Observation of nonlinear self-trapping in triangular photonic lattices

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We experimentally study light self-trapping in triangular photonic lattices induced optically in nonlinear photorefractive crystals. We observe the formation of two-dimensional discrete and gap spatial solitons originating from the first and second bands of the linear transmission spectrum. © 2007 Optical Society of America

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Photonic crystals are expected to find many applications in modern optical technologies because of their unique properties arising from the effects of microperiodicity. In particular, the photonic bandgaps allow one to strongly modify and even suppress the propagation of light in certain directions and at certain frequencies.[1] Therefore photonic crystals and periodic structures in general offer a wealth of new possibilities to efficiently manipulate the flow of light in optical systems.

Two-dimensional (2D) periodic structures can be fabricated in various geometries. Among them triangular lattices are known to support larger bandgaps, and therefore most of the currently fabricated planar photonic crystal structures possess the triangular lattice symmetry. Furthermore, the same geometry appears naturally in the stacking method fabrication of photonic crystal fibers.[2]

Embedding structural defects into otherwise regular periodic structures allows for the realization of photonic crystal waveguides[3] and fibers, and high-Q optical cavities.[4] In these devices light is bound to a lattice defect by modified total internal reflection or Bragg reflection from the surrounding periodic structure. Efficient trapping, however, requires careful engineering and fabrication of the periodic structure as well as the embedded defects, and this typically represents a limiting factor in the realization of such devices.

Alternatively, beam self-trapping can be used to dynamically introduce refractive index defects in lattice structures with a strong nonlinear response, resulting in the formation of spatial lattice solitons.[5] This approach avoids the need for structural defects to trap the light, and shows inherent advantages for all-optical applications. Nonlinear directional transport[6] and immobile localizations[7,8] were recently demonstrated experimentally in square lattices. However, such effects remain largely unexploited in triangular lattices. In this Letter we report what we believe to be the first experimental study of light self-trapping in triangular lattices in the form of discrete and gap solitons,[5] which can be considered a nonlinear equivalent of high-Q cavities in photonic crystals.

In our experiment we optically induce a 2D triangular lattice in a biased photorefractive SBN:60 crystal by interfering three ordinarily polarized broad beams from a frequency-doubled Nd:YVO_4 cw laser. The experimental setup resembles those described earlier.[6,9] Because of strong electro-optic anisotropy the lattice writing beams propagate linearly in the crystal, while extraordinarily polarized probe beams simultaneously experience the induced periodic potential and a strong photorefractive self-focusing nonlinearity.[10]

The propagation of an optical beam along the triangular lattice is governed by the parabolic equation for the slowly varying amplitude of the electric field[7,9,10]

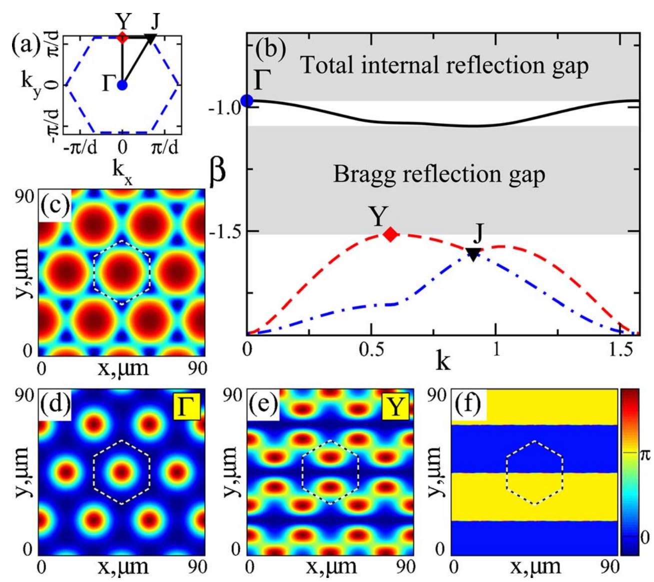

Fig. 1. (Color online) (a) Lattice unit cell in Fourier space; (b) Bloch-wave dispersion along the contour passing through the high-symmetry points marked in (a); (c) refractive index profile of the triangular lattice; (d), (e) Bloch waves corresponding to the Γ and Y points in (a) and (b); (d) intensity at the Γ point of the first band; (e), (f) intensity and phase at the Y point of the second band.

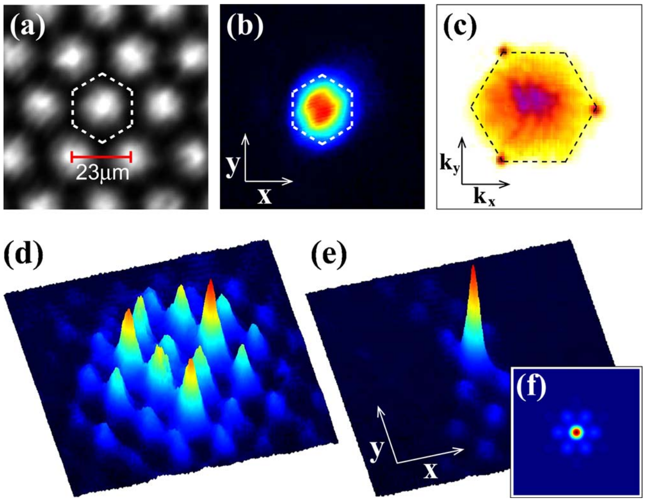

Fig. 2. (Color online) Experimental images of (a) triangular lattice (period 23 μm), (b) single-beam input intensity distribution, and (c) Fourier spectrum of input and lattice beams. In (a) and (b) the dashed hexagon indicates the lattice unit cell, and in (c) the edge of the first Brillouin zone as defined by the three lattice beams. (d), (e) Measured linear discrete diffraction and nonlinear self-trapping, respectively, from the top of the first band. The plot dimensions are 150 μm along both x and y. (f) Numerically calculated intensity of discrete soliton.

$$i\frac{\partial E}{\partial z}+D\left(\frac{\partial^2 E}{\partial x^2}+\frac{\partial^2 E}{\partial y^2}\right)+\mathcal{F}(x,y,|E|^2)E=0, \qquad (1)$$

where x and z are the transverse and propagation coordinates normalized to the characteristic values $x_s=1$ μm and $z_s=1$ mm, respectively; $D=z_s\lambda/(4\pi n_0 x_s^2)$ is the diffraction coefficient; λ is the wavelength in vacuum; and n_0 is the average refractive index of the medium. The function $\mathcal{F}(x,y,|E|^2)=-\gamma[I_b+I_p(x,y)+|E|^2]^{-1}$ characterizes the total refractive index modulation induced by the optical lattice and the probe beam. Here, $I_b=1$ is the normalized constant dark irradiance, $I_p(x,y)=I_g|\exp(ikx)+\exp(-ikx/2-iky\sqrt{3}/2)+\exp(-ikx/2+iky\sqrt{3}/2)|^2$ is the three-wave interference pattern that induces a triangular lattice [see Fig. 1(c)] with period along the x axis $d=4\pi/(3k)$, I_g is the lattice intensity, and γ is a nonlinear coefficient proportional to the applied dc field.[11] The parameters are chosen to match the experimental conditions: $n_0=2.35$ is the refractive index of the bulk photorefractive crystal, $\lambda=532$ nm is the laser wavelength in vacuum, the lattice period is $d=23$ μm or $d=30$ μm, $\gamma=2.36$, and $I_g=0.49$. The applied electric field is 5 kV/cm.

Light propagation in the linear regime is characterized by the spatially extended eigenmodes or Bloch waves.[1] The Bloch waves are found as solutions of the linearized equation (1) in the form $E=\psi(x,y)\exp(i\beta z+iK_x x+iK_y y)$, where $\psi(x,y)$ possesses the same periodicity as the underlying lattice. The dispersion relations $\beta(K_x,K_y)$ are periodic and fully defined by their values in the first irreducible Brillouin zone,[12] shown in Fig. 1(a). The calculated bandgap spectrum is shown in Fig. 1(b) for lattice period $d=30$ μm. The lattice exhibits a full 2D bandgap for typical experimental parameters.

In a self-focusing medium, the nonlinear response increases the beam propagation constant, shifting it inside the gaps for modes associated with the top of the dispersion bands (i.e., points with maximum β), and allowing for the formation of self-trapped waves or spatial solitons.[5] In a triangular lattice, self-trapping can occur in the form of discrete solitons,[10,13] originating from the Γ point at the top of the first band (edge of total internal reflection gap), and gap solitons,[14] originating from the Y point at the top of the second band (edge of Bragg reflection gap) [see Fig. 1(b)].

To excite both types of self-trapped waves in the experiment, we shape the probe beams so as to approximate the symmetry of the Bloch waves associated with the corresponding points in the linear transmission spectrum. The calculated Bloch wave at the top of the first band (Γ point) is shown in Fig. 1(d). It exhibits a strong intensity modulation with peaks coinciding with those of the lattice [see Fig. 1(d)], and a constant phase in the transverse plane. This fundamental Bloch wave is excited by a Gaussian beam focused onto a single lattice site at the input face of the crystal [Figs. 2(a) and 2(b)]. The spectral components of the input beam are centered around the Γ point in

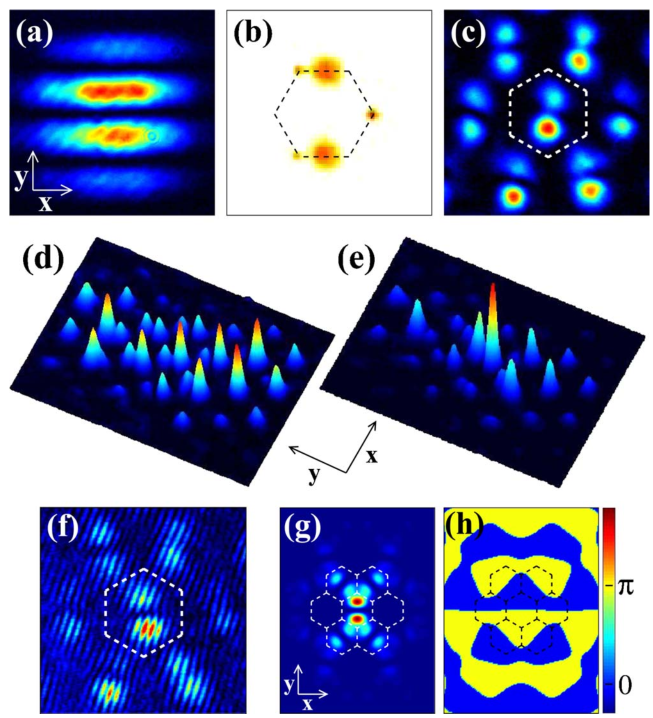

Fig. 3. (Color online) Experimental images of (a) two-beam input intensity distribution, (b) Fourier spectrum of input and lattice beams, and (c) linear second band Bloch wave at the crystal output. In (b) the dashed hexagon indicates the edge of the first Brillouin zone, and in (c) the lattice unit cell. (d), (e) Measured linear diffraction [as in (c)] and nonlinear self-trapping, respectively, from the top of the second band. The plot dimensions are 150 μm along x and 200 μm along y. (f) Measured phase interferogram for the self-trapped beam in (e). (g), (h) Numerically calculated gap soliton intensity distribution and phase, respectively. The lattice period is 30 μm.

Fourier space [Figs. 1(a) and 2(c)]. At low laser power (10 nW) the beam experiences characteristic discrete diffraction,[15] and most of the light is coupled out of the central lattice site upon propagation, as shown in the 3D plot of the output beam intensity distribution in Fig. 2(d). At high laser power (1 μW), on the other hand, the beam localizes at the central lattice site [see Fig. 2(e)], resembling the discrete soliton theoretically predicted for such lattices.[10,13] The soliton profile calculated numerically for our experimental conditions is shown in Fig. 2(f), and the agreement with the observation in Fig. 2(e) is good.

The calculated Bloch wave associated with the Y point at the top of the second band is shown in Figs. 1(e) and 1(f). It has a more complex intensity and phase structure and represents a state with a reduced symmetry. The phase structure of the second band wave is staggered in the vertical direction with a π-phase jump between each zigzag-shaped intensity band extending in the horizontal direction. The intensity peaks are positioned off center with respect to the lattice sites.

The second band wave is excited experimentally by a two-beam interference pattern with a staggered phase structure along the vertical direction [Fig. 3(a)]. The period of the interference fringes is matched to that of the corresponding Bloch wave, and the spectral components of the two input beams are centered around the Y point in Fourier space [Figs. 1(a) and 3(b)]. Despite the rather crude approximation to the Bloch wave profile, the second band wave is successfully excited in the experiment, as seen in Fig. 3(c), which shows the central part of the linear output.

At low power the second band wave strongly diffracts in the lattice [Fig. 3(d)], while at high power it localizes to almost a single lattice site with two out-of-phase and off-center lobes, thus preserving the Bloch wave symmetry. This is verified by interferometric measurements revealing a clear π-phase jump at the center of the localized beam [Fig. 3(f)]. Numerical calculations confirm the observed intensity [Fig. 3(g)] and phase [Fig. 3(h)] structure of the localized beam. Again we find that observations agree well with theory, although the symmetry of the observed second band wave appears to be slightly rotated at the crystal output. Such a rotation can be associated with mode transformation to a different family of gap solitons originating from the J point of the second spectral band[14] [Figs. 1(a) and 1(b)], where the phase structure at the soliton core is rotated by 30° compared with the Y state. According to numerical calculations, the internal energies of the Y and J gap solitons are similar under our experimental conditions, and transformation between these states could therefore be induced by a small input beam asymmetry. On the other hand, we find that the nonlinear gap state remains strongly trapped at the central lattice site subject to small variations in the tilt of the input beams. The observed immobility demonstrates a different regime of soliton dynamics compared with the previously reported strong directional mobility of reduced-symmetry gap solitons in square lattices.[6]

In conclusion, we have experimentally demonstrated light self-trapping and the formation of 2D discrete and gap spatial solitons in optically induced triangular photonic lattices. We believe that our results may be useful for other types of nonlinear periodic structures with similar geometry such as planar photonic crystals and microstructured optical fibers.

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