Nonlinear photonic lattices induced by periodic phase modulation in a photorefractive nonlocal self-focusing medium

C. Denz, Nina Sagemerten, Denis Träger, Johannes Jägers, and Jörg Imbrock
Institut für Angewandte Physik, Westfälische Wilhelms-Universität Münster
Corrensstr. 2/4, 48149 Münster, Germany

Anton S. Desyatnikov, Dragomir N. Neshev, and Yuri S. Kivshar
Nonlinear Physics Centre and Centre for Ultra-high bandwidth Devices for Optical Systems, Research School of Physical Sciences and Engineering, Australian National University, Canberra, Australia

Wieslaw Krolikowski
Laser Physics Centre, Research School of Physical Sciences and Engineering, Australian National University, Canberra, Australia

Alexander Dreischuh
Department of Quantum Electronics, Sofia University, Bulgaria

Abstract: *We study theoretically and investigate experimentally nonlinear photonic lattices of different symmetries generated by pixel-like solitons in a photorefractive medium. The light-induced periodically modulated nonlinear refractive index is highly anisotropic and nonlocal, and it depends on the lattice orientation relative to the optical axis of the crystal. We discuss the stability of these induced photonic structures and their guiding properties.*

1 Introduction

The study of nonlinear effects in periodic photonic structures has recently become of high interest due to its potential to control light propagation, and to allow for beam steering and trapping. The idea behind this approach is that a periodic modulation of the refractive index modifies the linear spectrum and wave diffraction and thereby strongly affects the nonlinear propagation and localization of light [1]. Photonic lattices can be optically induced by linear diffraction-free light patterns created by interfering several plane waves [2]. However, the induced change of the refractive index depends on the light intensity and, in the nonlinear regime, it is accompanied by the self-action effect [3]. In contrast, nonlinear diffraction-free light patterns in the form of stable self-trapped periodic waves can propagate without change in their profile, because they represent eigenmodes of the self-induced periodic potentials and thereby provide a simple realization of nonlinear photonic crystals.

Nonlinear photonic lattices created by two-dimensional arrays of pixel-like solitons have recently been demonstrated experimentally in photorefractive crystals with both coherent [4] and partially incoherent [3], [5], [6] light. Up to now, they were created by amplitude modulation, so that every pixel of the lattice induces a waveguide which can be manipulated by an external steering beam [4], [6], [7]. However, the spatial periodicity of these lattices is limited by soliton interaction that may lead to their strong instability. In this investigation, we analyze theoretically and generate experimentally two-dimensional nonlinear lattices with periodic phase modulation in a photorefractive medium. An advantage of using nonlinear periodic lattices when compared with in-phase lattices or incoherent soliton arrays is that such lattices can be made robust with smaller lattice spacing. In the following sections, we discuss the stability of these induced photonic structures and their guiding properties.

2 Theory

Spatially periodic nonlinear modes appear naturally because of self-focusing and modulational instability [1]. When self-focusing compensates for the diffraction of optical beams, it may support both isolated spatial solitons and periodic soliton trains or stationary periodic nonlinear waves. The latter include the well-studied cnoidal waves, solutions to the nonlinear Schrödinger equation [1],

$$i\partial_z E + \nabla_\perp^2 E + n(I)E = 0 \ , \qquad (1)$$

where $I = |E|^2$ and $\nabla_\perp^2 = \partial_x^2 + \partial_y^2$. Similar stable periodic waves exist in different nonlinear models, including quadratic and Kerr-type saturable nonlinearities. The family of two-dimensional nonlinear periodic waves[8] can also be extended to the case of rectangular geometry with two different transverse periods because these anisotropic deformations of a square lattice do not enhance its modulational instability. Stabilization of phase-engineered soliton arrays was reported recently for an anisotropic model[7]. In this contribution, we consider a photorefractive crystal as an example of an anisotropic and nonlocal nonlinear medium. In this case the nonlinear contribution to the refractive index in Eq. (1) is given by [9]

$$n(I) = \Gamma \partial_x \phi \quad , \tag{2}$$

where the electrostatic potential ϕ of the optically induced space-charge field satisfies a separate equation:

$$\nabla_\perp^2 \phi + \nabla_\perp \phi \nabla_\perp \ln(1+I) = \partial_x \ln(1+I) \quad . \tag{3}$$

Here, the intensity I is measured in units of the background illumination (dark) intensity necessary for the formation of spatial solitons in such a medium. The physical variables $\tilde{x}$, $\tilde{y}$, and $\tilde{z}$ are represented by their dimensionless counterparts as $(\tilde{x}, \tilde{y}) = x_0(x, y)$ and $\tilde{z} = 2\kappa x_0^2 z$, where x_0 is the transverse scale factor and $\kappa = 2\pi n_0/\lambda$ is the carrier wave vector with linear refractive index n_0. The parameter $\Gamma = x_0^2 \kappa^2 n_0^2 r_{\text{eff}} E$ is defined through the effective electro-optic coefficient r_{eff} and the externally applied bias electrostatic field E.

Stationary solutions to the system of Eqs. (1) - (3) are sought in the standard form $E(x,y,z) = U(x,y)\exp(ikz)$, where the real envelope U satisfies the equation

$$-kU + \nabla_\perp^2 U + \Gamma \partial_x \phi U = 0 \quad . \tag{4}$$

We look for periodic solutions, $U(X,Y) = U(X+2\pi, Y+2\pi)$, and solve Eqs. (3) and (4) using the relaxation technique with the initial ansatz in the form of a linear periodic mode, $U_{\text{lin}}(X,Y) = A \sin X \sin Y$. We find that at least two distinct families bifurcate from the linear wave U_{lin}, depending on their orientation: a square pattern parallel to the c axis with $(X,Y) = (x,y)$ and a diamond pattern oriented diagonally with $(X,Y) = (x \pm y)/\sqrt{2}$. Fig. 1(a) and Fig. 1(b) show the field and refractive-index distributions in the low $(k = -1.9, A \approx 0.9)$ and relatively high $(k = -1.5, A \approx 3.6)$ saturation regimes for both families.

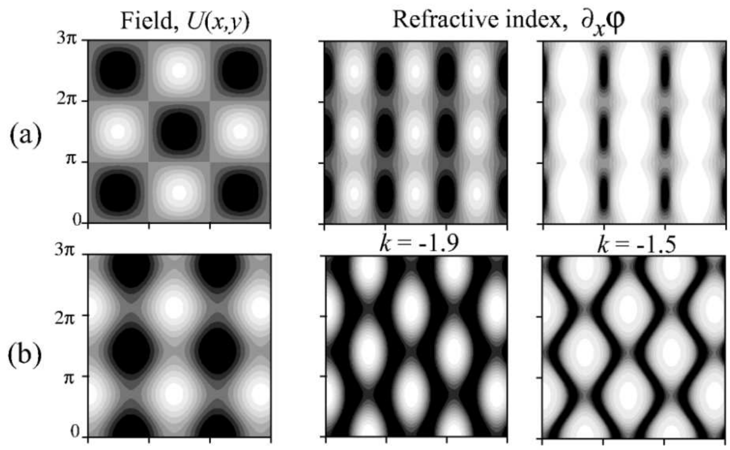

Figure 1: (a) Square and (b) diamond self-trapped stationary periodic patterns in the model in Eqs. (1) - (3) at $\Gamma = 1$.

The main difference between the two solutions, clearly seen in Figs. Fig. 1(a) and Fig. 1(b), comes from the refractive index: The regions with effective focusing lenses are well separated for the diamond pattern and fuse to effectively one-dimensional stripes for the square pattern in the limit of strong saturation.

To test the lattice stability, we propagate numerically two types of initially perturbed periodic solutions and observe robust propagation for distances exceeding the experimental crystal length. Figure Fig. 2 demonstrates an example of stable propagation for the parameters close to our experimental situation.

3 Experimental setup

In our experiments we investigated the existence of the periodic pattern in a photorefractive medium. As a light source we use a frequency-doubled Nd:YAG laser at a wavelength of 532 nm. The light passes a liquid crystal programmable spatial light

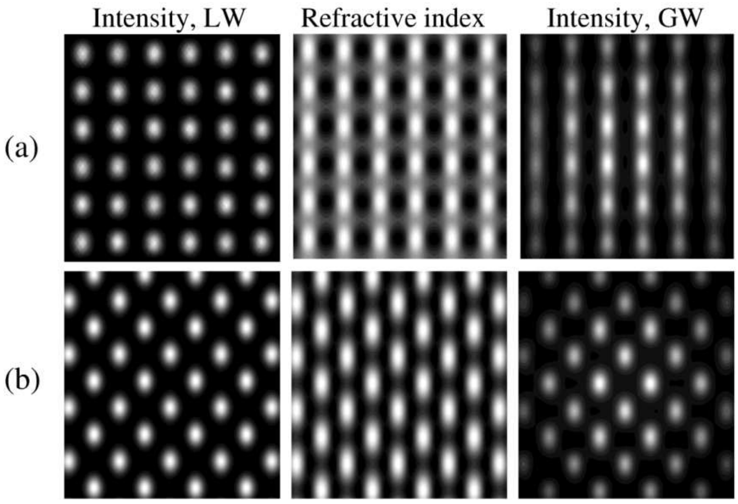

Figure 2: Numerical results for the propagation of (a) square and (b) diamond self-trapped patterns for $\Gamma = 11.8$ in the low-saturation regime with $A \approx 1$ and $k = -0.5$. LW=linear wave, GW=guided wave

modulator (SLM) with 640×480 pixels. The SLM imprints a phase pattern onto the laser beam. It is imaged through a high numerical aperture telescope, whose demagnification is 10, onto a photorefractive SBN crystal. The light is polarized parallel to the c-axis of the crystal in order to exploit the large electrooptic coefficient. Therefore it experiences a strong nonlinearity. The crystal is externally biased with a static electric field of 1000 V/cm and illuminated with white light to control the dark conductivity. The phase pattern from the spatial light modulator transforms into an amplitude modulation at the front face of the crystal. Higher spatial frequencies are filtered out to reduce the noise.

The advantage of this experimental setup is that different patterns can easily be written in and erased from the crystal. To erase the pattern we simply increase the intensity of the white light.

4 Experimental results

To realize the numerically found periodic solutions in the square and diamond pattern, we implemented a chessboard-like phase pattern on the spatial light modulator, where the bright squares have a relative phase of 0 and the dark squares a relative phase of π . We find out that at zero electric field the pattern propagates through the crystal without being disturbed. This is because the generated periodic pattern represents a non-diffracting periodic wave. Only in the nonlinear regime, i.e. when the crystal is biased and illuminated with white light, a refractive index grating is created. To probe this grating we switch off the spatial light modulator, thereby sending a broad plane wave onto the crystal.

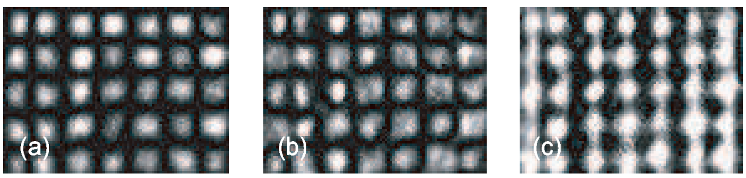

Figure 3: Square pattern: (a) linear output, (b) nonlinear output, (c) guided wave

Fig. 3 (a) shows the linear output. In (b), the output in the nonlinear regime (with the crystal biased and illuminated with white light) does not differ significantly from the previous. However, the light is guided in the channels written by the solitons. This can be seen in Fig. 3 (c).

As an additional result, the lattice spacing can be decreased compared to a lattice composed of in-phase solitons while maintaining a stable structure as predicted in the numerical calculations of Fig. 2. A typical lattice spacing is 40 μm.

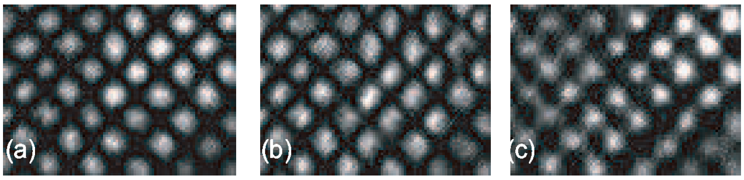

Figure 4: Diamond pattern: (a) linear output, (b) nonlinear output, (c) guided wave

Next, we considered a diamond-like pattern as can be seen in Fig. 4. This pattern also is very stable even for small lattice spacings. As in the case of the square lattice, it represends an eigenmode of the crystal. In the case of a square pattern oriented along the principal axis of the crystal the induced refractive index change is almost one-dimensional - the horizontal modulation is much stronger than the modulation along the vertical direction. In the case of diagonal orientation - diamond pattern, we get a more pronounced two-dimensional structure. The periodic patterns are in good agreement with the numerical simulations.

5 Conclusions

We have studied theoretically and generated experimentally two-dimensional nonlinear photonic lattices in an anisotropic photorefractive medium. We have found two distinct classes of self-trapped robust spatially periodic waves with out-of-phase neighbouring sites, the square pattern oriented parallel to the crystal axes, and the diamond pattern oriented diagonally in the transverse plane. We have demonstrated that the highly anisotropic refractive index distribution induced by the lattice depends strongly on the lattice orientation.

Acknowledgements

This work was initiated by visits supported by the Australian-German Exchange Program of the Deutscher Akademischer Austausch Dienst (DAAD). It was also supported by the Australian Research Council, the Alexander von Humboldt Foundation and the Deutsche Forschungsgemeinschaft, Graduate School *Nonlinear Continuous Systems*.

References

[1] Yu. S. Kivshar and G.P. Agrawal, *Optical Solitons : From Fibers to Photonic Crystals* (Academic, San Diego, 2003)

[2] J.W. Fleischer, M. Segev, N.K. Efremidis, and D.N. Christosoulides, Nature 422, 147 (2003)

[3] Z. Chen, and K. McCarthy, Opt. Lett. 27, 2019 (2002)

[4] J. Petter, J. Schröder, D. Träger, and C. Denz, Opt. Lett. 28, 438 (2003)

[5] D. Neshev, Yu. S. Kivshar, H. Martin, and Z.G. Chen, Opt. Lett. 29, 486 (2004)

[6] H. Martin, E. D. Eugenieva, Z. Chen, and D.N. Christodoulides, Phys. Rev. Lett. 92, 123902 (2004)

[7] M. Petrovic, D. Träger, A. Strinic, M. Belic, J. Schröder, and C. Denz, Phys. Rev. E 68, 055601R (2003)

[8] Ya.V. Kartashov, V.A. Visloukh, and L. Torner, Phys. Rev. E 68, 015603 (2003)

[9] A.A. Zozulya, D.Z. Anderson, A.V. Mamaev, and M. Saffman, Phys. Rev. A 57, 522 (1997)