Optical control of arrays of photorefractive screening solitons

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We discuss the creation of an array of 9 × 9 photorefractive spatial screening solitons in a strontium barium niobate crystal. We investigate the waveguide properties of each channel with a beam of different wavelength and find that the waveguides guide the probe beam independently. A supplementary beam is used to influence the paths of the array solitons and to effectively combine two channels by use of mutual attraction of solitons. To our knowledge this is the first all-optical control of an array of photorefractive solitons. Furthermore, we show that in principle image procession is possible with parallel propagation of photorefractive solitons. © 2003 Optical Society of America

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Optical switches and all-optical interconnects are a major challenge in the fast-growing field of optical networking. Spatial optical solitons in photorefractive material are by now known for the potential of providing a solution to the problem of all-optical routing and switching. Because of their properties of mutual interaction these solitons may influence their own paths and make all-optical switching feasible. Although the creation of photorefractive solitons and their characteristics have been studied thoroughly, they are still an active topic of recent research (see, e.g., Refs. 1–3). Their waveguide properties were shown,[4] as was their capability to route or split paths of optical beams.[5,6]

However, in only a few works has the parallel propagation of several spatial solitons been studied.[7,8] To our knowledge, none of these studies was performed for the special case of a photorefractive nonlinearity. A crucial point in the parallel propagation of photorefractive spatial solitons is their anisotropic mutual interaction. Because of the nonlocality of their electrostatic potential, the refractive-index modulation induced by each single soliton reaches beyond its effective waveguide. Therefore, depending on their mutual distance in the incoherent case the solitons may repel, attract, or even fuse, as shown in Ref. 9. In the case of mutual coherent solitons interaction becomes even more complex, as their mutual phase may cause an exchange of energy between them and annihilation or the creation of solitons may occur.[10] In this Letter we demonstrate the creation of an array of coherent solitons propagating through a crystal in parallel. Using a separate beam located between two channels of the array, we are able to exploit the mutually attractive force between coherent solitons to let them fuse into a single output at the back face of the crystal. This ability demonstrates the potential for all-optical control of single channels in a large photorefractive soliton array. Furthermore, the waveguide properties of such an array are tested with a separate beam of a He–Ne laser. Here we find that each channel guides the red probe beam properly.

To create an array of solitons in the photorefractive crystal we used the setup shown in Fig. 1. The beam of a frequency-doubled Nd:YAG laser emitting at $\lambda = 532$ nm illuminates a spatial light modulator, which imprints the image of a spot array onto the beam. Passing a set of lenses, the spatial light modulator is reproduced in demagnified form on the front face of a photorefractive $Sr_{0.60}Ba_{0.40}Nb_2O_6$ crystal. The crystal has dimensions of 5 mm × 5 mm × 20 mm, and the propagation always is along the 20-mm side. In the direction of its crystallographic c axis (5-mm side) an electric dc field of approximately $E_0 = 2$ kV/cm is applied. To exploit the dominant electro-optic coefficient r_{33} of SBN:Ce the light is linearly polarized parallel to the c axis. The back face of the crystal is monitored with a CCD camera. In every experiment we ensured that two-dimensional steady-state screening solitons were always formed by controlling the level of saturation with a wide beam of incoherent background illumination, as was done in previous experiments.[10,11]

In a first step the creation of the soliton array and its waveguiding properties were examined. A regular pattern of 81 spots with a diameter of 15 μm and an intensity of $\approx$20 mW/cm^2 for each spot was imaged onto the front face of the crystal (Fig. 2a). In the linear case—without an applied electric field—the 81 beams diffract on their way through the crystal and interfere at the back face of the crystal, as depicted in Fig. 2b. When the electric field is applied, the 81 solitons, each

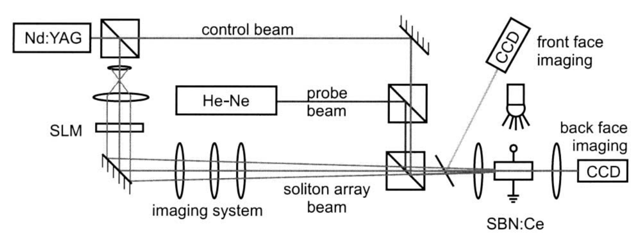

Fig. 1. Setup for the creation, probing, and control of an array of photorefractive screening solitons. SLM, spatial light modulator.

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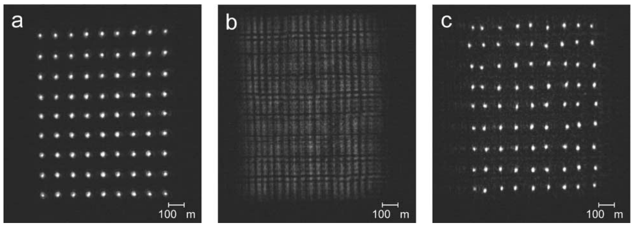

Fig. 2. Realization of a 9×9 waveguide array induced by photorefractive solitons: (a) front face of the crystal where the spot array is imaged, (b) interference pattern that is due to linear propagation of the 81 beams, (c) array of 81 focused solitons.

with a diameter of ~ 12 μm (FWHM), form from the interference pattern within several seconds and form 81 separate waveguides, as described for a single soliton in Ref. 12. This situation can be seen in Fig. 2c. As the crystal length is not a multiple of the Talbot length, the pattern that appears at the back face of the crystal in the linear regime is not due to self-imaging of the pattern on the front. To obtain propagation without initial mutual interaction we made the initial distance between the single channels just large enough that the solitons would not interact. Because of the anisotropic character of the photorefractive refractive-index modulation, the distances in the direction perpendicular to the applied electric field have to be larger than in the direction of the applied field to yield parallel propagation of the solitons.[11,13] Therefore, to be sure to obtain propagation of the solitons without mutual interaction within the length of the crystal, we chose the distance between the spots on the front face to be $\delta x = 100$ μm and $\delta y = 120$ μm (where x is the direction of the applied electric field). A distance less than 30 μm in the x direction and 50 μm in the y direction in either case would cause the solitons to interact because of their own mutual attraction and repulsion, as was found numerically[13] as well as experimentally.[10] The slight increase of the size of the soliton pattern compared with the initially imaged pattern in this case as well as in the case shown in Fig. 5, below, is due to the imaging optics and is not caused by the mutual interactions of the solitons in the array. Mutual stabilization of the solitons to form this exact configuration is unlikely to be stable and immediately would break the pattern.

In another example of a 3×3 array we used the beam of a He–Ne laser with an intensity of ≈ 150 mW/cm^2 and equal size (diameter, 15 μm FWHM) to test for the waveguide properties of the single channels of such a soliton array. In this case the distance of the induced spots was reduced to 50 μm. This configuration is necessary for the control experiments that were performed later in the same configuration (see below). The slight deviation of the symmetry of the output pattern is due to inhomogeneities of the crystal. Since the photorefractive material is less sensitive to light in the red wavelength region, the induced refractive-index modulation could be scanned with an even more intense probe beam without actually being influenced or erased. Positioning the red probe beam successively to the positions of the previously induced solitons on the crystal's front face, we found the probe beam to be guided solely in each of the nine channels. The scan of this array with the red probe beam is shown in Figs. 3(b) and 3(c). To obtain a picture of the complete array, we scanned every single channel separately. Afterward, the nine individual pictures were added electronically.

Because of the low dark conductivity of our crystal we found the induced refractive-index change to be present for several hours after we switched off the writing beam and the background illumination. Hence we were able to scan the previously written structure with the red probe beam. Figure 3b shows the scanned array directly after the writing process, and Fig. 3c shows a scan of the array after the crystal has been kept in the dark for more than 15 h. Even though no particular fixing procedure was applied, one can see that every single channel still is clearly distinguishable and guides the probe beam with only minor loss. Exposing the crystal to a homogeneous bright light would eventually erase the written structure. The larger diameter of the spots of the guided beam in Figs. 3b and 3c is due to the higher intensity of the probe beam, which overexposes the CCD camera.

Next, a controlled interaction between two channels of the array was induced. Using the mutual attractive interaction between spatial solitons a third soliton that is positioned between two adjoining channels increases the refractive index in this region and causes all three solitons to fuse during their propagation through the crystal. To perform this control we focused a separate beam of the Nd:YAG laser onto the front face of the crystal.

Although in this experiment the array solitons had an intensity of 55 mW/cm^2 each, the separate controlling beam, which was positioned between the two spots of the array, had an intensity of ≈ 160 mW/cm^2 (see the circled $\times$ in the inset of Fig. 4b). In Fig. 4a the back face of the crystal with the uncontrolled array is shown. Once the control beam was positioned between the central lower two solitons and the electric field was applied, the new soliton array formed. Because of the additional beam between the two lower central channels, the refractive index between these channels is increased, causing the two solitons to attract and eventually fuse. Figure 4b shows the red probe beam guided in each channel of the controlled array separately (again single snapshots were added electronically). Here the fusion of the two lower middle channels is obvious. Therefore, the case of coupling the probe beam into the central or the lower

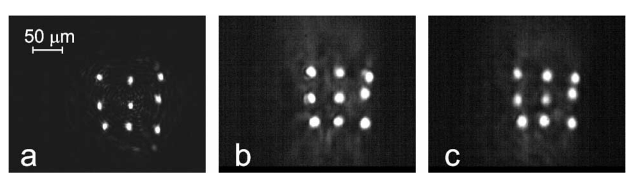

Fig. 3. Creation and probing of a waveguide array induced by photorefractive solitons: (a) focused soltions as seen at the back face of the crystal, (b), (c) waveguide array probed by the He–Ne beam directly after writing and after the crystal was kept in the dark for 15 h, respectively.

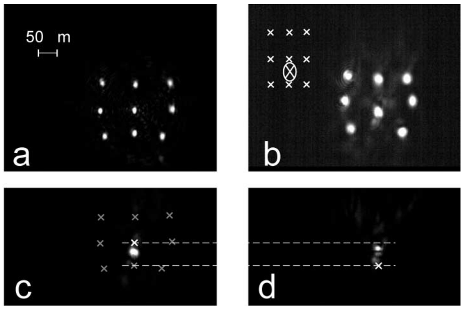

Fig. 4. Optical control of a soliton array: (a) uncontrolled soliton array, (b) controlled array probed by a read beam, (c), (d) probe beam coupled into the central and the lower middle channel of the controlled array, respectively. The probe beam leaves the crystal at the same position. The dashed lines are a guide for the eye.

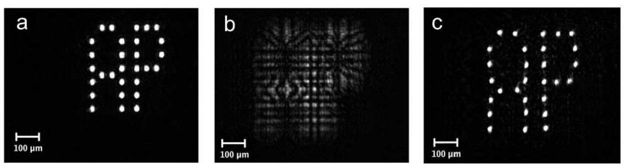

Fig. 5. Image processing with photorefractive solitons: (a) spot pattern at the front face of the crystal, (b) diffraction pattern of the beams at the back face of the crystal, (c) reconstruction of the image with focused soliton beams.

middle channel on the front face of the crystal leads to guiding of the probe beam into the same output. This also can be seen in Figs. 4c and 4d. There the probe beam was coupled into either of the two channels alternatively but leaves the crystal at the same spot on its back face. For a better comparison, the crosses mark the position of the exit of the channels in the uncontrolled array. In principle, the fusion of neighboring channels in the direction of the electric field is also possible. In this case, because of the anisotropy of the photorefractive nonlinearity the distance between the control beam and each channel has to be smaller than 27 μm (Ref. 9) to create an effective increment of the refractive-index modulation between the beams. This result shows, for the first time to our knowledge, the control of single channels of an waveguide array by just a beam of light and illustrates the capability of using spatial solitons for the realization all-optical switches and interconnects.

The formation of larger soliton patterns in principle is not limited to symmetric figures or arrays. As shown in Ref. 7 for a χ^2 material and also in photorefractive material, different soliton patterns and digitized pictures can be processed, as long as the separation of the digits–solitons is not smaller than 30 μm in the x direction and 50 μm in the y direction. So, as an example we imaged the pattern of the letters A and P as a spot array onto the front face of the crystal (Fig. 5a). Once the external electric field was applied, the solitons formed out of the interference pattern and clearly reproduced the image of the two letters (Fig. 5c). Such a system can find application in the reconstruction of blurred images, as suggested in Ref. 7.

In this Letter we have presented what is to our knowledge the first control of an array of photorefractive solitons by a separate beam of light. Here we were able to show that a stable propagation of several parallel solitons in an array geometry, and therefore the formation of a waveguide array, is possible. Furthermore, the all-optical control of single channels of the array was shown by induction of a determined fusion of two channels of the array, creating a Y coupler within the waveguide array. All experiments were done with mutually coherent beams. In the case of mutually incoherent beams a more stable propagation of the beams can be expected as the mutual phase of the single beams may not influence the structure. These experiments are currently under way.

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