Transmission of images through highly nonlinear media by gradient-index lenses formed by incoherent solitons

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Received September 29, 2000

We experimentally demonstrate image transmission through a noninstantaneous self-focusing medium. A partially spatially incoherent soliton is used to form a multimode waveguide in a photorefractive crystal, and the modes of that waveguide are used to transmit an incoherent image through this nonlinear medium.
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OCIS codes: 060.0060, 190.0190, 110.2350, 190.5530.

The transmission of images through phase-distorting and (or) optically nonlinear media has been a challenging task for the past three decades.[1–8] In fact, transmission of even a simply plane wave (or a broad Gaussian beam) suffers from serious problems, because the beam breaks up into filaments with a characteristic width close to that of a spatial soliton under the same conditions of intensity and nonlinearity.[2] Thus far, several methods of image transmission through thick nonlinear media have been demonstrated: forming a spatial soliton from the optical beam itself,[3,4] bleaching the nonlinearity at a particular resonant frequency by means of electromagnetically induced transparency,[5] and employing phase conjugation.[6–8] The first two methods[3–5] actually apply for simple Gaussian-like beams and do not support the transmission of images, whereas phase conjugation[6–8] typically requires a round trip in the nonlinear material. In this Letter we show that a multimode soliton that is formed by spatially incoherent light can be used as a means of image transmission through a thick nonlinear medium.

Optical spatial solitons are formed in nonlinear materials when diffraction is exactly balanced by self-focusing.[3,4] In other words, a soliton is formed when a light beam writes a waveguide in the medium and then gets self-trapped in this waveguiding channel.[9] Until recently, solitons were considered to be solely coherent entities. However, incoherent solitons that are formed by partially incoherent light were recently demonstrated experimentally[10–12] and investigated theoretically.[13–18] Incoherent solitons are multimode or speckled beams for which the instantaneous intensity distribution varies randomly with time. They can exist only in noninstantaneous media, e.g., a nonlinear self-focusing material with a response time that greatly exceeds the characteristic phase fluctuation time of the beam. Such a medium, therefore, responds only to the average intensity of the beam and cannot react to the instantaneous intensity fluctuations. An incoherent soliton is formed when the time-averaged intensity induces a multimode waveguide and traps itself in the waveguide by populating the guided modes in a self-consistent fashion.[10–12]

We show that when the incoherent soliton is sufficiently broad that the number of guided modes is large enough, the waveguide can be used for image transmission. There are two methods that can give rise to such image transmissions through incoherent solitons. The first one is to superimpose, at low visibility, an image on the envelope of the incoherent beam such that the image takes part in the formation of the incoherent soliton. In this case the image is an inherent part of the soliton, and it propagates in a stationary manner, which means that (neglecting absorption) the image transmission length is finite. The second method is to use the induced multimode waveguide in a passive fashion, as a gradient-index lens that enables incoherent light patterns to be transmitted over a finite distance. In this Letter we follow the latter idea; i.e., we use a scheme in which the image does not take part in the soliton formation. This method is much easier to implement because the features of the transmitted images are not restricted to a spatial size that is within the range of existence (multimode) of incoherent solitons.[15,16] The drawback is the finite transmission distance, which is limited by the modal dispersion[1,6]: The maximum distance must be shorter than the inverse of the difference between the propagation constants of lowest and highest populated modes.

It is important to note that only an incoherent image can be transmitted. In the coherent case, destruction of the image information is caused by both modal

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dispersion[1,6] and modulational instability, which lead to filamentation of parts of the image.[2] When the image is incoherent, however, modulational instability occurs only if the nonlinearity exceeds a specific threshold that is set by the degree of coherence (correlation distance).[19,20] If the correlation distance is short enough, all perturbations are suppressed, and the beam propagates in a stable fashion. This idea is what has facilitated the observation of antidark solitons,[21] that is, bright self-trapped beams on nonzero background.[22] Such beams suffer from modulational instability and disintegrate if the background is coherent. The idea also led to the experimental demonstration of a stable bright (1 + 1)D soliton solution in a bulk Kerr-like medium.[23]

We perform our experiments with a photorefractive $Sr_{0.61}Ba_{0.39}Nb_2O_6$ (SBM) crystal and a setup (Fig. 1) that is similar to that used in the first observation of incoherent solitons.[10–12] The crystal's dimensions are $a \times b \times c = 4.8$ mm $\times$ 4.8 mm $\times$ 3.1 mm. The beam is initially split into an ordinarily (o) and an extraordinarily (e) polarized beam. The o beam is used for uniform illumination of the crystal, producing a homogeneous background conductivity. The e beam is used to generate the incoherent soliton and the incoherent image. This beam is made spatially incoherent by being passed through a rotating diffuser, which, in turn, provides a new phase and amplitude distribution every 1 μs, much faster than the response time (1 s) of the nonlinearity. The e beam is then split into two: a soliton-forming beam, which has a smooth, Gaussian-like intensity distribution, and an image beam, which passes through a resolution target and acquires pictorial information. The ratio between the peak intensity of the soliton and the intensity of the background beam is 15. The ratio between the intensity of the soliton and that of the image-bearing beam is 15 as well. The image beam is then combined with the soliton-forming beam, and the beams are launched simultaneously into the crystal, so the crystal input face is at the image plane of the image-bearing beam. A CCD camera monitors the crystal input and output faces.

We control the degree of spatial incoherence of the soliton beam by adjusting the distance of the focusing lens to the diffuser and by changing the size of the aperture. In our experiments we use a ratio of beam diameter to speckle size of $\sim$10. The diameter of the soliton beam on the input face of the crystal is 40 μm (FWHM), which linearly diffracts to 110 μm after 4.8 mm of propagation (Figs. 2a and 2b). When an electric field is applied along the (negative) c axis, charge redistribution leads to partial screening of the field in the part of the crystal illuminated by the soliton beam, which results in a tapered waveguide structure in the regions illuminated by the soliton beam. The soliton forms at a particular field (7.2 kV/cm) at which diffraction is fully compensated for (Fig. 2c).

After the incoherent soliton is formed, the image beam is transmitted by the soliton-induced gradient-index lens. With the help of the resolution target and an additional slit, three spots are imaged onto the crystal's front face (Figs. 2d and 2e). The image beam is adjusted to copropagate with the soliton beam. Without the field, the output image is completely blurred because of natural diffraction (Fig. 2f). The fact that this is a spatially incoherent image actually increases diffraction effects. When the incoherent soliton beam is blocked, but with the field on, the output image beam further deteriorates as a result of the nonlinear behavior of the crystal (Fig. 2g). This beam cannot form a soliton by itself (its modal decomposition is not commensurate with the range of existence of solitons: It has too much power in high modal components). In any case, when the soliton beam is absent, with the applied field or without it, there is always a significant loss of pictorial information. Only when the soliton beam is present and an appropriate field (7.2 kV/cm) is applied is the image information transmitted through the crystal and the former distortions strongly reduced. Typical results of successful image transmission are shown in

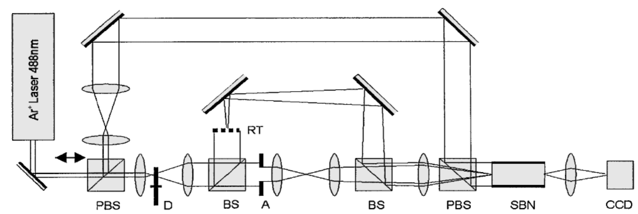

Fig. 1. Experimental setup: PBS's, polarizing beam splitters; D, rotating diffuser; BS's, beam splitters; RT, resolution target; A, aperture; SBN, nonlinear crystal; CCD, CCD camera.

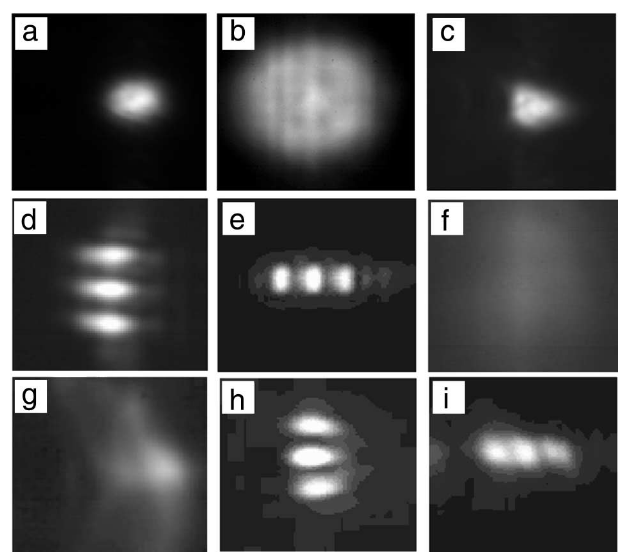

Fig. 2. Images of the soliton and the image beam on the input and output faces of the crystal: a, soliton beam on the input face; b, diffracted soliton beam on the output face without a field; c, trapped soliton beam on the output face for $E = 7.2$ kV/cm; d, e, image beams on the input face; f, diffracted output of the image beam (vertically aligned spots) without a field; g, output of the image beam (vertically aligned spots) with $E = 7.2$ kV/cm but with the soliton beam off; h, i, output of the image beam (vertically and horizontally aligned spots) with $E = 7.2$ kV/cm and the soliton beam on. The picture size is 150 μm $\times$ 150 μm for a–c and 50 μm $\times$ 50 μm for d–i.

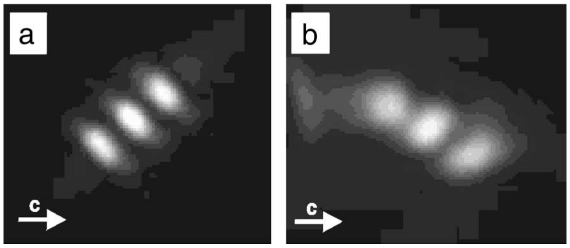

Fig. 3. Image of the three spots aligned at 45° with respect to the c axis: a, image beam on the input face; b, image beam on the output face with $E = 7.2$ kV/cm and the soliton beam on. The c axes are marked by arrows. Picture size is 50 μm × 50 μm.

Figs. 2h and 2i: In both cases a sharp output picture is obtained. Furthermore, in a limited range of the electric field the strength of the induced lens can be tuned, and the focal plane can be moved either inside the crystal (higher field) or outside it (lower field).

Photorefractive crystals are in general anisotropic, so self-focusing is anisotropic as well, thus yielding different focusing powers along the two transverse dimensions. This anisotropy is present in our imaging transmission experiment: When the input image consists of three spots aligned at 45° with respect to the c axis, the image on the output face is mirrored at a plane that contains the c axis; i.e., it is inverted in the direction perpendicular to the c axis and is unchanged in the parallel direction. This behavior is demonstrated in Fig. 3. We identify the plane of inversion by blocking one of the three spots of the input image, e.g., the lower left input spot, in which case the upper left output spot is missing. We believe that this effect occurs because the induced lens is stronger (has a shorter focal length, $f_{\|}$) in the direction of the c axis, whereas it is weaker (longer focal length, $f_{\perp}$) in the perpendicular direction. Because of the stronger focusing power in the c direction, we have at least one extra inversion (or three, or five, and so on) of the image in the direction of the c axis. When we assume that the anisotropy is not too large (i.e., $|f_{\perp}^{-1} - f_{\|}^{-1}|$ is small), the ratio of the focusing powers will have to be a rational number of the form $f_{\perp}/f_{\|} = (2s)/(2s-1)$, where s is a small integer. In the simplest case, the focal length of the gradient-index lens parallel to the c axis ($f_{\|}$) is half of that perpendicular to it ($f_{\perp}$). Therefore, to obtain a correct two-dimensional imaging of the input at the output face, one must fulfill the above condition within the range of existence of the incoherent soliton that forms the gradient-index lens.

In summary, we have shown that the transmission of images through self-focusing optical media is possible by use of a gradient-index lens induced by an incoherent soliton if the nonlinearity is noninstantaneous. This method works well only for finite propagation distances as long as intermodal dispersion, between the guided modes of the soliton-induced waveguide, does not destroy the image. We are currently investigating the even more promising possibility of superimposing the incoherent image as an integral part of the envelope of an incoherent soliton, a method that should guarantee stationary (indefinite) diffraction-free and distortion-free propagation.

This research was funded by the Multidisciplinary University Research Initiative program, the Israeli Ministry of Science, the Deutsche Forschungsgemeinschaft, and the State of Niedersachsen, Germany. D. Kip's e-mail address is dkip@uos.de.

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