Spatial soliton pixels from partially incoherent light

Zhigang Chen and Kathryn McCarthy

Department of Physics and Astronomy, San Francisco State University, San Francisco, California 94132

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We report what is to our knowledge the first observation of pixellike spatial solitons from partially spatially incoherent light. We created an array of as many as 32×32 soliton pixels by launching a spatially modulated incoherent light beam into a noninstantaneous self-focusing photorefraction medium. These solitons were stable and robust, forming a steady-state two-dimensional waveguide array in which optical coupling and control of local waveguide channels could be realized. © 2002 Optical Society of America

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During the past ten years, optical spatial solitons have received considerable attention, in large part because the universality and diversity of optical solitons give rise to intriguing nonlinear phenomena that are attractive for research.[1] From single-component solitons to two-component vector solitons, from multicomponent composite solitons to incoherent solitons,[2–4] the study of spatial solitons in various nonlinear optical systems has led to many important findings, which may prove to be relevant to similar phenomena in other areas of physics. For instance, recent demonstrations of solitons with coherent matter waves in Bose–Einstein condensates strongly resemble those in nonlinear optics.[5]

Apart from their value for fundamental research, optical solitons are of interest because of their potential applications for all-optical technology. In particular, spatial solitons have been proposed and demonstrated for applications such as optically induced directional couplers and nonlinear frequency converters because of the unique properties of photorefractive soliton-induced waveguides.[6,7] In addition to one- or two-waveguide structures, which involve only a few solitons, spatial soliton pixels and soliton-based waveguide arrays have been proposed for applications in signal processing and information technology.[8,9] Recently, pixellike spatial solitons were demonstrated in a semiconductor microcavity[10] and in a cavityless optical parametric amplifier.[11] In all those previous studies, spatial soliton arrays were generated with coherent light waves.

In this Letter we report what is to our knowledge the first experimental observation of pixellike spatial solitons from partially spatially incoherent light. We create an array of as many as 32×32 solitons by launching a spatially modulated incoherent beam into a self-focusing photorefractive nonlinear crystal. These spatial solitons are stable and robust, provided that the coherence of the beam and the strength of nonlinearity are set at an appropriate value. If the coherence is too high or the nonlinearity is too strong, the beam tends to break up into disordered patterns rather than into ordered soliton structures. Once the soliton pixels form in steady state, they induce a two-dimensional waveguide array capable of guiding an intense probe beam of a longer wavelength. Optical waveguiding and control of nearby waveguide channels in the array are demonstrated in experiments. These soliton pixels may find particular applications in image transmission and information encoding, as there is no or only weak correlation among the various pixels in the soliton array owing to the nature of incoherent light.

Our experimental setup is illustrated in Fig. 1. We generate a partially spatially incoherent light beam by converting an argon-ion laser beam ($\lambda = 488$ nm) into a quasi-monochromatic light source with a rotating diffuser. We can vary the spatial coherence of the beam conveniently by changing the spot size of the laser beam focused onto the diffuser, and we can monitor it from the average speckle size when the diffuser is set to be stationary.[2] (The speckle size is roughly equal to the spatial coherence length, within which any two points remain phase correlated.) Such a diffused laser source has the advantage of providing an incoherent beam with controllable degrees of coherence and intensity that are suitable for experiments, as used previously for demonstration of incoherent solitons.[2–4] A biased photorefractive crystal (SBN:60, 5 mm $\times$ 5 mm $\times$ 20 mm) is used to provide self-focusing noninstantaneous nonlinearity, as the rotating diffuser creates random phase fluctuations on a time scale much faster than the response time of the crystal. This noninstantaneous nonlinearity is essential for modulational instability, soliton clustering, and pattern formation of incoherent waves.[12–15] To generate a gridlike intensity pattern for observation of soliton pixels we use an amplitude mask to modulate the uniform extraordinarily polarized incoherent beam

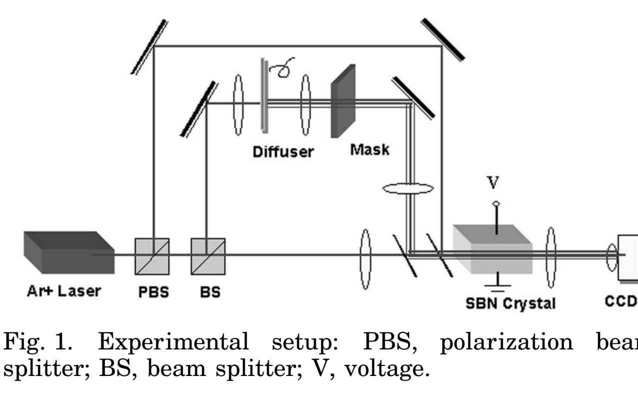

Fig. 1. Experimental setup: PBS, polarization beam splitter; BS, beam splitter; V, voltage.

after the diffuser. The mask is then imaged onto the input face of the crystal. A broad and uniform ordinarily polarized beam from the same laser is used as dark illumination to fine-tune the nonlinearity. A dc field is applied along the crystalline c axis, which is oriented perpendicularly to the propagation direction of all beams in the crystal. In addition, a coherent Gaussian beam from the laser is launched in parallel with the incoherent soliton-pixel beam and is aimed at one of the intensity nulls of the gridlike pattern. This focused Gaussian beam is used as a control beam, as it interacts with nearby solitons when they all propagate through the crystal. We also use a red beam from a He–Ne laser (not shown in the figure) as a probe beam to test the waveguides induced by the soliton pixels. The input and output faces of the crystal are monitored with an imaging lens and a CCD camera.

Typical experimental results of spatial soliton pixels are shown in Fig. 2. At the input to the crystal, the transverse pattern of the incoherent beam consists of 32×32 Gaussian-like intensity pixels, with a 30-μm FWHM diameter for each pixel and a 70-μm peak-to-peak separation between pixels. Because of magnification in imaging to the CCD camera, only part of the beam (7×8 pixels) is recorded, as shown in Fig. 2(a). Without the bias field, individual intensity spots diffract dramatically, as expected from experience with incoherent light. As the whole beam propagates through the 20-mm-long crystal, diffraction washes out the fine structures in the beam, leaving a fairly uniform intensity pattern at the crystal output [Fig. 2(b)]. When an electric field of 2400 V/cm is applied across the crystal, the incoherent beam breaks up at the output of the crystal as a result of induced modulational instability.[14] After transient evolution, the input intensity pattern is restored in steady state, forming an array of spatial soliton pixels as shown in Figs. 2(c) and 2(d). The size of each soliton pixel and the separation between pixels are approximately the same as at the input, as all solitons propagate in parallel through the crystal. For the experiment shown in Fig. 2 the spatial coherence of the beam is fixed at 20 μm, smaller than the size of each pixel. The intensity ratio between the soliton beam and the ordinarily polarized background beam is set at 4. Under these conditions, the induced modulation instability experiences a maximum growth rate at a spatial frequency related to the input perturbation period[12] and eventually leads to steady-state soliton pixels of incoherent light. Formation of such soliton pixels is a combined outcome of diffraction, modulational instability, and nonlinearity experienced by the incoherent beam. The mechanism for formation of a single incoherent soliton by means of noninstantaneous photorefractive screening nonlinearity was discussed previously in the literature.[1–4]

Once the spatial soliton pixels are formed, it is possible to use a probe beam to test the waveguide arrays induced by the solitons. To do so, we launch in parallel with the soliton beam an extraordinarily polarized beam from a He–Ne laser ($\lambda = 633$ nm) into the crystal. When the probe beam is tightly focused at the input [Fig. 3(a)], it diffracts rapidly to a very broad beam after 20 mm of linear propagation [Fig. 3(b)]. However, after we turn on the nonlinearity and create the incoherent soliton pixels, the probe is guided well into one of the channels at which it was initially aimed [Fig. 3(c)]. When the probe is a broad beam (quasi-plane wave) at the input, it breaks up and fits into the waveguide array at the output, as expected [Fig. 3(d)]. It is worth mentioning that the waveguide array, although it is created from incoherent light, can be used to guide an intense coherent laser beam at longer wavelengths without being damaged, and such soliton-induced waveguides can even be fixed in the crystal permanently.[16]

Should these soliton pixels and waveguide arrays be employed for applications in information technology, it would be desirable to be able to manipulate individual pixels and to switch energy from one pixel into another. Here we demonstrate the coupling between soliton pixels by introducing another control beam. The control beam is a well-focused Gaussian-like beam (~25 μm FWHM) from the same argon laser and is launched in the middle of four pixels, as shown in Fig. 4(a). Because the soliton pixels are partially spatially incoherent, the interaction between them and the control beam

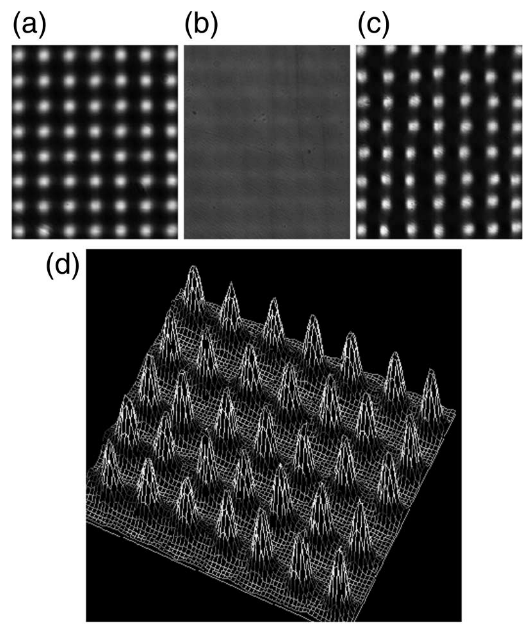

Fig. 2. Spatial soliton pixels of partially incoherent light. Shown are intensity patterns from (a) input, (b) output with linear diffraction, and (c) output with nonlinearity. (d) Three-dimensional intensity plot of (c).

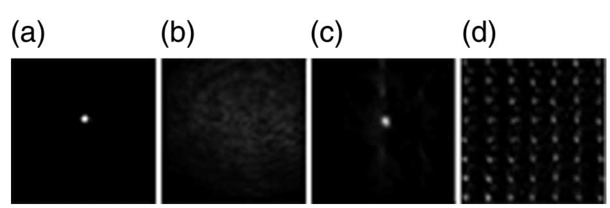

Fig. 3. Waveguide arrays tested by (a)–(c) a focused beam and (d) a broad beam. Shown are (a) input, (b) diffraction, (c) guidance of the focused beam into a soliton channel, and (d) guidance of a broad beam into all waveguide channels.

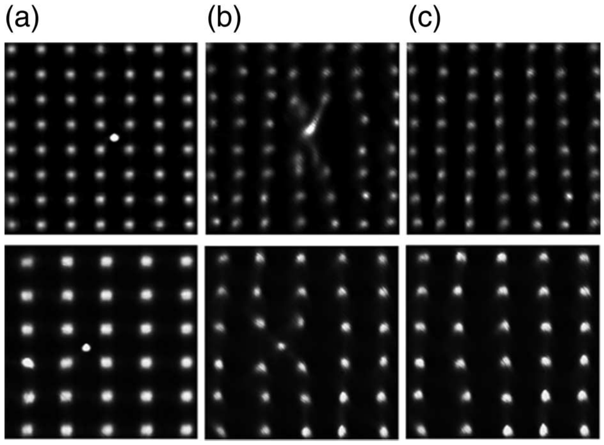

Fig. 4. Control of soliton pixels. Shown are intensity patterns from (a) input, (b) nonlinear output with the control beam on, and (c) nonlinear output with control beam off. The pixel spacing is 70 μm (top) and 110 μm (bottom).

is mutually incoherent interaction, which causes them to attract each other.[1] When the intensity of the control beam is made greater than five times higher than that of the pixel beam, all four nearby solitons are dragged together toward the central control beam by mutual attraction. This attraction is observed clearly in the transient evolution, as our crystal has a slow response time (~30 s for the intensity that we used). When the crystal reaches a new steady state, the lattice gets distorted near the control beam: The four nearest solitons have moved away from their original positions, and almost all of them have merged with the control beam [Fig. 4(b), top]. In fact, strong local coupling between waveguides is observed because of the presence of the control beam. Such a process of coupling between adjacent waveguide channels by a control beam can be used for optical switching, as proposed previously.[17] When the control beam is turned off, the array of soliton pixels is restored in a new steady state [Fig. 4(c)]. The results in the top row of Fig. 4 were obtained at a different location of the crystal but under the same experimental conditions as for Fig. 2, so the separation between pixels is 70 μm. If we replace an amplitude mask to increase the spacing between soliton pixels to 110 μm (Fig. 4, bottom), their interaction with the control beam is weaker, and one can see hardly any dragging or coupling, because the structure of soliton pixels remains the same with or without the control beam.

In addition to the experiments described above, we performed a series of other experiments at different degrees of spatial coherence and different strengths of nonlinearity as well as with different pixel spacings at the crystal input, all of which control the growth rate of the induced incoherent modulation instability. Details will be reported elsewhere.[18] Our focus in this Letter is the formation of incoherent soliton pixels, which occurs only under some critical conditions. For example, when a spatially coherent beam (without the diffuser) is used, even at a much lower bias field the beam tends to break up into many disordered filaments because of the presence of strong coherent modulational instability.

In summary, we have observed, for the first time to our knowledge, spatial soliton pixels from partially spatially incoherent light. Apart from potential applications in optical switching and image transmission, these incoherent soliton-induced waveguides might offer a new way of generating light-induced real-time three-dimensional nonlinear photonic crystals.

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