Annihilation of photorefractive solitons

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We investigate experimentally the interaction of two-dimensional solitary beams in photorefractive strontium barium niobate crystal. We show that simultaneous collision of many solitons can result in complete annihilation of some of them. This effect depends on the relative phases of the solitons and may be useful for application in the formation of multiport waveguide junctions.

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Photorefractive crystals biased with a dc electric field have been shown to support the formation and propagation of so-called screening spatial solitons. As an optical beam propagates in a photorefractive crystal the distribution of photoexcited charges induces a space-charge electric field that screens out the external dc field. The effective spatially varying electric field modulates the refractive index of the medium in such a way that the beam becomes self-trapped by a locally increased index of refraction and can propagate as a soliton.[1–6] The ease of their formation and manipulation by very low laser power (microwatts) makes screening solitons attractive subjects of study.

One of the most interesting aspects of soliton physics is soliton interaction and collision. It is well known that solitons governed by integrable models, such as one-dimensional solitons in Kerr media, behave as particlelike objects. Solitons completely preserve their identities and form during collision.[7] On the other hand, nonintegrable models such as those that describe saturable nonlinear media lead to inelastic collisions,[8–10] which was confirmed by recent experiments with atomic vapors and photorefractive crystals. In particular, soliton fusion and phase-dependent energy exchange between solitons were observed.[11–14]

We recently demonstrated experimentally that two in-phase colliding two-dimensional photorefractive screening solitons may give rise to the formation of a new soliton (soliton birth).[15] Here we demonstrate that the converse is also possible: Solitons can be annihilated by mutual interaction. Soliton annihilation was predicted theoretically some time ago[10] but to the best of our knowledge was not previously observed.

We consider here collision of three solitons, as shown schematically in Fig. 1. The experimental setup used for this interaction is shown in Fig. 2. The beam from an argon-ion laser ($\lambda = 514.5\ \mu$m) was split into three coherent extraordinary polarized beams that, after propagating the same distance, were focused to three spots (15 μm in diameter) on the entrance face of the photorefractive cerium-doped (0.002-% wt.) strontium barium niobate (SBN:60) crystal. The sample measured 10 mm × 6 mm × 5 mm ($\hat{a} \times \hat{b} \times \hat{c}$), where the longest dimension corresponds to the propagation direction. The crystal was biased with a high-voltage (3-kV) dc field applied along its polar ($\hat{c}$) axis. A supplementary wide beam that was incoherent with the three signals provided uniform background illumination of the crystal. We aligned the relative positions and angles of incidence of all three beams in such a way that they would intersect approximately in the common region of the crystal. We ensured that all beams were propagating in a plane perpendicular to the $\hat{c}$ axis of the crystal to avoid any two-wave-mixing process that might originate from index gratings formed by the intersecting beams.

Photorefractive nonlinearity is of a saturable character. Thus the parameters of screening solitons are determined by the degree of saturation, which is given by the ratio of the soliton peak intensity to the intensity of the background irradiation. In all our experiments the power of each beam did not exceed a few microwatts. In particular, the central beam (C) was usually the strongest one (1.7 μW), and the side beams (A) and (B) were approximately four times weaker. The power of the background beam was always set to 5 mW, which gives a degree of saturation of ~2 for the strongest beam. We checked that with these parameters all beams would always form slightly elliptically shaped solitons (≈10 μm wide) when they were propagating individually in the crystal.

Soliton collisions in saturable nonlinear media depend critically on the relative phase of the solitons. Here we chose it in such way that beams A and B were

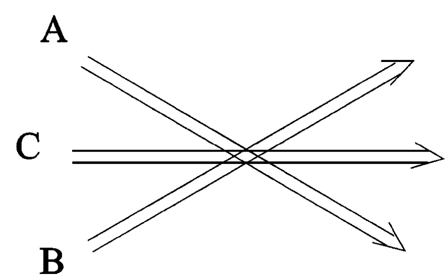

Fig. 1. Schematic of the three-soliton interaction.

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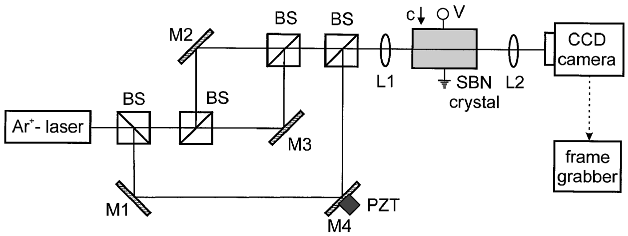

Fig. 2. Experimental setup: BS's, beam splitters; M1–M4, mirrors; L1, L2, lenses; PZT, piezoelectric transducer; V, voltage.

always in phase, which was easily verified by observation of their direct collision. For an intersection angle less than 1°, A and B collided without appreciable energy exchange. The phase of beam C (relative to the phase of A and B) measured at the output face of the crystal was used as a control parameter. It was adjusted by a piezoelectric transducer-mounted mirror. The most interesting results of the three-soliton collision are presented in Fig. 3, which shows the light intensity of the outgoing beams after interaction, as seen on the exit face of the crystal. In the example depicted in Fig. 3(a) the relative phase among A, B, and C is close to $\pi/2$. The very bright spot corresponds to the central soliton (C), and the two faint spots correspond to the side beams (A and B). Careful examination of this figure reveals that the power of the central beam increases at the expense of A and B, which still propagate as very well-defined solitary beams, although they are weaker. The situation changes dramatically when the relative phase of beam C is adjusted to $-\pi/2$ [Fig. 3(b)]. Clearly the central beam is now virtually gone after interaction, and two new, strong symmetrically located solitons appear. Note that the relative locations of these new beams differ from those in Fig. 3(a). In fact it appears that soliton C was just split into two separate beams by a simultaneous hit of A and B.

The underlying process responsible for annihilation of the central beam is the ability of colliding solitons to exchange energy.[8–10] For fixed relative velocities (or rather, intersection angle) the rate of energy transfer depends on the relative phase of the solitons. We demonstrated previously that by varying this phase one can also control the direction of the energy exchange.[15] In the first instance shown in Fig. 3(a) the relative phase of the beams is chosen such that if soliton C collided separately with A or B it would be always amplified. Therefore, when the three propagate simultaneously, both A and B supply energy to C. When we change the phase of beam C to $-\pi/2$ [Fig. 3(b)] we achieve exactly the opposite case. This time the power flows outward to the side beams. As a consequence, solitons A and B are amplified at the expense of C, which results in effective annihilation of C. This effect strongly depends on the accuracy of alignment of all beams and the proper choice of the relative phases. For instance, Fig. 4 illustrates a different situation in which all the beams are of approximately the same power and annihilation of beam C is incomplete. Although most of the power of beam C was transferred to side solitons A and B, some remains are still visible in the center of Fig. 4. However, it no longer forms a soliton but propagates as a broad radiation field instead. Note also that the position of the side beams is basically the same as in Fig. 3(a). This result, together with those shown in Fig. 3(b), indicates that full annihilation of the central soliton involves not only its gradual energy drainage by both satellites but also formation of completely new solitons in the area of the collision.

As propagating solitons create their own waveguides, soliton collision results in formation of waveguide structures such as X and Y junctions, which may be useful for all-optical circuitry.[16,17] Consequently,

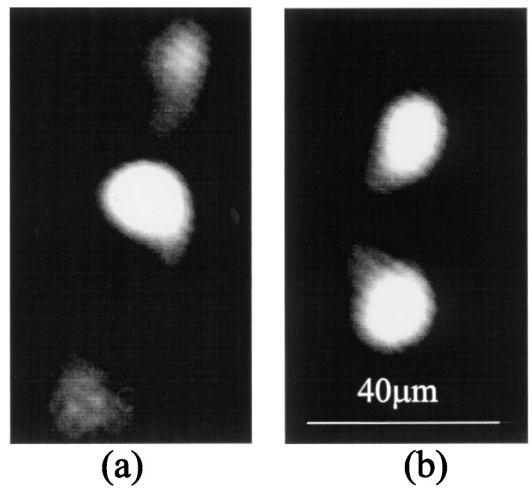

Fig. 3. Light-intensity distribution of interacting beams on the exit face of the crystal; $P_A = P_B = 0.4\ \mu W$, $P_C = 1.7\ \mu W$. (a) Relative phase between A and C $\approx \pi/2$, (b) relative phase between A and C $\approx -\pi/2$.

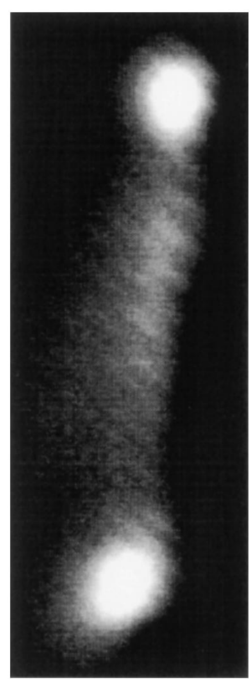

Fig. 4. Another example of three-soliton collision: incomplete annihilation. In this case $P_A = P_B = 2.4\ \mu W$, $P_C = 2.7\ \mu W$; the relative phase between C and A again is $\approx -\pi/2$.

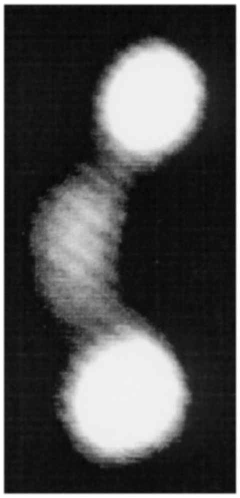

Fig. 5. Light-intensity pattern on the exit face of the crystal that corresponds to the waveguide structure formed by colliding solitons. This picture was taken a moment after both side beams were blocked.

annihilation (or splitting) of the central soliton gives rise to a 3×2 waveguide junction. Since the response time of our photorefractive crystal is relatively slow we can actually observe the operation of the soliton-formed waveguide structure by blocking some of the interacting beams. Then the remaining beam serves as a signal whose power is split among the still-existing waveguides. In Fig. 5 we show the output light-intensity distribution experienced by the central beam right after both side beams were blocked. One can clearly see two strong spots that correspond to two waveguides. A weak centrally located spot indicates formation of the soliton by the central beam as it erases the existing waveguide structure.

In conclusion, we have investigated multiple soliton interaction in photorefractive crystal. We showed that by proper choice of relative phase, solitons can be annihilated on collision. This effect is initiated by phase-dependent energy transfer among solitons.

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