Waveguides formed by quasi-steady-state photorefractive spatial solitons

Matthew Morin, Galen Duree, and Gregory Salamo

Department of Physics, University of Arkansas, Fayetteville, Arkansas 72701

Mordechai Segev

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

Received May 18, 1995

We show that a quasi-steady-state photorefractive spatial soliton forms a waveguide structure in the bulk of a photorefractive material. Although the optically induced waveguide is formed by a very low-power (microwatts) soliton beam, it can guide a powerful (watt) beam of a longer wavelength at which the medium is nonphotosensitive. Furthermore, the waveguide survives, either in the dark or when guiding the longer-wavelength beam, for a long time after the soliton beam is turned off. We take advantage of the solitons' property of evolution from a relatively broad input beam into a narrow channel and show that the soliton induces a tapered waveguide (an optical funnel) that improves the coupling efficiency of light into the waveguiding structure. © 1995 Optical Society of America

It has been established for several years that spatial Kerr-type solitons induce guidance of a typically much weaker beam[1,2] through cross-phase modulation. In fact, the optical control of one beam by another has interesting potential applications in all-optical switching and beam-steering waveguide devices.[3,4] All these effects are based on Kerr-type solitons, and, as such, they carry over their characteristic properties: (i) waveguides induced by bright Kerr solitons exist only in one transverse dimension[1] (implying that all potential device applications must be planar), (ii) the dimensions of the induced waveguide depend on the soliton intensity, and (iii) the guided beam is much weaker than the soliton (guiding) beam.[1]

Photorefractive solitons[5] have been shown to exist in several forms. Quasi-steady-state solitons[5–13] appear during the slow screening process of a field applied externally to a photorefractive crystal. Solitons of this type are transient by nature, and we refer to their time window of existence as a quasi-steady state. Their most distinct properties are independence of the absolute light intensity[5–8,12,13] (for intensities much larger than the dark irradiance) and the capability of trapping in both transverse dimensions.[7–9,12,13] Experimental observations have proved the existence of one- and two-dimensional bright solitons,[7–9] planar dark solitons, and vortex solitons.[12,13] The second type of photorefractive soliton is the screening soliton,[14] which appears in the steady state, after the external field is screened nonuniformly as a result of the transversely nonuniform intensity distribution. This effect is local and results in an index perturbation that is inversely proportional to the sum of the optical and dark irradiances. Recent experimental observations have confirmed the existence of one- and two-dimensional screening solitons.[15,16] The third type of photorefractive soliton exists in materials that are both photorefractive and photovoltaic. These photovoltaic solitons[17] stem from photovoltaic currents that generate an index perturbation analogous to the nonlinearity in a saturable absorber. A recent observation[18] confirmed the existence of dark photovoltaic solitons in $LiNbO_3$. Some of these experimental observations[18,19] have shown that illumination of the crystal by a second (uniform) beam in the presence of the soliton leads to guidance of light in the soliton region. Finally, a recent paper predicted the existence of photorefractive vector solitons.[20]

In this Letter we show that quasi-steady-state photorefractive spatial solitons may serve as optical waveguides for other optical beams. Photorefractive solitons are especially attractive for light-induced waveguiding because they form in two transverse dimensions and require very little power (they exist even at microwatts or less). Furthermore, since the nonlinearity is based on space-charge fields that result from charges occupying deep traps, all photorefractive solitons leave behind them a waveguide structure that persists in the dark. One can utilize this memory property further by using the induced waveguides to guide light of nonphotosensitive wavelengths (typically much longer than that of the soliton) that cannot photoexcite the trapped charges. In this scheme a very weak photorefractive soliton beam can guide and control a very intense beam. Another interesting manifestation of the soliton guidance is the evolution from a relatively broad input beam into a narrow channel, where the photorefractive soliton induces a tapered waveguide, or an optical funnel. We study the guidance properties and measure the lifetime of these soliton-induced waveguides. We then use these waveguides to guide a near-infrared beam of intensity 2×10^4 W/cm^2, approximately 5 orders of magnitude larger than that of the soliton beam (roughly 0.1 W/cm^2). Finally, we point out that the two-dimensional soliton trapping properties[7–9,12,13,15] hold the promise of forming light needles (two-dimensional waveguides) in a bulk material. These and related two-dimensional guidance experiments by bright and

0146-9592/95/202066-03$6.00/0

vortex photorefractive solitons are currently under investigation.

Creating optical waveguides with quasi-steady-state photorefractive solitons seems to be preferable to inducing them with the screening (steady-state) solitons for several reasons. First, we have found experimentally that the quasi-steady-state solitons require a lower trapping voltage than the screening solitons in the same material (in $Sr_{0.6}Ba_{0.4}Nb_2O_6$, for example, quasi-steady-state solitons require $\sim$400 V/cm, whereas screening solitons require $\sim$3–4 kV/cm). Second, the quasi-steady-state solitons appear much earlier in time than the screening solitons of the same intensities ($\sim$100 ms versus $\sim$1 s for $\sim$ 1-μW power on a 20-μm bright soliton in SBN). Third, for quasi-steady-state solitons the trapping is independent of the beam intensity (for an intensity much larger than the dark irradiance), while bright screening solitons are narrowest for soliton peak intensities of the order of the dark irradiance.[14,15] This implies that bright screening solitons require uniform background illumination[15,16] to generate artificial dark irradiance; otherwise either their trapping voltages become very large (for peak intensities much larger than the dark irradiance) or their response time (dielectric relaxation time) becomes extremely long (for peak intensities of the order of the dark irradiance). The immediate consequence is that they require much higher total laser powers than the quasi-steady-state solitons do. All these reasons motivate the study of optical guiding with quasi-steady-state solitons.

In this Letter we restrict our experiments to guidance with quasi-steady-state dark photorefractive solitons. It is, however, obvious that the other realizations of these solitons, namely, the one- and two-dimensional bright solitons and the dark vortex solitons, should be explored as well.

We used an experimental setup similar to that shown in Fig. 1 of Ref. 13. For the best guidance results, one needs to capture the index profile that traps the dark solitons by shutting off the illumination at the soliton wavelength at the point in time when they are the narrowest (before screening effects start to take place). Typical times for generating dark solitons at 457-nm wavelength and of $\sim$20-μm size at $\sim$75-μW power are of the order of 700 ms. We generate the soliton waveguides in rhodium-doped SBN:60 by applying negative voltages of ~ -400 V (parallel to the c axis) across the 5-mm-wide crystal. To generate the planar dark solitons we launch a dark notch on an extraordinarily polarized beam that possesses a π phase jump in its center. The notch is obtained by insertion of a thin glass slide in one half of the beam, and the phase is adjusted (until the notch is obtained) by tilting the glass slide. The beam is then focused and enters the crystal with a notch size of 30 μm (FWHM). The output beam is split and monitored by a photodetector (to locate the quasi-steady-state time window) and by a CCD camera (to watch the image of the beam at the crystal output face). A second CCD camera is located above the crystal so that we can image and observe the propagation of the beam throughout the entire crystal length at any given time (in this manner the photographs in Refs. 8 and 12 were taken). A computer-controlled shutter located close to the argon laser output blocks the 457-nm light at the point when the dark soliton is narrowest. A top-view color photograph of the dark soliton is shown in Plate I(a). A careful examination of this plate reveals that the dark notch narrows at the first 2 mm of the crystal and forms a dark funnel before reaching its stationary (nonvarying) soliton size. For comparison, we show in Plate I(b) a color photograph of the dark notch experiencing normal diffraction when no voltage is applied to the crystal.

After the 457-nm beam that generated the dark soliton is blocked, we launch an extraordinarily polarized 633-nm He–Ne laser beam into the induced waveguide. Plate II(a) shows a top-view color photograph of the red beam guided to $\sim$11-μm diameter (FWHM) by the dark (blue) soliton-induced waveguide. The guided beam is funneled from a broader input into a slightly narrower width. In this manner the dark soliton induces an optical funnel that resembles tapered waveguide. For comparison, we show in Plate II(b) a top-view color photograph of the red beam in the normal diffraction regime (zero voltage or ordinary polarization), where the beam diameter (FWHM) at the crystal exit face is 55 μm. Figure 1 shows the profiles of the He–Ne beam at the entrance face of the crystal (left), at the exit face in the normal diffraction regime (no voltage, middle), and when guided by the dark soliton (right).

We have measured the lifetime of the induced waveguide guiding a red He–Ne beam and a 1319-nm Nd:YAG beam as a function of the guided (or probe) beam intensity when the soliton beam is blocked. Since the soliton is formed by a space-charge field that results from charges trapped in deep traps, we expect that at nonphotosensitive wavelengths (typically much longer than that of the soliton) the photoexcitation from the deep traps will diminish and the waveguide will persist for very long times. Some slight degradation is expected since the guided beam will excite charges from shallower traps that will mask (in part) the field generated by the charges trapped in the deep traps. Figure 2 shows the lifetime of the soliton waveguide measured from the moment the soliton beam is blocked as a function of the guided beam intensity for the 1319-nm Nd:YAG beam. The curve follows an accurate inverse-intensity dependence. A similar but much shorter time curve was observed with

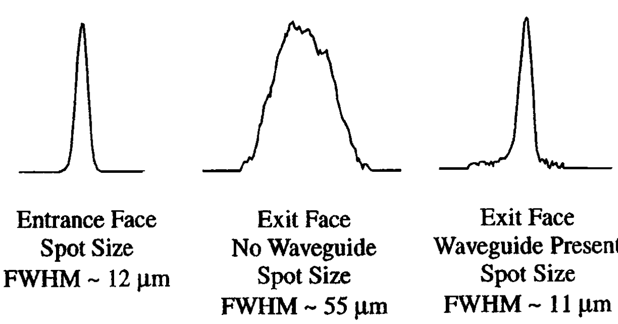


Fig. 1. Profiles of the red He–Ne beam at the entrance face of the crystal (left), at the exit face of the crystal in the normal diffraction regime (no voltage, middle), and when guided by the dark soliton (right).

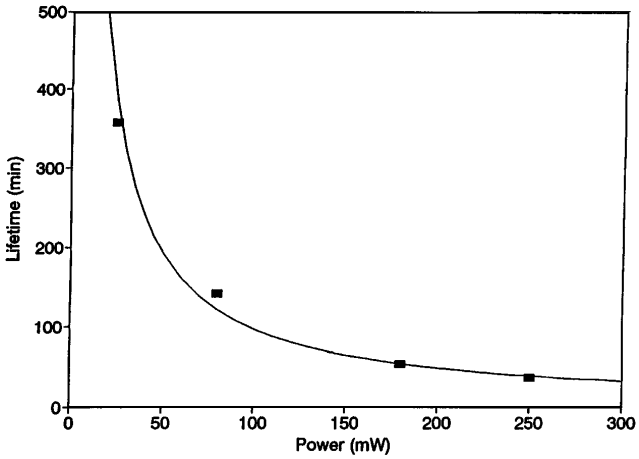


Fig. 2. Lifetime of the soliton-induced waveguide, measured from the moment the soliton is blocked, as a function of the guided beam intensity for a 1319-nm Nd:YAG beam. The lifetime follows an accurate inverse-intensity dependence.

the guided He–Ne beam. In all cases the power of the guided beam greatly exceeds the power of the soliton beam. We expect that a very intense (1-MW/cm^2) guided beam near 1500 nm will not perturb the soliton-induced waveguide if short pulses are used so that no thermal effects are present.

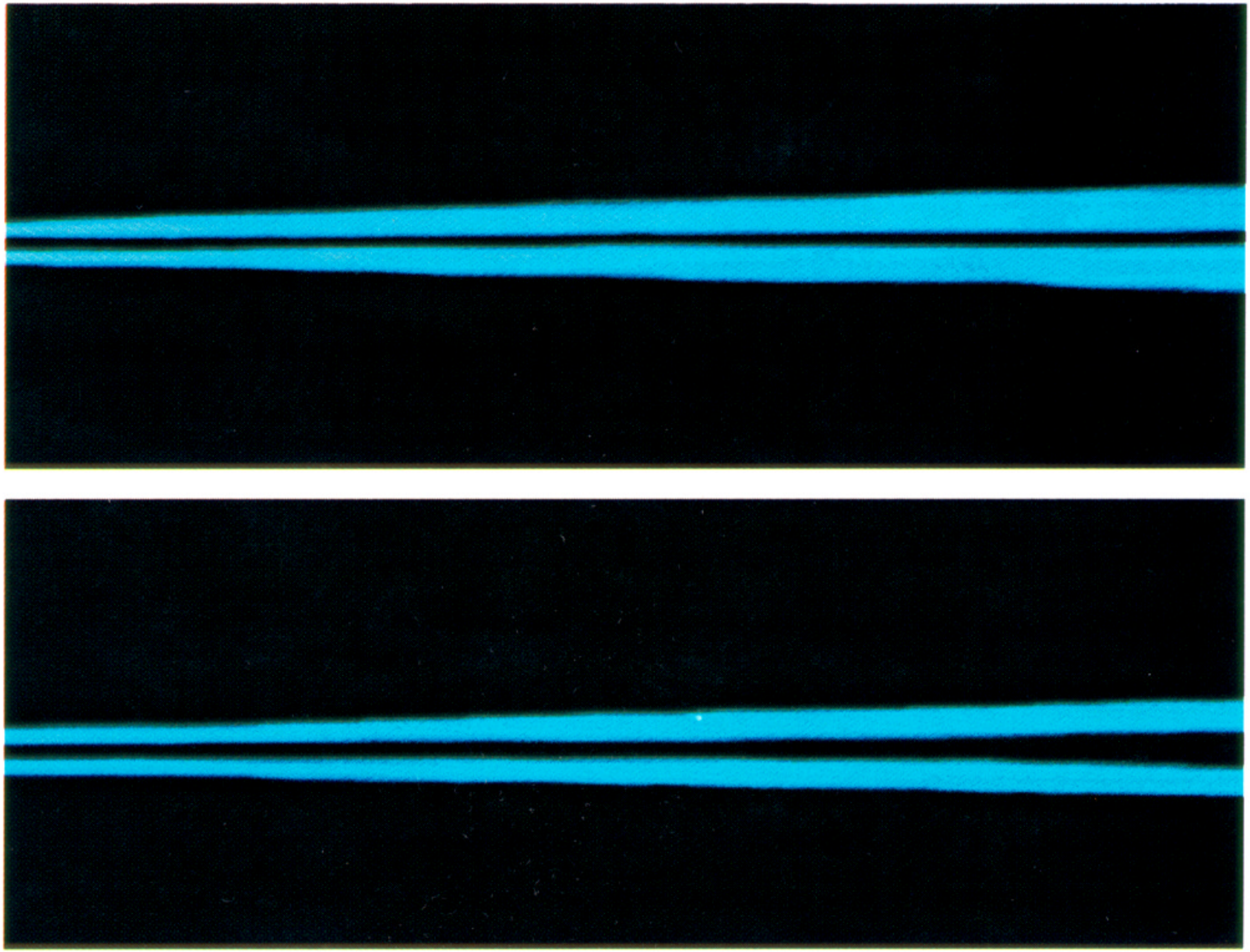
In conclusion, we have demonstrated the use of quasi-steady-state photorefractive dark spatial solitons as waveguides for intense beams of a longer wavelength. Although the soliton is formed by a beam as weak as a few microwatts, it guides near-infrared beams of the order of 1-W power. The waveguides form in a bulk material and persist for a long time after the soliton beam is blocked, even in the presence of an intense near-infrared beam. In current experiments we are testing the possibility of generating two-dimensional waveguides that are based on the ability of photorefractive solitons to trap in both transverse dimensions.

The authors express their gratitude to Bruno Crosignani and Paolo Di Porto of the University of L'Aquila, L'Aquila, Italy, for many useful discussions. M. Segev gratefully acknowledges the support of a Sloan Fellowship and the generous support of Hughes Research Laboratories.

References

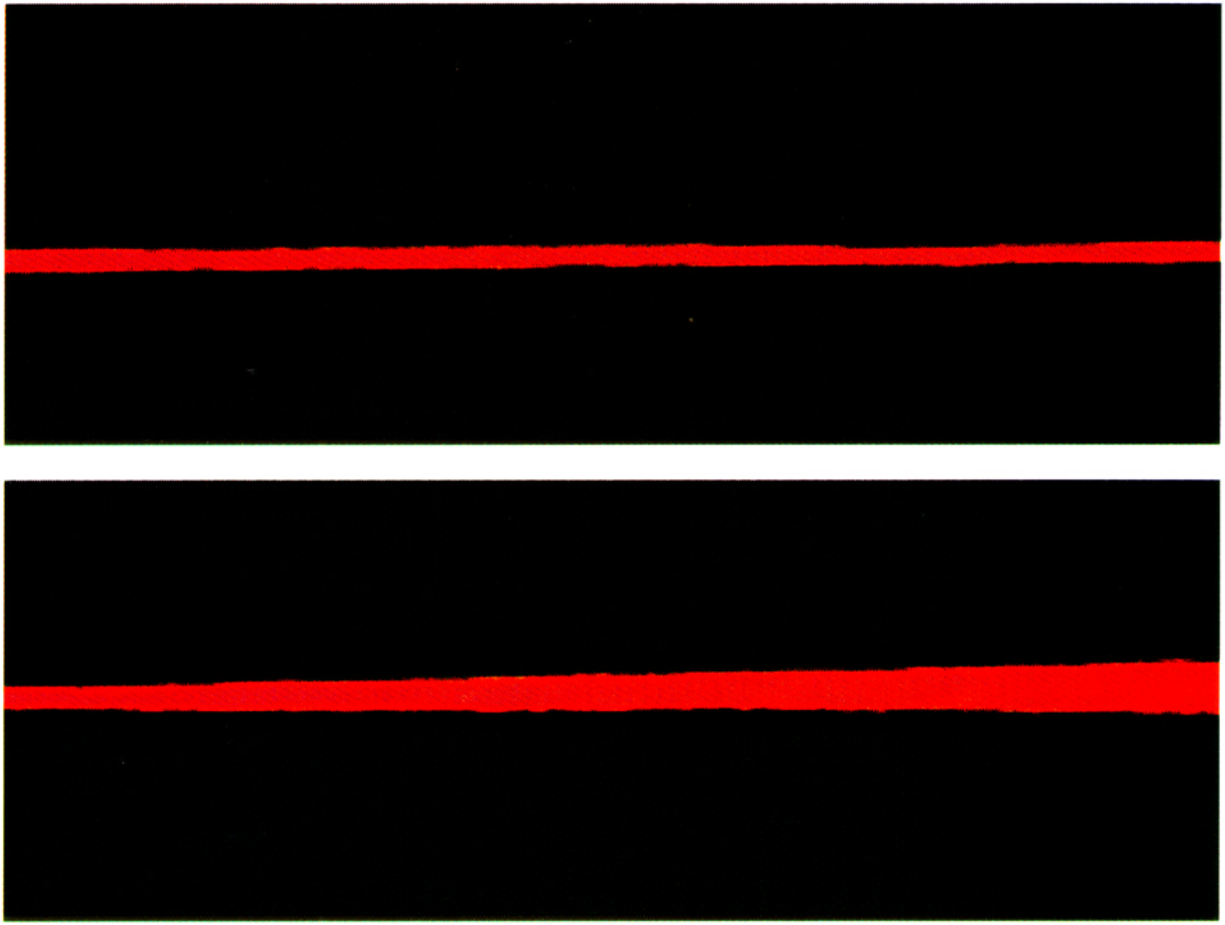
1. R. De La Fuente, A. Barthelemy, and C. Froehly, Opt. Lett. **16,** 793 (1991).
2. B. Luther-Davies and X. Yang, Opt. Lett. **17,** 1755 (1992).
3. C. Bosshard, P. V. Mamyshev, and G. I. Stegeman, Opt. Lett. **19,** 90 (1994).
4. P. V. Mamyshev, A. Villeneuve, G. I. Stegeman, and J. S. Aitchinson, Electron. Lett. **30,** 726 (1994).
5. M. Segev, B. Crosignani, A. Yariv, and B. Fischer, Phys. Rev. Lett. **68,** 923 (1992).
6. B. Crosignani, M. Segev, D. Engin, P. DiPorto, A. Yariv, and G. Salamo, J. Opt. Soc. Am. B **10,** 446 (1993).
7. G. Duree, J. L. Shultz, G. Salamo, M. Segev, A. Yariv, B. Crosignani, P. DiPorto, E. Sharp, and R. R. Neurgaonkar, Phys. Rev. Lett. **71,** 533 (1993).
8. M. Segev, A. Yariv, G. Salamo, G. Duree, J. Shultz, B. Crosignani, P. DiPorto, and E. Sharp, Opt. Photon. News **4**(12), 8 (1993).
9. G. Duree, G. Salamo, M. Segev, A. Yariv, B. Crosignani, P. DiPorto, and E. Sharp, Opt. Lett. **19,** 1195 (1994).
10. M. Segev, A. Yariv, B. Crosignani, P. DiPorto, G. Duree, G. Salamo, and E. Sharp, Opt. Lett. **19,** 1296 (1994).
11. D. N. Christodoulides and M. I. Carvalho, Opt. Lett. **19,** 1714 (1994).
12. M. Segev, G. Salamo, G. Duree, M. Morin, B. Crosignani, P. DiPorto, and A. Yariv, Opt. Photon. News **5**(12), 9 (1994).
13. G. Duree, M. Morin, G. Salamo, M. Segev, B. Crosignani, P. DiPorto, E. Sharp, and A. Yariv, Phys. Rev. Lett. **74,** 1978 (1995).
14. M. Segev, G. C. Valley, B. Crosignani, P. DiPorto, and A. Yariv, Phys. Rev. Lett. **73,** 3211 (1994).
15. M. Shih, M. Segev, G. C. Valley, G. Salamo, B. Crosignani, and P. DiPorto, Electron. Lett. **31,** 826 (1995).
16. Observations of steady-state self-focusing effects in $Bi_{12}TiO_{20}$ were presented by M. D. Iturbe-Castillo, P. A. Marquez-Aguilar, J. J. Sanchez-Mondragon, S. Stepanov, and V. Vysloukh, Appl. Phys. Lett. **64,** 408 (1994).
17. G. C. Valley, M. Segev, B. Crosignani, A. Yariv, M. M. Fejer, and M. Bashaw, Phys. Rev. A **50,** R4457 (1994).
18. M. Taya, M. Bashaw, M. M. Fejer, M. Segev, and G. C. Valley, Phys. Rev. A **52,** 3095 (1995). This observation was also reported by G. C. Valley, M. Segev, A. Yariv, M. Taya, M. Fejer, M. Bashaw, B. Crosignani, and P. DiPorto, "Spatial photovoltaic and screening solitons in photorefractive materails," in *Proceedings of IEEE Conference on Nonlinear Optics* (Institute of Electrical and Electronics Engineers, New York, 1994).
19. M. D. Iturbe-Castillo, P. A. Marquez-Aguilar, J. J. Sanchez-Mondragon, S. Stepanov, M. B. Klein, and B. A. Wechsler, presented at Optical Society of America Annual Meeting, Dallas, Tex., October 4–10, 1994, paper WD4.
20. M. Segev, G. C. Valley, S. R. Singh, M. I. Carvalho, and D. N. Christodoulides, Opt. Lett. **20,** 1764 (1995).

(a)



(b)

Plate I. Top-view color photographs of (a) the dark soliton and (b) the normally diffracting dark notch when the voltage applied to the crystal is set to zero.



(a)

(b)

Plate II. Top-view color photographs of (a) the guided red He-Ne beam and (b) the red beam in the normal diffraction regime.