Steady-state photorefractive soliton-induced Y-junction waveguides and high-order dark spatial solitons

Zhigang Chen, Matthew Mitchell, and Mordechai Segev

Department of Electrical Engineering and Advanced Center for Photonics and Optoelectronic Materials, Princeton University, Princeton, New Jersey 08544

Received January 22, 1996

We report the experimental observation of steady-state photorefractive Y junctions and sequences of high-order dark photorefractive screening solitons in a biased bulk strontium barium niobate crystal. The parameters that characterize the properties of the high-order dark screening solitons are measured and compared with the theoretical prediction for the fundamental dark screening soliton. The high-order dark solitons induce stable waveguides in one transverse dimension that can guide other, possibly very intense, beams of different wavelengths. © 1996 Optical Society of America

Self-focusing and self-defocusing of light and the formation of spatial solitons have been studied for three decades.[1] They have stimulated much interest partly because spatial solitons provide a new way of controlling light by light and are thus promising for use in photonic devices. Both bright[2] and dark[3] one-dimensional Kerr-type solitons along with their ability to guide and switch other beams[4,5] have been demonstrated.

Recently a new type of spatial soliton, namely, the photorefractive soliton,[6–14] has attracted interest because of its advantages over the Kerr-type soliton (existence at very low power and stable trapping in both transverse dimensions). Photorefractive solitons were first predicted and observed in quasi-steady state.[6] Then theoretical and experimental studies revealed their existence in steady state also as photorefractive screening solitons[7–10] and photovoltaic solitons.[11] Because the photosensitivity of photorefractive materials varies with wavelength, one can generate a soliton-induced waveguide in a photorefractive medium with a very weak optical beam and guide in it a very intense beam of a nonphotosensitive wavelength. Thus, unlike waveguides induced by Kerr solitons, photorefractive soliton-induced waveguides can guide other beams with much higher intensities than that of the soliton beam itself.[12] One-dimensional waveguides formed in bulk photorefractive media by use of fundamental dark solitons of steady state as well as of quasi-steady state have been reported.[11–14] In this Letter we report new experimental results on one-dimensional high-order dark photorefractive screening solitons, namely, Y, triplet, and quadruplet junctions, and their steady-state waveguide properties.

Photorefractive dark screening solitons can be understood in the following manner.[8] When a narrow dark notch on an otherwise-uniform light beam propagates in a biased photorefractive medium, the conductivity in the illuminated region increases and the resistivity decreases. Thus the voltage drops mostly in the dark region and leads to a large space-charge field around the notch. The induced index perturbation is proportional to that field (by means of the Pockels effect), and it has a self-defocusing effect on the illuminated portions of the beam. As a result, the illuminated regions expand their inner boundaries and the size of the notch is preserved to form a dark soliton. The fundamental dark screening soliton requires an antisymmetric amplitude profile,[8,9] i.e., a π phase jump at the center of the beam (an odd initial condition). In an earlier paper[14] we reported generating a fundamental dark screening soliton and confirmed the shape-preserving behavior. Based on observations of Y junctions in Kerr media,[5] we launch a dark notch with a uniform phase (an even initial condition) into a biased bulk photorefractive crystal and find that this leads to a pair of antiphased dark solitons diverging from each other: a Y-junction soliton. We observe such Y junctions and the waveguides that they induce.

The experimental setup is similar to that of Ref. 14. A 488-nm, cw laser beam is collimated and extraordinarily polarized. Using reflection of this beam from a mirror with a $\lambda/4$ step or with an amplitude notch (gold wire), we generate a dark notch on an otherwise-uniform Gaussian beam. The dark notch is imaged onto the input face of the crystal (SBN:61) with the notch-bearing beam covering the entire input face. This is essential for the observation of steady-state photorefractive dark solitons, especially when the background illumination is absent, because it affects the boundary conditions (the free carrier density near the electrodes).[8,9] The beam propagates along the crystalline a axis, with the narrow direction of the dark notch oriented parallel to the c axis. We observe dark solitons by applying the appropriate (magnitude and polarity) field parallel to the c axis. In addition, a uniform ordinarily polarized beam (488 nm) is used (when necessary) as background illumination,[7,10,14] and an extraordinarily polarized He–Ne laser beam (632.8 nm) is used to test the guiding properties of the dark solitons. The input–output beam from the crystal is monitored by a CCD camera.

To form a Y-junction dark soliton we use a mirror crossed by a fine 20-μm-wide gold wire to create an amplitude jump in the beam. Typical experimental results showing photographs and beam profiles are presented in Fig. 1. We emphasize that the input beam consists of a single dark notch, because the small

0146-9592/96/100716-03$10.00/0 © 1996 Optical Society of America

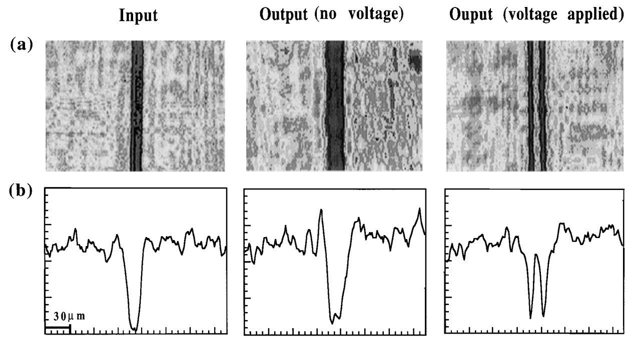

Fig. 1. (a) Photographs and (b) horizontal profiles of the input beam (488-nm), the normally diffracting output beam, and the Y-junction soliton output beam.

reflection from the wire is almost filtered out completely by the numerical aperture of our system. The notch at the input face of the crystal is 18 μm (FWHM), which diffracts in the absence of an external field to 30 μm after 5-mm propagation. A trapping voltage of $V = -250$ V (negative relative to the crystal's c axis) applied between electrodes spaced by $\ell = 4.5$ mm results in a pair of 8-μm-wide gray solitons. This antiphased soliton pair forming a Y-junction splitter is observed without background illumination. As for fundamental dark screening solitons,[8,9,14] background illumination is not necessary for observation of Y-junction solitons, provided that they are generated on a beam of infinite extent. If the notch-bearing beam does not cover the entire crystal, the Y junction appears in quasi-steady state but disappears in steady state. For the data shown in Fig. 1 the input average intensity is ~5 mW/cm^2, much greater than the dark irradiance, for total beam power of 2 mW. We observed the Y junction without adjusting the voltage even when the beam power was reduced to 80 μW.

A dark photorefractive soliton induces an effective graded-index single-mode waveguide that can guide other beams of different wavelengths.[11–14] Waveguide structures formed by Y-junction dark solitons and by high-order dark solitons are of particular interest for applications of all-optical beam steering of high-power beams by low-power (soliton) control beams. Shining a He–Ne laser beam (with an average intensity of 180 mW/cm^2) into the soliton-induced Y-junction waveguide, we observe good steady-state guidance. Figure 2 shows photographs and beam profiles of the red beam guided by the waveguide induced by the soliton of Fig. 1. At zero voltage, the red beam diffracts from 8 to 75 μm (FWHM). At $V = -250$ V, more than 80% (normalized to Fresnel reflections and absorption in the crystal) of the input power of the red beam is guided into the pair of Y output beams. Note that for Kerr-type solitons the intensity of the soliton beam must greatly exceed the intensity of the guided beam,[5] whereas here the average intensity of the guided beam is more than 30 times larger than that of the soliton beam. As Figs. 1 and 2 show, the structure that we show here is a Y junction in which a single input is split into two waveguides by the photorefractive nonlinearity. The Y junction can be made asymmetric or converted into a single soliton-induced waveguide by addition of uniform illumination to one of the branches (thus modifying the intensity ratio locally) or by change of the input condition and adjustment of the applied voltage.

For steady-state photorefractive screening solitons the theory predicts a universal relation between the width of the soliton and the ratio of the soliton irradiance to the sum of the dark irradiance and a uniform background irradiance.[8,9] In previous experiments we investigated this relation experimentally and found good agreement with theory.[14] For photorefractive Y-junction dark solitons there is no analytical theory available yet. One would expect, though, that twice the voltage will be needed to generate a Y-junction soliton pair of the same size for a large enough intensity ratio, because the applied voltage now drops mostly in two dark regions. Using a broad, uniform, ordinarily polarized beam for background illumination, we measure the voltage required for forming a Y junction as a function of the soliton-to-background intensity ratio. Figure 3(a) shows the normalized soliton width $\Delta\xi = \Delta x k n_b (r_{\text{eff}} V/\ell)^{1/2}$ (where Δx is the FWHM in dimensional units, $k = 2\pi n_b/\lambda$, λ is the free-space wavelength, n_b is the unperturbed refractive index, and $r_{\text{eff}} = r_{33}$ is the electro-optic coefficient[8,9]) versus u_∞, the square root of the intensity ratio at the crystal boundaries, for the theoretical prediction of the fundamental dark screening soliton (solid curve) and the experimental measurement of the Y-junction soliton (dashed curve). The two curves follow the same trend but differ by roughly a factor of $\sqrt{2}$ at a high intensity ratio. When the intensity ratio is large ($u_\infty > 2$, almost to infinity where there is

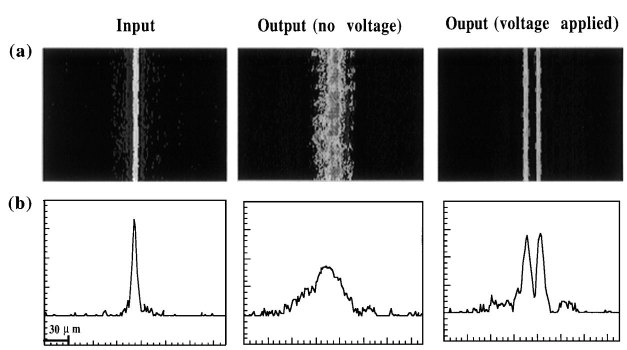

Fig. 2. (a) Photographs and (b) horizontal profiles of the red beam guided by the waveguide induced by the Y-junction dark soliton shown in Fig. 1.

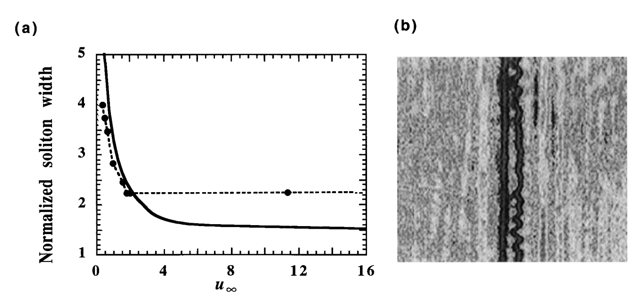

Fig. 3. (a) Normalized soliton width $\Delta\xi$ versus u_∞. Solid curve, theory of the one-dimensional fundamental dark soliton. Dashed curve, experimental measurements of Y-junction dark solitons. (b) Photograph showing breakup of the Y-junction soliton as the experimental parameters of $\Delta\xi$ deviate more than 25% from the soliton curve.

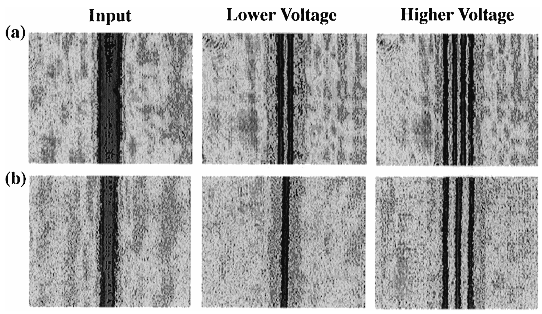

Fig. 4. (a) Transition from a Y-junction dark-soliton pair to an even number of higher-order solitons under an even initial condition (amplitude jump). (b) Transition from a fundamental dark soliton to an odd number of higher-order solitons under an odd initial condition (phase jump).

no background illumination), the trapping voltage does not change with u_∞ and is roughly twice the voltage required for a fundamental dark soliton in this intensity region.[14] The lowest trapping voltage occurs for the intensity ratio much larger than unity, and background illumination is not required for observation of Y-junction solitons. In the region of low intensity ratios the voltage required for Y-junction solitons coincides with that required for support of the fundamental dark screening solitons.

As discussed above, the Y junction exists on a single-value curve of the normalized soliton width versus the soliton-to-background intensity ratio. A large deviation from this curve, either in applied voltage or in intensity ratio, results in breakup of the Y-junction dark soliton. This is more obvious when background illumination is absent. Further increase of the applied voltage from the value (in this case, -250 V) required for generating the steady-state Y junction causes distortions in the dark soliton. Figure 3(b) shows such an example for $V = -400$ V, where we see little bumps in the one-dimensional dark-soliton pair. These bumps are not due to the impurities in the crystal, because as we translate the crystal to a different position the bumps disappear in transient state but come back to the same location in steady state. Moreover, we can restore the soliton shape of the Y junction by either readjusting the voltage or adding additional background illumination. This instability results from a large deviation from the soliton curve [Fig. 3(a)]. The higher voltage can support a dark soliton of a higher order but not the Y-junction soliton.

Finally, we observe sequences of higher-order dark solitons. An even (odd) initial condition leads to an even- (odd-) number sequence of dark solitons as for solitons in Kerr media.[5] Figure 4(a) shows an example of an even-number sequence found in our experiments when the input wire width is increased to 29 μm. With this amplitude notch we clearly observe as many as four pairs of dark solitons. We can achieve the transition from a Y-junction soliton pair to multiple high-order soliton pairs by either increasing the trapping voltage at a fixed soliton-to-background intensity ratio or increasing the intensity ratio at a proper applied voltage. We obtain the results shown in Fig. 4(a) by changing only the applied voltage while keeping the background illumination at a fixed value. For each bifurcation to the next higher order, approximately twice the trapping voltage is needed. With an odd initial condition (phase jump caused by a $\lambda/4$ step mirror[14]), we observe an odd-number sequence of dark solitons, as shown in Fig. 4(b). For both conditions, by shining a red beam into the soliton area we observe significant guidance of the red beam into the multiple dark soliton stripes. In all these experiments both the power of the soliton beam and that of the background beam are of the order of several milliwatts.

In summary, we have observed Y junctions and higher-order dark spatial solitons when a laser beam containing an amplitude or a phase jump propagates through a biased bulk photorefractive crystal. We show that these solitons form waveguide structures that can guide other, possibly very intense, beams of different wavelengths.

M. Segev gratefully acknowledges the support of a Sloan Fellowship and of Hughes Research Laboratories.

References

1. R. Y. Chiao, E. Garmire, and C. H. Townes, Phys. Rev. Lett. **13,** 479 (1964).
2. J. S. Aitchison, A. M. Weiner, Y. Silberberg, M. K. Oliver, J. L. Jackel, D. E. Leaird, E. M. Vogel, and P. W. E. Smith, Opt. Lett. **15,** 471 (1990).
3. G. A. Swartzlander, Jr., D. R. Andersen, J. J. Regan, H. Yin, and A. E. Kaplan, Phys. Rev. Lett. **66,** 1583 (1991).
4. R. De La Fuente, A. Barthelemy, and C. Froehly, Opt. Lett. **16,** 793 (1991).
5. B. Luther-Davies and X. Yang, Opt. Lett. **17,** 496 (1992).
6. M. Segev, B. Crosignani, A. Yariv, and B. Fischer, Phys. Rev. Lett. **68,** 923 (1992); G. Duree, J. Schultz, G. Salamo, M. Segev, A. Yariv, B. Crosignani, P. DiPorto, E. Sharp, and R. R. Neurgaonkar, Phys. Rev. Lett. **71,** 533 (1993).
7. Steady-state self-focusing effects were first observed by M. Iturbe-Castillo, P. Marquez-Aguilar, J. Sanchez-Mondragon, S. Stepanov, and V. Vysloukh, Appl. Phys. Lett. **64,** 408 (1994).
8. M. Segev, G. C. Valley, B. Crosignani, P. DiPorto, and A. Yariv, Phys. Rev. Lett. **73,** 3211 (1994); M. Segev, M. Shih, and G. C. Valley, J. Opt. Soc. Am. B **13,** 706 (1996).
9. D. N. Christodoulides and M. I. Carvalho, J. Opt. Soc. Am. B **12,** 1628 (1995).
10. M. Shih, M. Segev, G. C. Valley, G. Salamo, B. Crosignani, and P. DiPorto, Electron. Lett. **31,** 826 (1995); Opt. Lett. **21,** 324 (1996).
11. G. C. Valley, M. Segev, B. Crosignani, A. Yariv, M. M. Fejer, and M. Bashaw, Phys. Rev. A **50,** R4457 (1994); M. Taya, M. Bashaw, M. M. Fejer, M. Segev, and G. C. Valley, Phys. Rev. A **52,** 3095 (1995).
12. M. Morin, G. Duree, G. Salamo, and M. Segev, Opt. Lett. **20,** 2066 (1995).
13. M. Iturbe-Castillo, J. Sanchez-Mondragon, S. Stepanov, M. Klein, and B. Wechsler, Opt. Commun. **118,** 515 (1995).
14. Z. Chen, M. Mitchell, M. Shih, M. Segev, M. Garrett, and G. C. Valley, Opt. Lett. **21,** 629 (1996).