Waveguides formed by incoherent dark solitons

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We demonstrate experimentally optical guidance of coherent light beams, using incoherent light. Such guidance is made possible by generation of partially spatially incoherent self-trapped dark beams (dark incoherent solitons) in a noninstantaneous nonlinear medium. In the one-dimensional case, the incoherent solitons induce single and Y-junction planar waveguides, whereas in the two-dimensional case, they form circular waveguides. These experiments introduce the possibility of controlling high-power laser beams with low-power incoherent light sources such as LED's or lightbulbs. © 1999 Optical Society of America

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Optical spatial solitons are considered to be among the prime candidates for controlling light by light. Since the demonstration of Kerr-type spatial solitons and their ability to guide and switch other beams,[1,2] there has been an increasing interest in soliton-induced waveguides and their applications. In particular, recent work on self-trapping and light guiding in various three-dimensional saturable nonlinear materials[3] opened up several avenues for possible applications of spatial solitons in optical interconnects, optical communications, and other areas. For instance, spatial switching with quadratic solitons[4] and directional couplers based on photorefractive soliton-induced waveguides[5] have been demonstrated. More recently, soliton-induced waveguides were even employed to achieve high-efficiency frequency conversion in nonlinear $\chi^{(2)}$ photorefractive media.[6]

For decades, solitons have been exclusively considered to be coherent entities, and optical solitons have been studied only with intense coherent light beams. Nature, however, is full of incoherent radiation sources. Can incoherent light also form a soliton and thus induce a waveguide? This intriguing and challenging question recently motivated several experiments[7,8] on self-trapping of incoherent light. A series of experimental and theoretical studies[7–12] clearly demonstrated that incoherent spatial solitons are indeed possible in slow-responding nonlinear media such as biased photorefractives. This brings about the interesting possibility of using low-power incoherent light beams to form solitons that can guide and control other high-power coherent laser beams.

A spatially incoherent beam is a speckled multimode beam of which the instantaneous intensity pattern consists of many speckles that vary randomly in time. In general, such an incoherent beam would not be able to self-trap in an instantaneous nonlinear environment, as each individual speckle forms a small lens, which in turn captures a small fraction of the beam. This eventually leads to a speckle-induced instability or beam fragmentation. However, this beam fragmentation can be avoided in noninstantaneous nonlinear media in which the nonlinearity responds to the time-averaged intensity. In fact, in a medium with a noninstantaneous response, self-trapping of an incoherent beam is achievable, as was demonstrated in photorefractives first by use of partially spatially incoherent light and then by use of fully (temporally and spatially) incoherent white light.[7] Following this work, much effort was dedicated to theoretical understanding of bright incoherent solitons.[9–11] On the other hand, self-trapping of incoherent dark beams, that is, of incoherent light beams that contain either a one-dimensional (1-D) dark stripe or a two-dimensional (2-D) dark hole in their optical intensity, has also been realized in experiments with a partially spatially incoherent source.[8] Although self-trapping of dark incoherent beams was first found numerically through the coherent density approach, the underlying mechanism remained unclear until a self-consistent modal approach was developed.[12] It is now understood that an incoherent bright soliton can have many modes populating its induced waveguide,[10] whereas an incoherent dark soliton results from a combination of radiation modes and bound states.[12] In either case, one can expect that the light-induced variation of the refractive index will form a waveguide structure in the self-trapped region.

In this Letter we report the experimental observation of waveguides induced by incoherent dark solitons. These induced waveguides allow optical guidance of other beams that may be coherent or incoherent. When the nonlinearity is of the photorefractive type, the guided beams can be very intense if

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they are at a less-photosensitive wavelength.[13–15] In this case, even a weak incoherent light beam can guide a strong coherent laser beam.

In our experiments we first convert a coherent beam from an argon-ion laser ($\lambda = 514$ nm) into a quasi-monochromatic spatially incoherent light source by passing it through a rotating diffuser.[7,8] The laser beam is focused by a lens onto the diffuser, and the scattered light from the diffuser is collected by another lens. The rotating diffuser provides random phase fluctuations, thus making the beam partially spatially incoherent. The spatial degree of coherence of this beam is revealed by the average size of the speckles borne on it. One can actually trace the temporally varying speckles with a fast camera, or, as we do here, monitor the beam when the diffuser is stationary. We then launch the speckled beam onto a phase or an amplitude mask and redirect the reflected dark beam onto the input face of a photorefractive crystal in a way similar to that previously followed in generating coherent dark screening solitons.[14–16] The photorefractive crystal used here is a 12-mm-long strontium barium niobate crystal grown at Stanford University by use of the vertical Bridgeman method. We first generate a 1-D incoherent dark stripe from a phase mask (odd initial conditions).[14] When the diffuser is stationary, what the crystal sees is the speckled pattern shown in Fig. 1(a). However, as the diffuser rotates at a time scale much faster than the response time of the crystal, the crystal sees a dark stripe superimposed on a smooth intensity profile [Fig. 1(b)] rather than the speckled pattern. This result illustrates that our photorefractive crystal responds to the time-averaged envelope and not to the instantaneous speckles. By providing an appropriate bias field, we obtain self-trapping of the incoherent dark stripe. We then launch a cylindrically focused probe beam from a He–Ne laser ($\lambda = 633$ nm) into the soliton to test its waveguide properties. Figure 2 shows typical experimental results. At input, the dark beam has a coherence length (estimated from the average speckle size) of ~ 15 μm. The incoherent dark soliton is 18 μm (FWHM) wide and is generated at a bias field of 950 V/cm. In the absence of nonlinearity, the probe beam diffracts from 20 μm [Fig. 2(a)] to ~ 68 μm [Fig. 2(b)] after linear propagation through the crystal. Once the dark incoherent soliton has formed, guidance of the probe beam is observed [Fig. 2(c)]. For this experiment the incoherent soliton beam has an average intensity of ~ 4.5 mW/cm^2, and the intensity of the probe beam reaches 50 mW/cm^2. At output, nearly 80% of the input power (normalized to Fresnel reflections and crystal absorption) of the probe beam is guided into the waveguide channel induced by the incoherent dark soliton.

Next we generate a dark stripe from an amplitude mask.[16] Such an amplitude mask can be a simple mirror crossed by a fine wire, which provides the even input conditions (because the phase across the beam is uniform) that are necessary to excite Y-junction dark solitons. Previously, this was demonstrated by use of coherent light beams.[2,16] Y-splitting of dark incoherent solitons was predicted in Ref. 12 and recently observed in the experiments reported in Ref. 17. Here we show that such a dark incoherent soliton Y-splitting also induces a Y-junction waveguide capable of guiding other beams. We perform experiments similar to that illustrated in Fig. 2, except that an amplitude mask has replaced the phase mask. Figure 3 depicts the generation of a Y-junction incoherent dark soliton pair as well as the guidance of the probe beam by the induced Y-junction beam-splitting waveguide. Interestingly enough, as the coherence of the dark beam decreases, the grayness of the soliton pair increases, but the spacing of the two incoherent gray solitons at the crystal output face remains the same. This is due to a special phase memory effect, as was discussed in Ref. 17. Thus the structure of the beam-splitting waveguides is nearly unchanged when Y-splitting is created by either incoherent or coherent dark solitons.

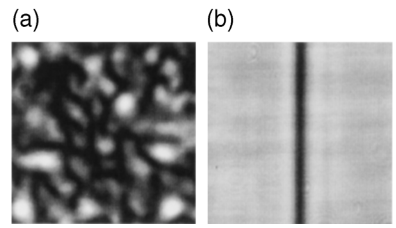

Fig. 1. Photographs of intensity patterns of a spatially incoherent beam (a) with the diffuser stationary and (b) with the diffuser rotating.

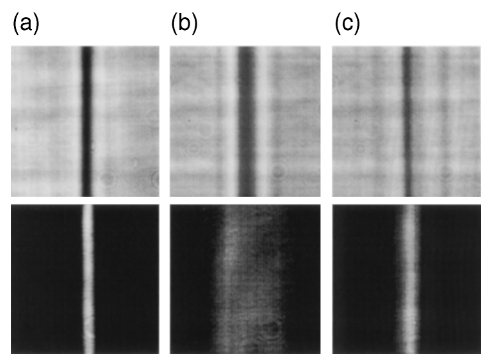

Fig. 2. Photographs showing guidance of a probe beam (bottom) by an incoherent dark soliton (top) initiated from a phase mask: (a) input, (b) output with linear diffraction, and (c) output with nonlinearity.

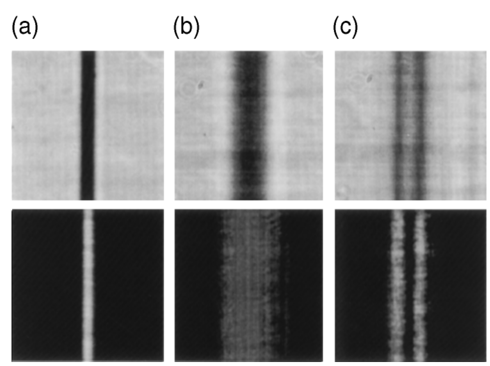

Fig. 3. Photographs showing guidance of a probe beam (bottom) by an incoherent Y-junction dark soliton pair (top) initiated from an amplitude mask: (a) input, (b) output with linear diffraction, (c) output with nonlinearity.

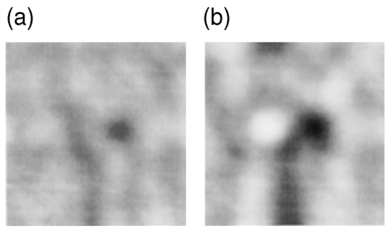

Fig. 4. Photographs showing (a) a self-trapped optical vortex carried by a partially spatially incoherent beam and (b) guidance of the carrier beam (bright spot) into the waveguide channel induced by the vortex as the crystal is translated slightly to the left.

Finally, recalling that a 2-D incoherent dark soliton also induces a fiberlike waveguide channel similar to that of a coherent vortex soliton, we test the guiding properties of such index structures as well. Using a helicoidal phase mask,[18] we create an optical vortex of unit topological charge nested in a broad partially spatially incoherent beam. As we decrease the coherence of the vortex beam, the grayness of the vortex soliton increases and reaches a point where the self-trapped hole is hardly noticeable (because of its grayness) at the crystal output face. However, this 2-D incoherent soliton gives rise to a circular waveguide that one can detect by launching another probe beam into it or simply by translating the crystal laterally to observe guidance of its own carrier beam. Figure 4 shows such an example. Once the vortex is self-trapped and steady state is reached [Fig. 4(a)], we translate the crystal slightly and observe strong guidance of the incoherent beam into the self-trapped channel left by the 2-D dark soliton [Fig. 4(b)]. Of course, what allows this observation is the noninstantaneous decay of the induced waveguide itself. (The dielectric relaxation time of the crystal is $\sim$1 s in our experiments.)

Although we have employed a quasi-monochromatic spatially incoherent light source, our experiments suggest that spatial solitons formed from fully (temporally and spatially) incoherent light sources (e.g., incoherent white light) can also induce waveguides capable of guiding other coherent and incoherent beams. In our guiding experiments with a probe beam the guided probe beam had an intensity nearly ten times higher than that of the incoherent soliton beam itself. We thus demonstrated the principle of guiding intense coherent light by incoherent light. It will certainly be interesting to study how the waveguiding properties of incoherent soliton-induced waveguides vary as a function of coherence. In particular, it is still unknown how the confinement factor and the number of guided modes might be affected by the degree of coherence of the underlying soliton beam. Since incoherent dark solitons can be made from a combination of both radiation modes and bound states,[12] in principle we can expect the induced waveguide to be capable of guiding even higher-order modes. This is in contradistinction with coherent dark solitons, which induce only single-mode waveguides in any nonlinear media.[15] In conclusion, we have demonstrated, for what is believed to be the first time, guiding light by incoherent light.

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