Russian Physics Journal, Vol. 49, No. 9, 2006

LINEAR AND NONLINEAR PROPAGATION OF LIGHT BEAMS IN TWO-DIMENSIONAL PHOTOREFRACTIVE PHOTONIC LATTICES FORMED IN LITHIUM NIOBATE

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UDC 535:621.372.8

Special features of linear and nonlinear propagation of coherent light beams in two-dimensional photorefractive photonic lattices optically induced in the lithium niobate crystal doped with iron are experimentally investigated. The two-dimensional gratings are formed by consecutive recording of two one-dimensional photorefractive gratings in the crystal. Experiments were performed using He–Ne *laser irradiation with a wavelength of 633 nm.*

The diffraction of light beams in a medium with periodic modulation of the refractive index differs significantly from the diffraction of light beams propagating in an optically homogeneous medium. In some cases, modulation can produce the waveguide effects, and the medium can be considered as an equivalent periodic structure of coupled planar or channel optical waveguides. Due to the effect of tunneling, the light energy exchange among the neighboring elements is possible in these structures. The possibility of nonlinear light field localization in periodic structures of coupled waveguides in the form of discrete spatial solitons was first predicted theoretically in [1], which stimulated the active research for nonlinear optical phenomena. As a result, the effects of linear discrete diffraction, discrete self-focusing and self-defocusing of light beams, discrete spatial and gap soliton regimes in periodic channel waveguide structures in gallium arsenide and lithium niobate ($LiNbO_3$) [2, 3] have already been observed and investigated. Some of these effects are also observed for one- and two-dimensional photorefractive photonic lattices optically induced in strontium barium niobate (SBN) crystals [4–6]. Of significant interest from the viewpoint of formation of periodic waveguide structures (photonic lattices) through their optical induction is the $LiNbO_3$ crystal whose photorefractive nonlinearity can vary in a wide range when the crystal is doped with an active impurity, for example, iron (Fe) or copper (Cu) ions [7, 8]. These structures can be stored in lithium niobate for a very long time (from hours to months), which allows different stages of their formation and the study of light propagation within them to be separated in time. Thus, effects of formation of gap photorefractive solitons in one-dimensional photonic lattices were demonstrated in [9, 10], and the effects of formation of two-dimensional periodic channel waveguide structures in the $LiNbO_3$:Fe crystal were studied in [11]. In the latter case, the spatial period and the transverse dimensions of waveguide channels were about 100 μm, which did not allow the authors to observe the effects resulted from the waveguide coupling. In the present work, based on the optically induced two-dimensional photonic lattices with different configurations of waveguide channel cross sections in the $LiNbO_3$:Fe crystal, we study some special features of linear and nonlinear regimes of light propagation in these structures.

1. EXPERIMENTAL METHODS OF FORMING TWO-DIMENSIONAL PHOTONIC LATTICES

In [6], four coherent interfering light beams forming two-dimensional stationary interference patterns were used to generate two-dimensional photonic lattices in the SBN crystals. An electric field applied along the optical axis of a crystal resulted in two-dimensional periodic modulation of the refractive index due to the photorefractive effect. The characteristic

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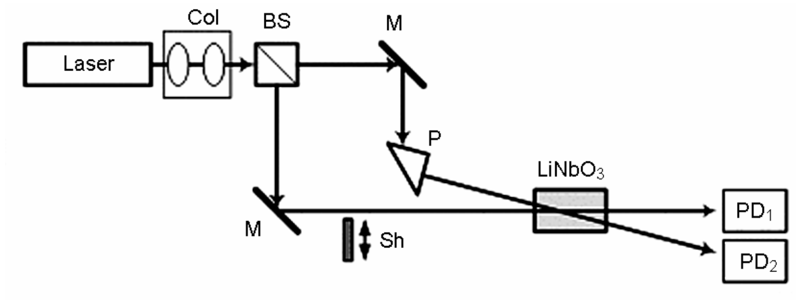

Fig. 1. Sketch of the experimental setup for recording one-dimensional photonic lattices in photorefractive lithium niobate.

time of forming the photonic lattice in SBN was units of seconds, like the relaxation time after switching off the external electric field. The time of forming the photonic lattice in the $LiNbO_3$:Fe crystal depends on the light intensity and can change from tens of seconds to several hours. In this case, to keep the stationary two-dimensional interference pattern unchanged, special care must be taken to stabilize the phase relations among the interfering light beams during the entire recording period, which is a complicated problem. We produced the two-dimensional photonic lattices by consecutive recording of two one-dimensional photorefractive gratings in the $LiNbO_3$:Fe crystal, which simplified significantly the experimental procedure. A sketch of the experimental setup is shown in Fig. 1.

Here a light beam of a He–Ne laser with a radiation wavelength of $\lambda = 633$ nm and power $P_0 \approx 1$ mW is expanded by a collimator (Col) up to ~3 mm and then is split into two beams of equal powers by a beam-splitting (BS) cube. The cube with mirrors (M) and a prism (P) form an interferometer at the exit from which beams are tilted at an angle γ and form an interference pattern with the period $\Lambda = \lambda/\sin\gamma$. Polarization of light corresponds to an ordinary wave in the crystal, and the direction of the lattice vector is parallel to the crystal optical axis. The recording beams are propagated in the crystal in the directions close to the X axis. A phase grating playing the role of a system of coupled planar optical waveguides is formed inside the crystal volume due to the photorefractive effect. The magnitude of refractive index perturbations is estimated from the diffraction efficiency of the grating measured with two photodiodes (PD_1 and PD_2) and a mechanical shutter (Sh).

To investigate the photonic lattices and effects accompanying the light propagation within them, He-Ne laser radiation was focused by a spherical lens onto the input plane of a crystal. In this case, light was extraordinarily polarized to obtain maximum photorefractive nonlinearity with electrooptical coefficient r_{33}. To change the light beam width at the input plane, the focal length of lenses was ranged from 25 to 200 mm. An imaging lens placed behind the crystal formed an image of the input or output planes on a photomatrix of a CCD camera. A rotating table with the examined sample allowed us to change with high accuracy the direction of light propagation in the photonic lattice.

2. EXPERIMENTAL RESULTS

To form two-dimensional photonic lattices, we used symmetric and asymmetric schemes of their recording in the $LiNbO_3$:Fe sample. By the symmetric scheme is meant recording of two one-dimensional photonic lattices whose wave vectors are tilted at angles of $\pm\theta$ to the optical axis of the crystal in the YOZ plane. This is equivalent to the formation of a two-dimensional photorefractive structure by two mutually incoherent pairs of coherent light beams. The interference of these beams gives the following light intensity distribution:

$$I_{+,-}(x,z) = I_{+,-}^{bg} + I_{+,-}^{0}\cos^2\left[(\pi z/\Lambda)\cos\theta \pm (\pi x/\Lambda)\sin\theta\right], \quad (1)$$

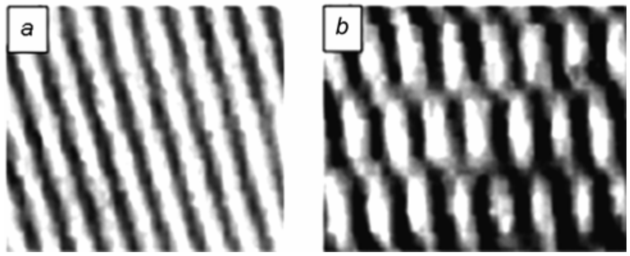

Fig. 2. Light field patterns on the output surface of the $LiNbO_3$: Fe crystal for different stages of forming the two-dimensional photonic lattices: *a*) excitation of a one-dimensional photonic lattice after its formation, and *b*) excitation of a two-dimensional photonic lattice.

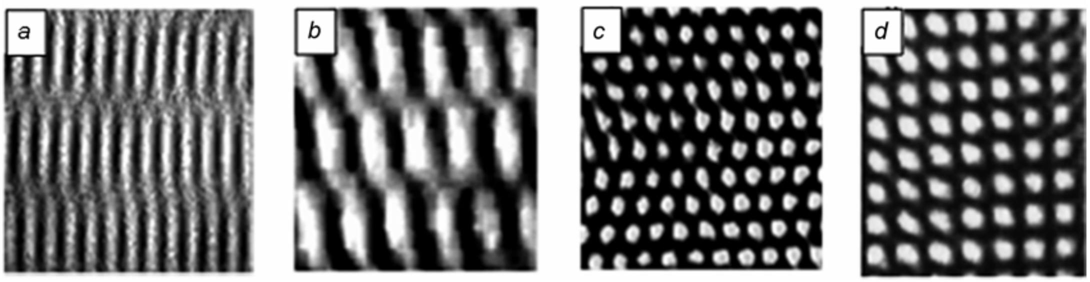

Fig. 3. Light field patterns in the output plane of the two-dimensional photonic lattices with the parameters *a*) $2\theta = 15°$ and $\Lambda = 18$ μm, *b*) $2\theta = 30°$ and $\Lambda = 15$ μm, *c*) $2\theta = 44°$ and $\Lambda = 15$ μm, and *d*) $\theta_1 = 0°$, $\theta_2 = 90°$, and $\Lambda = 15$ μm.

where $I^{bg}_{+,-}$ and $I^{0}_{+,-}$ are the constant and variable components of the light intensity in interference patterns for each pair of beams indicated by subscripts "+" or "–" depending on the sign of the angle θ, Λ is the spatial period of the interference pattern, and *z* and *x* are transverse coordinates along and perpendicular to the optical axis of the crystal, respectively. In the asymmetric scheme, the angles between the wave vectors of the one-dimensional photonic lattices and the optical axis may differ. In particular, in our experiments we have created the two-dimensional photonic lattice with the vector of the first one-dimensional grating parallel to the optical axis and the vector of the second one-dimensional grating perpendicular to the optical axis.

The procedure of forming the two-dimensional photonic lattice in different stages is illustrated by the light intensity distribution over the output crystal plane shown in Fig. 2. The $LiNbO_3$: Fe sample with sizes of 9 × 6 × 8 mm along the *X*, *Y*, and *Z* axes was probed by a parallel extraordinarily polarized light beam. The pattern shown in Fig. 2*a* corresponds to light excitation in the one-dimensional photonic lattice with the spatial period $\Lambda = 18$ μm and angle $\theta = 15°$ formed in the first stage. Light is trapped in layers of the photonic lattice with higher refractive index visualizing a system of parallel planar optical waveguides. The pattern shown in Fig. 2*b* corresponds to light excitation in the two-dimensional photonic lattice formed in the two-stage process. In this case, the photonic lattice represents a periodic structure of parallel channel optical waveguides with elliptic cross sections.

The two-dimensional photonic lattices with different degrees of cross-sectional ellipticity of waveguide channels can be formed depending on the tilt angles θ of the wave vectors of one-dimensional photonic lattices with the optical axis of the crystal. Figure 3 illustrates the light intensity distribution over the output plane of the two-dimensional photonic lattices that differed by the tilt angles θ of the one-dimensional photonic lattices during their recording in the crystal. In our experiments, the angle 2θ between the wave vectors of the one-dimensional gratings changed from 15 to 45°, and the grating periods Λ changed from 13 to 20 μm. The special case is the formation of photonic lattices using the asymmetric

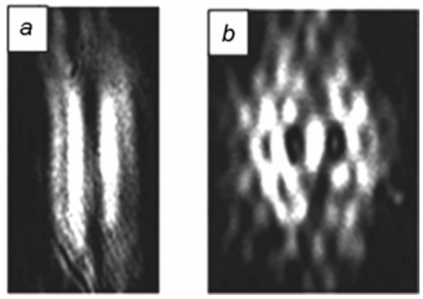

Fig. 4. Light field patterns in the output plane of the two-dimensional photonic lattices corresponding to the linear discrete diffraction of light excited in the forward direction in a single waveguide channel for the photonic lattices with $2\theta = 15$ (*a*) and 44º (*b*).

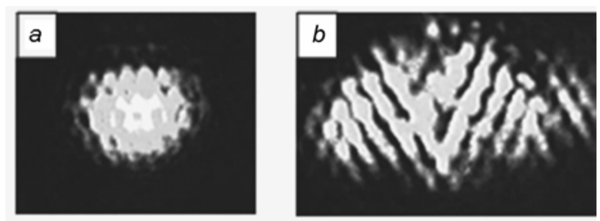

Fig. 5. Light field patterns at the exit facet of the photonic lattice for discrete self-defocusing of the light beam at $t = 0$ (*a*) and 90 min (*b*).

scheme, because the anisotropy of the crystal physical properties results in different characteristics of recording and readout of the one-dimensional photonic lattices with different angles θ. Thus, the one-dimensional photonic lattice cannot be formed in principle in optically homogeneous region of the $LiNbO_3$:Fe crystal with the wave vector perpendicular to the optical axis at the expense of the photovoltaic effect. However, this becomes possible after formation in the crystal of the one-dimensional photonic lattice with the wave vector parallel to its optical axis, which was realized in our experiments.

The parameters of waveguide elements of the periodic structure determine the parameters of linear and nonlinear light diffraction in one-dimensional and two-dimensional photonic lattices. The basic characteristics of discrete diffraction (including the coefficient of coupling between the neighboring channels) can be estimated when light is excited in a single element of the periodic structure [2]. For the two-dimensional photonic lattices, these characteristics depend significantly on the degree of waveguide channel ellipticity, that is, on the symmetry of photonic lattices in their cross sections. To illustrate this dependence, Fig. 4 shows the light field pattern in the output plane of the structures shown in Fig. 3*a* and *c*. In this case, the light beam width on the input surface of the photonic lattices was ~15 μm. It can be seen that the discrete diffraction of light is observed for the first structure dominantly in the direction of the crystal optical axis (in the direction of smaller width of the channel with the elliptic cross section) as in the case of the one-dimensional photonic lattices. For the photonic lattices with $2\theta = 44°$, the strong enough discrete diffraction of the light field is also observed in the orthogonal direction.

The photorefractive optical nonlinearity of $LiNbO_3$ is self-defocusing, that is, the refractive index of the material in the illuminated region decreases. The photorefractive spatial self-action of the light beam in $LiNbO_3$ is caused by the induced nonlinear negative lens that changes the diffraction beam divergence. The optical nonlinearity of the periodic structures of coupled waveguides induces defects of the photonic lattices in the illuminated region. These defects can cause self-defocusing or self-focusing of light beams depending on the properties of the photonic lattice and the direction of light propagation [2]. In the case of propagation in the region of normal discrete diffraction in the $LiNbO_3$-based photonic lattice, discrete self-defocusing of light beams is observed. This is illustrated by the light field patterns in the output plane of the photonic lattice with the parameters $2\theta = 44°$ and $\Lambda = 15$ μm (Fig. 5). Here the light beam with a power of 20 μW and an

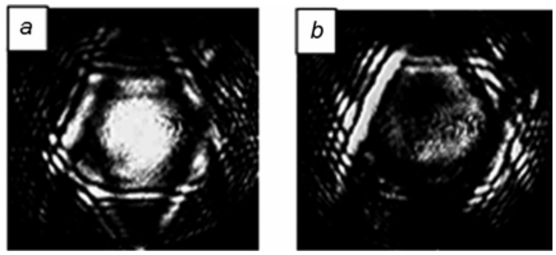

Fig. 6. Single-channel light excitation in the photonic lattices with 2θ = 44°. Light field in the far-field zone for t = 0 (a) and 90 min (b).

aperture of ~70 μm excites the photonic lattice in the forward direction. At the initial moment of time (t = 0), the light field structure in the photonic lattice is determined by the discrete linear diffraction. In this case, the illuminated region in the output plane has approximately identical cross-sectional sizes in the orthogonal directions. The photorefractive effect results in beam defocusing with time mainly in the direction of the photovoltaic current in the crystal excited by the light field (Fig. 5*b* for t = 90 min).

Information on the diffraction characteristics of one- and two-dimensional photonic lattices in the linear regime can be obtained by two methods. According to the first method, light is excited in a single waveguide element, and light field patterns are studied in the near-field zone (in the output plane of the photonic lattice). These patterns give information on the degree of coupling between the neighboring elements of the structure. In the second case, light is excited in all directions in the photonic lattice (for example, by the light beam with the cross-sectional dimensions less than the waveguide channel width), and patterns of the transmitted light field are studied in the far-field zone. This gives information on the presence of directions in which light propagation is forbidden due to the Bragg reflection effects. The given directions specify the boundaries of the Brillouin zones. Thus, the last approach allows us to visualize the structure of allowed and forbidden photonic lattice zones, which is of special interest for the two-dimensional photonic lattices [12]. This approach can also be realized when a large number of photonic lattice elements are excited by the light field with a low degree of spatial coherence.

Figure 6 shows an example of the diffraction patterns in the far-field zone under excitation of the above-discussed photonic lattice with 2θ = 44° by the coherent light beam having a width of ~10 μm and power of 5 μW. In the linear regime (t = 0), the dark region surrounding the illuminated central part in Fig. 6*a* shows the boundaries of the first Brillouin zone. In the nonlinear regime, the photorefractive self-action effect results in a significant reduction of light power in the region of normal discrete diffraction (the central part). At the same time, the boundary of the first allowed zone becomes more clearly pronounced owing to partial self-focusing of the light field in the region of anomalous discrete diffraction (Fig. 6*b*).

Thus, the method of holographic recording of one-dimensional photorefractive gratings allows two-dimensional periodic structures of coupled optical waveguides to be formed in the $LiNbO_3$: Fe crystals. Based on these structures, optically controlled photonics elements can be developed.

This work was supported in part by the Ministry of Education and Science of the Russian Federation (grant 2.1.1.2097).

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