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ABSTRACT / RESUMEN

A fundamental study on the capability of a crossing of two optical waveguides based on dark-spatial solitons to act as a controllable optical beam splitter is presented in this work. It is based on the fact that the guided beam is diffracted at the waveguide crossing by an effective phase screen formed by the soliton collision profile. It was found that when the two dark solitons are immersed into the same finite bright background, the energy of a guided beam can be split into the desired optical channel according to the collision angle. On the other hand, when each dark soliton is immersed into its own bright background, the corresponding optical junction can not operate. This is because the finite width of the backgrounds acts as a low-pass filter over the diffracted beam, and because the onset of the cross-phase modulation instability effect occurs for small enough collision angles.

Se presenta un estudio básico sobre la capacidad de utilizar el cruce de dos guías de onda ópticas basadas en solitones espaciales obscuros, para actuar como un divisor de haces ópticos controlable. El estudio se basa en el hecho que; la luz guiada es difractada en la zona de cruce de la guía de onda por una pantalla de fase efectiva, formada por el perfil de la colisión de los solitones. Se encontró que cuando los dos solitones obscuros están inmersos en el mismo fondo de luz brillante finito, la energía del haz guiado puede ser desviada hacia el canal óptico deseado, al modicar el ángulo de colisión. Sin embargo, cuando cada uno de los solitones está inmerso en su propio fondo de luz, la correspondiente unión óptica no funciona adecuadamente. Esto se debe a que el ancho finito de la luz de fondo actúa como un filtro pasa-bajas sobre el haz difractado. Además, el efecto de inestabilidad modulacional de cruzamiento de fase ocurre solamente para ángulos de colisión suficientemente pequeños.

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Mechanisms of crossing for two optical waveguides based on dark spatial solitons.

Mecanismo de cruce para dos guías de onda ópticas basadas en solitones espaciales obscuros.

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INTRODUCTION

In the search of ultrafast switches for communication systems, the photonics proposals seem to be some of the best options to implement in our days. In this area, the spatial solitons have been under study by several years because of their ability to guide and control light. The control of a spatial solitons can be carried out, for example, by the presence of another soliton through the inherent forces between them (De la Fuente *et al.*, 1991, Luther-Davies *et al.*, 1992). Optical logic gates based on the changes of position that take place during a bright-spatial solitons collision (Akhmediev *et al.*, (1993), Torres-Cisneros *et al.*, (RMF) 1993, Krolikowsky *et al.*, 1997), or during the interaction of two close solitons (Kodama *et al.*, 1991; Shalaby *et al.*, 1991; Shalaby *et al.*, 1992) can be constructed.

In this way, spatial solitons can also control the trajectory of weak beams if they are used as optical waveguides. Two fundamental ways of doing so with bright spatial solitons have been proposed. In the first approach, a weak beam guided by one spatial soliton follows the resulting trajectory when the soliton interacts with another close soliton (Snyder *et al.*, 1991). In the second case, the trajectory of the weak beam is controlled by an effective grating phase diffraction when the soliton collides with another soliton (Torres-Cisneros, 1995). On the other hand, controlling weak beams is also possible in a self-defocusing medium, and a good example is the optical Y junction obtained

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when a weak beam is forced to follow the optical waveguides emerging from a secondary dark spatial soliton generation (Shalaby *et al.*, 1992). An attempt to explore the possibilities of controlling weak beams through the use of dark-spatial solitons interaction was made by Ladouceur *et al.*, 1997, but it was made by using repelling (not colliding) solitons.

The interaction between two ideal dark solitons is governed by an effective repulsive force in contrast with the force between two bright solitons, which depends on the relative phase of the solitons (Shalaby *et al.*, 1991).

However, ideal dark spatial solitons are impossible to obtain because they require finite transversal intensity as $x \to \pm\infty$. Instead, a real dark spatial soliton consists of an intensity depletion into a finite bright background. Numerical results have demonstrated that real dark-spatial solitons exhibit quasi soliton behavior, provided the width of the bright bac-kground, which should be at least ten times the width of the soliton (De la Fuente *et al.*, 1991). A similar conclusion applies for the collision of two real dark solitons, if they are immersed into the same bright background (Akhmediev *et al.*, 1993). However, if the spatial solitons are used as optical waveguides, a practical situation is that each dark soliton possesses its own finite bright background beam. Each of these bright background beams will become chirped, because of the simultaneous effects of diffraction and self-defocusing (Akhmediev *et al.*, 1993) and it is expected that they will affect the dynamics quasi-dark soliton of a collision of two optical channels (Akhmanov *et al.*, 1992). In a previous work, Torres-Cisneros *et al.*, 1995, studied the behavior of the X-type commuter based in two real dark spatial solitons (RDSS). They found that the cross condition for RDSS depends on certain combinations of the collision angle and the intensities of the beams, but no guided properties were studied.

In this paper we study, both theorically and numerically, the physical properties of a collision of two optical waveguides based on dark spatial solitons to evaluate their practical potential to conform controllable optical junctions. Considering that the initial probe beam is diffracted by the waveguide cross profile, we characterize in section II the abilities of a collision of two ideal dark spatial solitons to act as an optical junction. In section III we discuss the influence of the width of the finite backgrounds on the angular spectrum of the probe beam diffracted by a collision of two real-dark spatial solitons and, finally, section IV presents the conclusions of our work.

CROSSING OF IDEAL WAVEGUIDES

We are interested in describing the behavior of a guided beam during a cross of two optical waveguides based on ideal dark spatial soliton. Physically this situation is met, for example, when the two dark solitons are immersed into the same wide enough bright background. The appropriate physical model is given by the coupling of two lasers beams with the same polarization, but with different wavelength, within a negative Kerr-type medium (De la Fuente *et al.*, 1991). We assume that the beams propagate in the positive direction of the *z*-axes, and that the physical conditions for a 2-dimensional approach are satisfied. Denoting by A_1 and A_2 the normalized trans-versal envelopes of the strong and weak beams, respectively, their evolutions within the nonlinear medium are governed by (Akhmanov *et al.*, 1992),

$$i\frac{\partial A_1}{\partial Z} = \frac{1}{2}\frac{\partial^2 A_1}{\partial X^2} - |A_1|^2 A_1 \qquad (1)$$

$$i\frac{\partial A_2}{\partial Z} = \frac{1}{2} r_n r_k \frac{\partial^2 A_2}{\partial X^2} - |A_1|^2 A_2 \qquad (2)$$

where the condition $|A_1|^2 >> |A_2|^2$ has been assumed. In eqs. (1) and (2) the propagation distance Z is measured in units of the diffraction length of the intense beam, while the transversal distance X is normalized to the initial width of the intense beam. In eq.(2) $r_n = n_{01}/n_{02}$, $r_k = \lambda_{02}/\lambda_{01}$, $\beta = 2/r_k$, with n_{0i} being the linear refractive index of the beam at wavelength λ_{0i}.

Because eq.(1) is the NLSE it admits single and multiple dark soliton solutions (Kodama *et al.*, 1991), and among them we take for this section that which describes the collision of two dark solitons. For the specific case of two dark solitons of the same amplitude, traveling with opposite transversal velocities, the two-dark solution takes the form (see eq.(10) of Krolikowsky *et al.*, 1997):

$$A_1(x,z) = (1-\upsilon^2) + \upsilon^2 \exp(2\upsilon x)[\exp(2\upsilon x) + \frac{2}{\upsilon}(1-2\upsilon^2)\cosh(4\upsilon\lambda z_0)] + \ldots$$

$$\ldots + 4i\lambda \sinh(4\upsilon\lambda)(1-\upsilon^2) + \upsilon^2 \exp(2\upsilon x) + \frac{2}{\upsilon}\cosh(4\upsilon\lambda z_0) \qquad (3)$$

and $\mu = \sqrt{1-\lambda_i^2}$. The two identical dark solitons involved in eq.(3) are fully described by the parameter λ, ($0 < \lambda_i < 1$), which determines their contrast, υ^2, their widths, $1/\upsilon$, and their transversal velocities, $V = k_0 n_0 x_0 \upsilon$ with $\upsilon = \pm\lambda$.

As the solitons posses opposite transversal velocities, the soliton collision takes place at the total collision angle of 2θ, with $\upsilon = \tan\theta$. For large enough negative (or positive) values of *z*, eq.(3) represents two well separated ideal dark solitons, and such an expression is used as the initial condition to eq.(1) in order to simulate the crossing of two ideal dark soliton waveguides.

The physical reason of the splitting of the probe beam energy into the two optical channels after the soliton collision resides in the presence of an effective diffraction phase grating generated by the soliton collision pattern (Torres-Cisneros *et al.*, 1993). Therefore, the angular spectrum of the probe beam after the channel cross, $\tilde{A}_2(k_x)$, can be expressed as

$$\tilde{A}_2(k_x) = \int A_2(x,0)\exp(-ih\beta\Psi(x))\exp(-ik_x x)dx \qquad (4)$$

where $A_2(x,0)$ is the initial probe beam profile, h is the thickens of the diffraction grating, and $\Psi(x)$ is the diffraction grating profile, which we take as the intensity of the collision pattern of the soliton collision given by eq.(3) with $z = 0$.

$$\Psi(x) = [1 + \frac{4\upsilon\exp(2\upsilon x)}{1 - 2\exp(2\upsilon x)(1+\cosh(2\upsilon x))}]^2 \qquad (5)$$

To determine the junction properties of such a cross, we launch into one of the soliton channels a weak beam with a transversal gaussian profile close to the single mode solution of the optical wave profile,

$$A_2(x,0) = \exp[\upsilon^2(x-c)^2/2]\exp(\pm iVx) \qquad (6)$$

where c stands for the initial transversal position of the guiding dark soliton.

In the case of a collision of bright solitons in a self-focusing medium, the initial probe beam can split its initial energy into the two optical channels emerging from the collision according to the collision angle (Torres-Cisneros *et al.*, 1993). In our case of a collision of two ideal dark solitons a similar behavior is also possible, and Figs. 1 and 3 corroborates this fact. Fig. 1a shows the numerical simulation of the crossing of two ideal dark spatial solitons waveguides with $\lambda = 0.12$, and it is expected that the solutions remain unchanged after the collision. On the other hand, Fig. 1b shows the splitting of the initial probe beam energy into the two optical channels after the collision. For the parameters used in Fig. 1, the original optical waveguide, channel 1, carries the 82% of the energy after the waveguide cross, while channel 2 carries the remainder 18% of the energy.

Fig. 2 gives the relative output energy in both optical channels after the soliton collision as a function of λ. For large values of λ, which represents relativity in large transversal velocities, the output energy of the probe beam is found completely in channel 1, while for small λ the

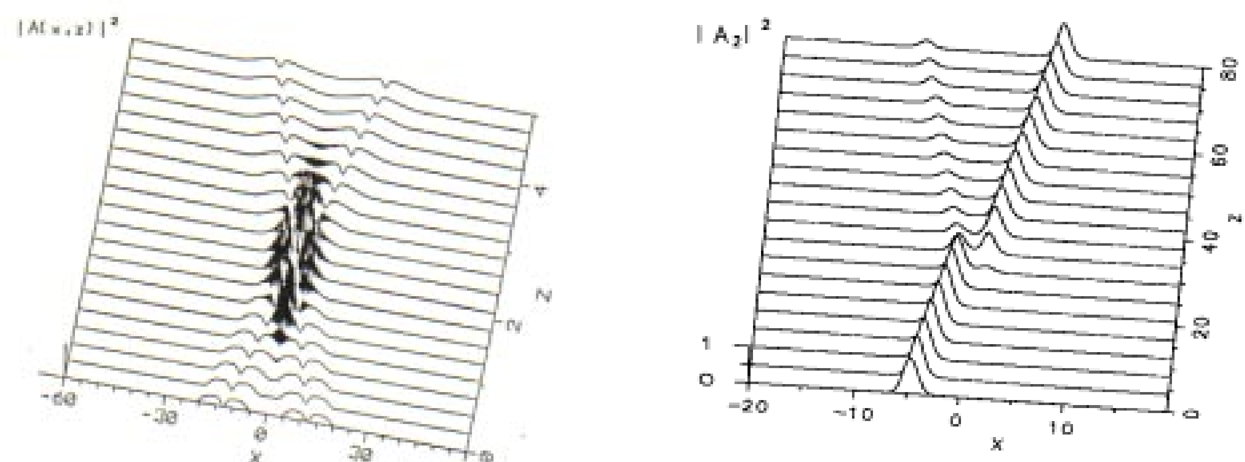

Figure 1a.

Figure 1b.

Figure 1a, 1b. Numerical simulation demonstrating the ability of crossing of two optical waveguides based on ideal dark spatial solitons to act as an asymmetric optical Y-junction. In (a) we show the soliton collision and in (b) the trajectory followed by the guided beam. The ideal solitons are characterized by the parameter λ = *0.12*, and in the eq.(1) we used: $r_k r_n = 1$ and β = *1.8*.

energy into channel 2 becomes monotonically larger.

CROSSING OF REAL DARK-SOLITONS WAVEGUIDES

We now proceed to determine the optical junction properties of a collision of two waveguides based on real dark spatial solitons. According to the previous section, one can expect that the finite width of the individual bright background affects the splitting abilities obtained in Fig. 2 for ideal dark solitons waveguide crossing. An estimation of the role played by the width of the finite bright can be obtained, numerically at least, if we compute the angular spectrum of the probe beam diffracted by the collision of two real dark solitons waveguide. Changing the supergaussian bright beams profiles into a hyperbolic secant, the phase of the diffraction grating, eq.(5), takes the form (using x_0 = *0*)

$$\Psi(x) = 4\sec h^2(x/t_0)[1-\sec h^2(x)]\cos^2(Vx) \qquad (7)$$

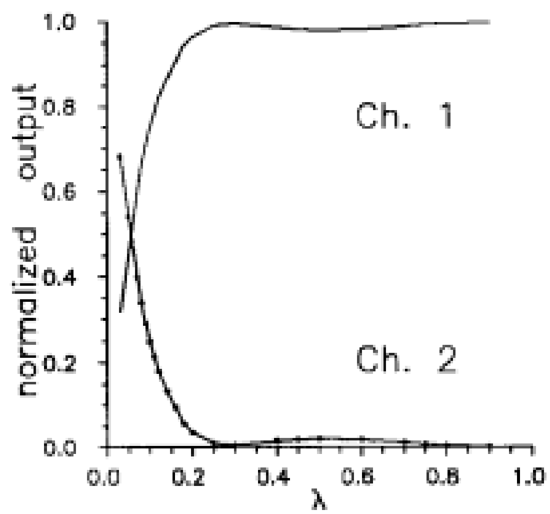

Figure 2. The normalized output energy of the probe beam in each optical channel after the collision of two ideal dark solitons as a function of the soliton parameter λ. For relative large collision angles, the probe beam basically follows the original waveguide (1), but for small angles the energy of the probe beam guided by second channel progressively increases. Here $r_k r_n = 1$ and b = *1.8*.

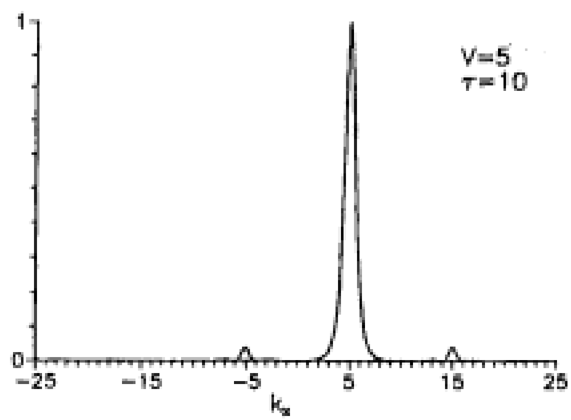

Figure 3a

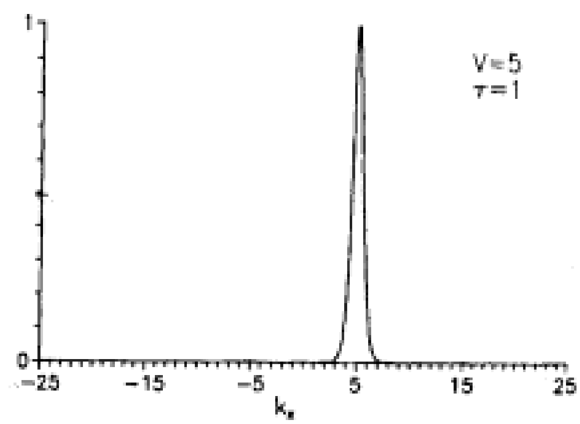

Figure 3b

Figure 3a, 3b. In a collision of two identical real dark spatial solitons for a relatively large collision angle $V = 5$, and $\tau = 10$, in a) exist three spectral components $c = -5$, $c = 5$ and $c = 15$. In this case there exists switching, but the energy is very small. In b), there exists only one spectral component, therefore waveguide maintain their original trajectory after the collision. The graph was obtained by numerically solving eq.(4) under the initial condition of eq.(7), with $A_0 = 1$ and $c = 10$.

Substituting this expression into eq.(4), it is possible to numerically perform the integration to obtain the angular spectrum of the diffracted probe beam. Fig 3 shows the probe beam spectrum after the waveguide crossing for the two different widths of the bright backgrounds τ in the case of relatively large collision angles $V = 5$. As it can be seen, for large background widths, $\tau = 10$, the angular spectrum consists in three components, which indicates that a fraction of the probe beam energy can be guided by channel 2 at $k_x = -V$. However, as τ decreases these lateral components also decrease in magnitude, Fig. 3b, and this practically disappears for $\tau = 1$.

A similar behavior is obtained in the case of small collision angles, $V = 1$. as it can be observed in Fig. 4a-4b. Though the distribution of the spectrum is not as simple as in the case of large V, a narrowing of the central component and a reduction of the magnitude of the lateral components of the spectrum is clearly appreciable. Therefore, the finite width of the background pulses reduces the ability of the cross to split the energy of the probe beam guided by the dark solitons.

CONCLUSIONS

The guide mechanisms for a weak beam in a X-type switch dark spatial solitons collision based have been studied. We showed that for ideal solitons, the energy of the probe-beam could be controlled as we varied the collision angle between the dark solitons. Nevertheless, in the real dark solitons case, the ability of switch channel for the probe beam depends of either the width of the immersed light back-ground or the soliton transversal velocities. The spectral analysis showed that narrower widths in the light background reduce or even disappear the side-band signal components of the angular signal spectrum. This result was also observed when we reduced the transversal velocities of the real dark solitons.

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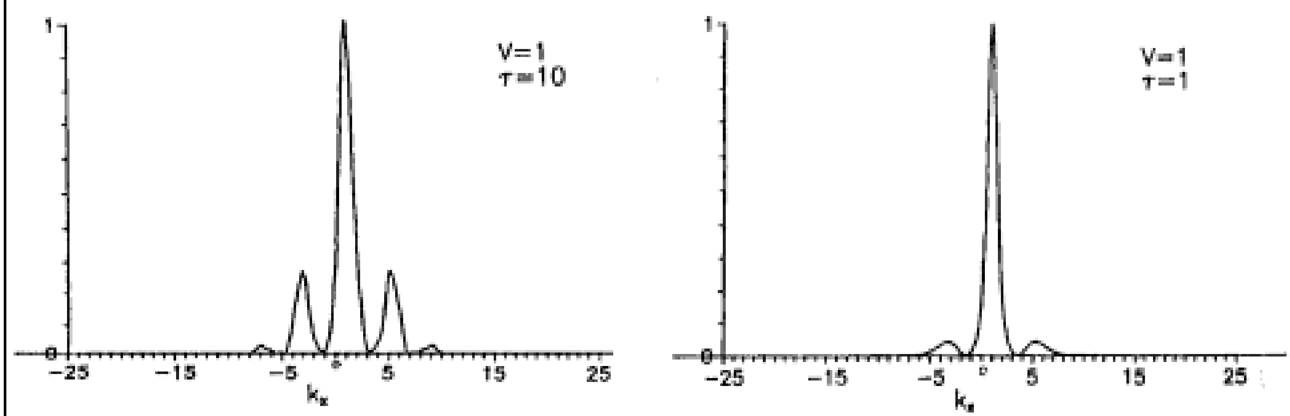

Figure 4a Figure 4b

Figure 4a, 4b. A collision of two identical real dark solitons for a small transversal velocity, $V = 1.0$, and $\tau = 10$. In contrast with Fig. 3a, the spectral components are closed, but its width and intensity are reduced while the width of the light background decreases, as it can be seen in b), for $V = 1$ and $\tau = 1$. The graph was obtained numerically solving eq.(4) under the initial condition of eq.(7), with $A_0 = 1$, $V = 0.5$ and $c = 10$.

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