# Primarily isotropic nature of photorefractive screening solitons and the interactions between them

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We present experimental evidence demonstrating that the photorefractive-index change responsible for the formation of photorefractive spatial screening solitons and coherent collisions between them is primarily isotropic in nature, even though the photorefractive medium is inherently anisotropic. 

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Optical spatial solitons[1] are created when a self-induced index change exactly compensates for the natural diffraction of the optical beam. In this sense the beam induces its own waveguide and offers the potential to guide, steer, and switch another optical beam. These ideas are particularly apparent in the case of collisions between photorefractive solitons. Although there have been several types of photorefractive soliton[2–10] reported, our study is focused on the isotropic nature of screening photorefractive solitons and the interactions between them.[5–16]

Intuitively, one can view the formation of bright screening photorefractive solitons by picturing a focused laser beam passing through an electrically biased photorefractive crystal. The beam excites charge carriers from dopant with energy levels deep in the forbidden energy gap, thereby increasing the conductivity (decreasing the resistivity) in the illuminated region. Therefore the applied voltage creates an electric field primarily in the dark high-resistance regions, whereas the electric field in the bright region is considerably lower. Since the index change created by the electro-optic effect is proportional to the electric field, the index is lowered (for an appropriate choice of direction of the applied field with respect to the principal crystalline axes) primarily in the dark region, and a graded-index profile is created that mimics the laser intensity distribution. This index profile leads to trapping of the beam and to the formation of an individual screening spatial photorefractive soliton.[5–7]

Observed photorefractive screening solitons have been so robust that they have presented a playing field on which to investigate soliton collisions.[11–16] For example, if the colliding solitons are coherent, the two beams interfere in the crystal as they propagate. When the relative phase between the two beams is zero and the collision angle is small, the interference produces a pattern that is predominantly one bright fringe that develops into a single soliton and two solitons that can fuse into one.[16] On the other hand, when the relative phase between the two beams is $\pi$ the interference is predominantly two bright fringes centered about a dark fringe. The two bright fringes then develop into repelling solitons.[16]

Photorefractive screening solitons[5–7] that have one transverse dimension are characterized by an existence curve that relates the soliton width $\Delta\xi = \Delta x k n_b{}^2 (r_{\text{eff}} V/l)^{1/2}$, where $\Delta x$ is the actual soliton intensity FWHM, $k = 2\pi/\lambda$, $r_{\text{eff}}$ is the effective electro-optic coefficient, and $V$ is the voltage applied across the crystal of width $l$, to $U_0{}^2 = I_0(I_b + I_d)$, the ratio between the incident soliton peak intensity $I_0$ and the sum of the background intensity $I_b$ and the effective dark intensity $I_d$. Solitons exist only for parameters that follow the existence curve, and large deviations (>10%) cannot support a soliton, as shown experimentally in many papers (see, e.g., Refs. 10, 12, and 16).

Although one-dimensional (1-D) screening solitons are well understood theoretically, little has been noted about the nature of the self-induced index change for a single 2-D soliton or for a collision between two 2-D solitons. An analytic theoretical analysis exists only for the 1-D case, whereas the theory for 2-D screening solitons relies mostly on numerics.[17] For example, despite the large amount of direct experimental evidence demonstrating the existence of circular screening solitons,[9,11,13,15] all numerical attempts have either failed completely to yield a soliton or have found an approximately nonevolving beam of an elliptical shape. Intuitively, the circular symmetry is broken by the boundary conditions as the voltage is applied between two planar electrodes. Furthermore, the electro-optic effect is fundamentally anisotropic. In fact, it is rather surprising that many photorefractive crystals can support circular solitons. Given the lack of a full 2-D theory and the inherent anisotropic nature of the photorefractive nonlinearity, the interaction behavior between 2-D screening solitons is not so intuitive as in the 1-D case. In this Letter we present experimental evidence demonstrating that the photorefractive-index change responsible for the formation of individual photorefractive screening solitons and the behavior

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of coherent collisions between them is predominantly isotropic.

In our experiments a beam from a single-mode 514.5-nm argon-ion laser was divided into two extraordinary polarized beams that were separately focused onto a strontium barium niobate (SBN) crystal of dimensions 0.5 cm × 0.5 cm × 0.6 cm, with $n_b = 2.35$ and $r_{\text{eff}} = r_{33} = 194$ pm/V. Both beams had identical intensities, which were varied from 4 to 24 W/cm$^2$, while the background intensity was held at 1 W/cm$^2$. We used a lens to image the exit face of the crystal onto a CCD camera. A dc voltage of 2.5 kV was applied to the crystal in the $c$-axis direction, and we used a glass slide in one of the two beams to control the relative phase between them by rotating the slide (changing the optical path). To control the nonlinearity, a background beam (ordinary polarization) that was incoherent with the two soliton beams illuminated the entire crystal and copropagated with the two beams.[9]

As shown in Fig. 1, the input beam has a circular cross section, and it retains its circular shape after evolving into a spatial soliton, to better than 10%, as limited by the CCD resolution. A circular beam of diameter 11 $\mu$m FWHM at the input face of a SBN:60 crystal (Figs. 1a and 1g), which diffracts to a circular beam of ~50 $\mu$m (Figs. 1b and 1h) at the exit face, self-traps (on application of the voltage) to form a circular 11-$\mu$m soliton (Figs. 1c and 1i). The circular cross section observed at the output face is a strong indication that the photoinduced waveguide is symmetrical about the propagation axis.

In this Letter we study collision of solitons with trajectories that always lie in a single plane, thus avoiding the additional potential complication of full 3-D spiraling collisions.[13] In all cases the solitons were launched with initially parallel trajectories. Two collision configurations are studied, one with the beams colliding in the horizontal ($a-c$) plane and the other with the beams colliding in the vertical ($a-b$) plane. In all cases the initial (input) separation between the beams was 18 $\mu$m. The results of a collision between two such solitons with zero input relative phase are shown in Figs. 1d and 1e (horizontal pair) and Figs. 1j and 1k (vertical pair). The same external field was applied along the $c$ direction in both cases. Independently of whether the collision was in the horizontal or the vertical plane, the two incident solitons fused into a single circularly symmetric soliton of the same 11-$\mu$m diameter. In addition, in the case of a 180° phase difference between the two solitons, the repulsive force between the beams was also the same, again independently of whether the collision was in the horizontal (Fig. 1f) or the vertical (Fig. 1l) plane. This conclusion is strengthened by Fig. 2, which shows a plot of the change in the scaled separation (actual separation divided by the 11-$\mu$m beam diameter $\Delta x$) between the two solitons at the output face as a function of the scaled initial separation for collisions in both the horizontal and the vertical planes. The data demonstrate that, independently of whether the collision is in the horizontal or the vertical plane, no significant difference is observed in either the attractive or the repulsive force between the solitons. Intermediate cases of a relative phase of 0° to 180° give results (not shown here) similar to those reported in Ref. 16.

More evidence for the symmetrical nature of the interaction of the photorefractive screening solitons is apparent from the soliton existence curve. Since a full theory for 2-D screening solitons does not exist, we must rely on an experimental existence curve. The experimental single 2-D soliton existence curve is shown in Fig. 3. The solid curve is merely a guide to the eye. In all our experiments (as well as in many other experimental papers, e.g., Refs. 9–12), we found that a photorefractive 2-D soliton forms only when the initial parameters for $\Delta\xi$ and $U_0$ are chosen to lie on this experimental curve. When two such beams are launched together in the horizontal plane with 0° relative input phase, they fuse and form a single 2-D soliton with parameters that follow the same 2-D existence curve (filled squares). That is, two solitons launched

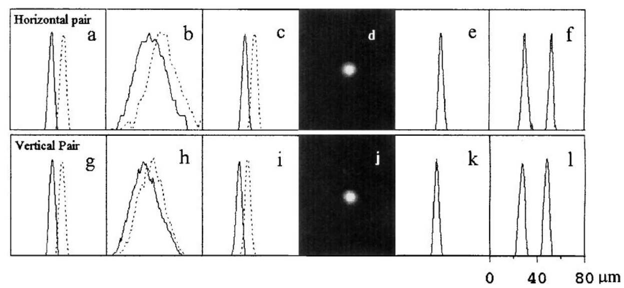


Fig. 1. a, g, Individual 11-$\mu$m-diameter input beam profiles. b, h, Individual 50-$\mu$m-wide diffracted output beam profiles in the horizontal or the vertical plane. c, i, Separately launched 11-$\mu$m-wide soliton profiles at the exit face in the horizontal or the vertical plane. d and e, j and k, 11-$\mu$m-wide single output beam and profile resulting from the collision between the beams colliding in the d, e, horizontal or the j, k, vertical plane when the phase between them is 0°. f, l, The two 11-$\mu$m beams after collision in the horizontal or the vertical plane when the phase between them is 180°. The soliton/background intensity ratio is 10 in all cases.

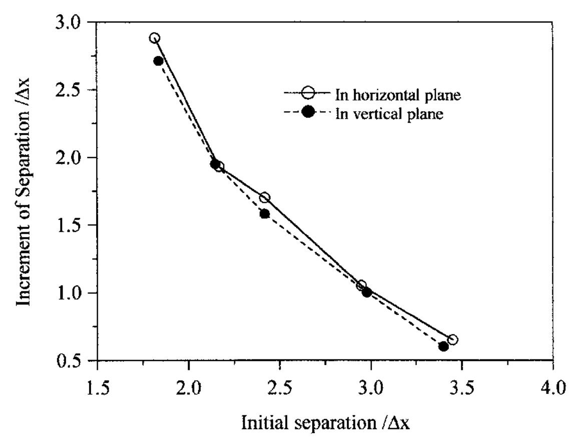


Fig. 2. Increment in the scaled separation (actual separation divided by the 11-$\mu$m beam diameter, $\Delta x$) that is due to repulsion between the two solitons measured at the exit face of the crystal as a function of the scaled initial separation at the entrance face. The collision is observed to be identical in the vertical and the horizontal planes.

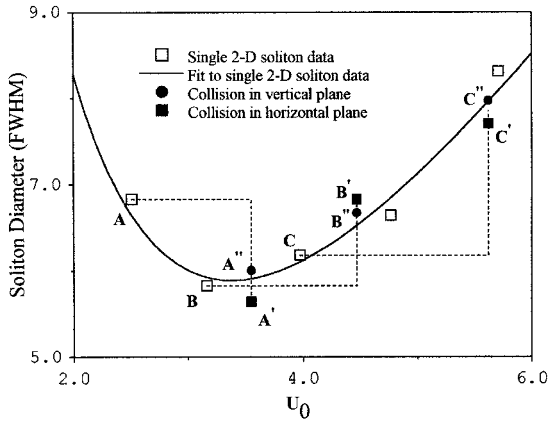


Fig. 3. Soliton existence curve. When the individual solitons are simultaneously launched and collide, they produce single 2-D solitons with parameters at another location on the existence curve.

in the horizontal plane with parameters that correspond to point A on the experimental existence curve fuse to form one soliton with parameters that correspond to A′ on the existence curve. Similar results are found for two solitons with parameters that correspond to points B fusing to B′ and C fusing to C′. For all three points the fused diameter is larger than the incident beam diameters. (One can avoid this difference if desired by choosing A and A′ to lie symmetrically on both sides of the minimum in the existence curve, as in Ref. 16). Importantly, when these in-phase beams are launched together in the vertical plane, they fuse and form a single 2-D soliton (filled circles), which has, to within a few percent, parameters identical to those of the horizontal fusion experiment. That is, two solitons launched in the vertical plane with parameters that correspond to point A fuse to form one soliton with parameters that correspond to those of A″. Similar results are found for two solitons with parameters that correspond to points B fusing to B″ and C fusing to C″. That this is so means that the result of the in-phase collision not only can be predicted by the single 2-D experimental existence curve[16] but also, under identical conditions, is independent of whether the collision occurs in the horizontal or the vertical plane.

To summarize, as shown in Figs. 1 and 2, 2-D photorefractive screening solitons colliding with trajectories lying in the $a-c$ plane exhibit fusion (when their relative phase is zero) and repulsion (relative phase of $\pi$) that are identical to those of solitons with trajectories lying in the $a-a$ plane. Furthermore, this predominantly isotropic interaction occurs at all intensity ratios that are accessible by any of the soliton existence curves. As shown in Fig. 3, in-phase circular solitons collide and fuse to form a new circular soliton that obeys the same existence curve, independently of whether the solitons are launched in the horizontal or the vertical plane.

*Note added in proof:* In some specific cases the interaction between two 2-D screening solitons exhibits some anisotropic features. One such case occurs during an incoherent collision between two 2-D screening solitons at a close proximity, at a shallow collision angle, and when the plane formed by the collision trajectories is normal to the $c$ axis (direction of applied field). It is rather easy to avoid the anisotropy. In fact, one needs to work very hard and be precise to be able to observe it, as was done for Ref. 18. In spite of this small anisotropy, the interaction between two 2-D screening solitons is predominantly isotropic.

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