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Controllable optical Y-junctions based on dark spatial solitons generated by holographic masks

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Abstract

We show that when the coherent superposition of two dark spatial solitons is used as the initial condition for an optical beam, it will form an asymmetric optical Y-junction after evolution in a nonlinear Kerr-like medium. Using a computer-generated holographic mask to provide such a required initial condition, we demonstrated that an asymmetric optical Y-junction can be formed in a photorefractive BTO crystal.

Keywords: Spatial solitons; Photorefractive effect

The use of dark spatial solitons as optical Y-junctions was experimentally demonstrated just a few years ago in a Kerr-type material [1]. In these materials, the transient evolution of an initial intense beam into a pair of identical dark-spatial solitons was used to construct the symmetric Y-junction, opening the possibility to use spatial solitons to guide optical signals in logic and interconnection of all-optical devices [2–5]. However, to produce dark spatial solitons requires the adequate initial conditions of the beam at the entrance of the nonlinear medium. Theoretically, dark solitons in Kerr media can be generated with a dip, no matter how small it be, in the transversal intensity profile of an enough intense beam [6]. It is possible, at least in principle, to know the soliton as well as the linear solutions, reminding that a given initial beam profile will be produced by solving the eigen-value problem associated to the nonlinear Schröedinger equation (NLSE) [7]. In the laboratory, such a perturbation is carried out using amplitude or phase masks. An amplitude obstacle, e.g., a wire, in front of the input beam will produce an even number of dark spatial solitons immersed on a bright background. On the other hand, a π-phase jump introduced on one half of the transversal input beam profile will produce an odd number of dark spatial solitons also immersed on a bright background [8]. In any case, higher order solitons will always be formed by pairs of identical solitons. In consequence, their dynamics will only produce symmetrical optical junctions.

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The purpose of this paper is to report the experimental observation of an asymmetrical Y-junction generated in a photorefractive BTO crystal under the presence of drift nonlinearity. This optical junction was formed by using the nonlinear superposition of two distinct dark spatial solitons as the initial condition of the beam. Such an initial condition was obtained by means of an adequate computer-generated hologram.

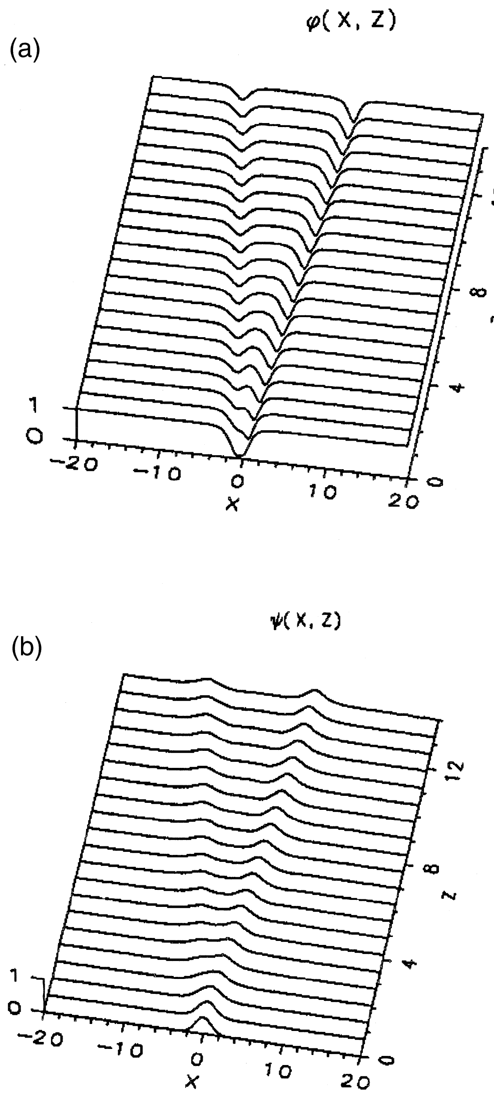

Fig. 1. Asymmetric Y-junction generated solving Eq. (2) with $\zeta_1 = -0.6$ and $\zeta_2 = 0.3$. Formation of the two distinct optical channels (a) and the trajectory followed by a probe beam (b).

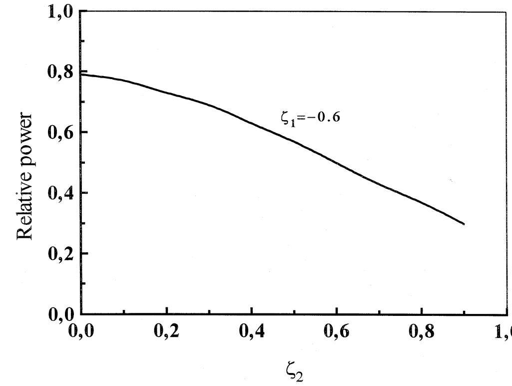

Fig. 2. Relative probe beam power guided by the optical channels at the output of an asymmetric Y-junction, as the parameter ζ_2 is changed ($\zeta_1 = -0.6$).

Within the usual (1 + 1)-dimensional approach, the evolution of a laser beam propagating in a negative Kerr-type medium is governed by the NLSE [8]:

$$i\frac{\partial \phi}{\partial Z} = -\frac{1}{2}\frac{\partial^2 \phi}{\partial X^2} + N^2 |\phi|^2 \phi, \tag{1}$$

where $\phi(X,Z)$ is the normalized (slowly varying) transversal envelope of the beam and $N^2 = L_d P_0 n_2 / n_0$ with P_0 the peak power of the beam and n_2 the nonlinear refractive index, $L_d = n_0 k_0 x_0^2$, n_0 is the linear refractive index, k_0 the wave number and x_0 the initial width of the beam. The transversal coordinate and the propagation distance have been normalized to $X = x/x_0$ and $Z = z/L_d$, respectively.

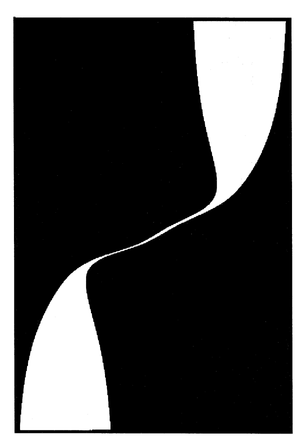

Fig. 3. Unit cell of the computer-generated hologram.

For $N=1$, Eq. (1) admits the fundamental dark soliton solution [9] $\phi(X,Z) = \tanh(X) \times \exp(-i\{1/2\}Z)$. Apart from this particular solution, there are many other analytical solutions to Eq. (1), which represent multiple dark solitons interacting under the influence of effective repulsive potentials. Among them, the two-solitons solutions are of remarkable importance for the present work, and are given by [10]:

$$\phi(X,Z) = 1 - \frac{2if(X,Z)}{g(X,Z)}, \tag{2}$$

where

$$f(X,Z) = \frac{2}{\mu_1+\mu_2}\left(\frac{1}{\zeta_1+i\mu_1} + \frac{1}{\zeta_2+\mu_2}\right) - (\zeta_1 - i\mu_1)\left(\exp[2\mu_1(X-2\zeta_1 Z)] + \frac{1}{\mu_1}\right) - (\zeta_2 - i\mu_2) \times\left(\exp[2\mu_2(X-2\zeta_2 Z)] + \frac{1}{\mu_2}\right),$$

$$g(X,Z) = (\zeta_1 - i\mu_1)(\zeta_2 - i\mu_2) \times\left(\exp[2\mu_1(X-2\zeta_1 Z)] + \frac{1}{\mu_1}\right) \times\left(\exp[2\mu_2(X-2\zeta_2 Z)] + \frac{1}{\mu_2}\right) - \frac{1}{(\mu_1+\mu_2)^2}\left(\frac{1}{\zeta_1+i\mu_1} + \frac{1}{\zeta_2+i\mu_2}\right)^2,$$

with $\mu_i = \sqrt{1-\zeta_i^2}$.

The two dark solitons are fully characterized by the parameters ζ_i, which lie in the range $1 < \zeta_i < 1$. The magnitude of ζ_i represents the width and the transversal distribution of the dark soliton. The sign of ζ_i indicates the direction of displacement of the transversal velocity V, $V = 2\zeta_i$. At $z=0$, Eq. (2) represents the exact nonlinear superposition of two dark spatial solitons, and they separate as Z is increased. Our main idea in this paper is that if we use the transversal distribution which exactly reproduces Eq. (2) at $Z=0$ as the initial condition for $\phi(X,0)$, its posterior evolution within the nonlinear medium acts as an asymmetric optical Y-junction when the solitons are used as optical channels for a second and weak beam. Fig. 1 demonstrates this idea. In Fig. 1a we show the optical waveguides,

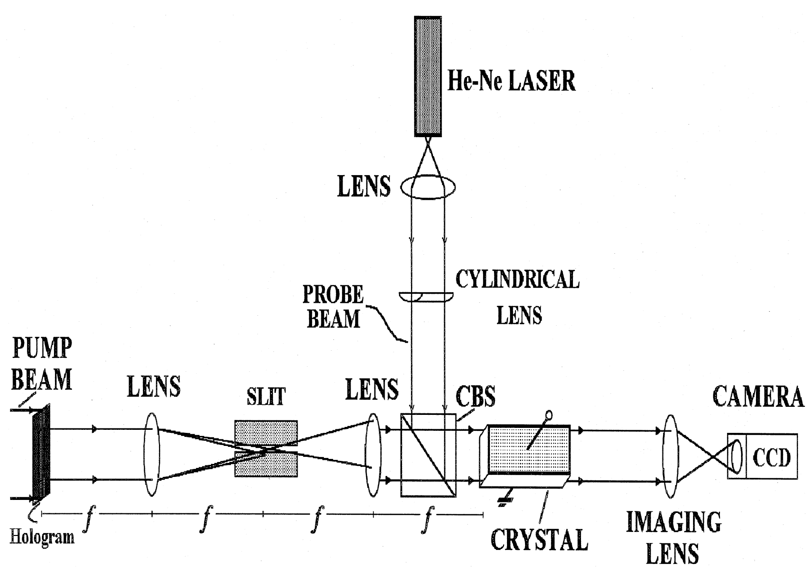

Fig. 4. Experimental set up for the generation of the asymmetric Y-junction. CBS: cube beam splitter.

starting from the profile of Eq. (2) with $\zeta_1 = -0.6$, $\zeta_2 = 0.3$, while in Fig. 1b, we show the trajectory followed by a probe beam. As it is evident, the probe beam splits its initial energy into the two formed optical channels. A direct numerical integration of the output probe beam intensity distribution of Fig. 1b indicates that the deeper channel guides 68% of the initial probe beam energy, while the other carries out the other 32%. The amount of the probe beam energy split into the two optical channels can be adjusted by changing the values of the parameters ζ_i, as can been seen in Fig. 2, where the sharpest soliton, i.e., smaller ζ_i, always guides the largest fraction of power.

In order to prove our basic idea, as an example, we experimentally constructed a 60–30 optical beam

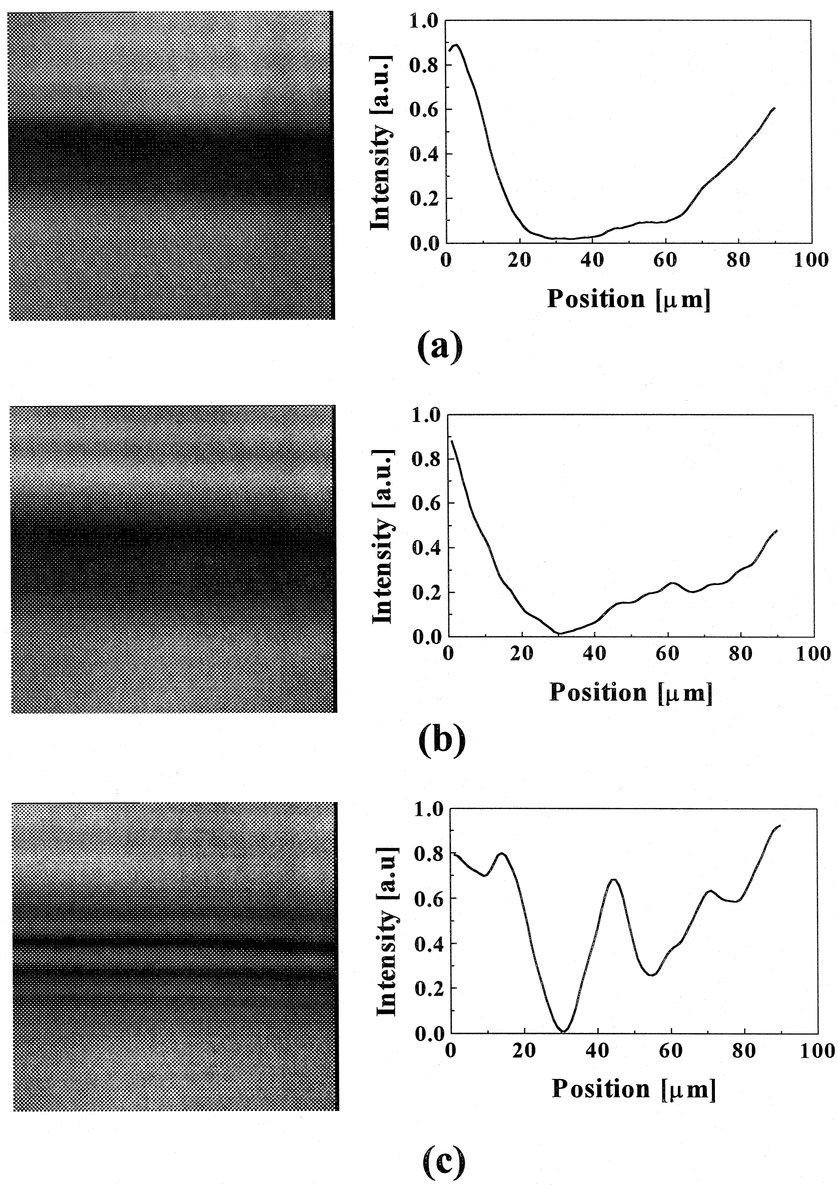

Fig. 5. Images and profiles for the pump beam: input (a), output (b) and output with 9.0 kV/cm external electric field applied (c).

splitter using as nonlinear media a photorefractive BTO crystal. Note that Eq. (2) is valid only for Kerr-type media, but under the influence of the drift nonlinearity, the photorefractive crystal behaves as a saturable Kerr-type media [11]. In these kinds of media, the saturation parameter (the ratio of the maximum beam power density to that of the dark intensity) can be easily controlled [12]. Furthermore, waveguides generated by fundamental dark spatial solitons in photorefractive media are always single mode [13] then their behavior on collisions is identical to that in Kerr media [14]. Theory and experiments on dark solitons and their waveguiding properties in photorefractive crystals always give symmetric Y-junctions [12–16].

The initial condition for our experiment was produced using a computer-generated hologram of unitary cell shown in Fig. 3. Following the elegant technique proposed by Ojeda-Castañeda and Lohmann [17], we encoded the amplitude profile of the superposition of the two solitons given by Eq. (2) as the width of the slit and the phase variations as the shape. This hologram was set in front of the pump beam in an experimental configuration shown in Fig. 4. The first He–Ne laser beam illuminates the holographic mask located at the input of a 4-f optical system. In the Fourier plane of the first lens, we set a slit to choose the first diffracted order. In this way, we exactly reproduce the amplitude and phase variations given by Eq. (2). Under these experimental conditions, a dark stripe was produced at the input face of the crystal (see Fig. 5a). After propagation in 9 mm of the crystal, the stripe was broadened (Fig. 5b). After application of an electric field of 9 kV/cm to the crystal, the initial dark stripe was divided into two (Fig. 5c). One can clearly see that the amplitude of one with dark stripes is deeper (upper in the image and the left in the profile) than the other (lower in the image and the right in the profile). It is clear from the last image that we generate an asymmetric Y-junction. To verify the result, it was necessary to see the waveguides properties of the structure with a probe beam. As it was shown in Ref. [18], in this kind of experiment, it is not necessary to use a uniform illumination to the crystal to generate dark spatial solitons [19]. Under our experimental conditions, we can say that the saturation parameter was lower than 1, then the Kerr-type behavior was obtained. We use the other He–Ne laser beam to obtain a (1 + 1)-D focused beam in the dark stripe using a 20-cm cylindrical lens. This beam was not continuously illuminating the crystal because it tends to destroy the waveguide. To avoid this, it is necessary to use a different wavelength. In Fig. 6, we show the input (a) and the output (b) profile of the probe beam without pump beam and voltage applied to the crys-

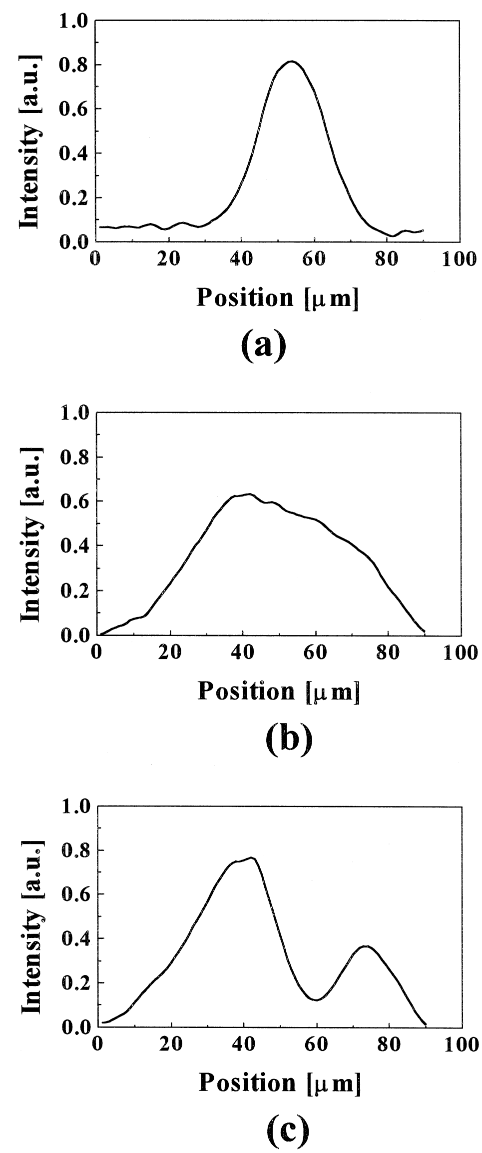

Fig. 6. Profiles for the probe beam: input (a), output (b) and output with 9 kV/cm external electric field applied (c).

tal. Once the asymmetric Y-junction was created, we allowed the probe beam to pass only for a few seconds and we observed that the beam was split into two (Fig. 6c). One guided portion, corresponding to the deeper dark stripe, had more power than the other. The power splitting ratio obtained experimentally was 66/34. This result is in good agreement with the numerical simulations presented above, both the pump and probe beam. The splitting of the input power of the probe is explained in terms of the mode requirements imposed by the two different dark solitons. The deeper soliton is expected to guide a great fraction of the input energy of the probe beam. Then different beam splitters can be constructed by changing the parameters of the interacting solitons encoded in the hologram.

In conclusion, we have proposed and demonstrated the generation of asymmetric optical Y-junctions in a photorefractive crystal. Such an optical device is based on the adequate generation of the input beam profile, which corresponds to the collision of two dark spatial solitons. The possibility of having such an asymmetrical Y-junction may have attractive potential applications in all-optical beam splitters and switches, just as a variable beam splitter in bulk media.

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