Dimensionality and size of photorefractive spatial solitons

Galen Duree and Gregory Salamo

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

Mordechai Segev* and Amnon Yariv

California Institute of Technology, 128-95, Pasadena, California 91125

Bruno Crosignani and Paolo Di Porto

Dipartimento di Fisica, Università dell'Aquila, L'Aquila, Italy, and Fondazione Ugo Bordoni, Roma, Italy

Edward Sharp

Army Research Laboratory, Fort Belvoir, Virginia 22060

Received March 10, 1994

We study experimentally self-trapping of optical beams in photorefractive media and show that the trapping is inherently asymmetric with respect to the two (transverse) trapping dimensions. We also present experimental results that show how the sizes of the resultant photorefractive spatial solitons are independent (within their range of existence) of the amplitude of the externally applied electric field used to generate them.

Self-trapping of optical beams in photorefractive (PR) media occurs when diffraction is exactly balanced by self-scattering (two-wave mixing) of the spatial (plane-wave) components the soliton beam.[1,2] Intuitively, since diffraction involves accumulation, by each plane-wave component of a beam, of a phase that is linear in the propagation distance, it is desirable to balance the diffraction by nonlinear phase coupling that leaves the complex amplitudes of the plane-wave components unchanged. PR materials, however, typically exhibit amplitude coupling (energy-exchange interaction) that is due to a dominant diffusion transport mechanism for the redistribution of the photogenerated charge carriers, which, inherently, cannot compensate for diffraction since it alters the amplitudes of the plane-wave components rather than balancing their phases. The presence of an external bias field, however, can cause strong phase coupling and is therefore required for the formation of PR solitons. We have predicted that PR solitons exist for a well-defined range of external fields, and, within this range, the soliton size (cross section) is independent of this external field. This property is a consequence of the optical nonlinear property of the medium: the perturbation in the refractive index is proportional to the light-induced space-charge fields, which depend primarily on the beam profile.

Our recent observation of what is to our knowledge the first PR spatial solitons[3,4] revealed, among a variety of features (such as independence of the absolute light intensity), that, unlike the Kerr-like solitons, the PR solitons may be trapped in two transverse dimensions and maintain their stability. We have also shown theoretically and experimentally[5] that the PR solitons are stable for perturbations in their waveforms that are much smaller (in size) than their transverse cross sections but break down for perturbations that are comparable with their cross sections. Our theoretical model, however, is at this point limited to a single transverse dimension and cannot fully explain the trapping in two transverse dimensions.

In this Letter we present experimental results that address the two-transverse-dimensional problem and point out where a one-dimensional analysis is valid. Furthermore, we find experimentally, in agreement with our predictions,[1,2] that the size of the PR soliton is independent (within the range of its existence) of the externally applied voltage used to generate it.

First, we address the trapping in two transverse dimensions. Assuming the anisotropy of the PR medium to be negligible, the only remaining asymmetry between the transverse dimensions can be associated with the direction of the external field. With this in mind, we recall that the influence of the external field is maximal for gratings whose **K** vectors are parallel (or antiparallel) to its direction and vanishes for gratings that are perpendicular to it. Consequently, we study the behavior of a beam that is narrow in one transverse dimension but very wide (virtually uniform) along the other direction, and we expect to observe a fundamental difference between self-trapping of beams that are uniform in the direction of the applied field and those that are uniform in the direction perpendicular to it. We perform this qualitative experiment using the setup shown in Fig. 1 of Ref. 3. As described there, the solitons are observed in a quasi-steady state, that is, after the gratings have been formed but before the external voltage has been screened. Our experimental observations indicate that the typical time for screening is roughly 2 orders of magnitude larger than the soliton formation time. By use of low in-

0146-9592/94/161195-03$6.00/0

tensities (of the order of 10 mW/cm^2) and complete elimination of beam fanning, this quasi-steady-state time window is now significantly larger than in Ref. 3 and exceeds 5–10 s in our Rhodamine-doped SBN:60 crystal. We identify the directions parallel and perpendicular to the direction of the external voltage with the transverse x and y axes, respectively, and recall that they correspond to the crystalline **c** and **a** axes, respectively. We employ a cylindrical lens to launch beams that are uniform in one transverse dimension and narrow in the other.

The experimental observations are shown in Fig. 1. In all the experiments the direction of the external field is kept parallel to the x axis and the beam is always extraordinarily (x) polarized. We also try to keep the location of propagation in the crystal as fixed as possible, since different locations sometimes require small modifications in the external voltage, which we want to keep fixed. First we examine trapping effects for an input beam that is uniform in the x direction (roughly 2 mm long) and narrow in the y direction (~50 μm wide). The grating's **K** vectors are perpendicular to the direction of the external field, and therefore the external voltage cannot influence the beam. In agreement with this intuitive picture, Fig. 1(a) shows the narrow (y) cross sections of the input and output beams. As Fig. 1(a) clearly shows, self-trapping was observed neither in the ordinary trapping fields nor at very high fields (~4 kV/cm). This observation indicates that a beam that is uniform in the direction parallel to the external field cannot be trapped. Next, we rotate the cylindrical lens and obtain an input beam that is uniform in the y direction and narrow in the x direction [Fig. 1(b)]. Unlike in the first case, the beam now can be easily trapped by fields as low as 400 V/cm and also exhibits transient trapping at high voltages (~4 kV/cm) in a manner similar to the one described in Ref. 3. The corresponding input and output beams' narrow (x) cross sections are shown in Fig. 1(b). Next we replace the cylindrical lens by a spherical lens and launch a circular beam with symmetric cross sections (~50 μm) in both x and y. Trapping is now present in both x and y directions, at fields identical to those of Fig. 1(b), as shown in Fig. 1(c). This implies that the trapping in the y direction relies on tilted gratings, that is, on nonuniform intensity distribution of the input beam, which has a significant projection in the x direction. Thus a beam that is narrow in the direction parallel to the external field can be trapped in either one or in two directions, at exactly the same external field. These observations emphasize the asymmetry between the transverse dimensions, as imposed by the vectorial nature of the external field.

Next we investigate the connection between the soliton cross section and the amplitude of the external field. We have shown theoretically in Refs. 1 and 2 that solitons exist in a rather narrow range of external fields, the values of which depend on the PR material properties, such as electro-optic coefficient, dielectric constant, density of traps, and refractive index and on the state of polarization of the beam. This was also experimentally verified and described in Ref. 3, in which the field ranged between 400 and 600 V/cm. An exception was the so-called high-voltage or transient soliton, for which the applied field was much higher than the upper value allowed, so that solitons were not observed in the quasi-steady state. Instead, in the transient regime, however, the space-charge field builds up inside the crystal and permits formation of solitons during the time interval when its values go through the allowed field region. In this part of the Letter we do not deal with transient solitons and restrict our experiments to low fields within the allowed region. According to the initial predictions,[1,2] the size of the PR soliton is independent of the value (amplitude) of the external field, provided that it is within the allowed region. Here we present experimental verification of the theoretical results.

At this point, the external field is held at 200 V/cm (the allowed region in the current experiment ranges from 200 to 400 V/cm), and we examine the propagation of circular-input spatial solitons of different sizes by varying the boundary conditions only, i.e., the diameter of the input beam. We recall that the transverse phase of the soliton is always uniform[2,3] and that any input beam of a nonuniform phase evolves into the soliton waveform. Therefore we first examine solitons that are launched with a uniform transverse phase and hence do not require evolution. We accomplish this by launching a Gaussian beam whose waist is always located at the input face of the crystal. We obtain the variation in the cross section of the input beam by using a set of different lenses and placing the waist generated by each lens at the entrance face of the crystal in each measurement. With the specific field of 200 V/cm we are able to trap beams of cross sections between 30 and 90 μm, in a 6-mm-long crystal. Narrower solitons require higher fields, and for broader beams diffraction is small for our crystal

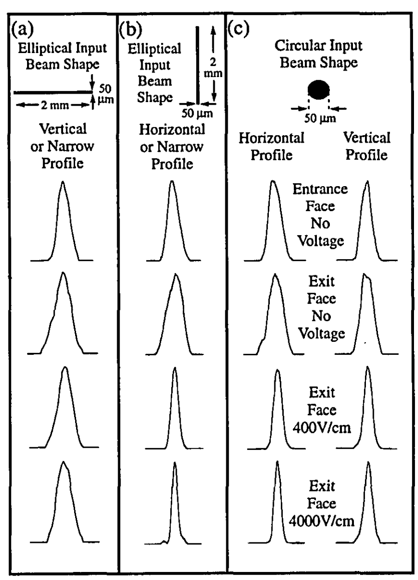

Fig. 1. Narrow profiles of an asymmetric beam focused by a cylindrical lens and elongated (a) parallel and (b) perpendicular to the direction of the external field and (c) the profiles of a circular input beam. The waveforms are normalized to the maximal amplitudes.

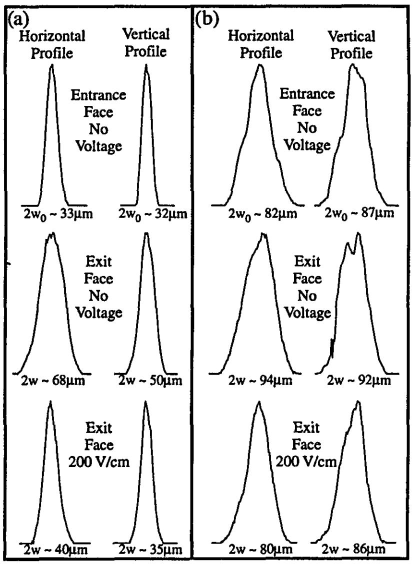

Fig. 2. Horizontal and vertical profiles of input (upper), diffracted output (middle), and self-trapped (lower) beams of (a) 35-μm and (b) 85-μm minimal waists, which are located at the input plane. The waveforms are normalized to the maximal amplitudes, and the spot sizes are determined through a Gaussian fit.

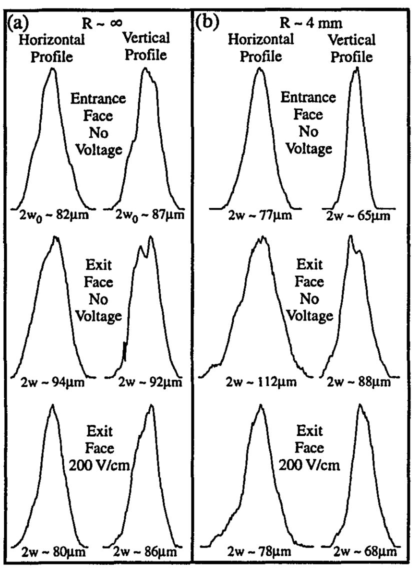

Fig. 3. Horizontal and vertical profiles of input (upper), diffracted output (middle), and self-trapped (lower) beams with a similar spot size (~80 μm) but with different radii of curvature [(a) infinity, (b) 4 mm] at the entrance face. The waveforms are normalized to the maximal amplitudes, and the spot sizes are determined through a Gaussian fit.

length, so that the comparison between self-trapping and diffraction yields an insignificant difference. A typical observation is presented in Fig. 2, in which the input, the diffracted output, and the self-trapped output are shown for input beam minimal waists of ~35 μm [Fig. 2(a)] and ~85 μm [Fig. 2(b)]. Our observations clearly indicate that the diameter of the soliton beam is not unique for a specific (allowed) value of the external field but rather depends on the diameter of the input beam and evolves into the solution that is the closest to the boundary condition.

Finally, we study the role of a nonuniform input phase on the formation of a PR soliton. We therefore vary the quadratic phases of the input beams investigated above and examine the self-trapping effects at the same (fixed) external field of 200 V/cm. Our observations indicate that the soliton formation takes place at the same values of external field, regardless of the quadratic input phase. This is illustrated in Fig. 3, which shows self-trapping with an input beam spot size of ~80 μm and two different radii of curvature (R): infinity [Fig. 3(a), which is identical to Fig. 2(b)] and 4 mm [Fig. 3(b)]. We investigate the transverse phase of the output soliton beam by imaging the output face of the crystal and find that the image is formed in accordance with a uniform transverse phase of the output beam. This behavior may be viewed as a manifestation of the stability of the PR solitons,[5] since the transversely nonuniform (quadratic) phases of the input beam evolve into uniform phases during the propagational evolution of the soliton beam. We find that larger quadratic phases, which require a more dramatic evolution stage for the soliton formation, result in solitons that differ in size from the original cross section. Clearly, since the soliton size is determined primarily by the input cross section and is not unique for a given external field, large phase deviations from the uniform solitary phase require evolution into a final soliton waveform and may lead to a soliton beam of a width that is different from the input width. Although such evolution effects were observed mainly in the transient regime of high external voltages,[3,4] they may be present even at lower fields.

In conclusion, we have shown that self-trapping of optical beams in photorefractive media is inherently asymmetric with respect to the two (transverse) trapping dimensions and presented experimental results that show that photorefractive solitons of various cross sections (sizes) are formed at the same value of external field.

*Present address, Department of Electrical Engineering, Advanced Center for Photonics and Optoelectronic Materials and Princeton Material Institute, Princeton University, Princeton, New Jersey 08544.

References

1. M. Segev, B. Crosignani, A. Yariv, and B. Fischer, Phys. Rev. Lett. **68,** 923 (1992).
2. B. Crosignani, M. Segev, D. Engin, P. DiPorto, A. Yariv, and G. Salamo, J. Opt. Soc. Am. B **10,** 446 (1993).
3. 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).
4. M. Segev, A. Yariv, G. Salamo, G. Duree, J. Shultz, B. Crosignani, P. DiPorto and E. Sharp, Opt. Photon. News **4**(12), 9 (1993).
5. M. Segev, A. Yariv, B. Crosignani, P. DiPorto, G. Duree, G. Salamo, and E. Sharp, "Stability of photorefractive solitons," Opt. Lett. (to be published).