Fusion and birth of spatial solitons upon collision

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We study experimentally the collision of photorefractive screening solitons in a strontium barium niobate crystal. Depending on the relative phase of the solitons and their intersecting angle, such effects as soliton birth, energy exchange, and soliton fusion have been observed. © 1997 Optical Society of America

Spatial optical solitons have been suggested for all-optical guiding and switching in nonlinear-optical media.[1] The concept of soliton-created optical devices is based on the fact that the soliton is a (fundamental) mode of the optical waveguide it creates in a self-focusing medium. These soliton-induced waveguides can then be used to guide and steer another optical beam. In fact, soliton-induced guiding and steering was already observed in many experiments.[2–4] The steerable waveguide, of course, constitutes the simplest optical element. More complex and interesting from the practical point of view are structures formed by intersecting waveguides such as X or Y junctions.[5,6] One natural way to create such intersecting waveguides is by collision of two or more solitons. It is well know from the classic research of Zakharov and Shabat[7] that spatial solitons of cubic (Kerr) nonlinearity remain unperturbed when they collide. Drastically different, though, is the collision of solitons propagating in non-Kerr material. Such a collision has an inelastic character, as reflected in the emission of radiation as well as a strong dependence of the outcome of the collision on the relative phase of the solitons.[8–11] In particular, it has been predicted that solitons can annihilate one another, fuse, or give birth to new solitons when propagating in nonlinear materials exhibiting saturation of nonlinearity and that this kind of behavior is rather generic, being independent of particular mathematical models for nonlinear media.[11] Fusion of solitons was already observed in incoherent soliton collisions in photorefractive crystal[12] as well as during interaction in atomic vapors.[13] To our knowledge no one has reported the birth of solitons.

Here we study coherent collision of solitons in a saturable medium, a photorefractive crystal. We show phase-dependent soliton fusion as well as, for the first time to our knowledge, the multiple birth of solitons upon collision. Our observation also corresponds to the qualitative theory advanced by Snyder and Sheppard.[11] They showed that such phenomena have a number of applications, including light guiding and steering by light as well as light-written optical devices. It was shown recently that photorefractive media support so-called spatial screening solitons that can be formed with very low laser power (microwatts). In this instance propagation of an optical beam in photorefractive crystal causes screening of the externally applied biasing dc field and leads to the modulation of the refractive index in a way that mimics light-intensity distribution. This effectively leads to a self-focusing effect and to trapping of the beam in a form of spatial soliton.[14–17] While the rigorous treatment of the problem of beam propagation in photorefractive crystal involves the necessity of simultaneous solution of Maxwell's equations, augmented by a set of relations governing the photorefractive effect,[18] the most important fact is that photorefractive nonlinearity is inherently saturable. This provides a unique opportunity for use of screening solitons in experimental studies of the generic properties of solitons of saturable nonlinear media and will be exploited here.

The experimental setup used for studies of soliton collision is shown schematically in Fig. 1. An optical beam derived from an argon-ion laser ($\lambda = 514.5$ nm) was split into two beams that, after propagating the same distance, were subsequently recombined by a beam splitter and focused into 13-μm (FWHM) spots on the a face of the strontium barium niobate crystal (5-mm^3 cube). The trajectories of both beams were slightly convergent so that they would intersect inside the crystal. The exit face of the crystal could be viewed by a CCD camera and processed by a frame grabber. One mirror (M2) was mounted upon a piezoelectric transducer, allowing for variable delay (and relative phase) between the two beams when the PZT was driven by a dc field. A dc electric field, necessary for soliton formation, was applied to the crystal by two electrodes painted on its c faces. In most cases a voltage of 3.5 kV was applied to the crystal. To control the degree of saturation, the crystal was also illuminated by a broad (6-mm-wide) incoherent beam copropagating with both signal beams.

Initially each beam propagated separately in the biased crystal. We found that, indeed, solitary beams were formed. For input power of ~ 1 μW and uniform background illumination of 1–5 mW the gener-

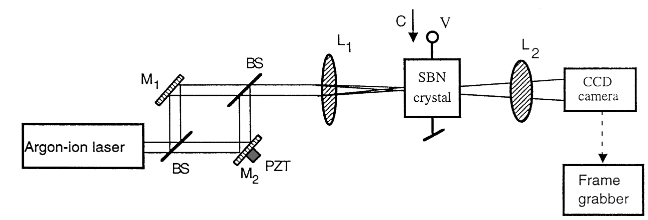

Fig. 1. Experimental setup used for collision of screening solitons in photorefractive strontium barium niobate (SBN) crystal: M_1, M_2, mirrors; BS's, beam splitters; L_1, L_2, lenses; PZT, piezoelectric transducer. V, voltage.

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ated solitons were almost circular, with a diameter of $\sim 10\ \mu m$. Soliton formation was also confirmed by side-view observation of the trajectory of the beam. These observations were limited to rather wide and high-intensity beams, as the scattering losses were very low in the crystal. The process of soliton formation was accompanied by a strong self-bending of the soliton trajectory (as large as $50\ \mu m$ over 5-mm propagation distance). This self-bending results from a nonlocal contribution to the nonlinear refractive-index change.[19–21]

In the next step we allowed both beams to intersect inside the crystal. Initially the intersection angle exceeded 1°. We found that in this case two solitary beams emerged from the collision. However, we clearly observed the energy transfer between solitons. After the collision one soliton would carry more power than the other. This effect is analogous to that found earlier in collision of solitons described by a perturbed nonlinear Schrödinger equation.[22,23] Similarly, as was shown in those studies, we could invert the direction of the energy transfer by varying the relative phase of the beams. The strong phase sensitivity of the soliton collision was particularly evident after the intersection angle was decreased below 1°. However, interaction of solitons propagating in the horizontal plane was always strongly affected by a direct two-wave-mixing process that involves phase-independent energy exchange owing to diffraction by an induced refractive-index grating. To suppress this effect, we occasionally rearranged the interaction geometry so that both incident beams would propagate in the vertical plane (perpendicular to the c axis). In this case the two-wave-mixing process was eliminated, and only pure soliton–soliton interaction remained. In Fig. 2, we demonstrate phase-induced energy exchange between solitons. The pictures show output intensity profiles of both beams. In this case both beams propagating in the vertical plane intersect at $\sim 0.6°$. The relative phase between beams is either close to 90° [Fig. 2(a)] or $-90°$ [Fig. 2(b)]. We also observed that, in accordance with theory, in-phase colliding solitons can collapse into a single beam, while out-of-phase solitons pass through each other. These properties are depicted in Fig. 3, in which we show the output intensity pattern as seen on the exit face of the crystal for solitons propagating in the horizontal plane. Clearly, when solitons are approximately in phase they merge into a single beam [Fig. 3(a)]. On the other hand, both beams emerge from the collision when they are initially out of phase [Fig. 3(b)].

It has been shown that collision of two solitons in a saturable medium can result in the birth of new solitons.[10,11] We observed this effect in our experiments. To this end we increased slightly the initial angle between both beams to ~0.8°. The angle and the relative phase between beams were chosen such that without an applied field we could clearly observe three distinctive interference fringes at the exit face of the crystal. Then, after the electric field was applied, these fringes evolved into three clearly defined optical beams, as shown in Fig. 4. Notice that the newly formed central beam does not propagate in the same plane as the two satellites. This is because of the higher rate of self-bending experienced by this beam.

The waveguide structures formed by colliding solitons could be used to redistribute and (or) control the external signal beam. We easily demonstrated this property in our experiments by blocking one of the interacting beams (after the steady-state was reached). Since the response of the photorefractive effect is slow, the already-formed refractive-index distribution decays slowly after one of the light beams is turned off. During this slow decay the remaining beam serves as an external signal. Its propagation through the soliton-induced structure results in redistribution of the beam power among all waveguide channels and was manifested (in the case depicted in Fig. 4)

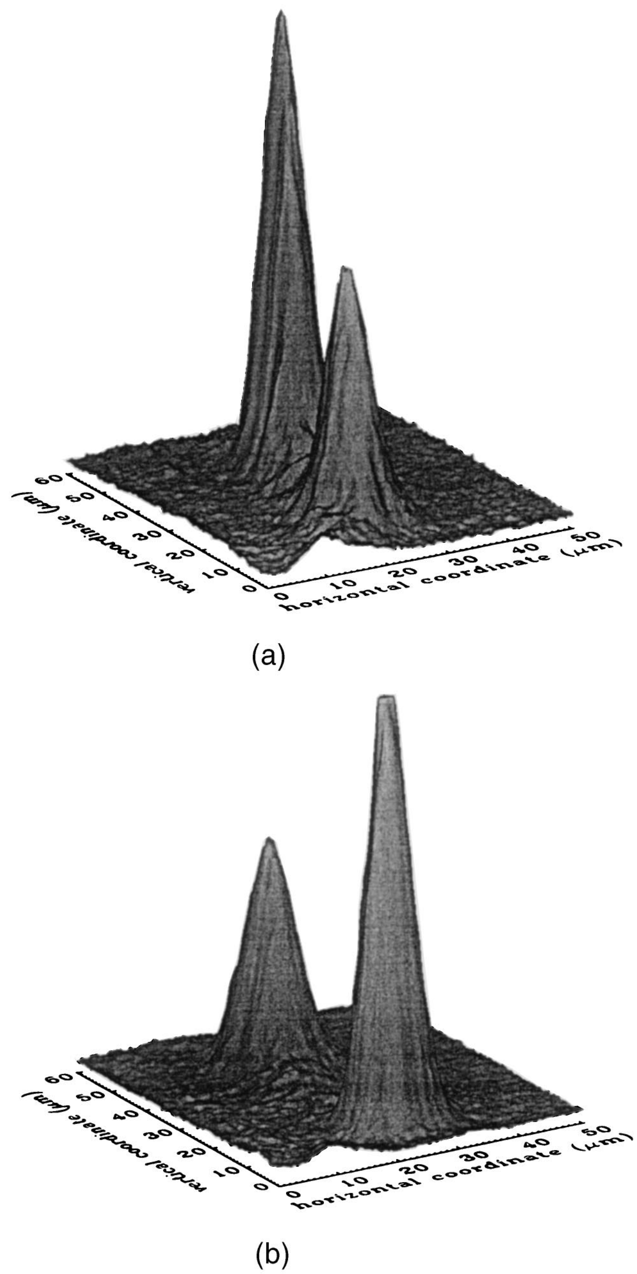

Fig. 2. Phase-dependent energy exchange between colliding solitons: (a) relative phase close to 90°, (b) relative phase close to $-90°$.

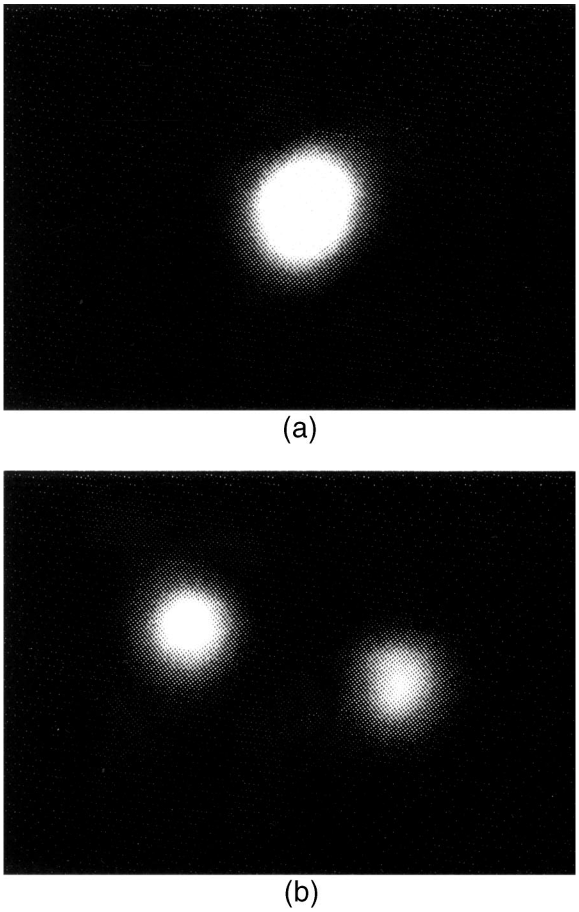

Fig. 3. Phase-dependent collision of two initially identical solitons: (a) in-phase solitons, (b) out-of-phase solitons.

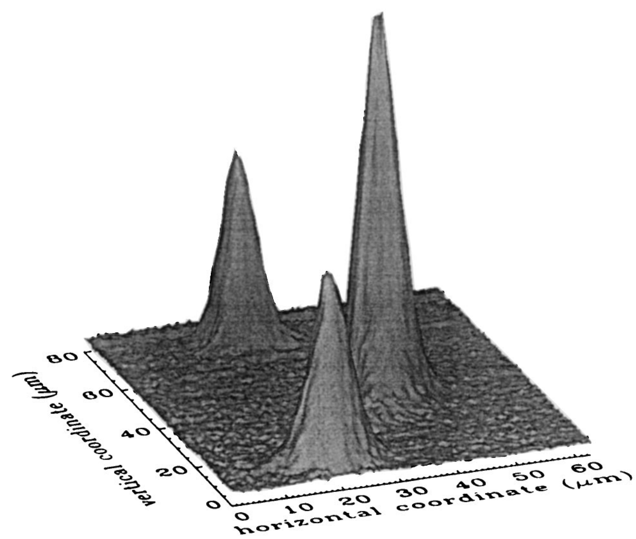

Fig. 4. Birth of a new soliton upon soliton collision (vertical geometry of interaction).

in the presence (over a short time) of three distinct bright spots corresponding to the three waveguides.

It should be noted that our experimental setup also allowed investigation of the incoherent collision. We achieved this by driving a PZT-mounted mirror with a sinusoidal signal of high frequency. The slow response of the photorefractive effect does not allow for the formation of the index grating, and the colliding solitons interact incoherently. For a sufficiently small value of the relative angle between beams (and even for diverging trajectories) we were able to observe attraction and fusion of the solitons that was similar to that reported in Ref. 12.

In summary, we have investigated collision of the screening solitons in photorefractive strontium niobate crystal. We observed the birth of solitons as well as phase-controlled soliton fusion and steering.

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