Observation of interaction forces between one-dimensional spatial solitons in photorefractive crystals

G. S. García-Quirino, M. D. Iturbe-Castillo, V. A. Vysloukh, J. J. Sánchez-Mondragón, and S. I. Stepanov

Instituto Nacional de Astrofísica, Optica y Electrónica, Apartado Postal 51, Puebla, Pue. 72000, México

G. Lugo-Martínez and G. E. Torres-Cisneros

Universidad de Guanajuato, Apartado Postal 215-A, Salamanca, Gto. 36730, México

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We propagate two coherent and parallel beams of a He–Ne laser through a $Bi_{12}TiO_{20}$ photorefractive crystal in the presence of drift nonlinearity. Our experimental results demonstrate that the beams attract or repel each other according to their initial phase difference. They attract each other when they are initially in phase and they repel each other when they are initially out of phase. These experimental results agree with numerical predictions recently published. © 1997 Optical Society of America

Among the most amazing properties of optical solitons, and also one of their more promising characteristics for practical applications in photonics, is the nonlinear interaction that takes place when two solitons propagate close enough within the corresponding nonlinear medium. The interaction forces between bright solitons in optical fibers were first investigated theoretically within the context of the nonlinear Schrödinger equation.[1] Two bright solitons traveling at the same velocity in the anomalous-dispersion regime of an optical fiber can attract or repel each other according to their relative phase. The magnitude of this interaction force depends on physical parameters, such as the time delay between the solitons and their relative amplitudes and widths. The two well-known extreme cases occur (1) when two identical solitons are in phase, in which case they form a bounded state, and (2) when they are out of phase and then repel each other. Temporal dark solitons, which are solutions of the nonlinear Schrödinger equation for the normal-dispersion regime of an optical fiber, also experience an interaction force, but it is always a repulsive one.[2] In the spatial domain similar interaction forces between optical solitons have also been observed in Kerr-type media.[3]

The interaction forces between neighboring optical solitons are important for photonic application purposes, and their influence on a specific photonic device can be desirable or undesirable. For soliton-based telecommunication systems, for example, two soliton pulses must be launched with a time delay of the order of 10 pulse widths[4] to avoid the interaction force between them. However, in the spatial domain the interaction force between two parallel solitons could lead to an optical switching operation,[5] and it can also be used to generate half-beat-length directional couplers.[6]

The predictions and observations of optical spatial solitons in nonlinear materials, which require considerably less laser power than Kerr-type materials, are the subject of increasing interest. Spatial solitons in photorefractive crystals (PRC's), for example, have been observed.[7–10] However, these spatial solitons do not obey the nonlinear Schrödinger equation, and the way in which they interact when they are close enough remains to be investigated. For the specific case of a PRC governed by a drift nonlinearity it was shown numerically that the interaction force between two bright spatial solitons follows a behavior similar to that for two solitons in a Kerr medium.[11] In this Letter we present what are to our knowledge the first experimental results that demonstrate the existence of interaction forces between two coherent bright spatial solitons in a PRC governed by a drift nonlinearity.

The scalar (1 + 1) dimensional model of laser beam propagation through a PRC with drift nonlinearity yields the following equation for the beam envelope[12,13]:

$$i\,\frac{\partial q}{\partial Z} = \frac{1}{2}\,\frac{\partial^2 q}{\partial X^2} + \mu R\,\frac{|q|^2}{1+\mu|q|^2}\,q\,. \qquad (1)$$

Here q represents the beam envelope normalized to $\sqrt{I_s}$, where I_s is the peak intensity of the initial beam. In Eq. (1) $\mu = I_s/I_0$ is the saturation parameter, where I_0 is the intensity of the uniform illumination provided to the crystal. $R = L_D/L_{\mathrm{NL}}$, where $L_D = n_0 k_0 {x_0}^2$ is the diffraction length and $L_{\mathrm{NL}} = 1/(k_0 \delta n_0)$ is the characteristic nonlinear length. n_0 is the linear refractive index, k_0 is the wave number, x_0 is the width of the initial beam envelope, and $\delta n_0 = (1/2) r {n_0}^3 V_0/L$ is the nonlinear contribution to the refractive index, where r is the electro-optic coefficient, V_0 is the externally applied voltage, and L is the transverse width of the crystal. Finally, $X = x/x_0$ and $Z = z/L_D$.

Figure 1 shows the experimental setup. The 10-mW cw He–Ne laser beam at the left was expanded and collimated to form a beam with a diameter of 1.5 cm. This beam illuminated a Twyman–Green

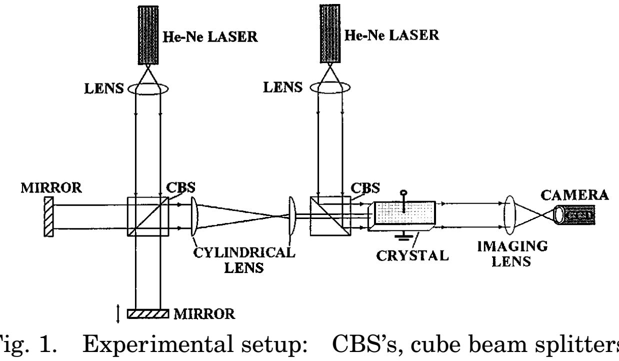

Fig. 1. Experimental setup: CBS's, cube beam splitters.

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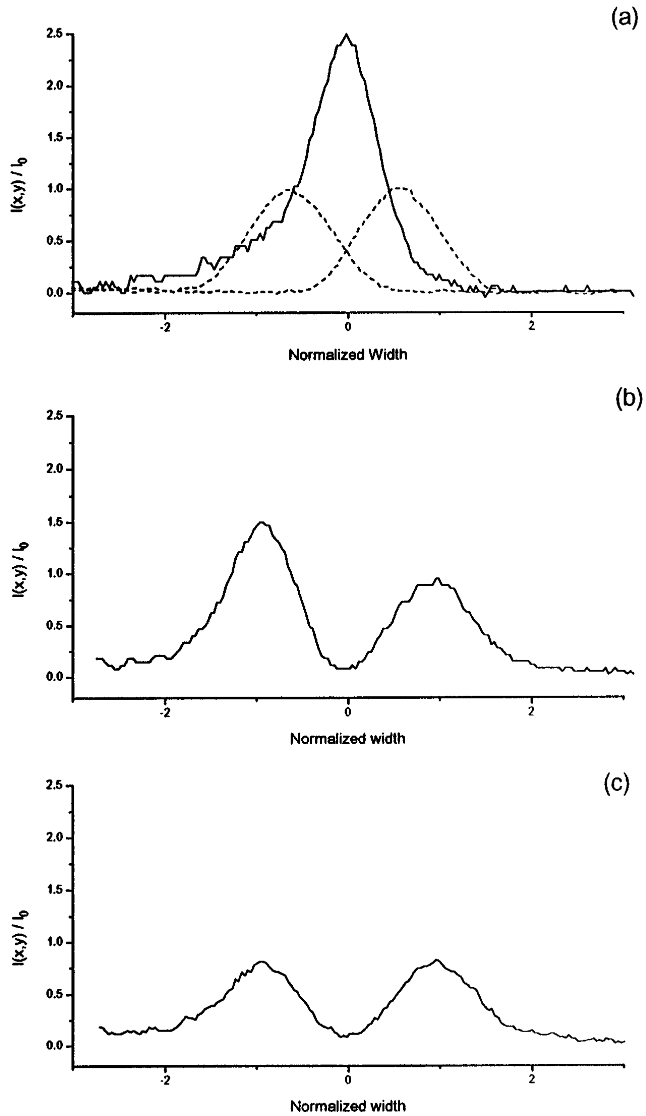

Fig. 2. Experimental output profiles for three values of the relative phase of the initial beams: (a) $\triangle\phi = 0$, (b) $\triangle\phi = 0.65\pi$, and (c) $\triangle\phi = \pi$. The input profiles of the initial beams are graphed with dashed curves in a.

interferometer, where it was split into two beams of equal intensity. We varied the relative phase between the two beams by changing the length of one of the arms of the inteferometer. We obtained appropriate widths for the beams arriving at the $Bi_{12}TiO_{20}$ crystal by using a pair of cylindrical lenses with 20- and 2.2-cm focal lengths. The other He–Ne laser beam was expanded and collimated to illuminate the crystal uniformly. The intensity of this uniform beam was equal to the peak intensity of the focused beams, that is, $\mu \sim 1$. The beams were polarized nearly parallel to the applied external field.

Figure 2 shows the output intensity profiles for some relative phases, $\triangle\phi$, between the initial beams. The dashed curves in Fig. 2(a) show the initial parallel beams. The width (FWHM) of each beam was $w_0 = 27$ μm, and the separation between them ws $1.1w_0$. The external applied voltage was set at 1.8 kV when the input and the output widths of an individually propagated beam were identical. This fact is a clear indication of the formation of a bright spatial soliton.[7] However, at this voltage the induced nonlinearity is still too small to permit us to observe other nonlinear effects, such as transverse modulation instabilities.[14] When $\Delta\phi = 0$ [Fig. 2(a)] the beams attract each other, and they merge at the end of our 9-mm PRC. When $\triangle\phi$ is near 0.6π the output beam at the left becomes more intense than the other, as shown in Fig. 2(b). Finally, when $\triangle\phi = \pi$, the beams repel each other [Fig. 2(c)], and the final peak-to-peak separation is close to $2w_0$.

Let us now compare these experimental results with those of the numerical solutions of Eq. (1) of Ref. 11. We assume that the input beams follow the Gaussian profile $\exp(-X^2/2)$, and then $x_0 \sim w_0/1.67 = 16.2$ μm. Using $n_0 = 2.25$, we have $L_D = 0.77$ cm and a normalized crystal length of $Z_{\mathrm{end}} = 1.17$. For our BTO crystal $r = 6.175 \times 10^{-10}$ cm/V, and we used $V_0/L = 9000$ V/cm. Therefore $L_{\mathrm{NL}} = 0.319$ cm and $R = 2.41$. The initial beams are depicted by dashed curves in Fig. 3(a).

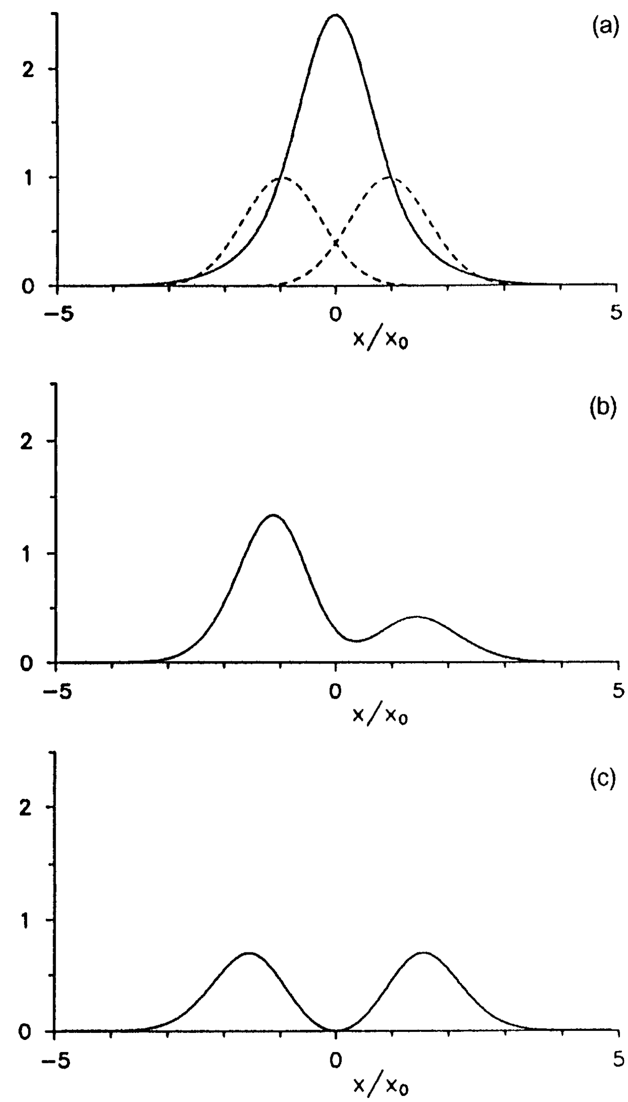

Fig. 3. Numerical results of Eq. (1) corresponding to the experimental parameters used in Fig. 2.

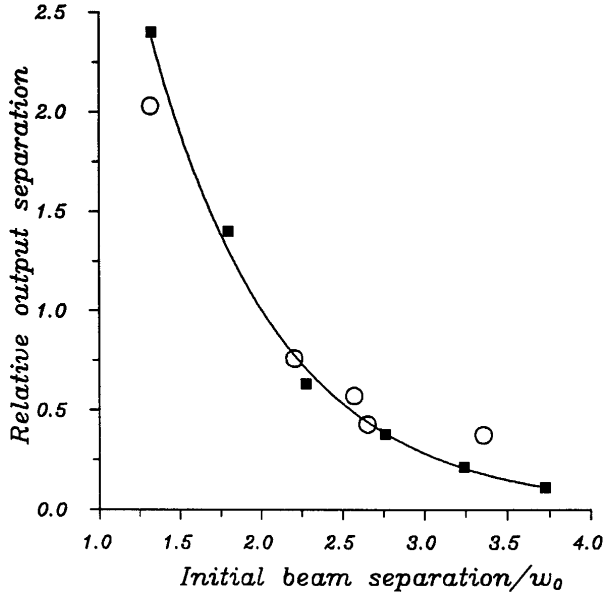

Fig. 4. Relative separation of the output beam with respect to the separation of the input beams as a function of the initial beam separation. Open circles are experimental results, and filled squares are numerical results.

The solid curve in Fig. 3(a) shows the numerical output profile when $\triangle\phi = 0$. The beams merge at the end of the crystal, just as in the experimental result of Fig. 2(a). As $\triangle\phi$ increases, the peak of the output profile moves to the left, its right wing becomes wider, and the other soliton is eventually evident in the form of a second and less intense peak. This is illustrated in Fig. 3(b), where $\triangle\phi = 0.65\pi$, in good agreement with the experimental result of Fig. 2(b). We remark here that, if the sign of $\triangle\phi$ is reversed, the soliton on the right dominates. Finally, if we further increase $\triangle\phi$, the peak intensity of the left soliton decreases and the peak intensity of the soliton on the right increases, until the two peak intensities are equal at $\triangle\phi = \pi$. This represents the repulsion of the two solitons [Fig. 3(c)], where the peak-to-peak separation is close to $3.2x_0$, in good agreement with Fig. 2(c).

The magnitude of the interaction forces between the solitons in the PRC is expected to depend on the initial separation of the solitons. We demonstrate this behavior by quantifying the repulsion force exhibited by two out-of-phase beams as the initial separation between them was varied. The experimental results obtained for the relative increment in the separation of the output beams are shown in Fig. 4 by open circles. Results of numerical computations are shown in the same figure by filled squares. From this figure it is clear that the repulsive force between the bright solitons decreases monotonically as the initial separation between them increases. In fact, the solid curve represents an exponential fit of the numerical data.

It is necessary to point out that Eq. (1) is similar to that which describes beam propagation in the presence of a saturable Kerr nonlinearity, which shows a bistable behavior.[15] This means that there are two possible solitonlike solutions for a given beam width. Thus our experiments correspond to the interaction between two solitons of the lower branch, and solitons of the upper branch follow a different behavior.[16] On the other hand, the observation of the soliton interaction forces has been possible only because of the coherence property of the two beams. The incoherent interaction between two beams shows a different behavior, which was recently reported.[17]

In conclusion, we have presented experimental evidence of the interaction forces between two bright spatial solitons in photorefractive crystals governed by a drift nonlinearity. This result opens the possibility of designing optical switches or optical logic gates based on the interaction forces between spatial solitons, similar to those in Kerr media.[5]

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