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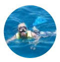

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Anisotropic Enhancement of Discrete Diffraction and Formation of Two-Dimensional Discrete-Soliton Trains

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We demonstrate anisotropic enhancement of discrete diffraction and formation of discrete-soliton trains in an optically induced photonic lattice. Such discrete behavior of light propagation was observed when a one-dimensional stripe beam was launched appropriately into a two-dimensional lattice created with partially coherent light. Our experimental results are corroborated with numerical simulations.

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Nonlinear discrete systems are abundant in nature. In optics, a typical example is a closely spaced nonlinear waveguide array, in which the collective behavior of wave propagation exhibits many intriguing phenomena [1–3]. For instance, the diffraction property of a light beam changes even in a linear waveguide array due to coupling between nearby waveguides, leading to discrete diffraction. When the waveguide array is embedded in a nonlinear medium, a balance between discrete diffraction and nonlinear self-focusing gives rise to the so-called discrete solitons (DS) [1]. During the last half-dozen years, DS have been successfully demonstrated in one-dimensional (1D) AlGaAs waveguide arrays, including in phase bright [4] and out-of-phase (staggered) darklike [5] DS configurations. Several exciting theoretical predictions about DS have been made as well, such as discrete vortex solitons [6], discrete diffraction managed solitons [7], discrete compact breathers and gap solitons [8], and DS navigations in two-dimensional (2D) waveguide arrays [9]. Recently, it has also been suggested that DS could form in optically induced (rather than fabricated) photonic lattices [10]. This soon led to experimental observations of discrete solitons in such waveguide lattices created by optical induction [11,12]. While DS have been predicted to exist in a variety of other nonlinear systems such as biology [13], solid state physics [14], and Bose-Einstein condensates [15], they have been demonstrated so far with good success in nonlinear optics. In fact, the study of DS in various optical settings might provide an insight for understanding similar phenomena in other discrete nonlinear systems.

Meanwhile, photonic lattices optically induced by pixellike spatial solitons have been created with partially spatially incoherent light [16] as well as with phase-engineered coherent light [17]. By exploiting the anisotropic photorefractive nonlinearity, the lattices could be conveniently operated in either the *linear* or the *nonlinear* regime. When the lattice beam is partially incoherent and created by amplitude modulation rather than by coherent multibeam interference, an enhanced stability of the lattice structure has been achieved even in the nonlinear regime due to suppression of incoherent modulation instabilities (MI). This in turn leads to interesting possibilities for studying, in addition to DS, nonlinear soliton-lattice interaction that might reveal many of the basic characteristic features relevant to other fields such as solid state physics. In particular, it has been shown that nonlinear interaction between a soliton and a solitonic lattice could lead to a host of new phenomena including soliton-induced lattice dislocation, lattice deformation, and a novel type of composite band gap solitons embedded in the lattices [12,18].

In this Letter, we report the first observation of anisotropic enhancement of discrete diffraction and formation of 2D discrete-soliton trains in a photonic lattice. Such DS trains are generated by sending a stripe beam into a 2D square lattice created in a photorefractive crystal with partially coherent light. When the lattice is operated in the linear regime (so that the lattice itself only experiences a weak nonlinearity and remains nearly invariant during propagation), we observe that the stripe beam breaks up into 2D filaments due to induced MI. Then, depending on the orientation of the stripe beam, it undergoes an enhanced discrete diffraction or evolves into a train of 2D discrete solitons as the level of the nonlinearity for the stripe beam is gradually increased. Our experimental observations are corroborated with numerical simulations. Discrete MI involves criteria significantly different from their continuum counterparts, and formation of soliton trains mediated from MI is a fundamental nonlinear wave problem as discussed recently also with coherent matter waves [19]. Our results may pave the way to observe similar phenomena in other relevant discrete nonlinear systems.

The experimental setup for our study is similar to those used in Refs. [12,16]. A partially spatially incoherent light beam is generated by converting an argon ion laser beam ($\lambda = 488$ nm) into a quasimonochromatic light source using a rotating diffuser. The spatial coherence of the beam can be varied by changing the spot size of the laser beam focused onto the diffuser and can be monitored from the average speckle size when the diffuser is set to stationary. Such a diffused laser source has previously been used for demonstration of partially incoherent solitons [20]. A biased photorefractive crystal (SBN:60, $5 \times 5 \times 8$ mm^3, $r_{33} = 280$ pm/V, and $r_{13} = 24$ pm/V) is used to provide a noninstantaneous self-focusing nonlinearity. To generate a 2D waveguide lattice, we use an amplitude mask to spatially modulate the otherwise uniform beam (*ordinarily polarized and partially coherent*) after the diffuser. The mask is then imaged properly onto the input face of the crystal, thus creating a pixellike input intensity pattern [16]. A Gaussian beam splitting from the same laser is cylindrically focused into a stripe beam (*extraordinarily polarized and fully coherent*), copropagating with the lattice along the same direction. In addition, a broad and uniform incoherent background beam is used as "dark illumination" for fine tuning the nonlinearity [20].

First, let us recall the anisotropic nonlinearity in a biased photorefractive crystal. In such a crystal, the nonlinear index change experienced by an optical beam depends on the bias field as well as the beam intensity and polarization relative to the crystalline c axis. Specifically, under appreciable bias conditions so that the photorefractive screening nonlinearity is dominant, the index change can be approximately written as $\Delta n_e = [n_e^3 r_{33} E_0/2](1 + I)^{-1}$ and $\Delta n_o = [n_o^3 r_{13} E_0/2](1 + I)^{-1}$ for e-polarized and o-polarized beams, respectively [10]. Here E_0 is the bias field along the c axis, and I is the intensity of the beam normalized to the background illumination. Because of the difference between the nonlinear electro-optic coefficient r_{33} and r_{13}, Δn_e is more than 10 times larger than Δn_o in our SBN:60 crystal under the same experimental conditions. Thus, the o-polarized lattice beam experiences only weak nonlinear index changes as compared with the e-polarized stripe beams, so the lattice can be considered as linear during propagation. Figure 1(a) shows a typical example of a 2D lattice pattern created in experiment. The square lattice has its principal axes orientated in the 45° directions relative to the x and the y axis, with a spatial period on 20 μm. Indeed, as the bias field is increased from 0 to about 4 kV/cm, the lattice structure remains nearly invariant, except for a slight change in its contrast at high bias due to nonzero r_{13}. In addition, we note that a stripe beam alone (without the lattice) can form a 1D screening soliton only when the stripe is oriented vertically, i.e., when its direction of intensity variation is parallel to the c axis (x direction). If the stripe beam is oriented horizontally, it diffracts normally in the y direction even at high bias, as if the nonlinearity were not present [18]. Such a preference in the direction of self-trapping does not occur in isotropic nonlinear media, and it is directly relevant to the experimental results presented below for different orientations of a stripe beam as illustrated in Fig. 1(b).

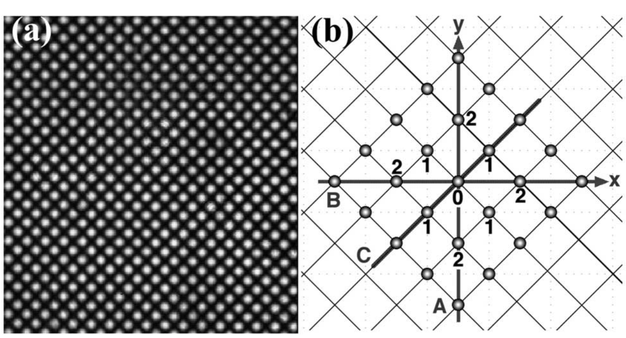

FIG. 1. (a) A 2D photonic lattice established in a bulk crystal by optical induction. (b) Illustration of the stripe beam orientation (A, B, and C) relative to the lattice.

Typical experimental results for the formation of 2D discrete-soliton trains are presented in Fig. 2, for which a stable lattice as shown in Fig. 1(a) is first created in the crystal. The spatial coherence length of the lattice beam is chosen such that each lattice site is incoherent with its far neighbors so that the lattice overall maintains a good stability even at a high nonlinearity. A vertically oriented stripe beam (with an intensity about 5 times weaker than that of the lattice) is then launched along one of the diagonal directions of the lattice [see stripe A in Fig. 1(b)], propagating collinearly with the lattice. Because of the modulation of the waveguide lattice, the stripe beam breaks up into many filaments, which exhibit discrete diffraction when the nonlinearity is low, but evolve into a train of 2D discrete solitons at an appropriate level of high nonlinearity. The first two photographs show the stripe beam at the crystal input [Fig. 2(a)] and its linear

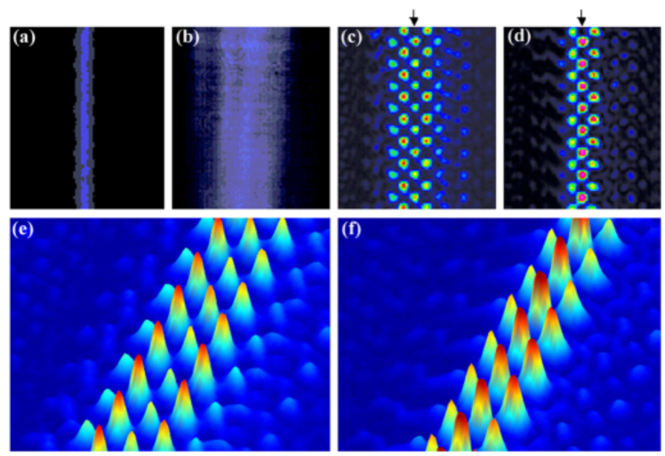

FIG. 2 (color online). Experimental demonstration of 2D discrete soliton trains. Shown are the transverse intensity patterns of a stripe beam taken from crystal input (a) and output (b)–(d) faces: (b) Normal diffraction; (c) discrete diffraction; (d) discrete-soliton trains. Arrows indicate the initial location of the stripe. (e) and (f) are 3D intensity plots corresponding to (c) and (d), respectively.

diffraction at the crystal output after 8 mm of propagation [Fig. 2(b)]. The other photographs show the 2D discrete diffraction [Fig. 2(c)] and the DS train formed at a bias field of 3.0 kV/cm [Fig. 2(d)] along with their corresponding 3D intensity patterns [Figs. 2(e) and 2(f)]. Figure 2(c) was taken immediately (<0.5 s) after the stripe was launched into the lattice, whereas Fig. 2(d) was taken after the stripe was launched for more than 5 min with the bias field on so to let the crystal reach a new steady state. Because of the noninstantaneous property of the photorefractive nonlinearity [20], it would take about 10 s for the stripe beam itself to develop appreciable self-focusing for the power level we used. Thus, the observed behavior of the stripe beam in Figs. 2(c) and 2(e) arises clearly from discrete diffraction, in which most of the energy of the stripe beam goes away from the center (indicated by an arrow) to the two sides due to the waveguide coupling. When the self-focusing nonlinearity comes to play a role for the strip beam at a new steady state, the DS train is observed with most of the energy being concentrated in the central column [Figs. 2(d) and 2(f)] to which the stripe beam was initially aimed. Such a DS state can be viewed as a series of single 2D discrete solitons formed by the secondary sources from the stripe-beam breakup in the lattice, but each has four shared neighboring sites along the principal axes of the lattice. In fact, by introducing a plane wave for interference with the soliton train, we discovered that the adjacent solitons (from the secondary sources) are all in phase with each other. Should the train consist of only two neighboring solitons (such as a dipole), the two solitons need to be out of phase rather than in phase for excitation of stable dipole solitons in the lattice [21].

Difference in discrete diffraction is observed between a single 2D spot beam and a 1D stripe beam traveling through the same lattice. For instance, if a spot beam is launched at a central site [indicated as 0 in Fig. 1(b)], most of its energy would flow from the center toward far neighbors (indicated as 2) along the diagonal directions of the lattice for the crystal length we used [12]. However, for a stripe beam [see stripe A in Fig. 1(b)], most of its energy goes to the closest sites (indicated as 1) under the same conditions, although coupling to the far neighboring sites is clearly visible [Fig. 2(c)]. This is because, intuitively, each closest site along the principal axes of the lattice now has contribution from two secondary sources from the modulated stripe beam as opposed to only one from a single spot beam.

The above experimental results are corroborated by numerical simulation of the stripe-lattice evolution equations using a fast Fourier transform multibeam propagation method as described in Ref. [12]. Figure 3 shows typical numerical results using parameters close to those from our experiment. A 2D lattice corresponding to Fig. 1(a) is first established with a partially coherent o-polarized beam, and then an e-polarized stripe beam is launched into the lattice, with the same vertical orientation as in Fig. 2. The stripe beam undergoes a transition from discrete diffraction [Fig. 3(a)] to discrete self-trapping into a train of 2D discrete solitons [Fig. 3(b)] when the strength of the nonlinearity as controlled by the bias field is increased, in good agreement with the observed experimental behavior.

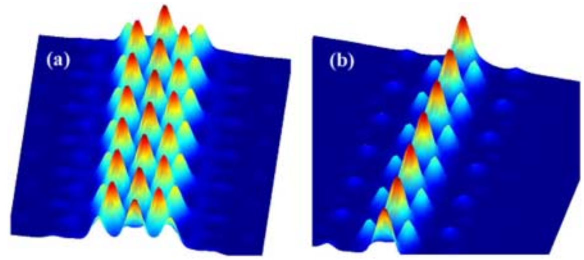

FIG. 3 (color online). Numerical simulation of the formation of 2D discrete-soliton trains. (a) Discrete diffraction of the stripe beam at a bias field of $E_0 = 1.5$ kV/cm and (b) discrete-soliton trains formed at $E_0 = 2.7$ kV/cm. Orientation of the plots is slightly different for better visualization.

Of particular interest is that, when the same stripe is oriented horizontally and launched along the other diagonal direction of the lattice [see stripe B in Fig. 1(b)], enhanced discrete diffraction is observed instead of discrete solitons as the level of the nonlinearity is increased. To form a train of DS, a delicate balance between waveguide coupling offered by the o-polarized lattice and the self-focusing nonlinearity experienced by the e-polarized stripe beam must be reached through fine tuning the experimental parameters. When the stripe beam is oriented vertically, an increase in the strength of the nonlinearity results in an increase in discrete self-focusing, as more and more energy flows from two sides towards the center, eventually leading to a DS state [Fig. 4, top]. However, when the same stripe is oriented horizontally, the opposite behavior is observed: an increase in the bias field leads to enhancement of discrete diffraction rather than self-focusing, as more energy flows from the center towards two sides (Fig. 4, bottom). As discussed earlier,

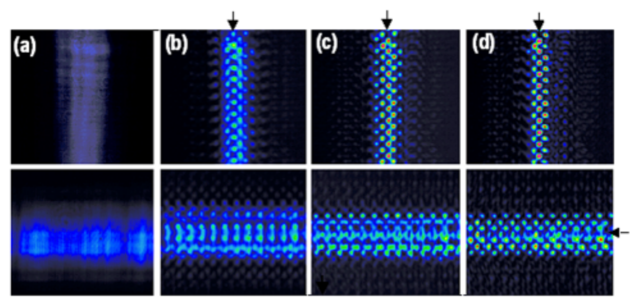

FIG. 4 (color online). Output intensity patterns of the stripe beam at various values of the bias field E_0 (kV/cm): (a) 0; (b) 1.0; (c) 2.0; (d) 3.0. The stripe exhibits an increased discrete focusing when oriented vertically (top) and an increased discrete diffraction when oriented horizontally (bottom).

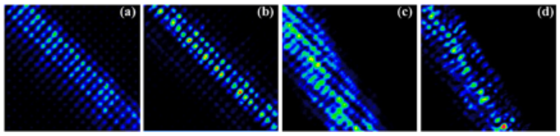

FIG. 5 (color online). Output intensity patterns when the stripe beam is oriented at 45° (a),(b) and 32° (c),(d) relative to the y axis. Shown are the intensity patterns obtained at $E_0 = 1.0$ kV/cm (a),(c) and at $E_0 = 3$ kV/cm (b),(d).

the stripe beam (although e polarized) in this horizontal orientation would not undergo any self-focusing or defocusing due to the anisotropic photorefractive nonlinearity. The enhanced discrete diffraction indicates that, as the bias field increases, the coupling between adjacent waveguides in the lattice also increases (since r_{13} is not null), resulting in an energy flow of the stripe beam further away from the center. The o-polarized waveguide lattice is nearly linear for a vertically oriented stripe beam, but it behaves more like an adjustable waveguide array for a horizontally oriented stripe beam due to the unique property of the anisotropic photorefractive nonlinearity.

Finally, we make the stripe beam oriented diagonally and launch it along one of the principal axes of the 2D square lattice [see stripe C in Fig. 1(b)]. Again, due to the anisotropic property of nonlinearity, the stripe beam in this orientation would not be able to form a 1D soliton itself, but rather it tends to break up into filaments and get distorted as the strength of the nonlinearity is increased [18]. Surprisingly, with the presence of the 2D waveguide lattice, the stripe beam experiences discrete diffraction [Fig. 5(a)] and stable discrete self-trapping [Fig. 5(b)] at an appropriate value of the bias field. The MI that causes beam distortion seems to be suppressed due to the lattice potential. However, if the stripe beam is oriented along an arbitrary direction [e.g., 32° relative to the y axis as show in Figs. 5(c) and 5(d)], it will be twisted and distorted, since in this case it no longer sees a symmetric lattice potential along its dimension and on its two sides. This suggests that, in a discrete system, the weak coupling offered by the periodic lattice potential enables stable trapping of spatial solitons with configurations that would otherwise not be possible in a continuous system. A closely related example is the existence of discrete vortex solitons in self-focusing nonlinear media [22].

In summary, we have demonstrated anisotropic discrete diffraction and formation of 2D discrete-soliton trains in an optically induced photonic lattice. Our results may prove to be relevant to similar phenomena in other discrete nonlinear systems.

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