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Discrete Diffraction and Spatial Self-Action of Light Beams in One-Dimensional Photonic Lattices in Lithium Niobate

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Abstract—Features of the behavior of light beams in one-dimensional photonic lattices in iron-doped lithium niobate have been experimentally studied. It is demonstrated that bright discrete spatial solitons and bright gap solitons can be formed in this system using 633 nm radiation on a microwatt power level. *© 2005 Pleiades Publishing, Inc.*

Light beams can exhibit diffractionless propagation (called spatial optical soliton regime) in a nonlinear optical medium, whereby the diffraction is completely compensated by self-focusing and self-defocusing effects [1–3]. In recent years, special attention has been devoted to the behavior of light beams in periodic arrays of coupled optical waveguides (OWGs) [4, 5]. In such arrays, the waveguide effect leads to certain features in the diffraction of light and changes the sign of optical nonlinearity for the light propagating in directions close to the Bragg angle [4]. This makes possible the self-focusing of light beams with the formation of bright discrete spatial solitons in a medium with defocusing nonlinearity and, on the contrary, the self-defocusing and the formation of dark discrete solitons in a medium with focusing nonlinearity. Such effects have been observed in one-dimensional arrays of GaAs-based channel OWGs with Kerr's nonlinearity for light with a wavelength of 1.53 μm at an instant power on the order of 10^2 watts [6]. These effects were also observed in one- and two-dimensional photonic lattices (PLs) representing optically induced waveguide arrays in photorefractive crystals of strontium barium niobate [7, 8], where the photorefractive optical nonlinearity allowed the spatial self-action effects to be observed on a microwatt power level. A high photorefractive optical nonlinearity is also inherent in lithium niobate ($LiNbO_3$) doped with iron (Fe), copper (Cu), and some other admixtures. In particular, the formation of bright spatial gap solitons in a one-dimensional channel OWG array in $LiNbO_3$:Cu was observed at a light beam power below 10 μW [9].

This Letter reports on the first experimental study of discrete diffraction and spatial self-action of light beams in one-dimensional PLs formed in $LiNbO_3$:Fe crystals.

The PLs were formed using a double-beam scheme of photorefractive hologram recording with He–Ne laser radiation (λ = 633 nm). The PL vector was oriented along the optical axis of a crystal and the total power of a recording beam was ~1 mW. The polarization of light corresponded to that of the ordinary wave in the crystal. In our experiments, the PL period was varied from 10 to 15 μm and the PL aperture was within 2–3 mm.

Figure 1a shows a schematic diagram of the experimental setup used to study the features of light propagation in the obtained PLs. The laser beam was focused onto the entrance plane of the PL by spherical lenses *4* with a focal length of F = 20–200 mm. The readout beam polarization corresponded to that of the extraordinary wave (i.e., the optical axis of the crystal is parallel to the polarization plane). This polarization allows the depth of the refractive index modulation for the readout beam in the PL region to be increased due to the electrooptical coefficient r_{33}. The image of the exit plane of the PL was projected by lens *5* onto CCD camera *6*. The crystal sample was mounted on a rotary table, which provided for a high-precision adjustment of the light propagation direction relative to the PL vector.

Since the PL represents a system of coupled OWGs, diffraction in the direction of the PL vector can be either completely absent or manifested due to the light tunneling to the adjacent waveguide layers. The discrete diffraction was experimentally studied upon the light wave excitation in one or several (up to six) PL layers. Figure 1b shows the light wave intensity profiles in the entrance (curve *1*) and exit crystal sample faces. The light was focused by a lens with F = 30 mm onto the PL entrance plane where the beam waist size was 15–17 μm. As a result of diffraction, the beam width increased to ~150 μm at the exit plane of a homogeneous crystal 9-mm-long in the direction of light propagation (Fig. 1b, curve *2*). The output intensity distribution in a crystal with the PL with a period of 15 μm illuminated with a parallel beam is depicted by curve *3*. For

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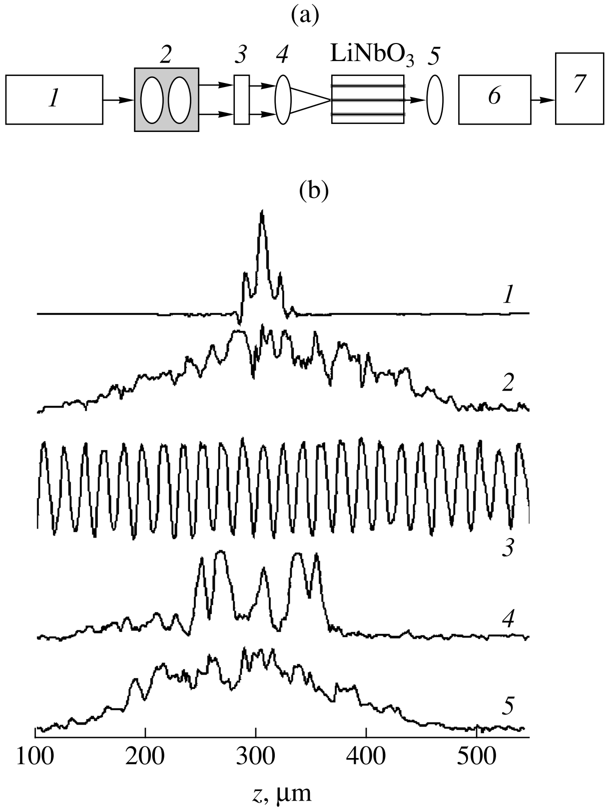

Fig. 1. (a) Schematic diagram of the experimental setup used to study the light field in PLs: (*1*) He–Ne laser; (*2*) collimator; (*3*) polarizer; (*4*) spherical focusing lens; (*5*) imaging lens; (*6*) CCD camera; (*7*) personal computer. (b) The patterns of discrete diffraction of a light beam in a one-dimensional PL, showing the light wave field intensity profiles (*1*) in the entrance plane, (*2*) in the exit plane in the absence of a PL, (*3*) in the exit plane for the PL excited by a parallel beam, (*4*) in the exit plane in the lattice vector direction for the excitation of a single waveguide layer, and (*5*) in the plane of a separate waveguide layer.

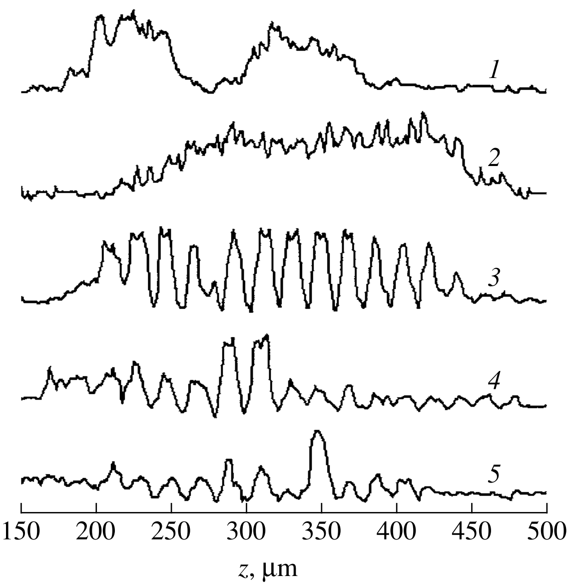

Fig. 2. The patterns of spatial self-action of a light beam, showing the light wave field intensity profiles (*1*) in the initial transmitted beam, (*2*) in the diffracted beam, (*3*) in the PL exit plane at $t = 0$, (*4*) in the PL exit plate at $t = 120$ min (in the stage corresponding to the formation of a discrete spatial soliton), and (*5*) in the PL exit plane at $t = 300$ min (in the stage corresponding to the formation of a spatial gap soliton).

this PL, the induced change in the refractive index is $\Delta n_e \sim 10^{-4}$. In the case of the excitation of a single waveguide, the main portion of the light energy at the PL exit plane is distributed (as a result of the light tunneling) between five waveguide layers, with a maximum at the periphery (Fig. 1b, curve *4*). This behavior well agrees with the previous experimental and theoretical results [5]. In the waveguide plane, the light beam exhibits diffraction similar to that in a homogenous medium (Fig. 1b, curve *5*).

The optical nonlinearity in photorefractive crystals is manifested even for the light beam power on a microwatt level. As was noted above, the optical nonlinearity changes sign in the region of anomalous diffraction (i.e., for the light propagating in the directions close to the conditions of Bragg's reflection). In the arrays based on $LiNbO_3$ (a material with defocusing photorefractive nonlinearity), this may result in the formation of bright discrete spatial solitons. In addition, the optical nonlinearity can remove the prohibition on light propagation in the directions corresponding to Bragg's reflection, thus leading to the formation of the so-called spatial gap solitons [10].

We have studied the phenomenon of spatial self-action using light beams with a power of 10–50 μW. The array was illuminated in the directions close or corresponding to the conditions of Bragg's reflection. Four to six waveguide layers were excited in this experiment; the light beam was focused onto the PL entrance plane by a lens with $F = 20$ cm. The light wave intensity profiles in the PL output plane are presented in Fig. 2. At the initial moment, immediately upon the excitation of light in the sample array, the distribution of light intensity in the output beam (separated from the total light field by means of spatial filtration) exhibits a characteristic minimum corresponding to the conditions of Bragg's reflection (curve *1*). The intensity of the part of the field reflected from the array is depicted by curve *2*, while curve *3* presents the total field intensity distribution in the PL exit plane.

The photorefractive self-action leads to a change in the light field intensity distribution in the PL exit plane with time. In particular, the field exhibited localization near a direction corresponding to the conditions of Bragg's reflection (Fig. 2, curve *4*), so that a significant part of the energy was concentrated within two waveguide layers. This situation corresponds to the formation of a bright discrete spatial soliton in the region of the field for which the angular spectrum components occur in the immediate vicinity of the first Brillouin zone edge. In some time, the bright discrete spatial soliton was broken, but a new region of the light wave localization appeared, as is seen in curve *5*. In this case, the light wave field was localized in a single waveguide layer occurring at equal distances from the region of minimum intensity in the transmitted beam (Fig. 2, curve *1*) and the region of maximum intensity in the reflected wave field (curve *2*). Apparently, this stage corresponds to the formation of a spatial gap soliton. Indeed, a gap soliton must correspond to a light beam propagating in the PL in the direction corresponding to the transmission band edge. However, in this case, the group velocity vector must point in the forward direction, so that the energy is transferred along the waveguide layer [10]. Accordingly, the localization of light in the PL exit plane can be expected in the same waveguide layers where the light is excited in the PL entrance plane.

It should be noted that the nonlinear localization of light observed in our experiments did not exhibit a stationary character and the gap soliton was broken with time (like the bright discrete soliton) at the edge of the first Brillouin zone. The main reason for this behavior is evidently the irreversible variation of the PL field upon readout with a beam possessing extraordinary polarization in the absence of recording beams. A certain role is also played by the diffraction of light in the plane of the waveguide layer, which makes the coefficient of coupling between adjacent waveguide layers dependent on the longitudinal spatial coordinate.

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