Self-Trapping of Partially Spatially Incoherent Light

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We report the first observation of self-trapping of a spatially incoherent optical beam in a nonlinear medium. Self-trapping occurs in both transverse dimensions, when diffraction is exactly balanced by photorefractive self-focusing. [S0031-9007(96)00610-2]

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Optical spatial solitons have been extensively studied during the last three decades[1]. Self-trapping of optical beams occurs when diffraction is exactly balanced by self-focusing due to an optical nonlinearity [2]. Self-focusing was first studied in gases [3], fluids [4], and solids [5] which possess Kerr-like nonlinearities. It has been found that self-trapping of a two dimensional beam in Kerr media is unstable, which leads to catastrophic self-focusing [6] and eventually to beam breakup. Furthermore, even self-trapping of a one dimensional beam in a bulk Kerr medium is unstable: It suffers from transverse instabilities that lead to beam breakup and filamentation [7]. Thus only self-trapping of a one dimensional beam in a slab waveguide is stable in a Kerr medium [5]. Theoretical studies have shown that saturable Kerr media should be able to support stable self-trapping of a two dimensional beam [8]. The first observation of stable two dimensional bright spatial solitons was found in a different nonlinear medium: photorefractive crystals [9,10]. More recently a two dimensional beam was trapped using a nonlinearity based on cascaded $\chi^{(2)}$ effects where a fundamental and second harmonic beam interact and trap each other [11]. All of these experimental observations and theoretical studies investigated self-trapping of spatially coherent light beams only. In other words, knowing the phase at a given point on the self-trapped beam, one can predict the phase at any point across that beam.

In this Letter we report the first observation of self-trapping of a "partially" spatially incoherent optical beam in a nonlinear medium. We have used the photorefractive nonlinearity associated with photorefractive solitons as the self-trapping mechanism and generated a stable, two dimensional, 30 μm wide, spatially incoherent self-trapped beam. Knowing the phase at a particular point on the self-trapped beam one can predict the phase only at a very short distance (much less than the beam width) away from that point. In other words, the correlation distance is much shorter than the width of the self-trapped beam. Thus this self-trapped beam can be considered as a quasi-homogeneous spatially incoherent beam [12,13].

Diffraction of a spatially incoherent light beam is very different from that of a spatially coherent beam. In a spatially coherent beam the complex amplitudes of the field at all points across the beam vary in unison with time and are therefore phase correlated at all times. In a spatially incoherent beam, the field amplitudes at all points vary in time in a completely uncorrelated fashion. Thus diffraction from a coherent source is given by a Fresnel integral over the complex amplitude of a beam, while diffraction of a spatially incoherent beam is given by an integral over the *time average* of the modulus square of its complex amplitude (intensity). Intermediate cases of partially spatially incoherent beam are characterized by a finite (nonzero) correlation distance τ, which is the average distance across the beam between two phase-correlated points. When τ is much smaller than the beam diameter, the beam can be considered as a quasihomogeneous spatially incoherent beam and its diffraction angle is determined mainly by τ. The angle is equivalent to the diffraction angle of a coherent beam from an object (feature) equal in size to a speckle defined by τ. For this reason, diffraction of a spatially incoherent beam is larger than that of a spatially coherent beam of the same width, i.e., the spatially incoherent beam diverges much faster. Therefore, self-trapping of a spatially incoherent beam requires stronger optical nonlinearities than self-trapping a spatially coherent beam.

The choice of the optical nonlinearity used for self-trapping of a spatially incoherent beam is driven by several considerations. The most important issue is the available light sources. We employ the method of converting a laser source into a quasithermal quasimonochromatic lamp using a dense scattering medium (diffuser) rotating on a time scale much faster than the response time of the nonlinear medium [14]. This method is commonly used for optical image processing purposes with spatially incoherent light for which the diffuser must vary in time much faster than the response time of the camera or the photographic plate can respond [15]. The diffuser generates irregular deformations of the wave front thus giving a sum of random contributions from various parts of the diffuser at any distant point. When the diffuser is rotated, the optical field changes randomly with time thus giving a fluctuating intensity equivalent to thermal light [12]. This rotating diffuser method provides random phase fluctuations that vary on a time scale associated

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with a mechanical rotation. This implies that in order for the medium to respond to this beam as a spatially incoherent beam, its response time must be much longer than the phase variation's characteristic time. The rotating diffuser for our experiment creates an independent spatial picture every 1 μs; it is thus required that the nonlinear medium have a response time much longer than this. Since the response time of photorefractive materials can be controlled by the beam intensity (0.1 sec for 1 W/cm^2 intensity in SBN crystals) and for their ability of self-trapping a two dimensional coherent beam, we have chosen this nonlinearity to perform the self-trapping of spatially incoherent light.

It is the noninstantaneous nature of the photorefractive effect that allows self-trapping to occur with low power densities thus allowing use of existing sources. The self-focusing mechanism for incoherent light in photorefractive media is similar to the effects supporting photorefractive screening solitons. An optical beam causes excitations from midgap states into the conduction band and an external field causes the electrons to drift in one direction leaving immobile positively charged donors behind. As the electrons drift into darker regions of the beam they start to fall back into the midgap. This creates a charge variation leading to a space charge field that partially screens the external field, depending on the local light intensity. The resulting field modulates the refractive index via the electro-optic (Pockels') effect. The optical beam thus creates an electric space-charge field that induces an effective graded-index waveguide which, in a self-consistent manner, is able to guide the beam itself. It is important to note that intensity variations drive the process, and phase differences across the beam are unimportant. Because of this nature of the nonlinearity, spatially and temporally incoherent beams should be trappable. The theory of self-trapping with partially incoherent light has yet to be developed.

The experimental setup is shown in Fig. 1. A 488 nm cw argon laser beam is split by a polarizing beam splitter. The ordinarily polarized beam is expanded and used as a background which illuminates the crystal uniformly and generates a bias level of electrons in the conduction band that optimizes the photorefractive self-focusing (see Ref. [10]). The extraordinarily polarized beam is sent through a rotating diffuser generating a partially spatially incoherent light source. The diffuser is rotating with a period much shorter than the response time of the photorefractive crystal. The beam is then sent through an aperture to reduce spherical aberrations and then to a focusing lens. The beam is recombined with the background beam and sent through a photorefractive SBN:75 crystal, propagating along its crystalline *a* axis with the polarization parallel to the *c* axis. Self-focusing occurs with the application of an appropriate voltage (magnitude and polarity) which gives rise to a space charge field that has a large component along the *c* axis,

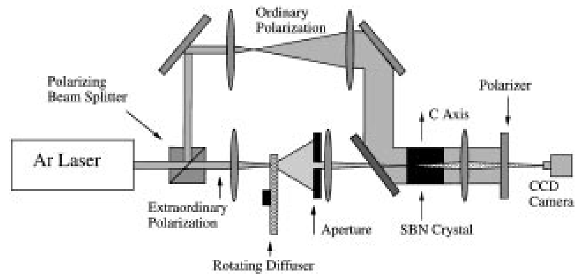

FIG. 1. The experimental setup.

thus using the $r_{33} = 1022$ pm/V electro-optic coefficient to create the index change required for self-trapping. A lens is used to image the extraordinarily polarized beam at the input and output faces of the crystal onto a charge coupled device (CCD) camera. In addition, we use a top-view imaging system to monitor the beam as it propagates throughout the crystal.

The coherence properties of the self-trapped beam are examined by rotating the polarization of the beam to be ordinarily polarized (with a wave plate) and interfering it with the background beam. When the diffuser is stopped, one can clearly see interference fringes superimposed upon a speckle pattern. When the diffuser is rotating and the interference pattern is monitored with a camera whose response time is roughly 3 msec (100 times faster than that of the photorefractive crystal at intensity 3 W/cm^2) no interference or speckles can be observed since all the phase information is washed out [16]. Figure 2 shows photographs of these two states.

In our experiments we control the degree of spatial coherence of the optical beam at the input face of the nonlinear crystal by adjusting the lens (located before the rotating diffuser) and the aperture right before the focusing lens. By adjusting the position of the lens and/or the size of the aperture, we adjust the ratio between the speckle size and the beam width at the crystal input face. The diffraction from the circular aperture forms Airy rings, whose visibility provides information about the speckle size and thus the correlation distance [12]. The self-trapping experiments are performed using input beams with a diameter to speckle size ratio of roughly

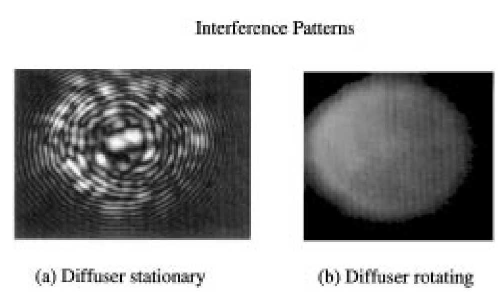

FIG. 2. Photographs of interference patterns of the self-trapped beam and the background beam (a) with diffuser stationary and (b) with diffuser rotating.

8. The size of the beam at the crystal input face is 30 μm (FWHM) which diffracts, in the absence of self-trapping, to 102 μm (FWHM) after 6 mm of propagation in the crystal. The large diffraction of this spatially incoherent beam demonstrates the difference from a spatially coherent beam, which would have diffracted to 35.75 μm (FWHM) in the same crystal length (refractive index $n_e = 2.3$). Applying 550 V between the electrodes separated by 6 mm results in self-trapping of the beam, which now maintains a constant width of 30 μm.

Figure 3 shows horizontal and vertical beam profiles of the input beam, diffracted output beam at zero voltage, and the self-trapped beam at 550 V. Figure 4 shows top view photographs of the self-trapped (above) and the normally diffracting (below) beams. The input widths of both beams in these photographs appear larger than in reality due to the limited dynamic range of the camera and the need to view the beam throughout the slightly absorbing crystal, which causes some saturation near the input, making it appear somewhat wider.

We point out that, since the nonlinear medium responds *only* to the time-average intensity pattern, it does not "see" the rapidly varying speckle pattern shown in Fig. 2(a). Instead, it responds to the smooth time-averaged pattern of Fig. 2(b). However, if we stop the diffuser such that the speckled pattern becomes stationary with time, and apply a voltage across the crystal, the nonlinear response leads to very strong filamentation: The beam breaks up into randomly organized multiple filaments that cross each other and intersect throughout propagation. Each speckle forms a filament which exists only for a short distance before it is intersected by other filaments. When the diffuser is again rotated much faster than the response time of the nonlinear medium, the filaments disappear and a single self-trapped beam reappears, as described above and as shown in Figs. 3 and 4. Thus although the self-trapped beam is composed of many (randomly varying) coherent components, their time-averaged intensity is a smooth single beam that induces a single smooth waveguide (via the photorefractive effect) and guides itself in a self-consistent manner. At any given instant, however, the guided beam is a speckled beam.

We have performed a series of similar experiments with other quasihomogeneous spatially incoherent beams and found that self-focusing and self-trapping of these beams in photorefractive media are dominated by four parameters: the beam diameter, the speckle size on the beam (or the correlation distance across the beam), both determining the beam's diffraction, the applied field, and the ratio of the beam peak intensity to the intensity of the background beam. For a fixed voltage, the size of the self-trapped beam increases as the ratio between its peak intensity and the background intensity is increased, for ratios larger than unity. It seems that, in a given crystal, a circular self-trapped beam exists within a narrow range of applied field for a given speckle size, beam diameter, and intensity ratio. This phenomenon is qualitatively similar to that obtained for two dimensional photorefractive screening solitons (i.e., with spatially coherent light). Small deviations from this existence curve yield elliptical beams, while larger deviations do not support self-trapping. Larger applied fields overcompensate diffraction and the beam undergoes continued focusing, and lower fields do not fully compensate diffraction. We expect that this dependence of the width of the self-trapped beam on the speckle size, applied field, and intensity ratio will be useful in formulating the theory of self-trapping of spatially incoherent beams in photorefractive media.

It is now useful to compare the strength of the nonlinearity required for self-trapping of the spatially incoherent beam in our experiment to that of a spatially coherent beam. The most meaningful characteristic of

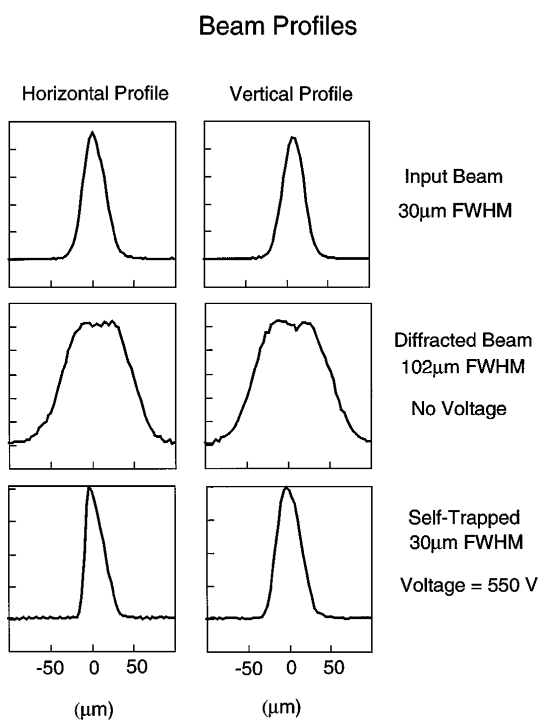

FIG. 3. Horizontal and vertical profiles of the input beam, diffracted output beam at zero voltage, and the self-trapped output beam at 550 V.

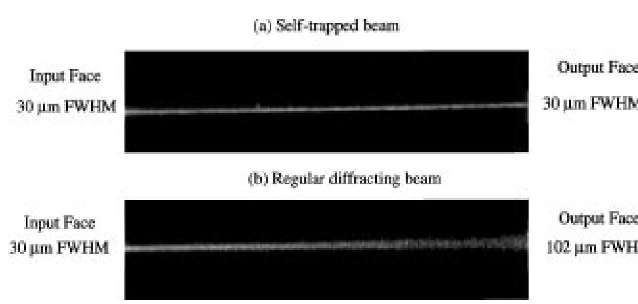

FIG. 4. Top view photographs of the self-trapped (above) and normally diffracting (below) beams.

the incoherent beam is its (far field) angle of diffraction, which is roughly 16.7 mrad. This angle is also the diffraction angle of a coherent 4.85 μm (FWHM) Gaussian beam. Using the theory of steady-state photorefractive screening solitons [17], we estimate that self-trapping of this 4.85 μm (FWHM) coherent beam, at intensity ratio roughly three, requires a refractive index difference of roughly 9×10^{-4} (between the center of the soliton and the margins of the beam). Comparing this to the refractive index charge induced by the electro-optic effect using the parameters of our crystal and the applied field, we find an index change of roughly 5.7×10^{-4}, which gives reasonable agreement. Thus the magnitude of the nonlinearity required to self-trap a spatially incoherent beam is close to that required to trap a coherent beam of the same diffraction angle. We point out, however, this is merely a qualitative estimate and the full theory of self-trapping of spatially incoherent light, including the actual structure of the correlation function characterizing the self-trapped beam, is yet to be developed.

In conclusion, we have reported the first observation of self-trapping of a spatially incoherent optical beam in a nonlinear medium.

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