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Guiding and dividing waves with photorefractive solitons

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Abstract

In this paper we show the guidance of a HeNe probe beam in photorefractive (2+1)D-solitons created by a beam of a frequency-doubled Nd:YAG laser in SBN. In the first part the development of a single soliton is shown in a time-resolved manner while the guided probe beam is found to follow exactly the movement of the soliton and even copies its shape. In the second part the guidance of a probe beam in interacting solitons is performed. When two (2+1)D-solitons propagate simultaneously different interaction scenarios can be observed, including the mutual exchange of energy. Using this effect, a guided probe beam can be divided effectively in two parts. Thus we present to our knowledge the first realization of a 1-to-2 waveguide divider using (2+1)D-solitons. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Photorefractive spatial screening solitons are the topic of extensive research in the last decade (e.g. Refs. [1–3]). Their creation and their characteristics have been examined thoroughly and also their capability of guiding another light beam was reported [5]. Because of their robustness and the simplicity of their creation at low laser power, the idea of deploying them in waveguide applications is evident. Furthermore, the non-local character of their anisotropic potential, which makes them unique among other types of spatial solitons, gives reason for different interaction scenarios between two or more of them and therefore enables the realization of different waveguide coupling devices or waveguide switches.

Photorefractive spatial screening solitons form when the self-focusing of a light beam inside the material exactly balances the diffraction of the beam. The refractive index modulation created by this light beam can be used to guide a second beam and therefore acts as a waveguide [5]. When looking for the development of this waveguide more thoroughly it can be seen that the guided wave exactly follows the trajectory of the soliton and even copies its shape. Due to the anisotropy of the electrostatic potential in the two transverse dimensions, the refractive index is modulated in an anisotropic way which results in a rather elliptical than circular shape of the waveguide [6].

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Additionally, the interaction of two solitons, which happens in photorefractive material due to the saturable character of the non-linearity, is strongly influenced by the anisotropy and causes two or more solitons to interact in a variety of different ways (e.g. attraction, fusion, repulsion, rotation, spiraling, see e.g. Refs. [7–10]).

Aligning two solitons parallel in the plane of the applied electric field they interact in an attractive or repulsive manner depending on their mutual distance. When the plane in which the solitons propagate is tilted to the x- or y-direction, they will rotate around their common center of mass. Additionally introducing an initial mutual angle can cause them to spiral around each other while propagation [11]. Furthermore under certain geometrical conditions situations involving a mutual exchange of energy between the solitons can be found [12]. When applying these interacting solitons for waveguide purposes it is possible to steer a probe beam guided in one soliton by launching a second one or to divide a probe beam by guiding it in a soliton which exchanges energy with a second one. This will be shown in detail in this paper.

2. Experimental setup

The experimental investigations were realized in a standard configuration [3]. One or two beams are derived from a frequency-doubled Nd:YAG laser ($\lambda = 532$ nm) and are focused to a size of nearly 10 μm (FWHM) each onto the front face of a photorefractive $Sr_{0.60}Ba_{0.40}Nb_2O_6$ (SBN:Ce) crystal. In our experiments two different samples of crystals of the same material and dopand (0.002 wt.% CeO_2) but of different length were used. The dimensions of the crystals were $5 \times 5 \times 13.5$ and $5 \times 5 \times 20$ mm^3 respectively. Both crystals are biased with an electric dc field (1.6–4.5 kV/cm) along their crystallographic c-axis. To make use of the dominant electrooptic coefficient r_{33} of the SBN crystals, the polarization of the beams is chosen to be parallel to the direction of the crystals c-axis while the beams always propagate along the long side of the crystal. The back face of the crystal is monitored with a CCD camera. The light-induced screening of the applied electric field is determined by the degree of saturation of the photorefractive non-linearity, which is proportional to the ratio between the soliton peak intensity and the background illumination. To control the level of saturation, the crystal is illuminated by a wide beam provided by an incoherent white light source. The background intensity was always set at an intensity ratio of $I_{\mathrm{beam}}/I_{\mathrm{background}} \approx 1$. The intensity of the background illumination was measured indirectly by two-beam coupling experiments where the coupling constant γ depends on the background illumination [4]. This measurement includes an uncertainty of ≈20% in the determination of the background illumination.

To test the waveguide capability of these solitons a probe beam derived from a HeNe laser ($\lambda = 632.8$ nm) is focused onto the same spot at the crystals surface on which the green beam is focused. At longer wavelengths solitons will not form below some certain power threshold and therefore the red beam can be used as a probe beam that does not write its own structures. To effectively couple in the red probe beam into the waveguide formed by the green beam, its focus is adjusted to the size of Ø ≈ 10 μm as well. This was done by changing its size with two additional lenses. Its polarization is also chosen to be parallel to the crystals c-axis.

3. Guidance of a single beam

In a first experiment, the principal guidance of a second beam in a (2+1)D-soliton is shown. One soliton is created using a low power beam of the Nd:YAG laser at 532 nm (intensity $I \approx 30$ mW/cm^2) while one probe beam of nearly the same power derived from a HeNe laser is focused on the same spot at the front face of the crystal. Here the propagation length is 13.5 mm. To clearly separate the green writing beam from the red probe beam, a prism is induced in front of the CCD camera, which makes the red probe beam appearing on the right hand side next to the green writing beam. Inside the crystal the beams propagate exactly along the same refractive index modulated path. Fig. 1 shows a time series of the developing soliton at the back face of the crystal.

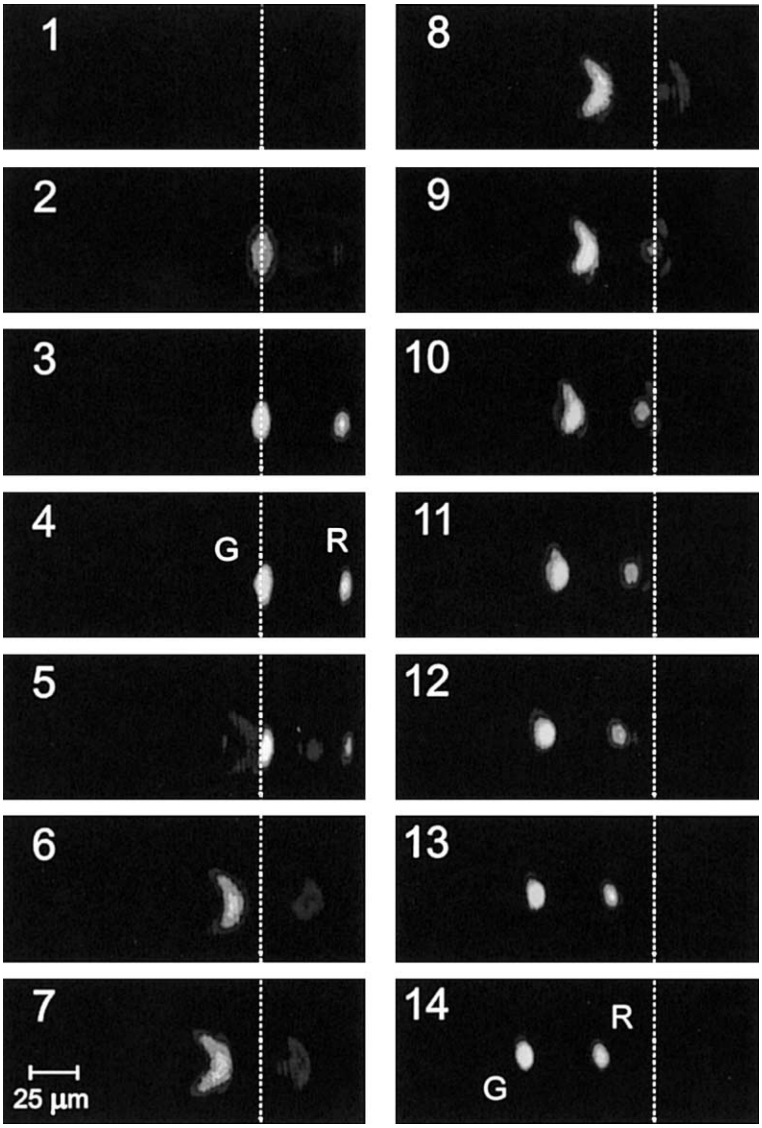

Fig. 1. Dynamics of soliton formation with guiding of a HeNe probe beam. G is the writing beam which forms the waveguide. The probe beam R is to be seen right next to the writing beam due to a prism in front of the camera. The time between consecutive snapshots is $\Delta t = 0.5$ s.

In the first four snapshots of Fig. 1 the writing beam G focuses to the size of nearly 10 μm (FWHM) while the soliton and therefore the waveguide forms inside the crystal (left spot). In this waveguide the red probe beam is effectively guided as can be seen in the right spot R in the snapshots. The shape of the writing beam as well as the shape of probe beam is rather elliptical than circular with an ellipticity of $dx/dy \approx 1/2$. This effect occurs due to the anisotropy of the electrostatic potential and is examined closely in Ref. [13]. Once the writing beam is focused to a small spot (Fig. 1, 5) the diffusion of the charge carriers becomes important. Even though the diffusion field is still approximately four orders of magnitude smaller than the external drift field, it causes the soliton to bend in the direction of the applied field [14,15]. The beam destabilizes in its shape and within the next 4.5 s it shifts for more than seven times of its diameter. During all this motion the red probe beam is always guided in the refractive index modulation created by the writing beam and consequently follows all of its movements and even copies its shape. This is impressively shown in Fig. 1, 6–13. After 7 s, the bending of the beam reaches a steady state, so that the beam settles at a position of about 70 μm shifted from its launching position (Fig. 1, 14). The exact knowledge of the position of the bended beam is essential when applying the system as a waveguide switching or coupling device, where the beam is supposed to be positioned at a certain place. This effect is examined thoroughly in Ref. [14].

In similar experiments the efficiency of the waveguide was determined by measuring the intensity of the probe beam at the front face of the crystal and at its back face, shortly after the writing beam was blocked. During these measurements it was taken care of measuring only the light guided in the soliton and blocking scattered light. Here, the efficiency, defined as the ratio between the intensities of the guided light vs. the incident intensity, was found to be $\eta \approx 22\%$ which equals a damping of 6.8 dB. It should be emphasized, that these values include all losses which stem from in- and outcoupling of the beam into the crystal. Although the size of the focus of the probe beam was adjusted, in our setup both beams still had a slightly different divergence when focused onto the front face of the crystal. This may cause some additional incoupling losses.

4. Waveguiding in interacting solitons

In a next experiment, the capability of guidance of two incoherent interacting solitons is examined. Here, two different cases of soliton interaction can be distinguished. Depending on the initial launching conditions (mutual distance in both transverse directions and tilt) the two solitons can propagate with or without a mutual exchange of energy [12]. To examine the waveguide capability of interacting solitons we extended the setup as shown in Fig. 2. To obtain a second soliton, the beam from the Nd:YAG laser is split into two beams using a couple of beam splitters and mirrors, from which one is mounted on a piezoelectric transducer driven at several hundred Hertz. Due to the slow response of the photorefractive material the mutual coherence of the beams is therefore destroyed effectively. As before, both beams are focused onto the front face of the crystal, each to a spot with a size of $\varnothing \approx 15$ μm FWHM. They are adjusted and tilted by the system of mirrors and beam splitters. Again, the probe beam derived from a HeNe laser is focused onto the front face of the crystal and adjusted to enter the crystal at the point where either one of the writing beams is launched.

In this experiment another sample of SBN:Ce crystal with a length of 20 mm is used while the

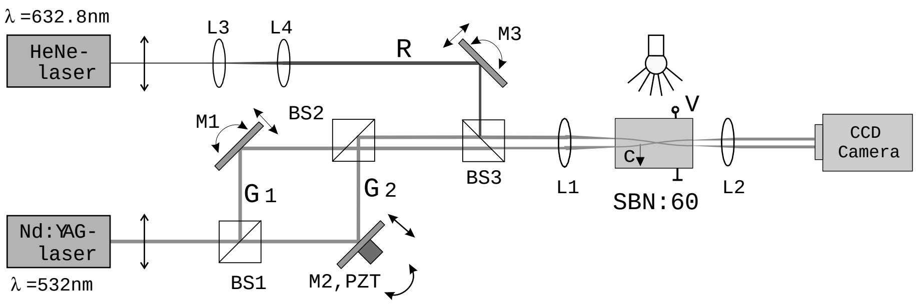

Fig. 2. Setup to examine the waveguide capability of interacting solitons. G1 and G2 are the writing beams, R is the probe beam. The mirror M2 is mounted on a piezoelectric transducer (PZT) to destroy the mutual coherence between G1 and G2.

two transverse dimensions were the same. In this crystal the focusing effect can be observed at lower light intensities ($I < 30$ mW/cm^2) and smaller applied external field (around 1.6 kV/cm). The time constant of this sample is much higher and it shows only very weak beam bending, less than one beam diameter. As an explanation of the inert reaction we assume despite of namely the same dopand supplementary charge carriers in one of the samples, that may lead to a change of the mobility of the charge carriers. As an advantage of this behavior, in the second sample the low dark conductivity leads to a persistence of the modulated refractive index structures for a long time period after the writing beam is blocked. So in this crystal we were able to detect waveguide structures several days after writing with no degradation. However these structures can be erased by illuminating the crystal with an intense beam of incoherent white light. They will also vanish after long exposure of low power laser light. To achieve permanent persistence of the written structures, electrical fixing can be applied [16–18].

5. Independent guidance in two interacting solitons

In case of no mutual exchange of energy between the two interacting beams, a soliton which guides a signal wave can be moved to another position by launching the second soliton as a controlling beam. This builds the basis for a real all optical switch. The switching time is ruled to the response time of the material which is rather slow (in the range of seconds). Anyhow, in this experiment the effects can be examined thoroughly and demonstrated well and therefore it can serve as a model for other, faster materials. In our experiment two beams with an intensity of $\approx$30 mW/cm^2 each are focused onto the crystal. Their transversal distance at the front face of the crystal is 15 μm in x- and 5 μm in y-direction. When self-focusing of the beams start, the two solitons form and interact strongly, thereby rotating around each other about an angle of 60°. Coupling the HeNe probe beam into either one of the soliton beams, the intensity of the probe beam can be found to be guided only in this soliton without energy coupling into the second one. An

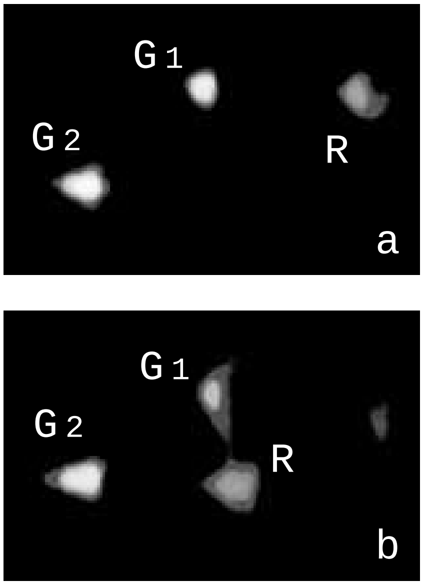

Fig. 3. Independent guidance of a beam in two interacting solitons. The snapshots show the guidance of the probe beam R in (a) the soliton G1 and (b) G2, respectively.

example of such a situation is shown in Fig. 3a and b, where the probe beam is guided in the soliton G1 or G2 respectively. The reason for the deformation of the beam G2 in this sample is due to inhomogeneities of the applied electric field in the crystal. Even though this beam propagates not in a perfect solitary form the probe beam R is guided properly in the structure written by the beam G2 (Fig. 3b). To use this situation as an all-optical switch e.g. beam G2 can be used as a steering beam for the beam G1, guiding the signal beam R.

6. Waveguide division with interacting solitons

In the case of mutual energy-exchange between the two interacting solitons a division of the probe beam can be realized. The principle of waveguide division due to such interaction was previously shown in Ref. [19], even though only for the one-dimensional case. In our experiment we investigated the case for two-dimensional beams. The foci of the two writing beams of which each had an intensity of 76 and 68 mW/cm^2 respectively, are

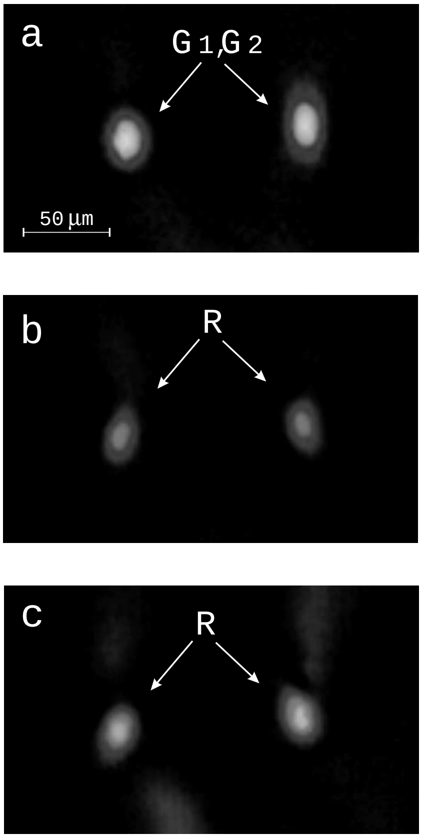

Fig. 4. Division of a beam with interacting solitons. Snapshot (a) shows the interacting solitons at the back face of the crystal. Snapshots (b) and (c) show the divided probe beam R while the writing beams are switched off. Again probe beam R alternatively is coupled into soliton G1 (b) or G2 (c), respectively.

adjusted on the front face of the crystal to a distance of approximately one spot diameter (15 μm) in the plane of the electric field which is set to 1.6 kV/cm. Additionally the beams are tilted with an angle of approximately 0.1° towards each other. The back face of the crystal is shown in Fig. 4a. The mutual exchange of energy of the two beams can easily be proved in blocking either of the beams, resulting in parts of the beams still apparent in both channels at the back side of the crystal. Due to the previously explained persistence of the waveguides once written in our sample the probe beam can be guided easily while the writing beams are blocked. Therefore in this experiment no prism is needed to separate the beams when the crystals back face is monitored with the CCD.

After the background illumination and the electric field are switched off, the modulation of the refractive index and therefore the written waveguide structure remain unchanged due to the low dark conductivity of our crystal. Thus it is possible to use this structure for the guidance of the probe beam which is focused on the same spot of the crystals front face where one of the writing beams were focused before. Looking for the back face of the crystal in that case one finds the intensity of the probe beam to be guided in both channels previously created by the green writing beams. This situation is shown in Fig. 4b and c. Since the single probe beam was launched into the channel of one soliton but leaves the crystal through both channels, a division of the probe beam is obvious. When the probe beam alternatively is focused to the spot where the second writing beam was focused on the crystals front face a very similar phenomenon can be found. The probe beam again leaves the crystal through both waveguide channels (Fig. 4c). Comparing pictures b and c from Fig. 4 one notes a lower intensity of the guided beam in case of Fig. 4b. The reason for this can be found in an improper adjustment of the probe beam and therefore a higher loss at coupling in the probe beam into the waveguide structure. A quantitative analysis of the guidance in this case and the losses due to division is currently under investigation.

7. Conclusion

In this paper we showed the principal guidance of a single beam in a photorefractive (2+1)D-soliton in a time-resolved manner. The guided beam can be found to follow exactly the path of the writing beam and yet copies its shape while the soliton forms. Moreover we show the first time to our knowledge the guidance of a probe beam in interacting solitons. Here two situations of interacting solitons with and without a mutual exchange of energy have been realized. While in the case of no energy exchange the probe beam can be guided in each soliton separately, in the case with energy exchange the probe beam is divided in both channels, representing a 1-to-2-waveguide coupler.

With these results we prove that the realization of all-optical switching devices as the realization of highly adaptive waveguide couplers using the interaction of photorefractive solitons is feasible.

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