Incoherent collisions between one-dimensional steady-state photorefractive screening solitons

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We report the observation of collisions between mutually incoherent, one-dimensional, bright, steady-state photorefractive screening solitons. Using the theory of planar dielectric waveguides together with the theory of photorefractive screening solitons, we explain how the collisions depend on the peak intensity of the solitons and the externally applied biased field. Finally, we compare the experimental results with direct numerical simulations. *© 1996 American Institute of Physics.* [S0003-6951(96)05053-X]

Photorefractive spatial solitons[1] have been attracting considerable interest recently because they can exist at low power levels (μW) and can self-trap in both transverse dimensions.[2–4] In addition, photorefractive solitons induce waveguides that can guide other, more intense, beams at less photosensitive wavelengths.[5] At present, three types of photorefractive solitons have been demonstrated: quasisteady-state,[2] photovoltaic,[3] and screening solitons.[4–6] All of these solitons form when diffraction is exactly compensated by photorefractive self-focusing effects.

One-dimensional (1D) bright screening solitons[7,8] occur when an externally applied electric field is partially screened in regions of higher conductivity driven by carriers photoexcited by the soliton beam. A refractive index change $\Delta n(x)$ is generated (via Pockels' effect) by the electric space charge field E_{sc}, with $\Delta n(x) \propto |E_{\mathrm{sc}}| \propto (I(x)+I_b+I_d)^{-1}$, where $I(x)$ is the soliton intensity profile, x is the transverse coordinate, I_b the background illumination, and I_d the dark irradiance. At a position x where $I(x)=I_b+I_d$, E_{sc} and $\Delta n(x)$ attain one half of their maximum values. The distance between two such points on each side of the soliton profile is d, which is the full width at half-maximum (FWHM) of the soliton-induced waveguide [Fig. 1(a)]. Thus, the higher the intensity ratio, the more a soliton-induced waveguide approaches a step–index structure. Photorefractive screening solitons are characterized by an existence curve[7,8] that relates the soliton width $\Delta\xi$ to $u_0^2=I(0)/(I_b+I_d)$, the so-called intensity ratio. Here, $\Delta\xi=\Delta x k n_b^2\sqrt{r_{\mathrm{eff}}V/l}$ is a dimensionless soliton FWHM and reaches a minimum roughly at intensity ratio 3. Δx is the actual soliton FWHM, k the wave number in vacuum, n_b the refractive index, r_{eff} the effective electro-optic coefficient, and V the voltage applied across the crystal of width l. For intensity ratio >3, one has to increase V to keep Δx constant with increasing intensity ratio.[4,7,8] This increases the maximum change to the refractive index, making the soliton-induced waveguide both wider and deeper [Fig. 1(b)] with increasing intensity ratios (for ratios above 3). This, in turn, implies that the induced waveguide has a larger critical angle and starts to guide higher order modes.[9] A similar behavior was predicted for solitons in general saturable nonlinear media.[10]

Collisions between spatial solitons can be conceptually viewed in terms of waveguide theory.[11] Each soliton induces its own waveguide and collisions of solitons can be described as ''coupling'' among waveguides subject to their guiding properties, e.g., the number of their guided modes and their critical angle for guidance. For photorefractive solitons, an additional interaction between two colliding solitons can occur via a photorefractive two-wave mixing process. In order to reduce the complexity, we use two mutually incoherent soliton beams and observe their collisions at the absence of two-wave mixing coupling, leaving coherent collisions for a future study. In our experiments, the relative phase between the beams varies much faster than the response time of the photorefractive medium (dielectric relaxation time), and thus, the collision is totally unaffected by it.

In a previous study,[12] we have reported experimental results on incoherent collisions of 2D photorefractive solitons. However, since theory of photorefractive solitons thus far exists only for 1D solitons,[7,8] we could not make any quantitative comparisons between theory and experiments. In this letter, we report observations of incoherent collisions between one-dimensional bright photorefractive screening solitons and compare them to simulations using the previously developed 1D theory of screening solitons.[7,8]

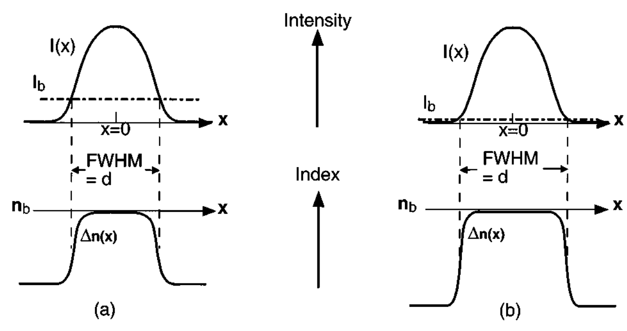

FIG. 1. Illustration of the refractive-index profiles of the waveguide induced by photorefractive solitons of intensity ratio 4 (a) and 20 (b).

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An intuitive way to understand incoherent collisions of solitons is by comparing the collision angle to the guiding angle of the soliton-induced waveguide. When the collision angle is shallower than the guiding angle, the waveguides become coupled and energy is transferred from one waveguide to the other. On the other hand, when the collision angle is larger, energy transfer does not occur since the beam emerging from one waveguide cannot excite guided modes in the other. In particular, the intensity ratio plays an important role for the screening soliton since the guiding angle and the number of guided modes are fully controlled by it.[9] At higher intensity ratios, the soliton-induced waveguide is multimode. As a result, the energy transferred during collision can excite higher-order guided modes. Furthermore, energy can be transferred from the fundamental mode (soliton) in each waveguide into higher guided modes within the same waveguide. Since the soliton is the fundamental guided mode of the soliton-induced waveguide, the additional energy in higher-order modes can change the intensity distribution and, thus, cause the beam to deviate from the perfect soliton profiles.[9]

The experimental setup is similar to that of Ref. 12 except that the two soliton beams, labeled A and B, are now 1D and launched using cylindrical lenses from an argon–ion laser with wavelength $\lambda = 488$ nm. Beam A is launched along the crystalline a axis and beam B is tilted by a small angle ($<1°$) towards the c axis (angles are measured inside the crystal). The beams at the input face are at their minimum waist, 9 ± 1 μm FWHM wide, and nearly uniform (2 mm long) in the other transverse dimension. The photorefractive crystal is a 5 mm long bulk strontium barium niobate (SBN:60) with $r_{\text{eff}} = 280$ pm/V and $n_b = 2.35$. The two 1D beams pass through each other and their positions exchange. An ordinarily polarized beam uniformly illuminates the entire crystal to establish the background illumination I_b.

We generate solitons A and B with intensity ratio 3.6 by applying external voltage $V = 840$ V across the electrodes separated by $l = 4.5$ mm and adjust the collision angle to 0.98°. Beam profiles and photographs of A and B at the input face of the crystal are shown in Fig. 2(a). At zero voltage, both A and B naturally diffract as shown in Fig. 2(b) taken at the exit face of the crystal. We first launch solitons A and B separately. Since most of the voltage drops in the region outside the solitons and since the width of each soliton is much smaller than l, we can generate solitons A and B simultaneously using the same voltage as for a single soliton (of the same width as A and B). Then, we observe the collision. We then compare the output profiles of soliton A and B [Fig. 2(c)] where each soliton is launched separately to the output profiles of A and B when collision occurs [A and B are launched simultaneously, Fig. 2(d)]. In this case, we find that both solitons are almost unaffected by the soliton collision. The FWHM of each of the soliton-induced waveguides, d, is 12 μm, which is the distance measured between the two points where $I(x) = I_b$ ($I_d \ll I_b$). With applied voltage of 840 V, we estimate the ''depth'' of the soliton-induced waveguide to be $\Delta n = [3.6/(3.6+1)] \times \frac{1}{2} r_{\text{eff}} n_b^3 V/l = 2.6 \times 10^{-4}$ (a rather rough estimate, which is accurate for $u_0^2 \gg 1$) and the corresponding (complementary) critical angle[13] as $\theta_c = \cos^{-1}[(n_b - \Delta n)/n_b] = 0.85°$. Using the theory of planar step–index dielectric waveguides,[13] we find that the soliton-induced waveguide contains at most two modes since $\sin\theta_c/[\lambda/(2d\,n_b)] = 1.7$. However, this result was obtained using a step–index waveguide to approximate the soliton-induced graded-index waveguide, which is not very accurate at this intensity ratio. A numerical analysis reveals that the second mode is very close to cutoff. We, therefore, conclude that, in this case, no energy can be transferred to higher guided modes and, thus, the soliton profiles remain unaffected after the collision. Top-view photographs of the soliton collision and the diffracting beams (at $V = 0$) are shown in Fig. 3(a) and (b). We note that, in practice, the collision angle is somewhat larger than the initial angle, because the solitons attract each other. Thus, the waveguide view on soliton collision can provide intuitive but not accurate information.

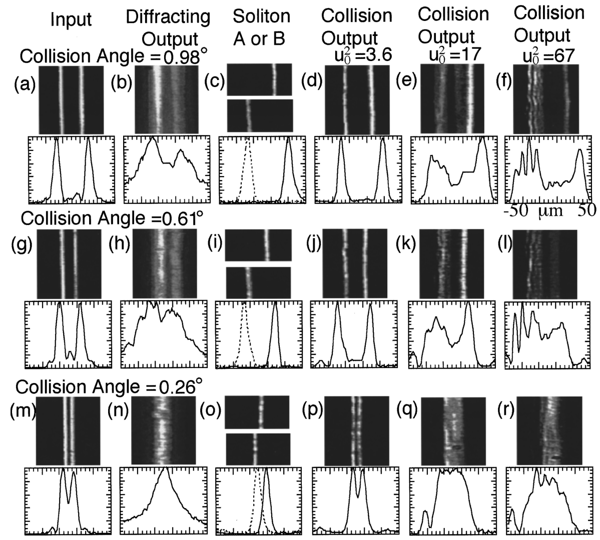

FIG. 2. Photographs and beam profiles at the input and exit faces of the crystal under different intensity ratios and collision angles. The scale of the photograph and the beam profiles are slightly different. The input beams in (a), (g), and (m) are initially separated by 37, 24, and 13 μm, respectively.

We then increase the intensity ratio to 17, adjust the voltage accordingly[14] to 1030 V and repeat the collision experiment. Under these parameters we get $\Delta n = 4.2 \times 10^{-4}$, $\sin\theta_c = 0.019$ and measure $d \approx 20$ μm. The soliton-induced waveguide is now certainly multimode since $\sin\theta_c$ is four times larger than $\lambda/(2d\,n_b) = 0.005$. In the experiment, we observe that some energy is transferred from the fundamental mode (soliton) to higher guided modes and this degrades both soliton profiles, as shown in Fig. 2(e). Then, we increase the intensity ratio to 67 and adjust the voltage to 1700 V, accordingly. At this intesnity ratio some fine structure is superimposed on the beam [Fig. 2(f)], which can indicate that energy is indeed transferred to higher-order

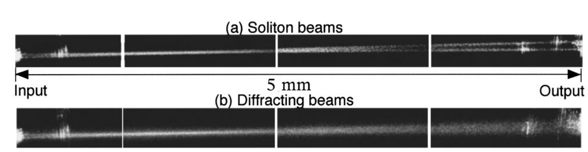

FIG. 3. Top-view photographs of (a) the colliding solitons and (b) the naturally diffracting beams.

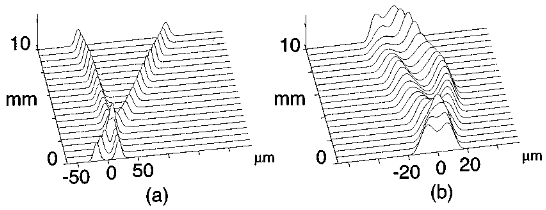

FIG. 4. Simulation results of soliton collision for 10 mm of propagation. (a) Collision angle 0.98° with intensity ratio 3.6. (b) Collision angle 0.26° with intensity ratio 67.

modes. We repeat the experiment for a smaller collision angle 0.61° and get similar results [Figs. 2(g)–2(l)]. We further decrease the collision angle to 0.26° [Figs. 2(m)–2(r)]. With intesnity ratio 3.6, solitons A and B pass through each other without any interaction. However, when we increase the intensity ratio to 17 and adjust the voltage to 1030 V, the beams tend to merge into a single beam[12] [Fig. 2(q)] since the guiding angle of the fundamental mode is now much larger than the collision angle. As a result, most of the energy of each beam is coupled into the other (multimode) waveguide.

Finally, we compare the experimental results with direct numerical simulations. The two evolution equations for solitons A and B are those of Ref. 15 with the exception that now one beam is tilted by the collision angle.[16] We also include first-order diffusion effects $[\propto(\nabla I/I+I_b+I_d)]$ in our computations, which lead to beam self-deflection and asymmetric power exchange interactions. The simulation parameters are close to those of the experiment. However, as we know from previous experimental work,[14] the soliton existence curve was found to be offset to values of $\Delta\xi$ that are somewhat higher than those predicted by the theory. This offset arises primarily because some of the background illumination is guided by the soliton (since $r_{13}\neq 0$), whereas the theory assumes uniform I_b. Thus, we use 11 μm wide solitons in the simulations instead of 9 μm in the experiments and a lower voltage (in accordance with the soliton existence curve). Figure 4 shows the simulation results for different collision angles and intensity ratios. As in the experiment, at an intensity ratio of 3.6, Fig. 4(a) shows that at 0.98° the two soliton beams are not affected by the collision, because at this intensity ratio the soliton-induced waveguide is (or close to) single mode. At intesnity ratio 67 and collision angle 0.26° the simulation shows considerable coupling between solitons [Fig. 4(b)]. At this intensity ratio and a larger collision angle (0.98°), a third peak appears between beams A and B, which resembles the experimental results (not shown here). However, for these values we do not observe in the simulation fine structure superimposed on the beams as we find in the experiment. We attribute this discrepancy to partial guidance of the background beam in the soliton-induced waveguide,[14] which depletes the background illumination around the solitons and introduces a fine structure between and around them.

In conclusion, we have made an observation and a direct comparison between theory and experiments of incoherent collisions of one-dimensional bright photorefractive screening solitons.

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