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Interaction of spatial photorefractive solitons in a planar waveguide

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Abstract. We report the observation of collisions between one-dimensional bright photorefractive screening solitons in a planar strontium–barium niobate waveguide. Depending on the intersection angle of the two solitons and their relative phase, we observe soliton fusion, repelling, energy exchange, and the creation of a third soliton upon interaction.

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In the past few years photorefractive spatial solitons have attracted considerable interest because of their formation at very low power levels in the range of microwatts [1–6]. These solitons are formed when the linear spatial dispersion is compensated exactly by a nonlinear photorefractive self-focusing mechanism. Up to now three different types of photorefractive solitons have been proposed and experimentally demonstrated, namely the photovoltaic soliton [4], the quasi steady-state soliton [1, 2], and the steady-state or screening soliton [5–8].

Among the most interesting properties of optical solitons is the nonlinear interaction that takes place when two solitons intersect or propagate close enough to each other within the nonlinear material. In Kerr media it is well known [9] that solitons in most respects behave as particle-like objects, leading to elastic collisions and a preservation of the solitons' identities. However, solitons in photorefractive crystals behave completely differently because of the saturable nonlinearity [10] that is responsible for the self-focusing effect. Here the collision has an inelastic character, where the outcome of the collision depends critically on both the phase relation and the intersecting angle of the interacting solitons.

Phase-dependent interacting forces between two coherent (1+1)-dimensional screening solitons have been observed in bulk bismuth titanate (BTO) [11] and strontium–barium niobate (SBN) crystals [12] leading to attraction or repulsion of the parallel propagating beams as well as to energy exchange between them. For the (2+1)-dimensional case, proper choice of relative phase and intersecting angle has resulted in a fusion of two solitons and the generation of a third beam upon interaction [13]. Very recently, the annihilation of solitons as a result of the interaction of three spatial solitons in a SBN sample has been demonstrated [14].

In a recent publication [15] we have demonstrated the formation of photorefractive spatial solitons in a planar SBN waveguide. In such a geometry (1+1)-dimensional solitons are formed in a true (1+1)-dimensional medium, thus getting rid of the transverse instability that is inherent to soliton formation in bulk crystals [16, 17]. In this paper we investigate collisions between two photorefractive solitons in a planar waveguide. The nonlinear interaction can lead to fusion, repelling, energy exchange, or the creation of a third soliton. These properties are of considerable interest for the development of soliton-based nonlinear couplers, reconfigurable interconnections, or optically modifiable waveguide junctions.

1 Experimental methods

In our experiments we used a congruently melting SBN crystal with a concentration of 0.1-wt. % CeO_2 in the melt. The dimensions of the x-cut sample were $2.0 \times 6.0 \times 3.3$ mm, with the 3.3-mm edges along the c axis (z direction) of the crystal. On both faces normal to the c axis electrodes were prepared with silver paste. The propagation length along the y axis was $l = 6.0$ mm. Waveguide formation in SBN by He^+ implantation is described in [18, 19]. The fabricated waveguide has a thickness of about $d = 4.5\,\mu$m and a damping coefficient of $\alpha = 0.17\,\mathrm{mm}^{-1}$ for extraordinarily polarized light and a wavelength of $\lambda = 632.8$ nm.

The experimental setup is shown in Fig. 1. The light of a red helium-neon laser is split into two beams with the help of a Michelson interferometer. The relative phase of these beams can be varied continuously by a piezo-mounted mirror (PZM) in the setup, and a small angle (not shown in the figure) between the two beams can be adjusted by slightly tilting mirrors M1 and PZM. The two beams that are extraordinarily polarized are coupled into the waveguide by a 20× microscope lens (NA = 0.4). Two cylindrical lenses in front

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Dedicated to Prof. Dr. E. Krätzig on the occasion of his 60th birthday

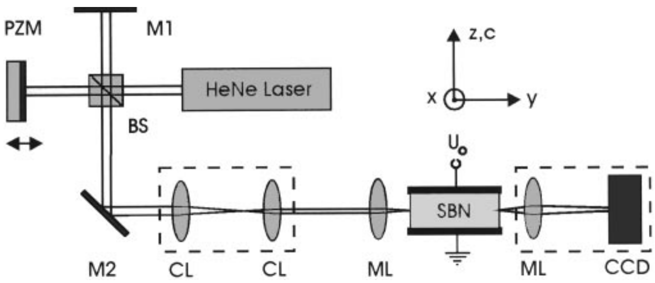

Fig. 1. Scheme of the experimental setup for the observation of spatial soliton interaction in the planar waveguide. M1, M2, mirrors; BS, beam splitter; PZM, piezo-mounted mirror; CLs, cylindrical lenses; MLs, microscope lenses; U_0, externally applied high voltage; SBN, SBN waveguide; CCD, CCD camera

of the incoupling lens are used to adjust the eliptical beam profile at the input face of the sample to be about $5 \times 10\,\mu\text{m}^2$ (FWHM values) in the x and z direction, respectively. The intensity distribution at the exit face of the sample is imaged by a 25× microscope lens on a calibrated CCD camera. Uniform background illumination of the waveguide is realized by a second (incoherent) helium-neon laser that illuminates the sample homogeneously from the top with ordinarily polarized light.

In all experiments the changes in the relative phase Φ of the two beams that are generated by a saw-tooth voltage on the piezo-mounted mirror are slow compared to the buildup time for the formation of the photorefractive solitons. The background intensity is $I_\text{d} \approx 10\,\text{mW/cm}^2$. In the following the input powers of the two beams are kept almost constant at $P_\text{in} = 3\,\mu\text{W}$. The applied electrical voltage is $U_0 = 2.6\,\text{kV}$, resulting in an external electric field $E_0 = 7.9\,\text{kV/cm}$. When the solitons are formed, we find an averaged width (FWHM) of the spatial solitons of about $w = 8\,\mu\text{m}$. Using these data we can estimate the ratio r of soliton intensity I and background intensity I_d to be $r \approx P_\text{in} \exp(-\alpha l/2)/(I_\text{d} w d) = 50$. If we we take into account the dark conductivity of the waveguiding layer (roughly estimated this value is about $10^{-8}\,\text{A/(Vm)}$) the ratio r may be somewhat lower. However, in our SBN waveguides photoconductivity σ_ph depends only sublinearly on intensity I, $\sigma_\text{ph} \propto I^x$, with an exponent $x = 0.49$ for $\lambda = 632.8\,\text{nm}$. Thus the ratio $\tilde{r}$ of photoconductivity generated by the soliton and that generated by the background illumination is reduced to $\tilde{r} = r^x \approx 7$.

It has to be mentioned that qualitatively the same results of soliton collisions as described further below can be obtained with different input parameters, for example, higher input power (about one order of magnitude) or a different external electric field (in the range from 6 to 10 kV/cm).

2 Experimental results and discussion

An example of coherent soliton collision is given in Fig. 2, where two beams intersect under a small angle of $2\Theta \approx 1.4°$ inside the waveguide. Shown is the output on the endface as a function of the relative phase Φ of the two solitons. Starting from the antiphase condition ($\Phi = 180°$) the two solitons are repelled, transfer energy to the soliton on the right-hand side, merge together, transfer energy to the soliton on the left-hand side, are repelled again and so on. For relative phases Φ

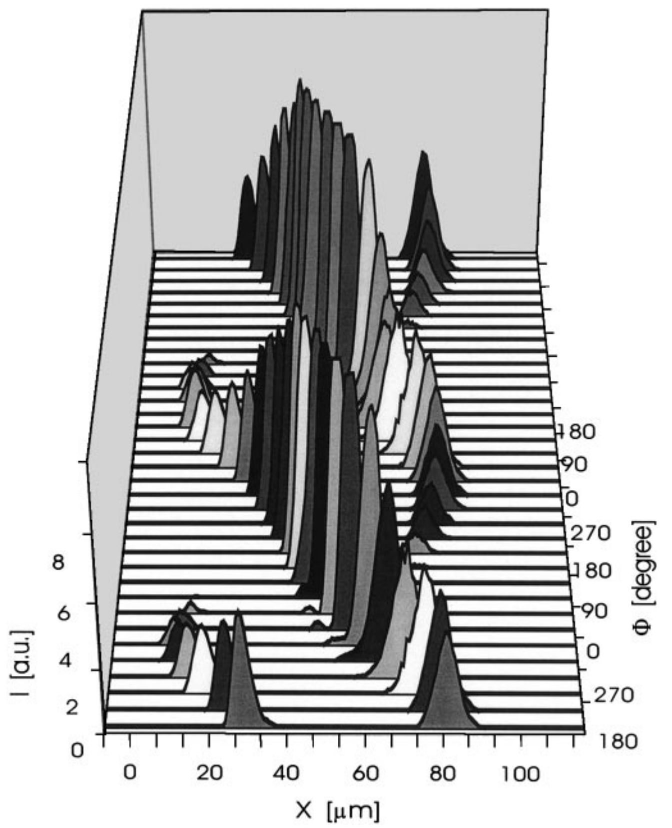

Fig. 2. Intensity distribution $I(x)$ on the endface of the planar SBN waveguide as a function of the relative phase Φ of two solitons that intersect at an angle $2\Theta \approx 1.4°$ inside the sample. The input power of each soliton is $3\,\mu\text{W}$ and the soliton width (FWHM) is about $8\,\mu\text{m}$

close to zero, the intensity of the smaller soliton (remainder of the left-hand soliton in Fig. 2) decreases and consequently becomes too low to still form a soliton, thus the soliton decays and the light diverges to a broad beam. This beam crosses the position of the remaining soliton (right-hand soliton in Fig. 2) from left to right for the case of exactly zero phase difference. Because of the limited bandwidth of the CCD this behavior is not seen in the figure. We have to note that a strong increase of the background intensity should lead to low values of the parameter $\tilde{r}$ which may result in a more Kerr-like, i.e., elastic, behavior of the soliton interaction. However, due to our limited laser power we were not able to reach this region.

For some specific values of Φ the outcome of the collision is presented in Fig. 3. When the two solitons are in phase (antiphase), they interfere constructively (destructively) and therefore increase (reduce) the refractive index in the intersection region. An increased refractive index leads to a deflection of both beams towards each other, and for a proper choice of the intersection angle the two beams merge together (solid curve in Fig. 3a). As a guideline, the grating period $\Lambda = \lambda/(2n_\text{e} \sin(\Theta))$, $n_\text{e} = 2.2028$, formed by the two intersecting beams has to be twice that of the soliton width w, thus only one bright fringe is formed in the overlap region for $\Phi = 0$ with minimal intensity in the side lobes [20]. Correspondingly, for the antiphase case ($\Phi = 180°$) a decreased refractive index in the center of the overlap region repels the two solitons. Their distance on the endface increases to $50\,\mu\text{m}$ (dotted line in Fig. 3a) when compared to the initial

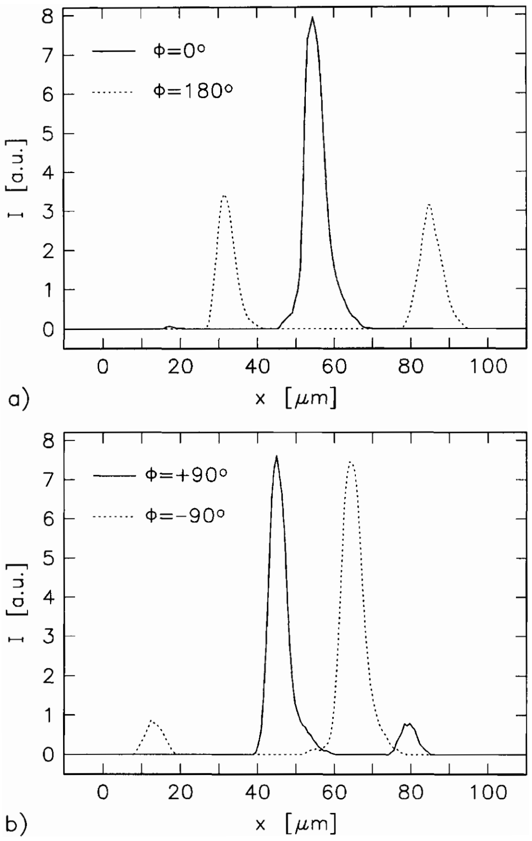

Fig. 3a,b. Intensity distribution $I(x)$ on the endface of the planar SBN waveguide for different relative phases Φ of the two beams. The two solitons intersect at an angle $2\Theta \approx 1.4°$ inside the sample, resulting in an initial separation of the two beams of 35 μm on the endface. The corresponding diffusion field $E_d = 135$ V/cm is small compared to the external electric field of $E_0 = 7.9$ kV/cm. **a** $\Phi = 0°$ (*solid line*, "fusion") and $\Phi = 180°$ (*dotted line*, "repelling"); **b** $\Phi = +90°$ (*solid line*) and $\Phi = -90°$ (*dotted line*), both cases show energy exchange

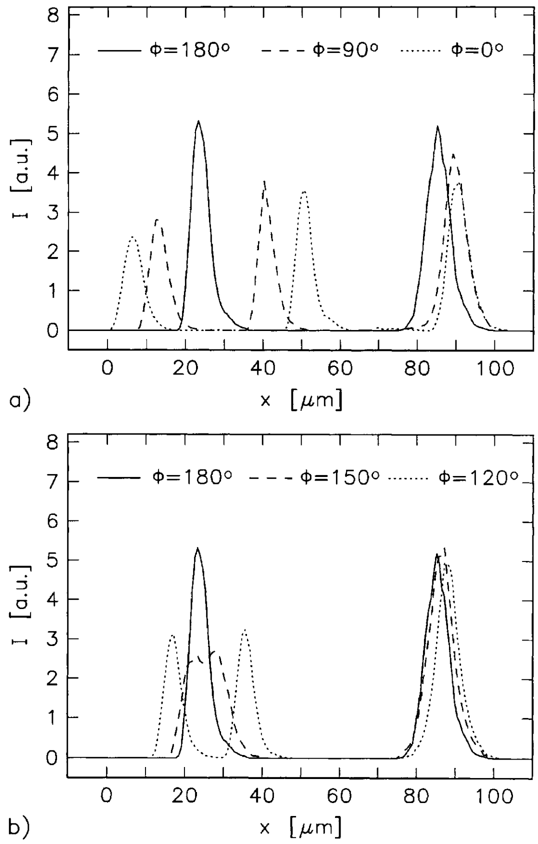

Fig. 4a,b. Intensity distribution $I(x)$ on the endface of the planar SBN waveguide for different relative phases Φ of the two beams. The two solitons intersect at an angle $2\Theta \approx 1.9°$ inside the sample, resulting in an initial separation of the two beams of 45 μm on the endface and a small diffusion field of $E_d = 160$ V/cm. **a** $\Phi = 180°$ (*solid line*), $\Phi = 90°$ (*dashed line*), and $\Phi = 0°$ (*dotted line*); **b** $\Phi = 180°$ (*solid line*), $\Phi = 150°$ (*dashed line*), and $\Phi = 120°$ (*dotted line*)

separation of 35 μm of the beams without external electric field.

The exchange of energy between two intersecting solitons having a relative phase difference of $\Phi = \pm 90°$ is shown in Fig. 3b. In both cases, a large part of the intensity initially guided in one beam is coupled into the other one. The direction of energy transfer solely depends on the sign of the relative phase difference of the two beams. No influence of the direction of the *c* axis is observed, pointing out that direct two-wave-mixing effects due to the diffusion field may be neglected here [21]. Here the corresponding diffusion field is only $E_d = 135$ V/cm and thus small compared to the external electric field of $E_0 = 7.9$ kV/cm. However, the diffusion mechanism leads to a bending of the soliton paths inside the waveguide towards the negative *c* direction [15, 22], as in this case the large propagation distance of 6 mm is responsible for this effect rather than the short interaction length of the intersecting beams.

If the intersecting angle of the two solitons is slightly increased, a third soliton can be formed upon interaction [13, 20]. This effect is shown in Fig. 4a for different relative phases of the two beams. When the two interacting beams are 180° out of phase, the interference pattern still consists of two symmetric maxima within the overlap region. Therefore the outcome of the collision is two solitons that are repelled from their initial positions due to the reduced refractive index in the symmetry plane of the interaction geometry. For the case of $\Phi = 0°$ three intensity maxima are formed by the two beams (because of the larger intersecting angle when compared with the results in Fig. 3.) that may have – depending on the correct intersecting angle – nearly equal intensity, thus leading to the creation of a third beam symmetrically located between the two others. As can be seen in the diagram, the three beams still repel each other. For a phase difference of $\Phi = \pm 90°$ we find an intermediate picture where the third soliton has formed already.

The splitting of the soliton on the left-hand sight can be seen in more detail in Fig. 4b. For a relative phase of $\Phi = 150°$ the soliton becomes unstable, and a further increase of the the phase difference results in a complete decay into two well-separated solitons of nearly equal width. At the same time, the soliton on the right-hand side only slightly changes its shape and position. After the splitting we observe an asymmetry in intensity of the three solitons that is growing with phase difference. This may be due to a slightly asymmetric intersecting angle and random defects of the waveguiding layer, that may strongly affect this sensitive three-particle-problem.

3 Conclusion

We have investigated the collisions between two coherent (1+1)-dimensional bright photorefractive screening solitons in a planar strontium–barium niobate waveguide. Soliton fusion, repelling, energy exchange, and the creation of a third soliton as a result of the interaction are observed. The outcome of the interaction depends critically on the intersecting angle and relative phase, however, very similar behavior is found for a rather wide spectrum of input light power and external electric field strength. These results are of considerable interest for the development of soliton-based nonlinear optical switches and couplers.

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References

1. M. Segev, B. Crosignani, A. Yariv, B. Fischer: Phys. Rev. Lett. **68**, 923 (1992)
2. G. Duree, J.L. Schultz, G. Salamo, M. Segev, A. Yariv, B. Crosignani, P. DiPorto, E. Sharp, R. Neurgaonkar: Phys. Rev. Lett. **71**, 533 (1993)
3. M.D. Iturbe-Castillo, P.A. Marquez-Aguilar, J.J. Sanchez-Mondragon, S.I. Stepanov, V.A. Vysloukh: Appl. Phys. Lett. **64**, 408 (1994)
4. G.C. Valley, M. Segev, B. Crosignani, A. Yariv, M.M. Fejer, M.C. Bashaw: Phys. Rev. A **50**, R4457 (1994)
5. M. Segev, G.C. Valley, B. Crosignani, P. DiPorto, A. Yariv: Phys. Rev. Lett. **73**, 3211 (1994)
6. M. Shih, M. Segev, G.C. Valley, G. Salamo, B. Crosignani, P. DiPorto: Electron. Lett. **31**, 826 (1995)
7. A.A. Zozulya, D.Z. Anderson: Phys. Rev. A **51**, 1520 (1995)
8. A.A. Zozulya, D.Z. Anderson, A.V. Mamaev, M. Saffman: Europhys. Lett. **36**, 419 (1996)
9. V.E. Zhakarov, A.B. Shabat: Sov. Phys. JETP **34**, 62 (1972); D.J. Mitchell, A.W. Snyder, L. Poladian: Phys. Rev. Lett. **77**, 271 (1996)
10. S. Gatz, J. Hermann: J. Opt. Soc. Am. B **8**, 2296 (1991)
11. G.S. Garcia-Quirino, M.D. Iturbe-Castillo, V.A. Vysloukh, J.J. Sanchez-Mondragon, S.I. Stepanov, G. Lugo-Martinez, G.E. Torres-Cisneros: Opt. Lett. **22**, 154 (1997)
12. H. Meng, G. Salamo, M. Shih, M. Segev: Opt. Lett. **22**, 148 (1997)
13. W. Krolikowski, S.A. Holmstrom: Opt. Lett. **22**, 369 (1997)
14. W. Krolikowski, B. Luther-Davies, C. Denz, T. Tschudi: Opt. Lett. **23**, 97 (1998).
15. D. Kip, M. Wesner, V. Shandarov, P. Moretti: Opt. Lett. **23**, 921 (1998)
16. K. Kos, H. Meng, G. Salamo, M. Shih, M. Segev, G.C. Valley: Phys. Rev. E **53**, R4330 (1996)
17. A.V. Mamaev, M. Saffman, D.Z. Anderson, A.A. Zozulya: Phys. Rev. A **54**, 870 (1996)
18. D. Kip, S. Aulkemeyer, P. Moretti: Opt. Lett. **20**, 1256 (1995)
19. D. Kip, B. Kemper, I. Nee, R. Pankrath, P. Moretti: Appl. Phys. B **65**, 511 (1997)
20. A.W. Snyder, A.P. Sheppard: Opt. Lett. **18**, 482 (1993)
21. This argument is confirmed by two-wave-mixing experiments in SBN waveguides as described in [16]. There only small beam coupling has been observed for $\lambda = 632.8$ nm even for much larger intersection angles and corresponding large diffusion fields
22. M.F. Shih, P. Leach, M. Segev, M.H. Garret, G. Salamo, G.C. Valley: Opt. Lett. **21**, 324 (1996)