta_1\frac{\partial u_2}{\partial \tau} + \frac{D_2}{2}\frac{\partial^2 u_2}{\partial \tau^2} + \left(NL_{XPM}|u_1|^2 + NL_{SPM}|u_2|^2\right)u_2 + K_{02}u_1 + iK_{12}\frac{\partial u_1}{\partial \tau} - \frac{K_{22}}{2}\frac{\partial^2 u_1}{\partial \tau^2} = 0 \tag{10}$$

The coupler in hand is symmetrical with identical cores through which pulses propagate operating at the same wavelength.

Therefore, the two pulses will not suffer from phase-velocity or group velocity mismatch. Taking into consideration that, due to the core separation, the XPM is extremely weak (Agrawal, 1989), the NLXPM coefficient can be set to zero. One last adjustment concerns the coefficients K_{21}, K_{22} which are usually very small compared with the rest of the coefficients.

Under all these assumptions, the system of coupled equations (9), (10) reduces to the following:

$$i\frac{\partial u_1}{\partial \xi} + \frac{D}{2}\frac{\partial^2 u_1}{\partial \tau^2} + NL_{SPM}|u_1|^2 u_1 + K_0 u_2 + iK_1\frac{\partial u_2}{\partial \tau} = 0 \tag{11}$$

$$i\frac{\partial u_2}{\partial \xi} + \frac{D}{2}\frac{\partial^2 u_2}{\partial \tau^2} + NL_{SPM}|u_2|^2 u_2 + K_0 u_1 + iK_1\frac{\partial u_1}{\partial \tau} = 0 \tag{12}$$

With $K_0 = k_0 Z_0$, $K_1 = k_1\frac{Z_0}{T_0}$

$NL_{SPM} = U_0^2 Z_0 C_{SPM}$, $D = -\frac{\beta_2 Z_0}{T_0^2}$,

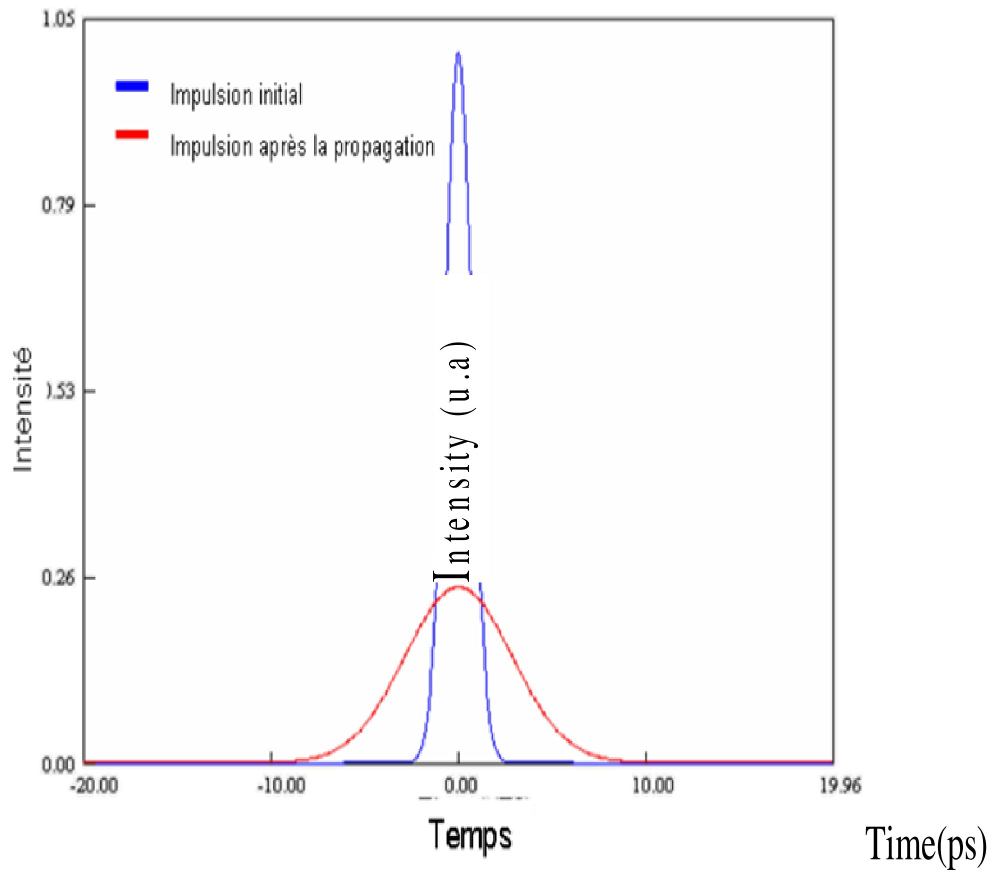

Figure 3. Profile of initial pulse and the pulse after propagation in a directional coupler.

Furthermore, if Z_0, U_0 are chosen as

$$Z_0 = \frac{T_0^2}{|\beta_2|}, \quad U_0^2 = \frac{|\beta_2|}{T_0^2 C_{SPM}},$$

Then for the case of anomalous dispersion ($\beta_2 < 0$) the following results are obtained:

$$D = 1, \quad NL_{SPM} = 1, \quad K_0 = \frac{k_0 T_0^2}{|\beta_2|}, \quad K_1 = \frac{k_1 T_0}{|\beta_2|},$$

and then (11) and (12) takes the following form

$$i\left(\frac{\partial u_1}{\partial \zeta} + K_1 \frac{\partial u_2}{\partial \tau}\right) + \frac{1}{2}\frac{\partial^2 u_1}{\partial \tau^2} + |u_1|^2 u_1 + K_0 u_2 = 0 \tag{13}$$

$$i\left(\frac{\partial u_2}{\partial \zeta} + K_1 \frac{\partial u_1}{\partial \tau}\right) + \frac{1}{2}\frac{\partial^2 u_2}{\partial \tau^2} + |u_2|^2 u_2 + K_0 u_1 = 0 \tag{14}$$

A numerical approach is often necessary to simulate the propagation of pulses in the couplers. Many numerical methods can be used for this purpose. One method that has been used extensively for dispersive media and non-linear method is the Split-Step Fourier (SSFM) because of its speed and accuracy (Agrawal, 2001)) .

SIMULATION RESULTS

The numerical method used to model the evolution of pulses in directional coupler.

Either a directional coupler (both single mode optical fibers in pure silica) of length L =11835 µm and 140 m width. Where the parameter value of group velocity: $\beta_2 = -10.2$ ps2/km at wavelength λ =1.55µm. The value of linear coefficient is used k0 = 1. The value of non-linear coefficient is used: K_1 = (-0.15, -0.8, -2).

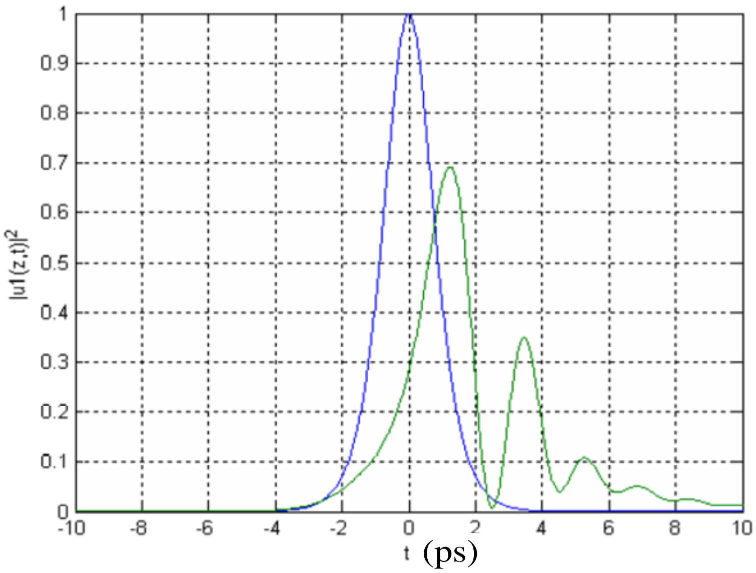

Figure 4. The evolution of the envelope u1 (z, t) in a directional coupler for k1 = -0.15.
Blue curve : the envelope of the pulse before the propagation.
Green curve: the envelope of the pulse after propagation.

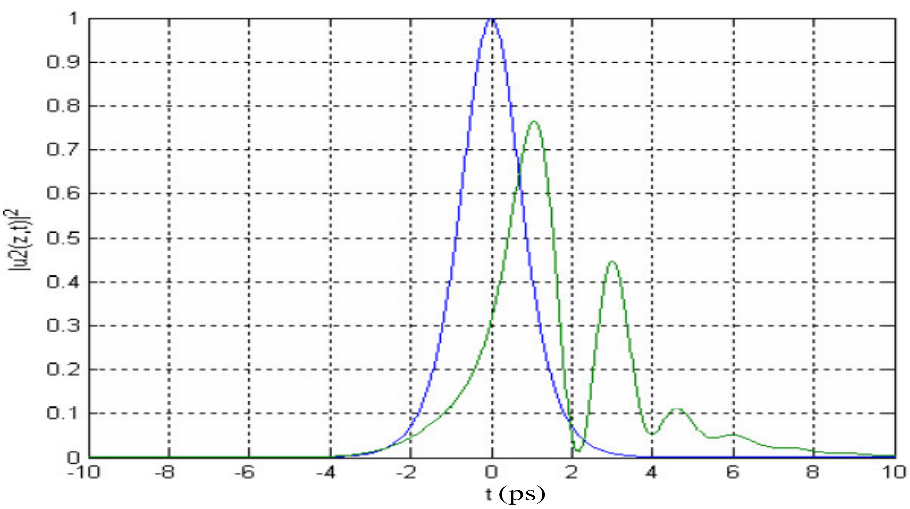

Figure 5. The evolution of envelope u2 (z, t) in a directional coupler for k1 = -0.15.

The input pulse is given in the form: U (0, t) = N sech (t), with N = 1 are nonlinear pulse solitary fundamental. The simulation results are shown in figures.

Figure 3 represents the initial pulse profile and pulse after propagation in an optical directional coupler. This figure shows that the pulse is changed, the question arises why this change? In order to answer to this question, now we will study the evolution chart of pulses in the coupler for the three characteristic values of k1, k1 = (-0.15, -0.8, -2) and are normalized intensity without unit.

The two Figures: Figures 4 and 5. It is obvious that for small values of K1= 0.15, the switching is not affected significantly since the major part of the pulse power manages to switch. For this value the IMD is rather weak and the effect of dispersion and nonlinearity is strong slightly distorted entity.

The two Figures: Figures 6 and 7. For the value K1 = - 0.8

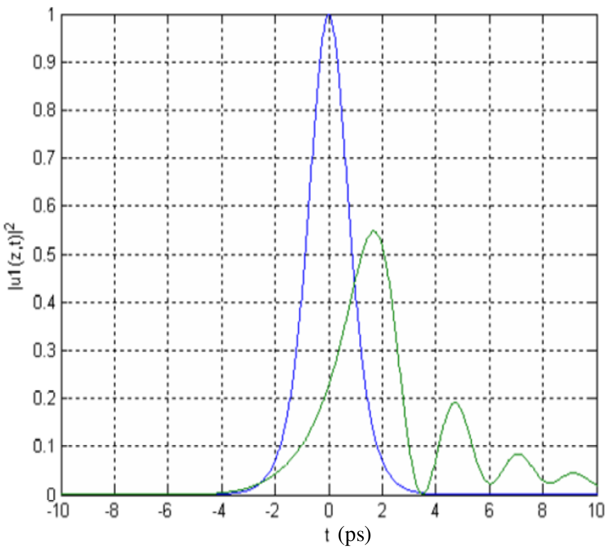

Figure 6. The evolution of the envelope u1 (z, t) in a directional coupler for k1 = -0.8.

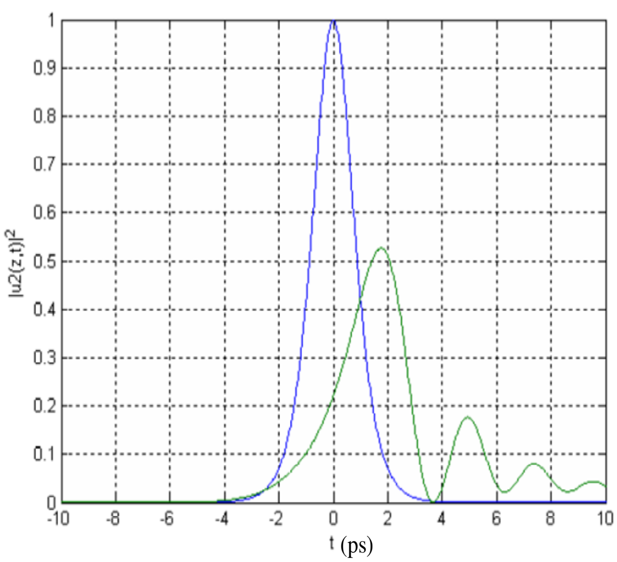

Figure 7. The evolution of the envelope u2 (z, t) in a directional coupler with k1 = -0.8

the IMD is rather strong and its effect is almost equal to that of the combination of dispersion and nonlinearity. As a result of this equally combined action the pulse deteriorates and spreads without being able to reshape.

The two Figures: Figures 8 and 9. Finally, for K1 = - 2 the intermodal dispersion is so strong that the combination of dispersion and nonlinearity does not manage to maintain the pulse.

The nonlinearity of the intermodal dispersion has an

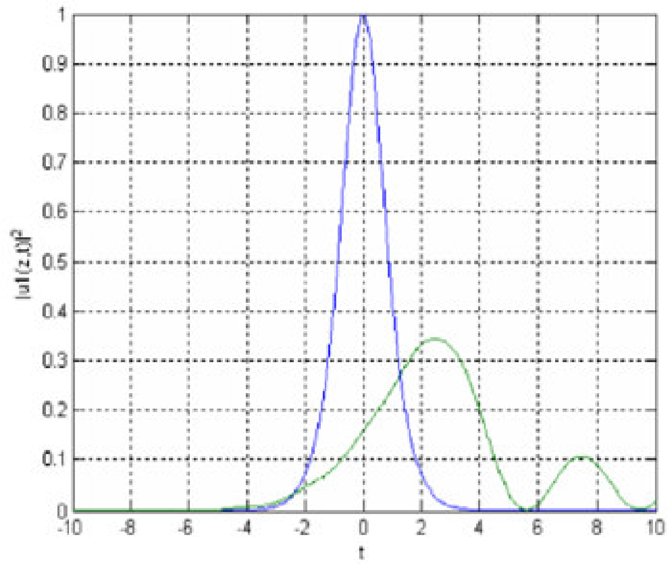

Figure 8. The evolution of the envelope u1 (z, t) in a directional coupler for with k1= -2.

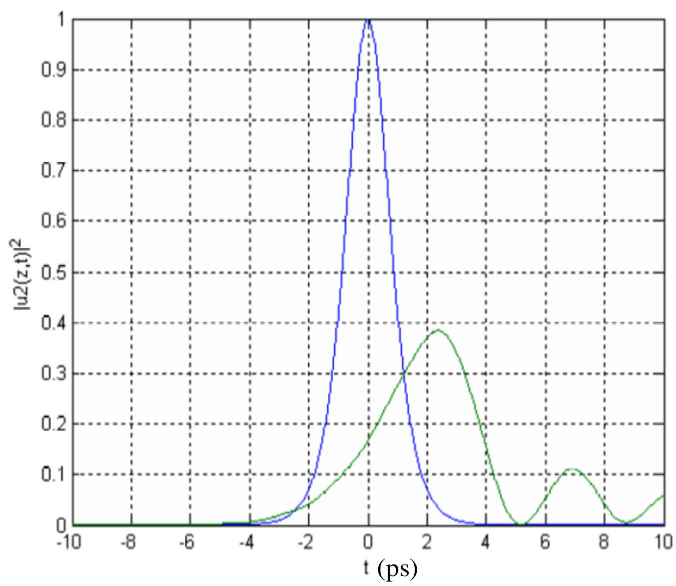

Figure 9. The evolution of the envelope u2 (z, t) in a directional coupler for k1 = -2.

influence on the propagation of pulses in the optical directional coupler; (Figures 10, 11, 12).

Remark

At this point, it is worth mentioning that simulations showed that the sign of K1 does not play any role as far as the total power of the pulses and the way this power

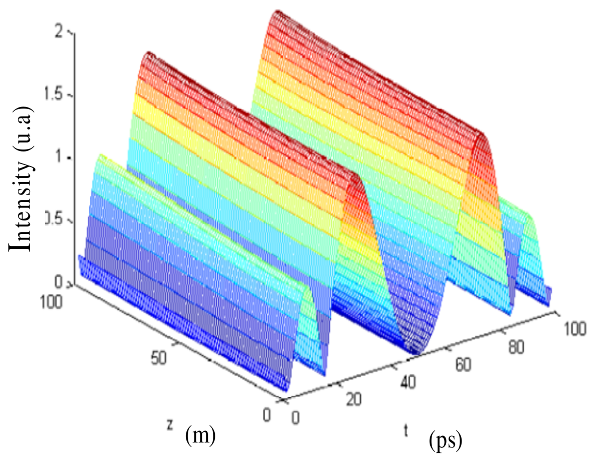

Figure 10. Three-dimensional evolution of the pulses in the optical directional coupler with (k1 = -0.15).

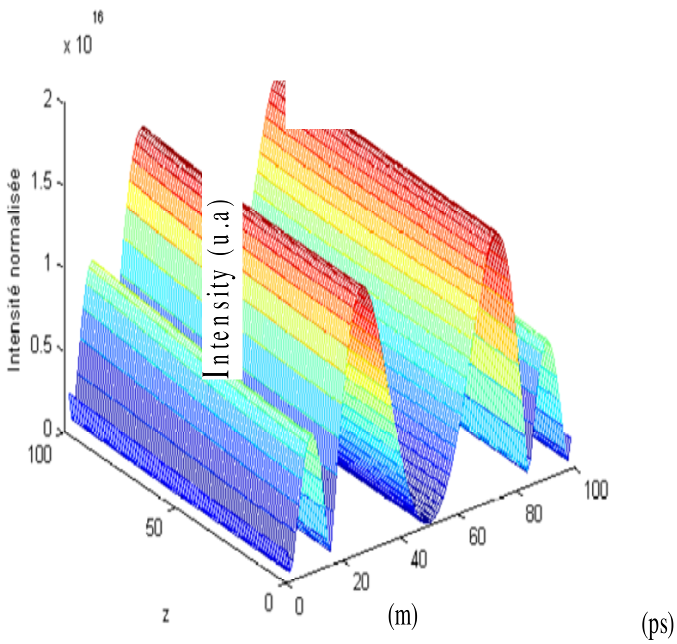

Figure 11. Three-dimensional evolution of the pulses in the optical directional coupler with (k1 = -0.8).

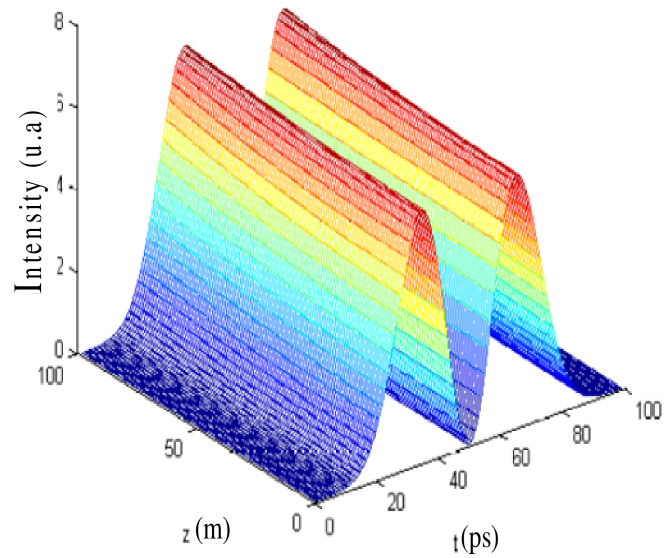

Figure 12. Three-dimensional evolution of the pulses in the optical directional coupler with (k1 = -2).

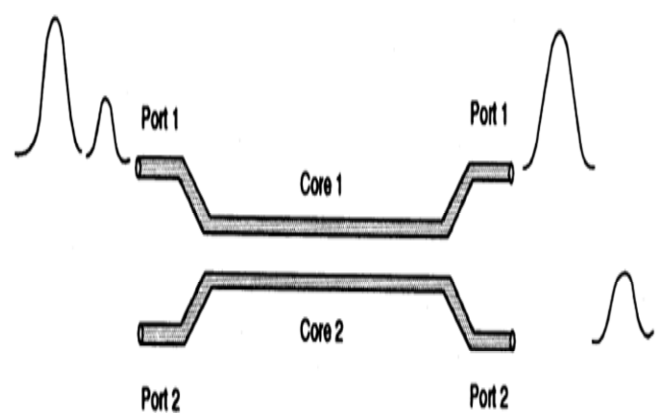

Figure 13. Schematic illustration of nonlinear switching in a fiber coupler Input.

fluctuates between the two cores are concerned. The only impact that the sign of K1 has is that it reverses the pulse profiles in terms of the time axis. The three-dimensional plots would have as plane of symmetry the plane and the contour plots would have as line of symmetry the line t = 0. This fact can be explained in two ways: from the perspective of the normal mode theory, an opposite sign at the K1 parameter imposes actually an inversion at the propagation constants of the two super modes (Ramos and Paiva, 1999). The increase of IMD tends to accelerate power (as soon as intensity) splitting as it can be observed in Figures 10, 11, 12.

The Influence of the nonlinear effect in term of power:

Pulses appear at different output ports depending on their peak powers.

Several different techniques can be used to make fiber couplers (Thibaut, 1999). Figure 13 shows schematically a fused fiber coupler in which the cores of two single mode fibers are brought close together in a central region such that the spacing between the cores is comparable to their diameters. A dual-core fiber, designed to have two cores close to each other throughout its length, can also act as a directional coupler. In both cases, the cores are close enough that the fundamental modes propagating in each core overlap partially in the cladding region between the two cores. It will be seen in this section that such evanescent wave coupling between the two modes can lead to the transfer of optical power from one core to another under suitable conditions. An important application of the nonlinear effects in fiber couplers consists of using them for optical switching. As shown in figure 13, an optical pulse can be directed toward different output ports depending on its peak power.

Figure 2 showed schematically how an optical pulse can be directed toward different output ports, depending on its peak power. We consider a symmetric coupler with identical cores to simplify the discussion (Jenson, 1982).

The physics behind all-optical switching can be understood by noting that when an optical beam is launched in one core of the f iber coupler, the SPM induced phase shift is not the same in both cores because of different mode powers. As a result, even a symmetric fiber coupler behaves asymmetrically because of the nonlinear effects. The situation is, in fact, similar to that occurring in asymmetric fiber couplers where the difference in the mode-propagation constants introduces a relative phase shift between the two cores and hinders complete power transfer between them. Here, even though the linear propagation constants are the same, a relative phase shift between the two cores is introduced by SPM. At sufficiently high input powers, the phase difference-or SPM-induced detuning-becomes large enough that the input beam remains confined to the same core in which it was initially launched.

Conclusion

The numerical analysis of solitary pulses propagation along coupler optics allowed us to understand the behavior of dispersive and nonlinear effects.

In this work the impact of intermodal dispersion IMD on the propagation of fundamental solitons in the NLDC has been studied. As long as IMD is kept weak the propagation of the solitons is slightly distorted. In general, even when IMD is present the system remains reliable up to a certain value for the IMD parameter.

The dominant nonlinear effect just affects the propagation is the effect Kerr (self phase modulation) and chromatic dispersion and intermodal both finally concluded that the intermodal dispersion IMD plays an important role on the stability of solitary pulses in optical directional couplers. Nonlinear effects have been studied and can lead to all-optical switching among other applications. We can conclude from this work that coupled-mode theory is a useful model (CNLSE) describing nonlinear optical phenomena in fiber couplers.

REFERENCES

Agrawa GPI (1989). Applications of Nonlinear Fiber Optics, Academic Press, New York.

Agrawal GP (2001). Nonlinear Fiber Optics, second ed. Academic Press, New York.

Akhmediev N, Ankiewicz A (1993). Novel soliton states and bifurcation phenomena in nonlinear fiber couplers. Phys. Rev. Lett. 70-2395.

Boumaza N (2008). Etude et Modélisation de la propagation d'une Impulsion Non Linéaire dans un milieu Matérial, Master Thesis, Tlemcen University.

Chang CC, Weiner AM (1994). ''Dispersion compensation for ultrashort pulse transmission using two-mode fiber equalizers'', IEEE Photon. Technol. Lett. 6: 1392-1394.

Chiang KS (1992). ''Intermodal dispersion in two-core optical fibers'', Opt. Lett. 20: 997 (1995).

Chiang KS (1997). ''Propagation of short optical pulses in directional couplers with Kerr nonlinearity'', J. Opt. Soc. Am. B. 14: 1437-1443.

Chu PL, Malomed BA, Peng GD (1992). Analytical solution to soliton switching in nonlinear twin-core couplers. Opt. Lett. 18-328.

Chu PL, Kivshar SY, Malomed BA, Peng GD,.Quiroga-Teixeiro ML (1995). Soliton controlling, switching and splitting in nonlinear fused-fiber couplers. J. Opt. Soc. Am. B12- 898.

Friberg SR, Silberberg Y, Oliver MK, Andrejco MJ, Saifi MA, Smith PW (1987). The nonlinear coherent coupler. Appl. Phys. Lett. 51-1135.

Jenson SM, IEEE J (1982). Quantum Electron. QE-18-1580.

Marcuse D (1982). 'Light Transmission Optics'. Ed. Van Nostrand Reinhold, New York.

Ramos PM, Paiva CR (1999). All-optical pulse switching in twin-core fiber couplers withintermodal dispersion. IEEE J. Quantum Electron. 35: 6-983.

Romagnoli M, Trillo S, Wabnitz S (1992). All-optical pulse switching in twin-core fiber couplers withintermodal dispersion. Opt. Quantum Electron.24S-1237.

Smith W (1987). Ultrafast All-Optical Switching in a Dual-Core Fiber Nonlinear Coupler. Appl. Phys. Lett. 51: 1135.

Sorin M (2002). TASCU, 'Etude en champ proche optique de guides optiques'Thèse de doctorat, Thèse de doctorat, Université de CLAUDE BERNARD LYONI.

Stéphane C (2002). Laser a fibre pour les télécommunications multiplexées en longueur d'onde. Thèse de doctorat, Thèse de doctorat, Université de CLAUDE BERNARD LYONI.

Thibaut S (1999). 'Amplification et conversion paramétrique, par procassus 'kerr et Raman dans les fibres optiques', Thèse de doctorat l'université de Franche-Comte.

Wang ZB, Yang HY, Li ZQ (2006). The Numerical Analysis of Soliton Propagation with Slit-Step Fourier Transform Method. J. Physics Conference Series 48-878882.