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Anisotropic photonic lattices and discrete solitons in photorefractive media

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ABSTRACT We study experimentally two-dimensional periodic photonic lattices optically imprinted in photorefractive nonlinear media, and explore the effect of anisotropy on the induced refractive-index patterns. The orientation anisotropy is demonstrated by comparing square and diamond lattices, while the polarization anisotropy is shown to distinguish ordinarily and extraordinarily polarized light. In particular, the extraordinarily polarized lattice induces much stronger refractive-index modulation for the same conditions. Finally, we exploit the photorefractive anisotropy to generate a quasi-one-dimensional refractive-index pattern for the observation of two-dimensional solitons and corroborate these experiments by numerical simulations.

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1 Introduction

Wave propagation in periodic nonlinear systems is associated with many exciting phenomena that do not have any counterpart in either homogeneous nonlinear media or periodic but linear systems. A well-known example is the discrete self-localized state known as a discrete soliton, which has been studied in different branches of science such as biology [1], solid-state physics [2], Bose–Einstein condensates [3], and nonlinear optics [4]. Periodic modulation of the refractive index of optical media can be pre-fabricated in photonic crystals [5] or induced optically in photorefractive materials [6–8].

The advantage of the method of optical induction certainly lies in the features of photorefractive materials such as wavelength-sensitive and reconfigurable nonlinear refractive-index patterns induced at very low power levels. To induce a photonic lattice, the anisotropic electro-optic properties of photorefractive crystals should be employed [9]. In this approach, a periodic light pattern is created by several interfering plane waves with the intensity uniform in the propagation direction. This diffraction-free wave induces a change of the refractive index via the screening photorefractive nonlinearity. If the lattice wave is ordinarily polarized, the relevant electro-optic coefficient is small and the lattice wave propagates in an essentially linear regime, maintaining its stationary transverse profile along the crystal. The induced refractive index follows the light intensity distribution, and it forms one- or two-dimensional photonic lattices. At the same time, any extraordinarily polarized beam (probe beam) experiences strong nonlinear effects in addition to a periodically modulated refractive index. The nonlinearity experienced by the extraordinarily polarized beam can be altered by varying the external biasing field, and it can even be switched from positive to negative by simply reversing the applied bias voltage.

An additional possibility to create stationary two-dimensional light patterns for all-optical induction is offered by using extraordinarily polarized periodic waves [10]. In this case the lattice wave is influenced by a strong photorefractive nonlinearity, and it propagates in the nonlinear regime. It forms a stationary nonlinear periodic wave becoming an eigenmode of the self-induced periodic potential. Therefore, due to the strong electro-optic or polarization anisotropy, the lattices can be operated in either linear or nonlinear regimes by simply switching the polarization state of the lattice wave.

Another consequence of the photorefractive anisotropy is that the induced refractive-index change strongly depends on the orientation of the lattice with respect to the c-axis of the crystal [10, 11]. Considering lattices with four-fold symmetry as a simple example of highly symmetric structures, we distinguish two orientations of the lattice: a square pattern with one high-symmetry axis orientated parallel to the c-axis, and a diamond pattern tilted by 45°. Anisotropy was shown to change the symmetry properties of the induced refractive-index pattern, resulting in an effectively one-dimensional refractive-index structure for the square pattern, in contrast to a two-dimensional structure for the diamond pattern. This effect does not depend on polarization of the lattice wave; thus, we identify it as the orientation anisotropy. However, the induced change of the refractive index does depend on the light intensity profile [12], which is different for linear and nonlinear periodic waves. Thus, it is important to study the influence of the lattice self-action effect on the refractive-index modulation.

To the best of our knowledge, there exist no systematic studies of the dependence of the induced periodic structure on the polarization of the lattice wave. Furthermore, the effects of anisotropy on the properties of lattice solitons were not investigated in detail. Particularly interesting is the relation between the symmetry of the lattice and the discrete

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soliton it may support [13]. For example, the two-dimensional solitons in quasi-one-dimensional lattices were recently predicted theoretically [14, 15] but they have not been studied experimentally.

The purpose of this paper is twofold. First, we present experimental results for the generation of two-dimensional photonic lattices with ordinary and extraordinary polarization and study the induced refractive-index structures in the real and Fourier spaces. We demonstrate that in the nonlinear regime the intensity of each lattice site is increased due to self-focusing, and it leads to a stronger modulation of the refractive index for extraordinarily polarized light than that for an ordinarily polarized lattice wave. Next, we extend our analysis to the linear and nonlinear wave propagation in photonic lattices and study experimentally two-dimensional discrete solitons in quasi-one-dimensional potentials as predicted theoretically in [14, 15]. To induce a quasi-one-dimensional refractive-index pattern, we utilize the orientation-dependent symmetry of the induced refractive-index change by using an extraordinarily polarized two-dimensional square pattern with chess-board-like phase profile as a lattice wave. The experimental results are in a good qualitative agreement with direct numerical simulations of the reduced-symmetry two-dimensional solitons.

The paper is organized as follows. In Sect. 2 we describe briefly our experimental setup. Sections 3 and 4 are devoted to the study of the properties of the induced photonic lattices modified, correspondingly, by orientation and polarization anisotropy. In Sect. 5 we compare the experimental and numerical results for the discrete solitons in the lattices of different symmetries, in particular for a novel class of reduced-symmetry two-dimensional discrete solitons generated in quasi-one-dimensional photonic lattices. Finally, Sect. 6 concludes the paper.

2 Experimental setup

The experimental setup is shown schematically in Fig. 1. A beam from a frequency-doubled Nd:YAG laser at a wavelength of 532 nm is sent through a combination of a half-wave plate and a polarizing beam splitter in order to adjust the intensities in both arms. The desired pure phase modulation of the transmitted beam is achieved by using two quarter-wave plates and a programmable spatial light modulator. The modulated beam is then imaged at the input face of a 20-mm-long $Sr_{0.60}Ba_{0.40}Nb_2O_6$ (SBN:Ce) crystal by a high numerical aperture telescope. The crystal is biased by an externally applied electric field and uniformly illuminated with a white-light source to control the dark irradiance. A half-wave plate is placed in front of the telescope so that lattices can be induced with ordinarily as well as extraordinarily polarized light. By switching off the modulator, the crystal can be illuminated with a broad plane wave to observe the waveguiding properties of the induced lattice. The second beam is passed through a rotating diffuser and the partially spatially incoherent output of the diffuser is imaged at the front face of the crystal. This results in partially coherent multi-band excitation of the lattice modes and enables a direct visualization of the lattice structure in Fourier space [16, 17]. To ensure that the light will experience the refractive-index modulation of the lattice, the beam is extraordinarily polarized using a half-wave plate. The output of the crystal is finally analyzed with two CCD cameras. CCD1 monitors the real-space output, whereas CCD2 is placed in the focal plane of a lens to visualize the Fourier power spectrum of the light exiting the lattice. By removing the rotating diffuser, two lenses, and iris diaphragm (dashed square), the setup can be changed to observe the evolution of Bloch waves on the lattice. This is achieved by focusing a Gaussian probe beam onto the front face of the crystal and analyzing the output using CCD1.

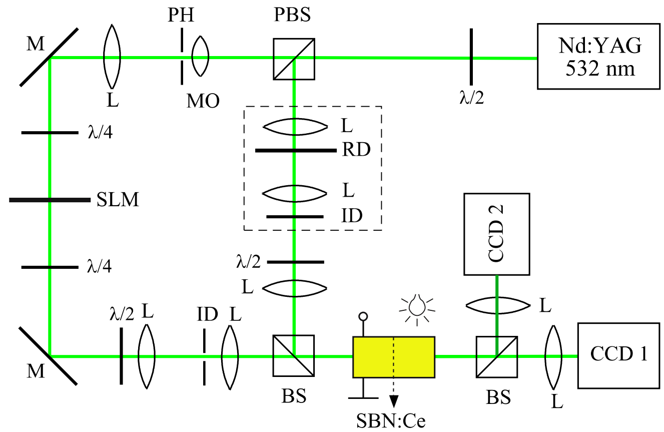

FIGURE 1 Experimental setup. (P)BS: (polarizing) beam splitter, MO: microscope objective, PH: pinhole, L: lens, M: mirror, SLM: spatial light modulator, ID: iris diaphragm, RD: rotating diffuser, CCD1: real-space camera, CCD2: Fourier camera

3 Orientation anisotropy

To investigate the structure of the induced refractive-index change, two different methods can be used. The first method is given by observing the waveguiding properties of the lattice [10, 11]. As the incident light pattern induces a periodic array of waveguides in the medium, illuminating the lattice with a broad plane wave leads to guiding of this wave and the output intensity pattern of the guided wave qualitatively maps the induced refractive-index change. By monitoring the far field of the output, the lattice structure can also be analyzed in Fourier space.

Another powerful diagnostic tool for analyzing the lattice structure in Fourier space is offered by the recently demonstrated Brillouin-zone spectroscopy [16, 17]. The aim of this method is a direct visualization of the lattice structure in Fourier space by mapping the boundaries of the extended Brillouin zones, which are defined through the Bragg-reflection planes. To map out the momentum space, the lattice is probed with a partially spatially incoherent beam, which has a uniform spatial power spectrum extending over several Brillouin zones and is broad enough in real space to cover numerous lattice sites. The light exiting the lattice is then analyzed by performing an optical Fourier transformation and measuring the power spectrum, which contains dark lines at the borders of the extended Brillouin zones.

Figure 2 demonstrates the results obtained using an extraordinarily polarized lattice wave (period: 22 μm) for diamond (left-hand column) and square (right-hand column) patterns. The lattice input is shown in real space (Fig. 2a) as well as in Fourier space (Fig. 2b). According to the four-fold lattice symmetry, the far field is represented by four beams, which also determine the boundaries of the first Brillouin zone [16, 17]. With the applied voltage (1 kV/cm), the input is influenced by anisotropic self-focusing leading to an output intensity distribution containing elliptical spots (Fig. 2c). The intensity distribution of the plane wave guided by the lattice is shown in Fig. 2d and its Fourier image in Fig. 2e. As the output intensity of the guided wave matches the induced refractive-index change, one can clearly see the differences in the refractive indices for the two orientations caused by the anisotropy of the photorefractive crystal. The waveguiding output consists of vertical lines for the square pattern (Fig. 2d, right-hand column), but keeps its fully two-dimensional structure for the diamond pattern (Fig. 2d, left-hand column). The Fourier image of the plane wave guided in the diamond lattice (Fig. 2e, left-hand column) consists of one dominating central peak surrounded by four side beams. Corresponding to the theory of Bloch waves in periodic structures [18, 19], the plane wave with zero transverse wave vector belongs to the central high symmetry point of the first Brillouin zone but, due to periodicity, it also excites the central points in higher-order bands of the transmission spectrum. Therefore, the four side beams indicate the central points of the second band from the extended Brillouin zone. In contrast, the Fourier image of the plane wave guided in the square lattice (Fig. 2e, right-hand column) contains only two side beams generated by resonant reflections in the guiding structure, corresponding to the one-dimensional refractive-index pattern. The orientation-dependent structure of the induced refractive-index change is clearly demonstrated in the Brillouin-zone pictures (Fig. 2f), too. For the diamond pattern the two-dimensional structure of the induced refractive-index change is revealed by the clearly visible first Brillouin zone of the diamond lattice. The Brillouin-zone picture of the square pattern, however, is dominated by two vertical lines representing the borders of the first Brillouin zone of the corresponding one-dimensional stripe pattern.

4 Polarization anisotropy

Due to the electro-optic anisotropy of axial photorefractive crystals like strontium barium niobate (SBN), one can distinguish between linear and nonlinear material response in order to create the desired photonic lattices. An ordinarily polarized light beam experiences only a negligible nonlinearity due to the small electro-optic coefficient and therefore propagates in an almost linear regime. On the other hand, an extraordinarily polarized light beam is influenced by a strong photorefractive nonlinearity and propagates in the nonlinear regime. For both polarizations the symmetry of the induced refractive-index change depends on orientation of the lattice wave with respect to the *c*-axis [10, 11] and the saturation of the refractive index depends on the intensity of the lattice wave. The larger the intensity, the stronger the saturation of the refractive index. However, when the lattice wave is extraordinarily polarized, the self-focusing effect increases the intensity of each spot such that the lattice is effectively induced with higher peak intensity. Consequently, for otherwise the same parameters (initial intensity, background illumination, and applied voltage) the refractive-index modulation induced with extraordinarily polarized light is stronger than that for ordinarily polarized light. This is illustrated in Figs. 3 and 4 showing the output of the guided plane wave for square

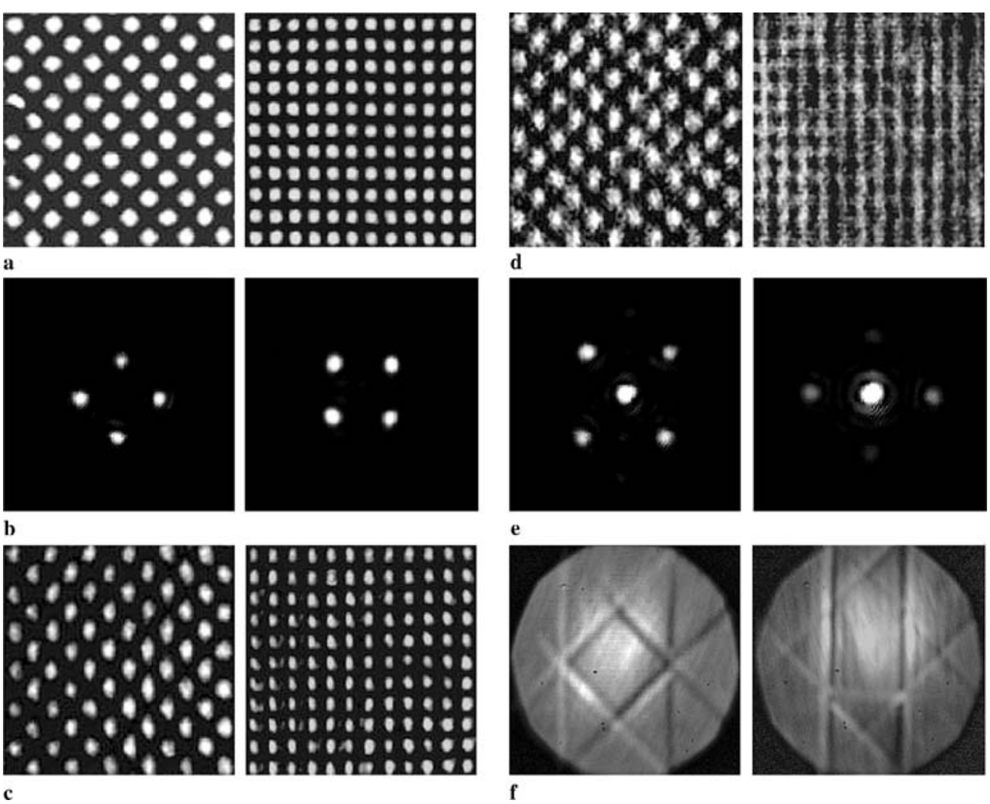

FIGURE 2 Structure analysis for diamond pattern (*left-hand column*) and square pattern (*right-hand column*). (**a**) Input, (**b**) far-field structure of the lattice wave, (**c**) nonlinear output, (**d**) guided wave, (**e**) far-field structure of the guided wave, (**f**) Brillouin zone

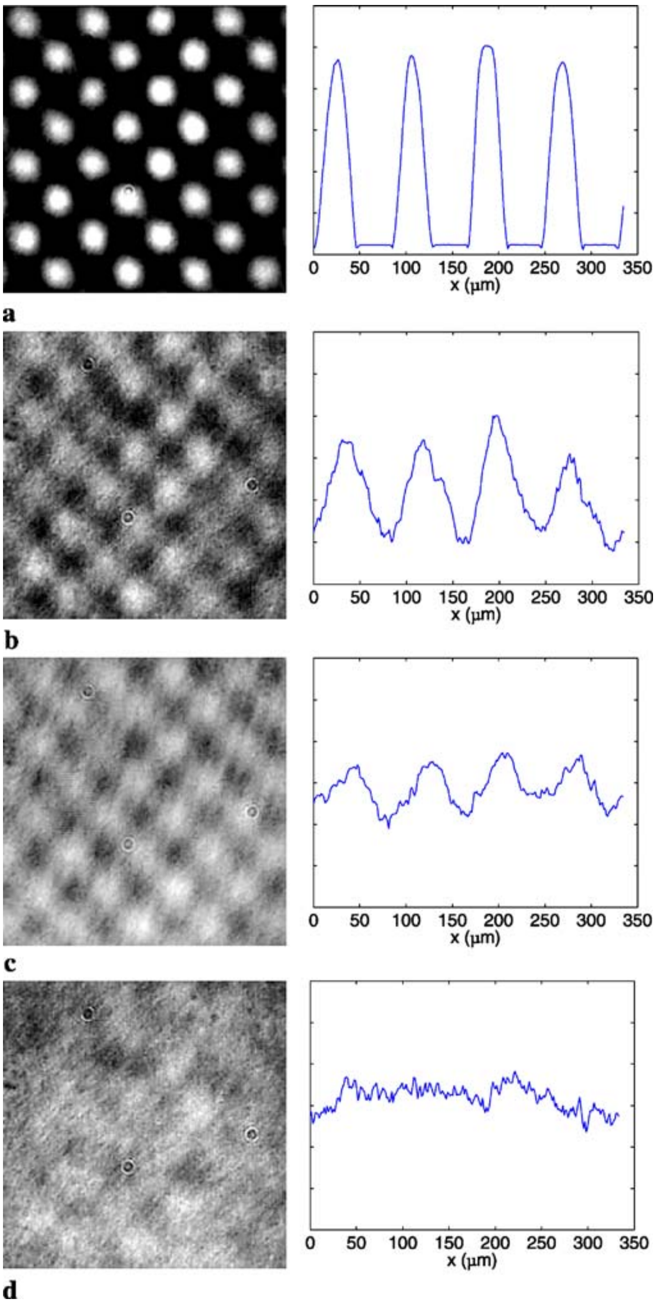

FIGURE 3 Guided wave output (*left-hand column*) and horizontal intensity profiles (*right-hand column*) of diamond pattern with varied polarizations for lattice wave and guided wave. (**a**) Lattice wave and guided wave e-polarized; (**b**) lattice wave e-polarized, guided wave o-polarized; (**c**) lattice wave o-polarized, guided wave e-polarized; (**d**) lattice wave and guided wave o-polarized

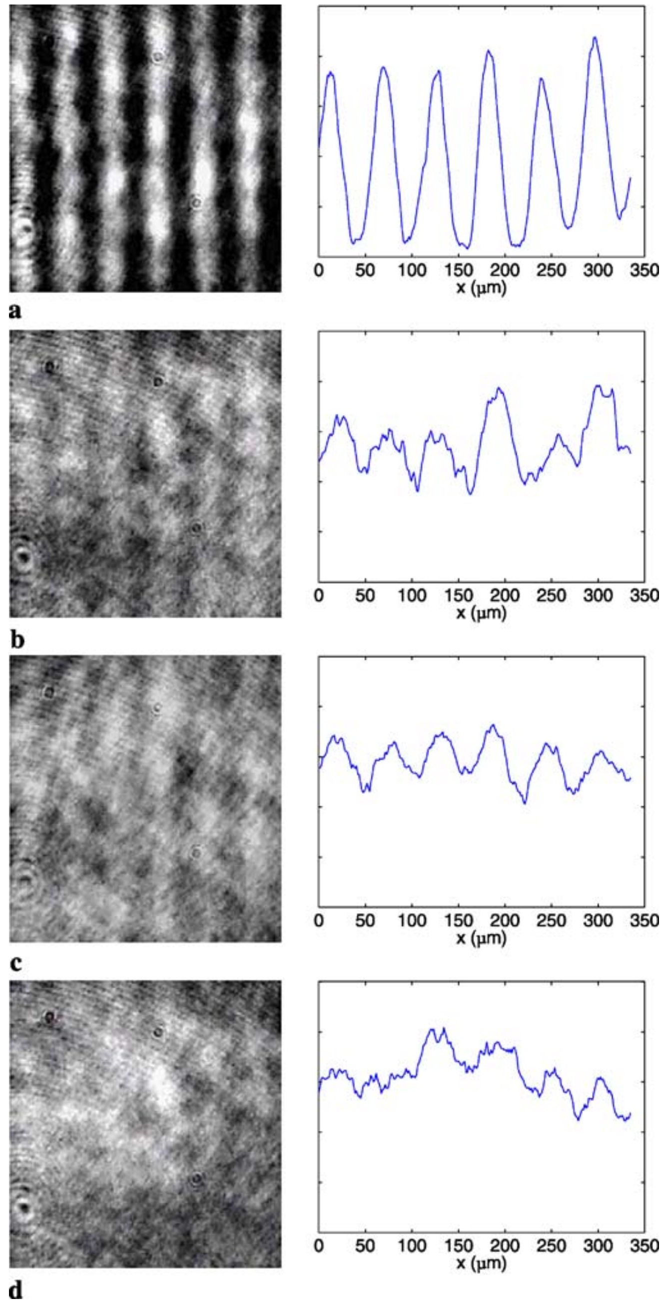

FIGURE 4 Guided wave output (*left-hand column*) and horizontal intensity profiles (*right-hand column*) of square pattern with varied polarizations for lattice wave and guided wave. (**a**) Lattice wave and guided wave e-polarized; (**b**) lattice wave e-polarized, guided wave o-polarized; (**c**) lattice wave o-polarized, guided wave e-polarized; (**d**) lattice wave and guided wave o-polarized

and diamond patterns, respectively [10, 11]. The lattices with period 60 μm are induced with either ordinary or extraordinary polarization using a very low power of 3 μW for the whole lattice wave. The polarization of the plane wave can be made ordinary (o) as well as extraordinary (e). As expected, the strongest modulation can be observed when the lattice wave and the probe plane wave are extraordinarily polarized. If the lattice and the plane waves are both ordinarily polarized, no modulation of the guided wave can be observed. Indeed, in the latter case the lattice intensity is too low to induce a significant refractive-index change as well as the coupling of the ordinarily polarized plane wave being weak due to a very small electro-optic coefficient.

5 Two-dimensional discrete solitons

In order to explore the influence of anisotropy of photonic lattices on the symmetries of discrete solitons, we generated two-dimensional solitons experimentally by focusing an extraordinarily polarized Gaussian beam into one lat-

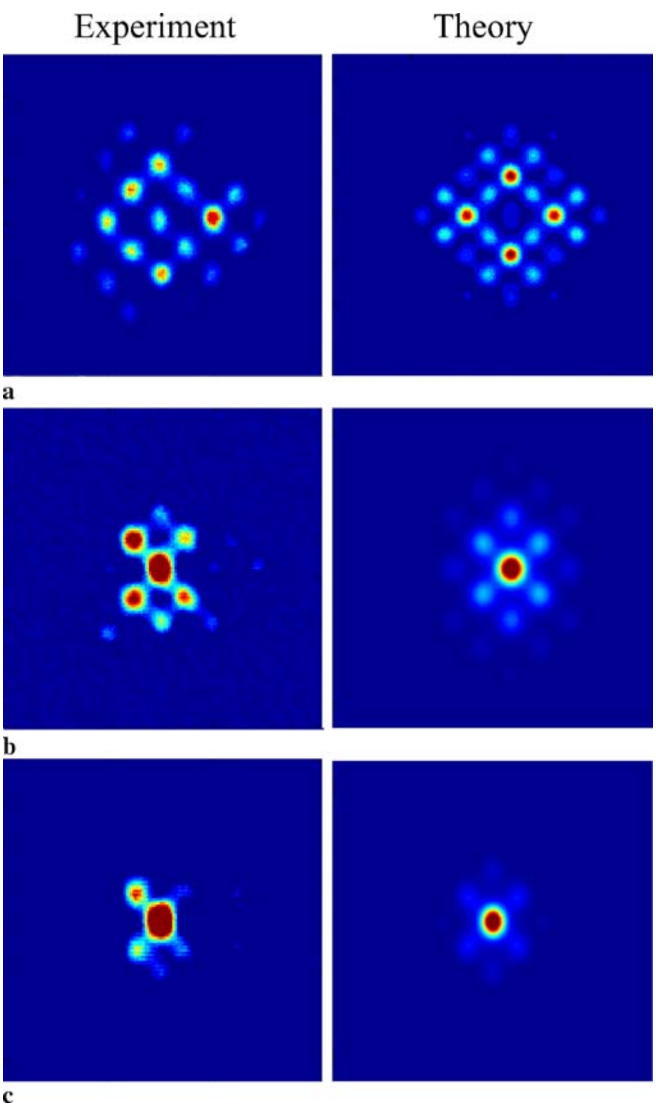

FIGURE 5 Experimental results (*left*) and numerical simulations (*right*) for the diamond pattern. (**a**) Discrete diffraction (linear propagation), (**b**) localized state at moderate intensity, (**c**) discrete soliton

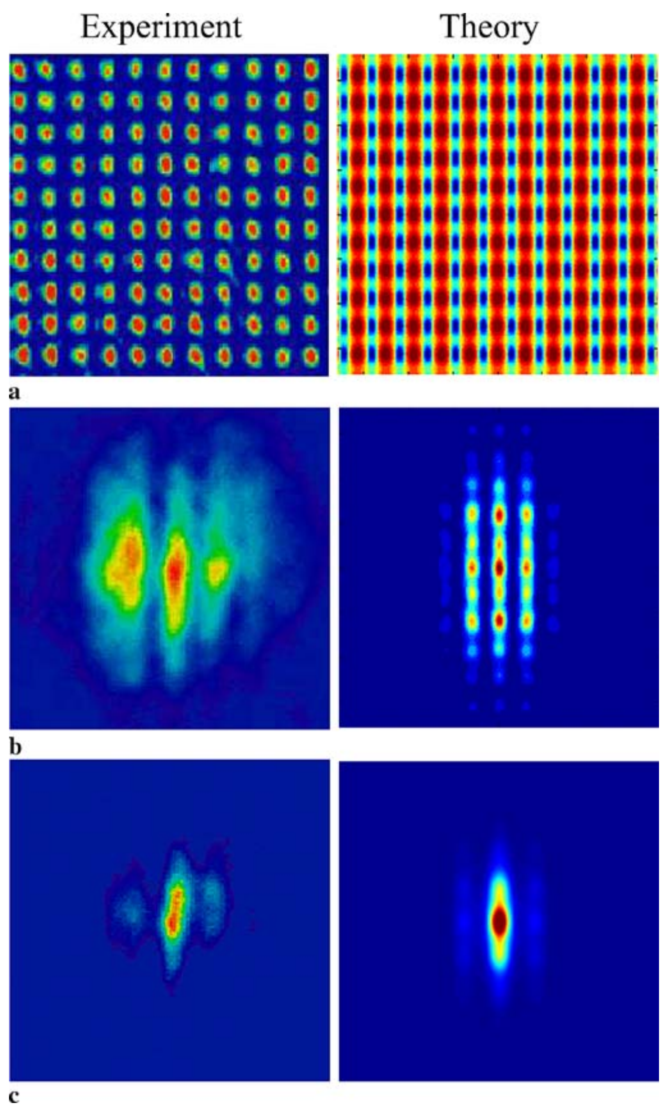

FIGURE 6 Experimental results (*left*) and numerical simulations (*right*) for the square pattern. (**a**) Lattice intensity and refractive index, (**b**) diffraction of the probe beam at low intensity, (**c**) localized state at high intensity

tice site at the front face of the crystal. The results for the diamond and square lattices are summarized in Figs. 5 and 6. Although the probe beam is extraordinarily polarized, we also observed its linear propagation (discrete diffraction) using the slow response of photorefractive nonlinearity. Indeed, the process of optical induction is much slower than the propagation of light and immediately after launching the probe beam the periodic refractive index induced by the lattice wave is undistorted. We observed that the discrete diffraction in the diamond lattice in Fig. 5a follows the dynamics known for a truly two-dimensional square photonic lattice, while corresponding images for the square lattice in Fig. 6b are significantly different. The modulation of the beam intensity after discrete diffraction, similar to the guided waves in Figs. 2d and 4, is effectively one dimensional.

To describe propagation of extraordinarily polarized light in the optically induced photonic lattices, we employ the nonlinear Schrödinger equation with the potential proportional to the corresponding component of the optically induced space-charge field (φ is the corresponding electrostatic potential):

$$\mathrm{i}\frac{\partial E}{\partial z} + \nabla^2 E + \mathcal{F}(I)E = 0\,, \tag{1}$$

$$\mathcal{F}(I) = \Gamma \frac{\partial \varphi}{\partial x}\,, \tag{2}$$

$$\nabla^2\varphi + \nabla\varphi\nabla\ln(1+I) = \frac{\partial}{\partial x}\ln(1+I)\,. \tag{3}$$

Here $\nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$, the parameter Γ is proportional to the electro-optic coefficient and the bias dc field, and the total intensity includes three terms, $I = 1 + V(x, y) + |E|^2$, the background illumination, the lattice wave intensity $V(x, y)$, and the probe beam (soliton) intensity $|E|^2$. We use the lattice intensity given by

$$V(x, y) = I_0 \cos^2 X \cos^2 Y\,,$$

where $X = (x+y)/\sqrt{2}$ and $Y = (x-y)/\sqrt{2}$ for the diamond lattice while $X = x$ and $Y = y$ for the square lattice. Matching our experimental conditions, we choose $I_0 = 2$ and $\Gamma = 6$. To obtain the discrete diffraction, Figs. 5a and 6b, we solve (1)–(3) with the total intensity $I = 1 + V$. The numerical results are in good qualitative agreement with corresponding experimental pictures.

Increasing the power of the probe beam and allowing a sufficient time for the self-action effect to take place, we record the formation of discrete solitons in Figs. 5b, 5c, and 6c. Numerically, we obtain the profiles of the solitons by solving (1)–(3) with the ansatz $E = U(x, y)\exp(\mathrm{i}\beta z)$ and total intensity $I = 1 + V + U^2$. Similar to the striking differences in the pictures of discrete diffraction in the square and diamond lattices, the discrete solitons carry the symmetry of the underlying nonlinear lattice, and the soliton in the square lattice is modulated only in the x-direction.

These observations closely resemble two-dimensional solitons in saturable media propagating in a one-dimensional lattice potential investigated theoretically in [14]. These solitons naturally show a strong anisotropy, making them essentially different from usual two-dimensional solitons. An additional advantage of using a one-dimensional lattice potential is that the remaining free direction offers the possibility of soliton movement and therefore allows the study of soliton collisions and the formation of bound states [15]. The mobility of two-dimensional solitons was also shown to be strongly anisotropic in other two-dimensional lattices [13].

To achieve a pure one-dimensional refractive-index modulation in the transverse direction which does not change during propagation, the stripe pattern with

$$V = I_0 \cos^2 x \tag{4}$$

can be used as a lattice wave. We generated a one-dimensional photonic lattice shown in Fig. 7a. The diffraction of the probe beam at low intensity in Fig. 7b and the formation of a localized state at higher intensity in Fig. 7c are clearly visible. The intensity of the entire lattice was 100 μW. At low power of the probe beam (25 nW), we observe diffraction resembling the formation of Bloch waves of the periodic potential (Fig. 7b). When the power is increased (250 nW) a localized state with well-pronounced side lobes forms; see Fig. 7c.

Equation (3) can be solved analytically for the intensity, which depends on x only (4):

$$\mathcal{F}(x) = -\frac{\Gamma}{1 + I(x)}\,, \tag{5}$$

so that the isotropic saturable model [15] applies. Using this model, we obtain the numerical results shown in Fig. 7 (right), in very good agreement with experimental data. To obtain the soliton profile in Fig. 7c the Fourier interaction method elaborated in [20] was used. Furthermore, we obtained similar results using the full anisotropic model (1)–(3) and did not find any qualitative differences.

Note that the stripe pattern propagates diffraction-free through the crystal and induces the desired refractive-index change in the linear regime. However, in the nonlinear regime, stripes break up into filaments due to modulational instability [21] and the lattice structure is destroyed. Therefore, the lattice wave has to be necessarily ordinarily polarized in this approach, such as the one we used in Fig. 7. On the other hand, our results for the square lattice in Fig. 6 offer an equivalent way of inducing the desired potential in the nonlinear regime. As a consequence of anisotropy, the two-dimensional square pattern induces the desired quasi-one-dimensional refractive-index change. Furthermore, because an extraordinarily polarized lattice wave requires less intensity to achieve a sufficient modulation of the refractive index, for the square lattice in Fig. 6 we used the lattice wave at a power of only 35 μW, much lower than that for the stripe pattern in Fig. 7.

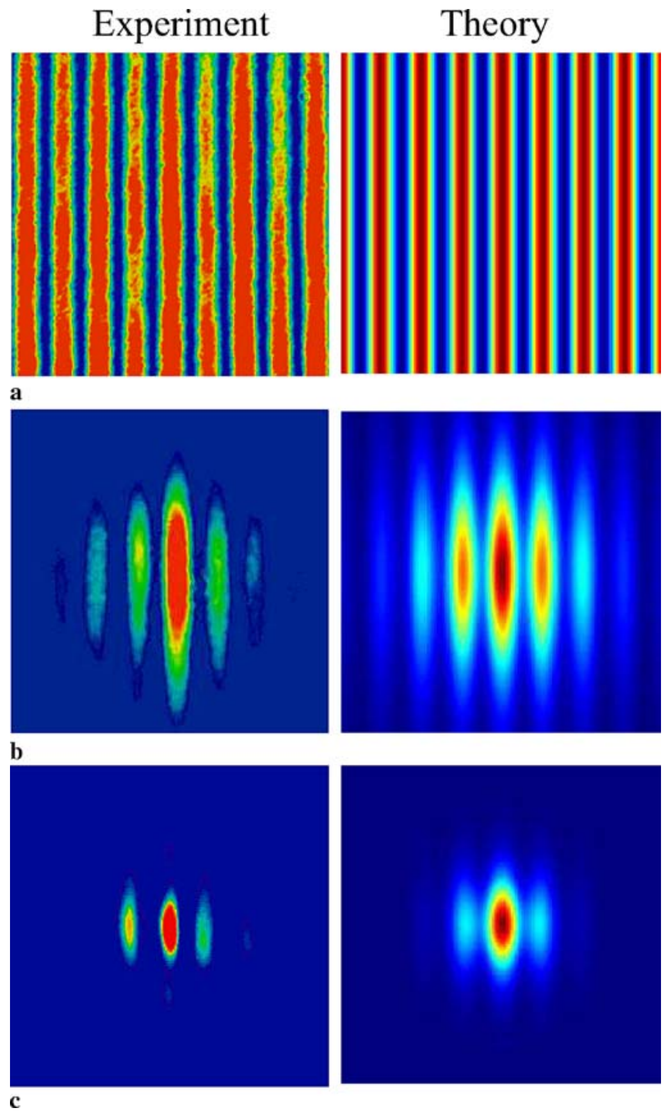

FIGURE 7 Experimental results (*left*) and numerical solutions (*right*) for the stripe pattern. (**a**) Intensity distribution of the lattice, (**b**) diffraction of the probe beam at low intensity, (**c**) localized state at high intensity

6 Conclusions

We have studied experimentally two-dimensional photonic lattices with different orientations in an anisotropic photorefractive medium and analyzed the induced refractive-index patterns by testing the waveguiding properties. We have demonstrated that the induced refractive-index modulation is much stronger for extraordinarily rather than ordinarily polarized light for the similar conditions. For the first time to our knowledge, we have studied experimentally two-dimensional discrete solitons localized in quasi-one-dimensional lattice potentials. In the latter case, we have employed the photorefractive anisotropy, which leads to an effectively one-dimensional refractive-index modulation induced by a two-dimensional nonlinear self-trapped periodic wave with chessboard-like phase structure. These results open the perspectives to generate reduced-symmetry moving solitons and to study soliton collisions and the formation of bound states.

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