Distortionless light-guided beams crossing

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Recibido el 12 de agosto de 1992; aceptado el 10 de junio de 1993

Abstract. We numerically show that two light-guided beams remain undisturbed when they cross each other in spite of the nonlinear dynamics which governs the interaction of their corresponding guiding light beams. Our results also indicate that such unexpected phenomenon occurs even when the guiding light beams are not spatially identical.

Resumen. A través de simulaciones numéricas se muestra que dos haces guiados por luz permanecen inalterados al cruzarse, a pesar de la dinámica nolineal que rige la interacción de los correspondientes haces guías. Los resultados también indican que tal fenómeno inesperado ocurrirá aun cuando los haces guías tengan diferentes propiedades espaciales.

PACS: 42.65.Jx; 42.79.Gn

Optical waveguides have renewed its potential of practical application with the discovery that a light beam can be optically guided by light [1]. This new phenomenon occurs when an intense (pump) beam propagates into a nonlinear medium generating one or more transversal stable structures called spatial solitons. Depending on the sign of the nonlinear refraction index n_2 of the medium, the formed spatial solitons can be either bright ($n_2 > 0$) or dark ($n_2 < 0$) solitons. The former represent an isolated light intensity profile while the dark solitons consist of an absence of radiation immersed on a continuous light background [2]. Moreover, joined to the stability of such structures is the fact that the intensity of the beam can modify the medium characteristics, causing its index of refraction to change according to the intensity profile of the spatial solitons. This is quite a remarkable effect since a second and weak (probe) beam can be introduced into the medium and it will see a transversal effective refractive index distribution that satisfies the guiding conditions [Fig. (1)] and therefore be actually guided.

Light beams guided by spatial solitons have a natural potential of applications in optical interconnecting devices, therein the importance of analyzing their relevant fundamental properties. For example, if spatial solitons are going to be used as channels for optical

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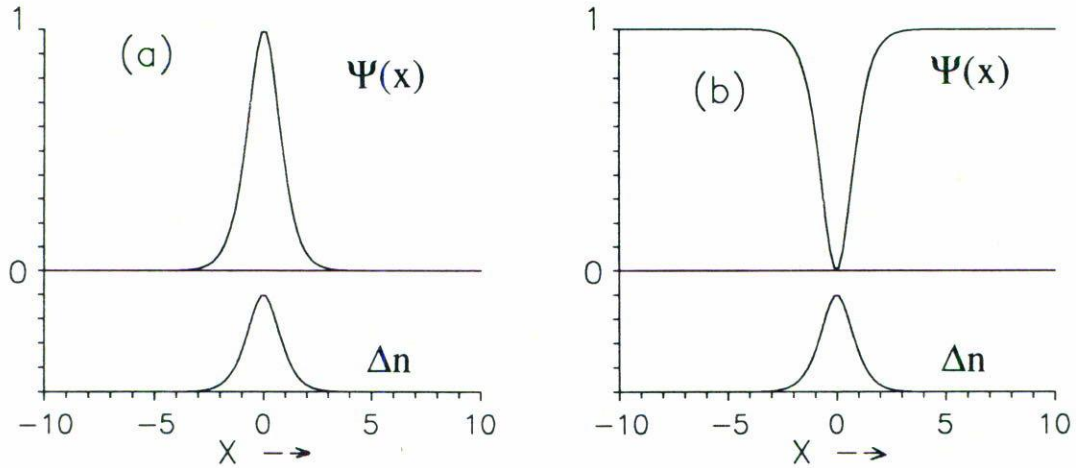

FIGURE 1. Typical spatial solitons structures, $\Psi(x)$, formed in a nonlinear medium, and the respective refractive index profiles induce by them in the medium, $\Delta n = n - n_0 = \delta|\Psi(x)|^2$. In (a), we show a bright soliton obtained when n_2 and δ are positive, while in (b) a dark soliton is shown which is formed when n_2 and δ are negative. Note that the waveguiding condition: n at the center of the guide greater than n at its extremes is satisfied in both cases. Therefore spatial solitons can guide low intensity probe beams.

communications, often a realistic (both desired or undesired) situations should be a crossing among them. Such a situation is not simple to describe because the dynamics of the guiding beams are not linear. By definition solitons have the characteristic of remaining unchanged under collisions. When two solitons collide, they interact in a very complicated way due to its nonlinear dynamics, but they emerge unscattered after the collision [3]. On the other hand, the guided beams are weak and they are expected to be highly perturbed, with the corresponding modification of the information they are carrying on, by the underlying nonlinear features of the spatial solitons crossing.

In this letter we investigate numerically what it happens with the guided beams when the guiding spatial solitons collide, and report the fact that a guided probe beam continues undisturbed on its original channel after the channel crossing, as if the nonlinear junction were absent.

In a two-dimensional scheme, the propagation of laser beam through a medium possessing a diffraction index n is described by the Maxwell equation [4]

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} + n^2 k_0^2\right) E(x,z) = 0, \tag{1}$$

where E is the electric field, and k_0 the wave number. We have ignored the variations on the other transverse direction.

A laser beam propagating on the z axis can be expressed as $E(x,z) = \Psi(x,z) \times \exp[\mp i n_0 k_0 z]$, where n_0 is the linear refractive index and the $\mp$ sign stands for the two possible directions of propagation. If we assume beam propagation in the positive z direction, we can take the minus sign on the exponential factor. Substituting $E(x,z)$ in Eq. (1)

and invoking the slowly varying envelope approximation for $\Psi(x,z)$ we obtain

$$2i\frac{\partial\Psi}{\partial Z}=\frac{\partial^2\Psi}{\partial^2 X}+\left(\frac{n^2}{n_0^2}-1\right)\Psi, \tag{2}$$

where the normalizations $Z=n_0k_0z$ and $X=n_0k_0x$ have been performed. For a weak beam, $n=n_0$ and Eq. (2) predicts the transverse broadening of an initial beam due to diffraction. However, if the beam is intense, $n=n_0+n_2|\psi|^2$, with n_2 ($\ll n_0$) as the Kerr nonlinear index of refraction, then Eq. (2) becomes the so-called nonlinear Schrödinger equation (NLSE) which admits both bright ($n_2>0$) and dark ($n_2<0$) solitons as stationary solutions [2].

The NLSE has been extensively studied in the optical fiber context where both kind of (temporal) solitons have been reported [5–9], in special the bright ones for their importance for long-distance optical communications [10]. In our case, spatial solitons obeying Eq. (2) have also been observed [11,12], including the more complicated 3–dimensional case [13]. Spatial solitons have the advantage of being easily produced in a laboratory, and among them dark-spatial solitons are preferable for practical applications in interconnecting devices, because at power levels above the fundamental solitons, they split into a number of individual fundamental dark-solitons which spread apart as they propagate into the nonlinear medium. In similar conditions, higher-order bright-solitons remain attached by exchanging their energies due to the presence of an effective attractive potential [10].

A controlled production of dark-spatial solitons can be obtained by placing an amplitude or a phase mask in front of the incident pump laser beam in order to produce the required boundary conditions [14]. A simple wire located at the entrance face of the nonlinear medium originates an even number of dark-spatial solitons, while a π–phase mask positioned across the middle of the beam produces an odd number of them [1,9]. An example of the former case is presented in Fig. 2a, where we show the numerical solution of Eq. (2) for an initially normalized transversal beam profile of the form $\sqrt{n_2}\,n_0k_0\Psi(X,0)=1-\exp[-x^2]$. It can be clearly seen the formation of two identical first-order dark-solitons, which spread apart as they advance into the nonlinear medium.

Spatial solitons have an obvious potential of practical applications, and a binary communication prototype device based on dark-spatial solitons has been recently proposed [15]. However, as was empathized in Ref. [1], the effective structure of the medium is changed by the presence of the spatial-solitons, and its refractive index can follow the spatial intensity profile of those. In such a case, we can consider a weak (probe) beam propagating behind the spatial-solitons former beam, and its transversal profile will follow the equation

$$2i\frac{\partial\phi}{\partial Z'}=\frac{\partial^2\phi}{\partial^2 X'}+\Delta|\Psi|^2\phi, \tag{3}$$

where Δ represents the maximum refractive index change induced in the medium and $Z'=n_0'k_0'z$ and $X'=n_0'k_0'x$ are the distances normalized to the probe beam wavelength. Note that Eq. (3) is coupled to Eq. (2) through the pump beam profile $|\Psi|^2$, and that Eq. (2) stands unperturbed by the presence of the probe beam because it has been assumed

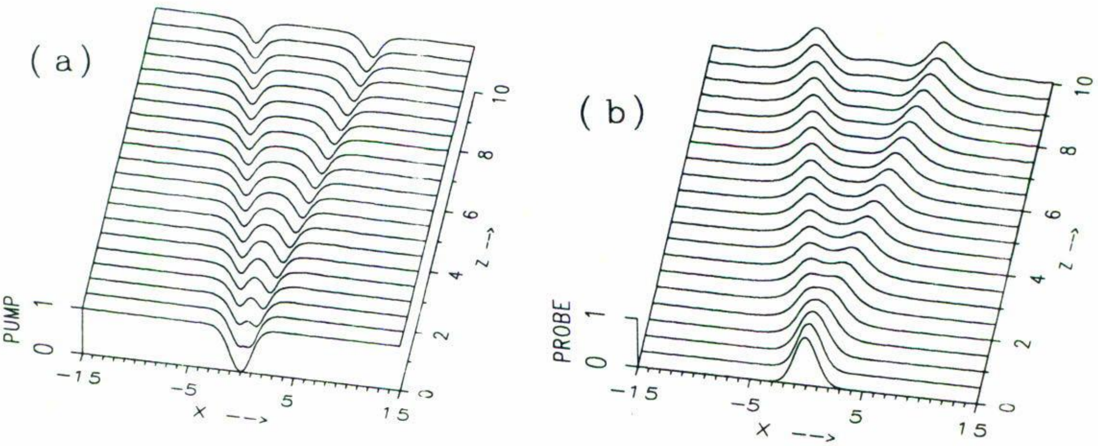

FIGURE 2. Numerical solution of the coupled Eqs. (2) and (3) showing the ability of dark-spatial solitons to guide probe beams. In (a) we show the spatial evolution of the pump (intense) beam, while in (b) the behavior of a probe (weak) beam traveling behind the pump beam is shown. The pump beam originates two dark-spatial solitons while the probe beam is guided by them. At $Z = 10$ the two formed identical solitons are perfectly distinguishable in (a), and each one guides the same fraction of the input probe beam (b).

to be considerably less intense that the pump beam. When the intensity of the two beams are of the same order Eqs. (2) and (3) have to be changed by those describing the cross phase modulation effect [10].

Physically, the solutions of Eq. (3) just give the transversal modes allowed by a planar waveguide with a refractive index distribution equal to $\Delta|\Psi|^2$. However, as Ψ is a solution of the NLSE, Eq. (2), the spatial evolution of ϕ is not easily described as in the case of linear waveguides. As an example of how the dynamics of the probe beam can be governed by the nonlinear behavior of the pump beam, we show in Fig. (2b) the result of numerically solving Eq. (3) under the refractive index distribution left behind by the formation of the two dark solitons of Fig. (2a). As it is shown, the probe beam is initially guided by the intense pump beam, but when it forms the two dark-spatial solitons, the probe beam equally splits its energy into the two formed channels. In Fig. (2b) we have plotted the normalized probe transversal envelope $\sqrt{\Delta}\, n_0' k_0' \phi(X', Z')$, and it has been assumed $Z = Z'$ and $X = X'$ for simplicity. The initial probe transversal profile was $\exp[-X'^2/2]$, which is close to the single-mode solution for a waveguide with a refractive index distribution similar to the formed spatial solitons [16]. The use of a probe beam with a transversal width differing considerably from the spatial solitons width leads to multimode or unguiding conditions, just as in the case of linear waveguides.

The fact that spatial solitons can guide probe beam broadens their potential applications for logical or connecting elements in all-optical communication systems, and the case showed in Fig. (2) represents a typical Y-junction [1]. However, if each dark-spatial soliton is thought as a channel and each probe beam plays the role of an information carrier, in a realistic application it may occur a crossing among them. The collision of two

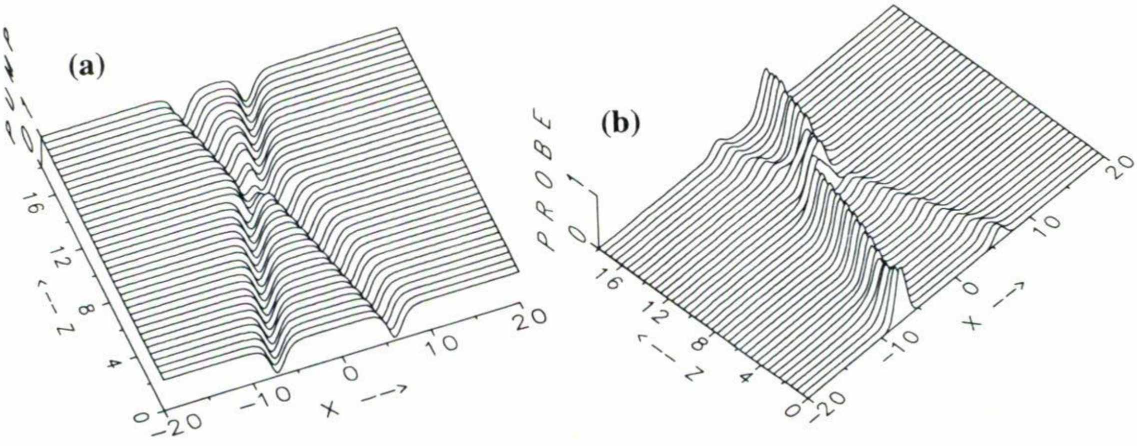

FIGURE 3. Numerical solution of the coupled Eqs. (2) and (3) showing that the guided (probe) beams maintain their original channel after a channel crossing. In (a) we show the dark-spatial soliton collision and in (b) we show the behavior of the corresponding guided beams launched into the channels. The initial pump profile was taking from the theoretical solutions for a pair of identical dark solitons giving in Eq. (10) of Ref. [17], with $\lambda_1 = -\lambda_2 = 0.3$. The initial probe beams have the same gaussian profile as in Fig. 2, but the energy of the right-hand one is one quarter of the other.

solitons is now well known [2], but to the best of our knowledge nothing is known about the behavior followed by the corresponding probe beams that use them as waveguides.

In order to investigate such a behavior, we solve the coupled Eqs. (2) and (3) with the analytical expression [17] for a pair of identical colliding dark-solitons as the input for the guiding beam. On each one of the produced channels, a beam of gaussian profile but different amplitude is launched. The width of such a beam has been chosen close to the soliton width in order to fall whitin the single-mode transversal distribution for the probe within beam. Fig. (3a) shows the spatial evolution of the two dark-spatial solitons and Fig. (3b) the behavior of the corresponding guided beams. The two solitons behave as expected and emerges unscattered after the collision. On the other hand, the guided beams traveling through the channel junction given by the soliton interaction zone, continue along their original channels and their amplitude are unaffected. This is quite a surprising behavior, because the guided beams are weak and they are expected to be affected by the nonlinear dynamics of the soliton collision. More in particular one expects that after the two original probe beams join, they would split their total energy into the two guiding channels.

Trying to identify the origin of such an anomalous behavior we repeat the numerical experiment but with two different dark solitons as the initial condition for $\Psi(X,0)$, in order to break the symmetry of the junction. Fig. (4) shows the results, where one can see that we basically obtain the same result: after the channel junction, each probe beam travels within its original channel. The influence of the relative width of the guided beam

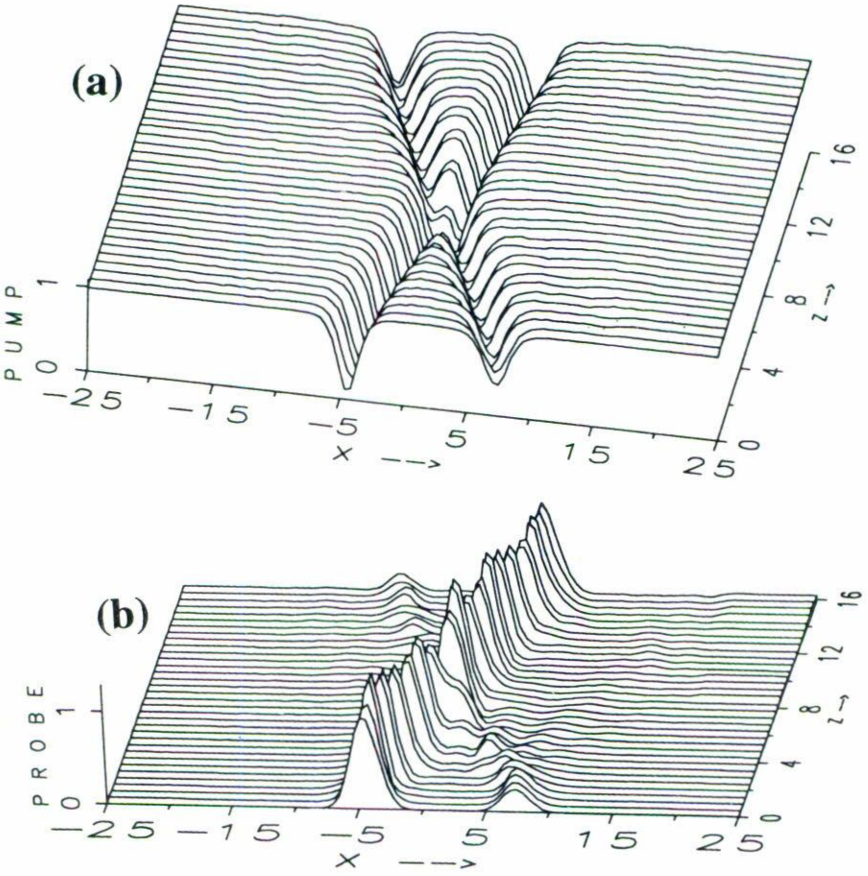

FIGURE 4. The same as in Fig. (3) except that the initial pump profile now consists of two different dark-solitons. Such a profile was taken from Ref. [17] with $\lambda_1 = -0.3$ and $\lambda_2 = 0.6$. Although the asymmetry of the channels, the behavior of the probe beams showed in (b) are essentially the same as in Fig. (3).

to that of the channel can also be observed in Fig. (4b) where some radiation spreads away due to pure diffraction. This is explained because the input probe beam launched at the broader soliton channel needs to increase its width in order to fill the single-mode distribution requirements. Such a reshaping process is more severe as the width of the channel is increased, of course. However, the conservation of the probe beam energy during the soliton channel collision is still valid, but it applies to the modified mode distribution instead to the input probe beam. For wide enough soliton channels multi-mode conditions are reached and the reshaping process of the initial probe beam profile to the proper mode distribution increases in complexity. Results of using dark spatial solitons as multimode weaveguides will be reported elsewhere.

Some additional numerical experiments have been carried out, including the introduction of constant phase factors on the guided beams, and the results shown drastic changes of the phases and, once again, unaltered amplitudes after the soliton channels crossing. This fact implies that the physical explanation to the phenomenon entirely resides in some inherent propriety of the nonlinear interaction of solitons, and it may be probably used to monitor the soliton-collision dynamics. Moreover, as the energy distribution per channel is maintained while the respective phases are altered by the process, for practical applications the guided beam should be restricted to carry information in an amplitude modulation fashion.

In conclusion we have shown that weak beams launched into dark-spatial soliton waveguides emerge into the same channel, and with no apparent energy loss after a channel crossing, in spite of the nonlinear dynamics of the involved soliton collision. Though a clear explanation of this phenomenon is not yet available, it has already relevant practical consequences as it opens the possibility of constructing multidirectional optical interconnectors bases on dark-spatial solitons.

ACKNOWLEDGEMENTS

We appreciate the calling of our attention to this problem by Prof. G.I. Stegeman. One of us, GETC, thanks Prof. Jorge Ojeda Castañeda and Dr. Alfonso Serrano Perez Grovas their hospitality at INAOE.

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