Formation of discrete solitons in light-induced photonic lattices

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Abstract: We present both experimental and theoretical results on discrete solitons in two-dimensional optically-induced photonic lattices in a variety of settings, including fundamental discrete solitons, vector-like discrete solitons, discrete dipole solitons, and discrete soliton trains. In each case, a clear transition from two-dimensional discrete diffraction to discrete trapping is demonstrated with a waveguide lattice induced by partially coherent light in a bulk photorefractive crystal. Our experimental results are in good agreement with the theoretical analysis of these effects.

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1. Introduction

Nonlinear discrete systems are abundant in nature. In optics, a typical example is a closely-spaced nonlinear waveguide array, in which collective behavior of wave propagation exhibits many intriguing phenomena [1, 2]. Even in a linear waveguide array, the diffraction property of a light beam changes due to evanescent coupling between nearby waveguide sites, 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 a localized state of light better known as "discrete solitons" [3].

Discrete solitons (DS) have been predicted to exist in a variety of other nonlinear systems such as biology, solid state physics, and Bose-Einstein condensates, but a convenient way to demonstrate such soliton states is to employ a fabricated or optically-induced waveguide array in nonlinear optics. Indeed, the first experimental demonstration of DS was carried out in fabricated one-dimensional (1D) AlGaAs semiconductor waveguide arrays [4, 5]. Recently, it has been suggested that DS could also form in optically-induced waveguide arrays [6]. This soon led to various experimental observations of DS in such waveguide arrays established with optical induction, either via coherent beam interference [7-9] or via amplitude modulation of a partially coherent beam [10, 11]. Meanwhile, in addition to fundamental discrete solitons, vortex discrete solitons have also been predicted theoretically [12, 13] and demonstrated experimentally [14, 15].

In this paper, we present a brief overview of our recent work on discrete solitons in 2D photonic lattices created in a bulk photorefractive material by optical induction. We demonstrate the formation of 2D fundamental discrete solitons, trains of such solitons, as well as vector and dipole solitons in the optically-induced photonic lattice. Different from previous experiments in which the lattice is created by *coherent* multi-beam interference [7-9], the DS reported here are hosted in a partially *incoherent* photonic lattice. This in turn enables stable lattice formation due to suppression of incoherent modulation instability [16]. In fact, it is in such a stable lattice that detailed features of transition from 2D discrete diffraction to formation of DS are clearly demonstrated [10, 11]. These results may pave the way to study many fascinating behavior of light in photonic structures.

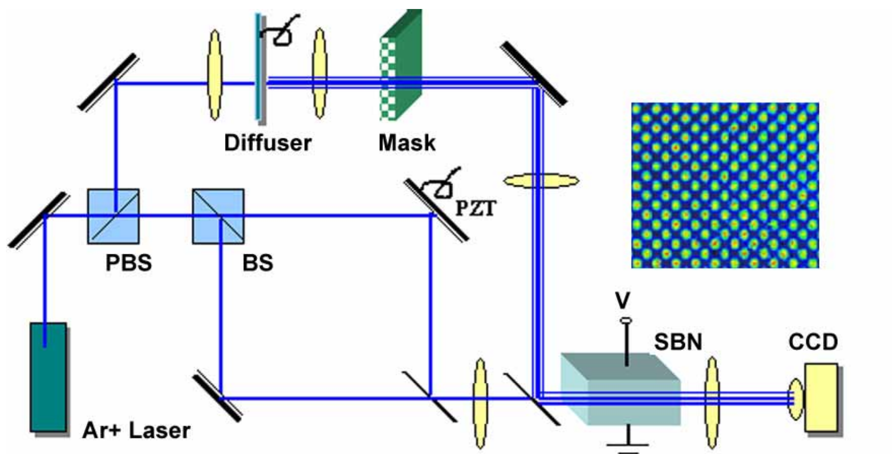

Fig. 1. Experimental setup. PBS: polarizing beam splitter; PZT: piezo-transducer; SBN: strantium barium niobate. The right insert shows a photonic lattice created by optical induction.

Our experiments are performed in a photorefractive crystal (SBN:60; 5 x 5 x 8 mm^3, r_{33}=280 pm/V and r_{13}= 24 pm/V) illuminated by an argon laser beam (λ=488 nm) passing through a rotating diffuser and an amplitude mask as shown in Fig. 1. The biased crystal provides a self-focusing noninstantaneous nonlinearity. The amplitude mask provides spatial modulation after the diffuser on the otherwise uniform beam, which exhibits a pixel-like intensity pattern at the input face of the crystal [17]. Another beam split from the same laser but without going through the diffuser is used as the probe beam, propagating along with the lattice. For fundamental 2D discrete solitons, this probe beam is focused with a circular lens into a 2D Gaussian beam and launched into one of the lattice sites, while for demonstrating a discrete soliton train, the beam is focused with a cylindrical lens into a quasi 1D stripe beam and launched into several lattice sites in a row. In experiments with dipole and vector lattice solitons, the probe beam is split into two by a Mach-Zehnder interferometer (Fig. 1). The two beams exiting from the interferometer are combined with the lattice beam, propagating collinearly through the crystal. When the two beams from the interferometer are made mutually incoherent by ramping a piezo-transducer mirror at a fast frequency, the vector components are realized by overlapping the two beams onto the same lattice site, where each beam itself is coherent and experiences a strong self-focusing nonlinearity [18]. When the two beams from the interferometer are made mutually coherent with a controlled phase relation, dipole-like discrete solitons are investigated by launching the two in-phase or out-of-phase beams into two neighboring lattice sites [19]. The two components are monitored separately with a CCD camera, taking the advantage of the noninstantaneous response of the crystal. In addition, background illumination is used for fine-tuning the nonlinearity.

We emphasize that, in all experiments reported here, the probe beam is extraordinarily polarized and "fully" coherent, while the lattice beam is ordinarily polarized and partially coherent. In general, in an anisotropic photorefractive crystal, the nonlinear index change experienced by an optical beam depends on its polarization as well as on its intensity. Under appreciable bias conditions, i.e., when the photorefractive screening nonlinearity is dominant, this index change is approximately given by $\Delta n_e = [n_e^3 r_{33} E_0 / 2](1+I)^{-1}$ and $\Delta n_o = [n_o^3 r_{13} E_0 / 2](1+I)^{-1}$ for e-polarized and o-polarized beams, respectively [6-11]. Here E_0 is the applied electric field along the crystalline c-axis (x-direction), and I is the intensity of the beam normalized to the background illumination. Due to the difference between the nonlinear electro-optic coefficient r_{33} and r_{13}, Δn_e is more than 10 times larger than Δn_o under the same experimental conditions. Thus, the o-polarized lattice beam experiences only weak nonlinear index changes as compared with the e-polarized probe beam, so the lattice can be considered as *linear* during propagation. In Fig. 1, the insert shows a typical example of a 2D lattice pattern created in experiment. The square lattice has its principal axes orientated in the 45^0 directions relative to the x- and y-axis, with a spatial period of 20 μm. Indeed, as the bias field is increased to more than 3 kV/cm, the lattice structure remains nearly invariant, except a slight change in its contrast at high bias due to nonzero r_{13}.

2. Fundamental discrete solitons

First, we present our results on 2D fundamental discrete solitons. A stable waveguide lattice (spacing 20 μm and the FWHM of each lattice site about 10 μm) is induced by an o-polarized partially coherent beam. Then, a probe beam (whose intensity is 4 times weaker than that of the lattice) is launched into one of the waveguide channels, propagating collinearly with the lattice. Due to weak coupling between closely spaced waveguides, the probe beam undergoes discrete diffraction when the nonlinearity is low, whereas it forms a 2D discrete soliton at an appropriate level of high nonlinearity. Typical experimental results are presented in Fig. 2, where the first two photographs show the Gaussian-like probe beam at the crystal input [Fig. 2(a)] and its linear diffraction at the crystal output after 8 mm of propagation [Fig. 2(b)]. Discrete diffraction in the square lattice is observed at a bias field of 900 V/cm [Fig. 2(c)], clearly showing that most of the energy flows from the center towards the diagonal directions of the lattice. Even more importantly, a DS is observed at a bias field of 3000 V/cm [Fig. 2(d)], with most of energy concentrated in the center and the four neighboring sites along the principal axes of the lattice. These experimental results are truly in agreement with expected behavior from the theory of discrete systems [8, 13, 20]. In fact, the above experimental observations are corroborated by our numerical simulations of the probe-lattice beam evolution equations using a fast Fourier transform multi-beam propagation method, in which the partially coherent lattice beam is described by the so-called coherent density approach [21]. Figure 3 shows typical numerical results. The parameters chosen in simulation are close to those from the experiment [10]. At a low bias field, discrete diffraction is observed (left), whereas at a high bias field the formation of a 2D discrete soliton is realized (right), in good agreement with experimental results.

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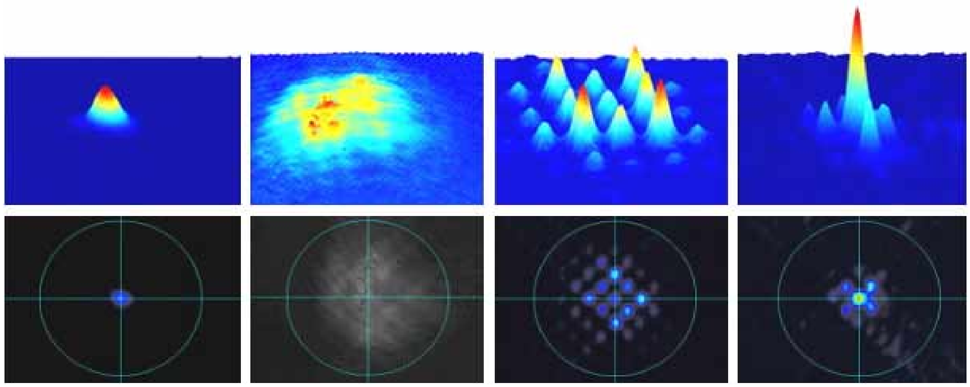

Fig. 2. Experimental demonstration of a discrete soliton in a partially coherent lattice. (a) Input, (b) diffraction output without the lattice, (c) discrete diffraction at 900 V/cm, and (d) discrete soliton at 3000 V/cm. Top: 3D intensity plots; Bottom: 2D transverse patterns. Animation of the experimentally observed process can be viewed in the multimedia file.

To form such a fundamental DS, a delicate balance has to be reached between waveguide coupling offered by the lattice and the self-focusing nonlinearity experienced by the probe beam through fine-tuning the experimental parameters (the lattice spacing, the intensity ratio, the bias field, etc.). A series of experiments are performed to show that large deviation in the beam intensities and/or the applied field (both controlling the strength of the nonlinearity) would hinder the DS formation. Figure 4 shows two examples of such variation, where the top panel displays the output intensity patterns of the probe beam at varying lattice-to-probe intensity ratio with a fixed bias field, and the bottom panel are the corresponding intensity patterns at varying bias field but with a fixed lattice-to-probe intensity ratio. In both cases, low nonlinearity results in discrete diffraction or partial focusing of the probe beam (Figs. 4(a) and 4(b)), whereas high nonlinearity leads to distortion of the soliton-forming beam associated with energy tunneling to the lattice sites far away from the center (Fig. 4(d)). Only the right nonlinearity gives rise to the 2D discrete solitons (Fig. 4(c)).

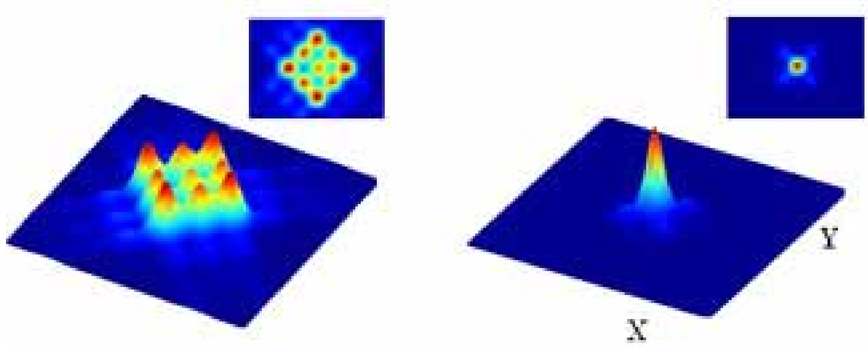

Fig. 3. Numerical results corresponding to Fig. 1(c-d). Inserts are 2D transverse patterns.

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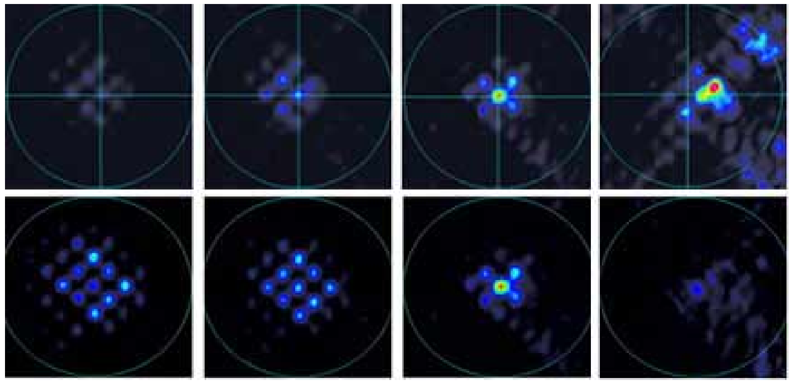

Fig. 4. Output intensity patterns of a soliton-forming beam as a function of the intensity ratio at a fixed bias field (top) and as a function of the bias field at an intensity ratio (bottom).

3. Discrete dipole and vector solitons

The sensitivity of DS formation to the probe beam intensity not only illustrates that forming DS is the outcome of nonlinear self-action of the probe beam in the lattice, but also it can be used as a test bench for two-component vector-like DS. Among all self-localized states in periodic structures, vector discrete solitons make up an important family [22, 23]. While vector solitons have been realized previously in continuum nonlinear systems, they have been observed only very recently in a discrete system of 1D AlGaAs waveguide arrays [24]. Here we demonstrate that two mutually incoherent beams can lock into a 2D vector soliton while propagating along the same lattice site, although each beam alone would experience discrete diffraction under the same conditions. Such mutually-trapped two-component vector solitons are attributed to the intensity-dependent nonlinearity. Typical experimental results of a 2D discrete vector soliton are presented in the first two rows of Fig. 5. The two mutually incoherent beams (Fig. 5(a), row 1 and 2) are launched into the same lattice site with combined peak intensity about 6 times weaker than that of the lattice beam. Discrete diffraction of each beam is observed at a low bias field of 1 kV/cm (Fig. 5(b)), but the two beams are coupled to form a discrete soliton pair at a high bias field of 2.9 kV/cm (Fig. 5(c)). These intensity patterns of each beam were taken immediately after blocking the pairing beam. In contrast, Figs. 5(d) show that, after the paring beam is removed and the remaining beam reaches a new steady state, each beam itself does not form a discrete soliton under the same conditions, since now the lattice-to-probe intensity ratio has been increased to be more than 10. These experimental results are also observed in our numerical simulations of the coupled 2D nonlinear wave equations with a periodic lattice potential [18]. The vector components are two mutually incoherent Gaussian beams centered at the same lattice site. Using the parameters close to those from experiment, we obtain numerical results shown in the bottom row of Fig. 5, where (a) shows the input, (b) the discrete diffraction at a low bias field, and (c, d) the coupled and decoupled components of a lattice vector-soliton at a high bias field. Since the two components are exactly the same, only one of the components is shown. The exact solutions of such vector lattice solitons along with their stability regions have also been investigated [18].

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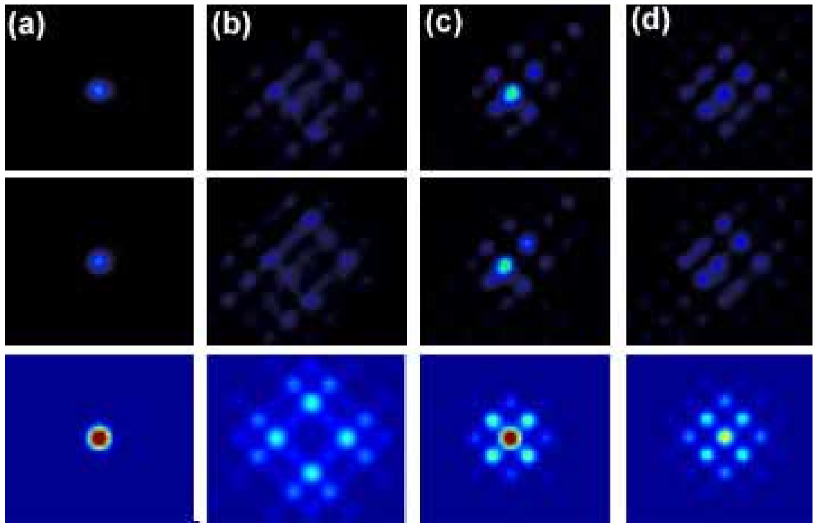

Fig. 5. Experimental and numerical results of a 2D discrete vector soliton. (a) input, (b) discrete diffraction at low bias field, (c, d) mutual trapping and decoupled output at high bias field, respectively. Row 1&2 show the two components of the vector soliton from experiment. Since the two components from simulations are the same, only one of the components from simulation is shown (Row 3).

Next, we demonstrate the formation of dipole solitons in a 2D optically induced photonic lattice by launching two mutually coherent beams into two neighboring lattice sites along the diagonal direction of the square lattice rather than overlapping them in the same lattice site. The two beams are made either out-of-phase or in-phase with each other, and we have found theoretically that both types of dipole-like solitons exist. The out-of-phase dipole solitons are linearly stable in a large range of parameter spaces with appropriate level of nonlinearity, while the in-phase solitons are always linearly unstable although their instabilities are rather weak in the low-intensity regime [19]. Experimentally, both types of lattice solitons are observed, but only the out-of-phase dipoles are found to be stable and robust under appropriate conditions, while the in-phase dipoles suffer from instability as well as the anisotropic effect of the photorefractive nonlinearity [25]. In the absence of the photonic lattice, these solitons cannot exist because of the repulsive or attractive force between the two humps which makes them diverge from or merge with each other. With the waveguide lattice, however, the lattice potential could trap the two humps against repulsion or attraction. These novel types of lattice solitons are related to the intrinsic localized modes found previously in 1D and 2D periodic nonlinear systems [26-28].

Typical experimental results of dipole lattice solitons are shown in Fig. 6, where the top panel is for the out-of-phase dipole and the bottom for the in-phase dipole. In these experiments, the dipole beams are oriented in the vertical direction (Fig. 6(a)), while the principal axes of the square lattice are oriented in diagonal directions as usual. The intensity ratio between the lattice beam and background illumination is about 3, and the intensity of the dipole beam is about 6 times weaker than that of the lattice. At a low bias field, both types of dipoles undergo linear discrete diffraction (Fig. 6(b)). A clear distinction between the two types of dipoles lies in the intensity redistribution after discrete diffraction: the intensity for the out-of-phase dipole extends along the original direction of the dipole, while that for the in-phase dipole extends along the orthogonal direction. Furthermore, due to destructive (constructive) interference, the minimum (maximum) intensity is located in the two sites between the two out-of-phase (in-phase) dipole lobes. At a high bias field, both

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types of dipoles are trapped by the lattice potential, leading to the formation of dipole-like lattice solitons (Fig. 6(c)). Note that the initial phase structures are preserved after the lattice solitons are created, as seen from their output intensity patterns. Should one of the dipole beams be turned off, the other forms a fundamental lattice soliton and redistributes the energy to its center as well as four neighboring sites along the principal axes of the lattice in a manner similar to that for Fig. 2.

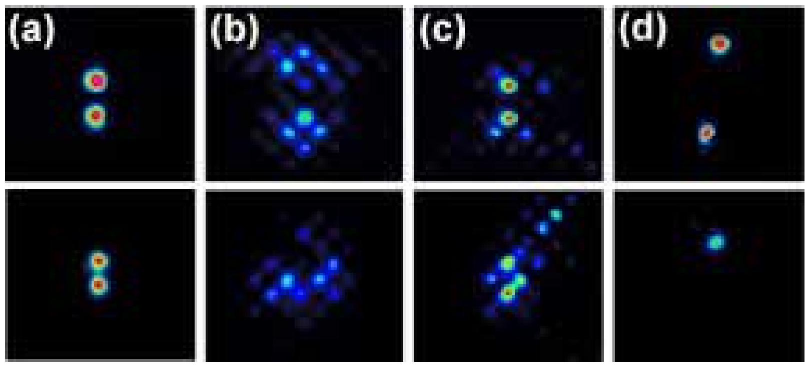

Fig. 6. Experimental results on dipole-like solitons in a 2D photonic lattice. Top panel: two beams are out-of-phase; Bottom panel: two beams are in-phase. (a) input; (b) output at a low bias field of 100V/mm; (c) and (d) output at a high bias field of 320V/mm with and without the lattice, respectively.

Without the lattice, the dipole diverges in the out-of-phase case and merges into a single soliton in the in-phase case (Fig. 6(d)) as expected. Although the exact solutions of lattice dipole solitons have been found in our theoretical model [19], it is desirable to directly simulate the nonlinear evolution of a pair of Gaussian beams in the lattice using the experimental conditions. Such simulation results are shown in Fig. 7, where the first column shows the input intensity pattern, the second column shows discrete diffraction at a low bias field, the third column shows self trapping of the two beams to form dipole-like solitons at a high bias field, and the last column shows the repulsion/attraction of Gaussian beams at the same high bias without the optical lattice. Qualitative agreement between numerical results and experimental observations is evident. In the experimental results of Fig. 6, in addition to attraction and repulsion, self-bending of the soliton elements towards crystalline c-axis (upward in Fig. 6(d)) is evident. This soliton self-bending due to the diffusion effect enhanced by the high bias field is well known [29], so it has not been included in our theoretical model for simplicity. In addition to the dipole solitons presented above, we have also found other configurations of dipole-like solitons as well as quadrupole solitons in 2D lattices [25].

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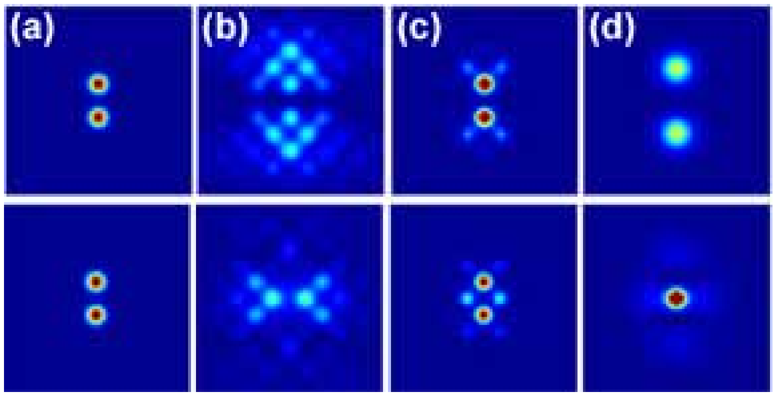

Fig. 7. Numerical results corresponding to Fig. 6. For simplicity, numerical model does not include self-bending and anisotropic effects associated with the photorefractive nonlinearity.

4. Discrete soliton trains

Finally, we report our work on formation of 2D discrete-soliton trains in a partially coherent photonic lattice. Such DS trains are generated by sending a stripe beam into a 2D square lattice. When the lattice is operated in the *linear* regime, we observe that the stripe beam breaks up into 2D filaments, and then it evolves into a train of 2D discrete solitons as the level of the nonlinearity for the stripe is gradually increased.

The first two photographs in Fig. 8 show the stripe beam at the crystal input [Fig. 8(a)] and its linear diffraction at the crystal output after 8 mm of propagation with the lattice absent [Fig. 8(b)]. The other photographs show the 2D discrete diffraction [Fig. 8(c)] and the DS train formed at a bias field of 3.0 kV/cm [Fig. 8(d)] along with their corresponding 3D intensity patterns [Figs. 8(e, f)]. The observed behavior of the stripe beam in Figs. 8(c, 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 stripe beam at a new steady-state, the DS train is observed with most of energy being concentrated in the central column [Figs. 8(d, f)] to which the stripe beam was initially aimed. These experimental results are corroborated by numerical simulation of the stripe-lattice evolution equations using a fast Fourier transform multi-beam propagation method [11] as shown in Fig. 9. The left panel shows discrete diffraction of the stripe beam propagating through a linear lattice (in the media file, each frame corresponds to an intensity pattern at a different propagation distance obtained with a fixed low field). The right panel shows self-trapping of the stripe beam as the nonlinearity increases (each frame corresponds to an intensity pattern at a fixed propagation distance of 8mm obtained with a fixed increment of bias field of 180 V/cm).

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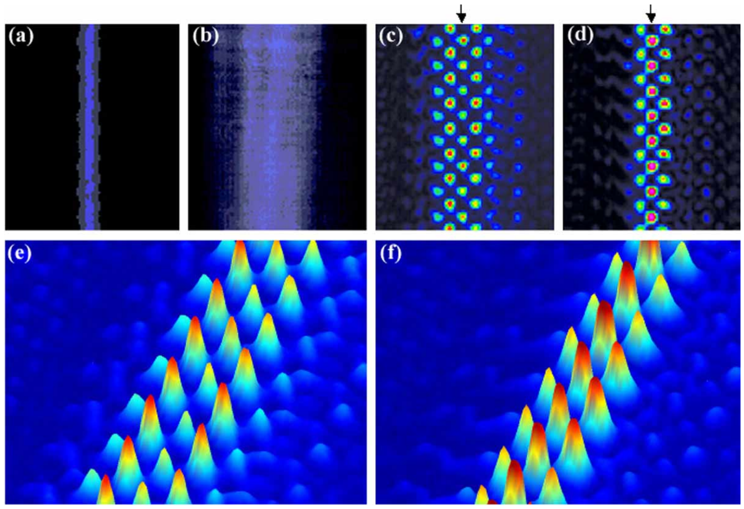

Fig. 8. Experimental demonstration of 2D discrete soliton trains. Shown are the transverse intensity patterns of a stripe beam taken from crystal input (a) and output (b-d) faces. (b) Normal diffraction, (c) discrete diffraction, and (d) discrete soliton trains. Arrows indicate initial location of the stripe. (e) and (f) are 3D intensity plots corresponding to (c) and (d), respectively.

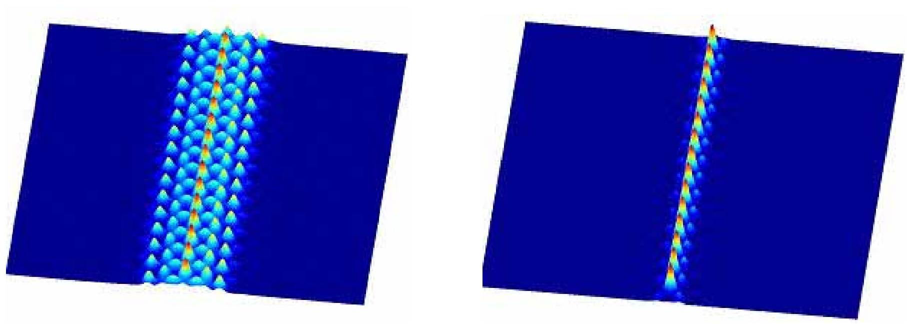

Fig. 9. Numerical results showing discrete diffraction (left) and discrete trapping (right) of a stripe beam in the lattice. Animations of the observed process as obtained from numerical simulations can be viewed in the media files.

The above 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. From the aforementioned dipole lattice soliton analysis, it seems that, in order to form closed neighbor in the lattice with good stability, the two discrete solitons need to be out-of-phase rather than in-phase with each other. This suggests that, to form a train of discrete solitons, neighboring solitons in the array must be out-of-phase with each other. However, to our surprise, we found that the adjacent solitons in the train are all in phase with each other after introducing a plane wave for interference measurement. It might be that the shared neighboring side lobes between two adjacent solitons offer the out-of-phase relation so to have enhanced stability, but experimentally it is difficult to measure such phase relation due to weak intensity and sensitivity to background noise. The stability of such DS trains as well as the formation of DS trains in other configurations such as a necklace-like ring discrete solitons certainly merits further investigation [30]. We note that the formation of soliton trains mediated from modulation instability is a fundamental nonlinear wave problem as discussed recently also with coherent matter waves [31].

It should be pointed out that all work presented in this paper are about discrete solitons in nearly linear waveguide lattices. Discrete solitons are so called because a delicate balance between self-focusing from nonlinearity and discrete diffraction from lattices has been reached for each of these self-trapped states, so that the wavepackets could propagate invariantly through the periodic medium. On the other hand, such balance may not be reached should the lattice beam itself experiences strong nonlinearity. In this latter case, however, it is possible to demonstrate a number of novel phenomena associated with soliton-lattice and vortex-lattice interactions, including soliton-induced lattice dislocation, lattice deformation and compression, and vortex-induced lattice twisting due to the transfer of angular momentum carried by the vortex into a nonlinear solitonic lattice [32].

5. Summary

In summary, we have successfully demonstrated a variety of discrete soliton states in optically-induced partially-coherent photonic lattices. Our results may pave the way towards the observation of similar phenomena in other relevant discrete nonlinear systems.

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