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Optical Logic Arrays with Weak Beams Guided by Bright-Spatial Solitons

M. Torres-Cisneros*, M. A. Meneses-Nava**, E. Alvarado-Méndez*, R. Jaime-Rivas*, O. Ibarra-Manzano*, R. Rojas-Laguna*, J. A. Andrade-Lucio*

RESUMEN / ABSTRACT

Se propone un prototipo de compuerta lógica óptica de 4 bits basada en haces débiles guiados por solitones espaciales brillantes. El principio de operación esta basado en el cruce de solitones espaciales, los cuales pueden guiar los haces débiles. La energía de los haces débiles puede ser transferida al utilizar diferentes valores de fase relativa entre los solitones espaciales para producir los 4 estados lógicos binarios: (0,0), (1,0), (0,1) y (1,1).

A basic four-bit logic optical array prototype operating with weak beams guided by bright-spatial solitons is proposed. The operation principle of the device is based on the crossing of spatial solitons, which guide the weak beam, over two parallel and well separated solitons. Selecting appropriate phase difference values of parallel solitons, the energy of the weak beam can be transferred into them to produce the four binary logic states: (0,0), (1,0), (0,1) and (1,1).

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* Departamento de Electrónica Facultad de Ingeniería, Universidad de Guanajuato. Avenida Tampico # 918. Salamanca, Guanajuato. 36730 MÉXICO

** Permanent address: Centro de Investigaciones en Óptica A. C.. León, Guanajuato. 37600 MEXICO

INTRODUCTION

Controlling light by light is one of the most fascinating challenges to implement fully-optical communication systems. An intense optical beam can guide a second weak beam when it propagates in an intensity-dependant refractive index medium. The self guided beam phenomenon was first theoretically established (Snyder *et al.*, 1991), but of remarkable practical applications were the posterior experimental demonstrations of the guidance of probe (weak) beams by bright (De la Fuente *et al.*, 1991) and by dark (Luther-Davies *et al.*, 1992) spatial solitons in Kerr-Type nonlinear media. The use of spatial-solitons as optical channels for probe beams has a direct impact in the development of logical and interconnecting devices. This fact has been corroborated in several experimental works (Akhmediev *et al.*, 1993, Krolikowsky *et al.*, 1997). The basic idea is, the transient evolution of an initial intense profile into two dark-spatial solitons in a self-defocusing medium ($n_2 < 0$) was used to equally split the energy of the probe beam into the two-formed optical channels. In a self-focusing medium ($n_2 > 0$), a similar use of high-order soliton formation is not so evident because they do not separate in the absence of non-symmetric perturbations (Akhmanov *et al.*, 1992). Later, a proposal of optical switch was built on the interaction (attraction, repulsion or merging) of two neighboring bright solitons, according to their phase difference (Kodama *et al.*, 1991; Shalaby *et al.*, 1991; Shalaby *et al.*, 1992). However, further applications of solitons wave-guides will require a more complete understanding not only of the soliton dynamics itself but also on specific behavior followed by probe beams they guide.

For example, it was noted (Torres-Cisneros *et al.*, 1993) that light guided by dark spatial-solitons exhibit an almost linear behavior in a crossing among them, in spite of the intrinsic nonlinear characteristics of a soliton collision.

PALABRAS CLAVE: Compuertas lógicas, Solitones, Materiales no-lineales

KEYWORDS: Logic gates, Solitons, Nonlinear materials

In this letter we study the conditions where the input probe beams energies can be split into two emerging soliton channels in a controlled way, in particular by properly adjusting the relative phase of colliding solitons. The logic optical gate can be built using the parameters of the interacting solitons. It is possible to actively control the switching of probe beam as it was done for just one soliton-based optical channel, without modifying the soliton junction itself (Shalaby *et al.*, 1992).

THEORY

In the standard 2-dimensional approach, the simultaneous propagation of an intense (pump) and a weak (probe) beams is described by (De la Fuente *et al.*, 1991).

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

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

where the subindex $i=1$ corresponds to the pump beam parameters. In Eqs.(1-2) A_i are the transversal beam envelopes normalized to $\sqrt{P_o}$, with $P_o = n_{01}/n_2 L_d$ being the transversal peak power associated to the first order soliton solution of Eq.(1), n_2 is the Kerr coefficient of the medium and $L_d = n_{01}^2 k_{01}^2 x_0^2$ is the adimensional diffraction constant. Moreover, x_0 is the initial transversal width of the intense beam, $X = x/x_0$ and $Z = n_{01}k_{01}z/L_d$ are the normalized transversal and propagation distances, respectively; $\beta = 2/r_k$, and $r_n = n_{01}/n_{02}$ and $r_k = k_{01}/k_{02}$ are the ratios of the linear refractive indexes and wave numbers, respectively.

In order to investigate the behavior of the guided probe beam A_2 during a bright soliton optical channels cross we use:

$$A_1(X,0) = \sec h(X+c)\exp[-iv(X+c)+i\phi] + \sec h(X-c)\exp[iv(X-c)] \qquad (3)$$

as the initial condition for A_1 Eq.(3) represents two identical spatial-solitons beams, initially separated by *2c* and propagating at angles $\pm\theta$ with respect to the Z axis, where $\tan\theta = v$. On the other hand, we will use $A_2(X,0) = \sec h(X-c)\exp[iv(X-c)]$ as the initial condition for the probe beam, which is close to the single-mode solution for an optical waveguide with a hyperbolic-secant transversal refractive index distribution (Snyder *et al.,* 1983).

NUMERICAL RESULTS

A typical numerical solution of the Eqs.(1-2) is depicted in Fig.1 for an in-phase (ϕ = 0) soliton collision. Fig.1(a) shows the bright spatial-soliton collision. As it is expected, the two solitons collide producing an interaction pattern, but then they emerge unchanged. On the other hand, Fig.1(b) shows the evolution of the probe beam. At the beginning, the probe beam is simply guided by the right soliton optical channel. However, it meets the soliton interaction region and splits its energy into the two emerging soliton channels. Physically, the probe beam energy splitting occurs because it passes through an effective phase diffraction grating formed by the soliton interference pattern (Torres-Cisneros *et al.*, 1993).

Fig. 2 shows the relative output energies in each channel after the soliton collision as a function of the initial angular separation, $v = \tan(\theta)$. For large values of v, almost all the output probe beam energy remains in the original optical channel. However, as v decreases it is possible to switch a considerable fraction of the input probe beam energy into the other optical channel. For the specific parameters used in Fig. 1, the special symmetric optical Y-junction occurs either for $v \approx 0.8$ or $v \approx 2.2$.

Fig. 3 characterizes the splitting properties of the optical Y-junction as a function of the

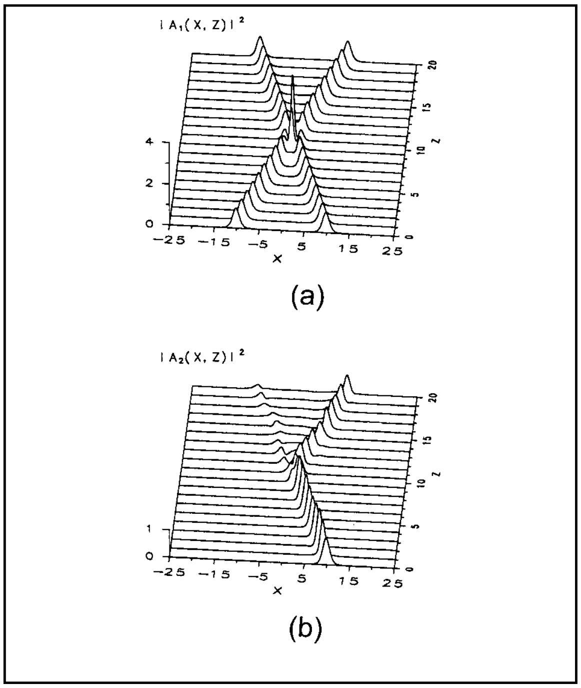

Figure 1.- Optical Y-junction formed by the collision of two bright spatial solitons. In (a) The soliton collision is shown in (b) the behavior followed by the probe beam is graphed. The parameters are $v = 1.2$, $r_k r_n = 1$, β=2 and ϕ=0.

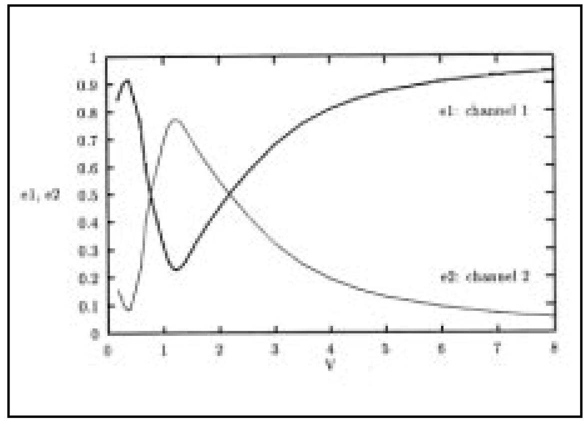

Figure 2.- Relative output probe energies in channels number one and two after soliton collision as function of the collision angle. Other parameters are the same as those in Fig.1.

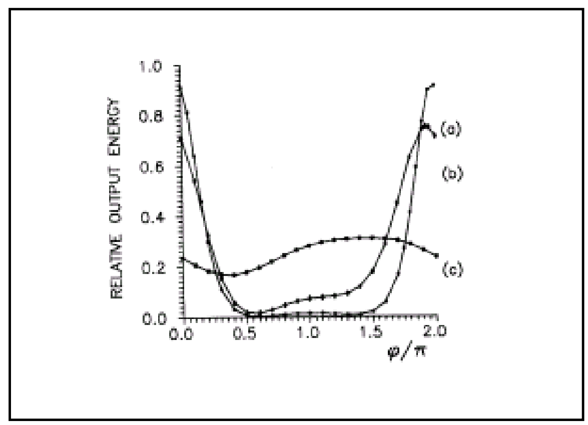

Figure 3.- Relative output probe energy in channel number one as the relative phase between the initial solitons is varied. In (a) $v = 0.375$, in (b) $v = 0.625$ and in (c) $v = 1.25$. Other parameters are the same as those in Fig.1.

relative initial phase difference of the two solitons ϕ. As can be seen, a nearly perfect switching from the input channel to the other can be obtained for $v \approx 0.375$ where the transmission, curve 1 of Fig. 2, has a maximum. In this particular case a complete switching is predicted for $\phi = 0.6\pi$.

As we stated before, an analytical description of the splitting of the probe beam during a two bright spatial-soliton channel crossing, resides in the diffraction of the probe beam by phase diffraction grating formed by the soliton collision pattern. Naturally, the profile of such diffraction grating varies with the distance Z, and an exact description is far from being simple. However, most of the characteristic features exhibited in Fig. 2 and 3 can be well described assuming a phase diffraction grating with central soliton collision profile, i.e. Eq.(3) with $c = 0$, and with a thickness equal to the length of the collision region, which is estimated to be $h = 2/v$.

Numerical results show that the device is wavelength, relative initial phase and transversal velocity sensible, as is depicted in Fig. (2) and (3) for the second and third cases, respectively, but because relative initial phase has the simplest experimental sep-up, we are interested only in it.

As an example, the perfect switching state (1,0) in our basic logic gate can be obtained selecting a relative phase between soliton of

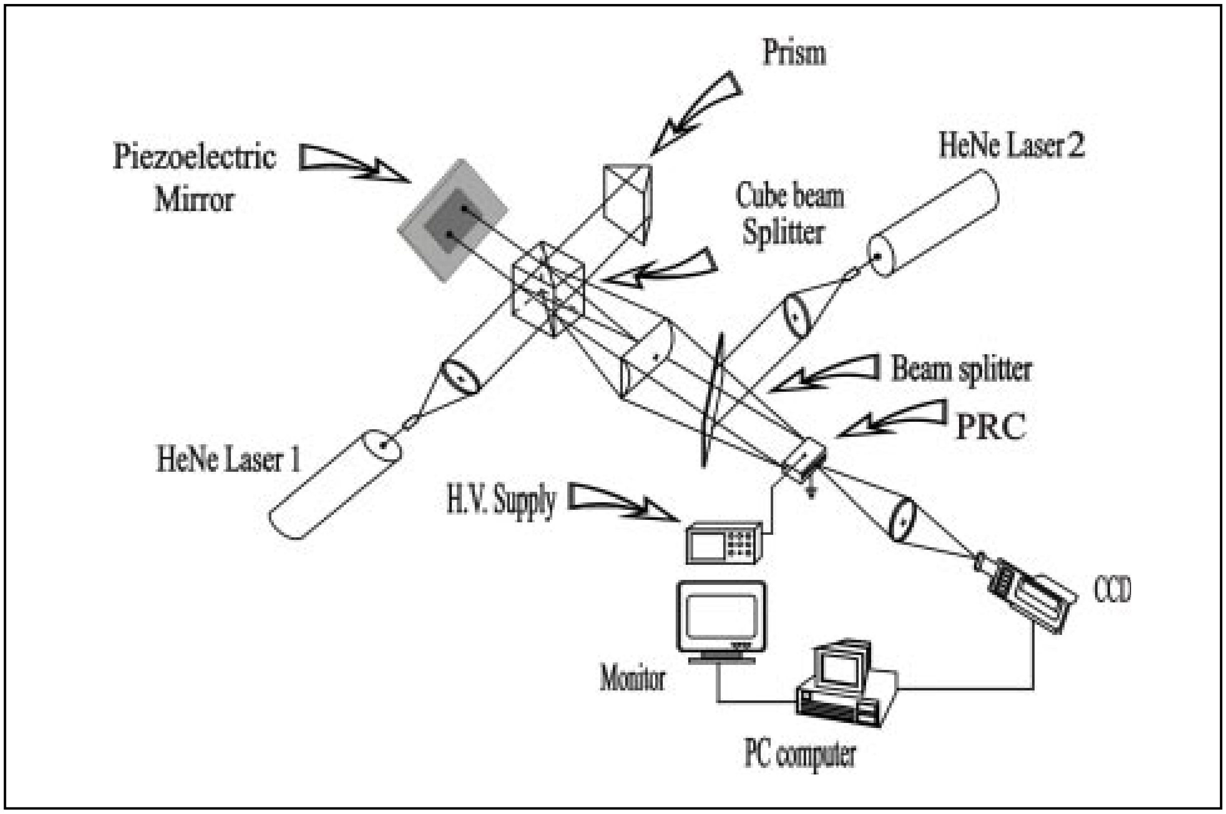

Figure 4.- Experimental set-up proposed for the spatial solitons based optical logic gate.

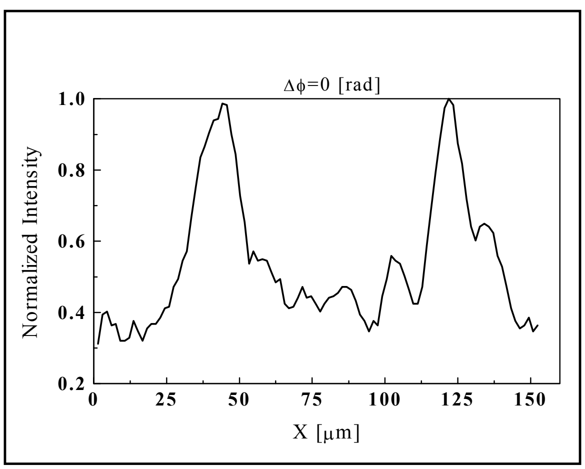

Figure 5.- Two intensity-symmetric bright spatial solitons emerging after collision. 0.8° angle of collision and relative phase of 0 rad. The rest of the experimental conditions are: He-Ne ($\lambda = 632.8nm$) beam widths of 13 μm, voltage applied to PRC of 2.3 KV/cm and the intensity of the uniform beam was equal to the peak intensity of the focused beams.

$\phi = 0.6\pi$, a transversal phase velocity of $v = 0.375$ and the other parameters as are described in Fig. (1). A change in the relative phase value to $\phi = 0$ will be able to get the (0,1) state, as is shown in Fig. (1). The symmetrical split condition which can be used to get the (0,0) and (1,1) states can be obtained keeping the same parameters values and selecting the relative phase $\phi = 0.3\pi$.

EXPERIMENTAL RESULTS

The variation of relative phase can be done using a piezoelectric mirror, as is shown in the experimental set-up proposed in Fig. (4). In this proposal, the split of the initial beam generated by the first He-Ne Laser is given by the prism. The initial separation between the beams can be modified by either the cube beam splitter or the plate beam splitter, while the piezoelectric mirror can control the relative phase between the beams varying the applied voltage. One-dimensional beams of $16\mu m$ width (FWHM) are obtained by using a *20 cm* focal length cylindrical lens. Both beams are focused at the front face of the (6x6x6mm) SBN:60 photorefractive crystal (PRC) Ce doped (0.005%). The second He-Ne beam is expanded and collimated to illuminate the crystal uniformly. As the numerical results predicted, the beams emerged from collision virtually unchanged for an angle of 0.8° and for a no phase difference ($\phi = 0$). This results agree with the numerical results showed in the Fig. 1.

In summary, we have shown that a collision of two bright-spatial solitons can be used to obtain controllable optical logic gate in self-focusing media. The experimental set-up for a optical logic gate has been proposed and its results agree with the numerical results.

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