Peculiarities of photonic lattices recorded by Bessel beam technique in LiNbO$_3$:Fe crystal

A Badalyan, R Hovsepyan, V Mekhitarian, P Mantashyan and R Drampyan
Institute for Physical Research of National Academy of Sciences of Armenia
Ashtarak-2, 0203, Ashtarak, Armenia
E-mail: rdramp@ipr.sci.am

Abstract. The aim of this work is the investigation of the peculiarities of recording of the refractive photonic lattices by Bessel beam technique in photorefractive Fe doped LiNbO$_3$ crystal. Optical C-axis of the crystal was oriented along the crystal surfaces. The Gaussian laser beam at 532nm wavelength with 17.7mW is transformed into the Bessel beam by an axicon. The intensity pattern of non-diffracting Bessel beam is imparted into the photorefractive medium, being irradiated, via electro-optic effect, thus creating radially modulated refractive index photonic lattices. The annular refractive photonic lattice created inside the LN:Fe crystal has 10 µm period in radial direction. The recorded photonic lattice has been tested by probe beam. The direct observation of recorded lattice by phase microscope was also performed. The azimuthal dependence of created lattice was observed. The qualitative explanation is given.

1. Introduction
Materials with spatial periodic structures such as the photonic crystals currently find applications in many fields of physics and optical device engineering, including guiding and trapping systems, optical devices, telecommunications, information storage, etc. Among different methods for the fabrication of the artificial periodic structures in dielectric materials the holographic technique [1] is one of the promising methods for the fabrication of photonic lattices. Holographic technique is based on the creation of spatially periodical structures by intensity modulated light beams in photosensitive materials. There are two main elements which are important for holographic recording: the method of creation of intensity modulated light beams and materials suitable for recording of photonic lattices. Numerous investigations are devoted to the study of dynamic and permanent optical refractive gratings using classic two-beam interference arrangement in atomic vapors [2], crystals [3, 4] and liquid crystals (see, for example, Ref. [5] and references therein).

The doped photorefractive crystals are very convenient materials for holographic recording. The illumination of photorefractive medium by spatially modulated beam leads to the refractive index modulation via electro-optic effect, thus creating refractive lattices. The light excites the electrons from impurity ion state to conduction band. Electrons migrate in the conduction band and finally are trapped by ions. The redistribution of the charges builds up an internal electric field $E$ and so changes the refractive index $\Delta n_i = r_{ij}E_j$, where $r_{ij}$ is the component of electro-optic tensor. The charge transport is mainly due to photovoltaic effect and diffusion mechanism [6-9].
Bessel beams [10] are very convenient for the creation of artificial periodical structures in photorefractive materials. Recently we developed travelling and counter propagating Bessel beam technique [11] for the formation of 1D and 2D micrometric scale photonic lattices, respectively. The aim of this work is the investigations of the peculiarities of photonic lattices recording by Bessel beam technique in photorefractive Fe doped LiNbO₃ (LN:Fe) crystal. Taking into account the annular symmetry of the recording beam the formation of annular photonic lattice will depend on the orientation of the C-axis of the crystal, i.e. whether C-axis is oriented along (Y-orientation) or perpendicular (Z-orientation) to the surfaces of the crystal. For this purpose, annular photonic lattice recorded in Y-cut LN:Fe crystal was tested both by probe beam technique and by phase microscope.

2. Experiment

2.1. Formation of Bessel beam by axicon

Bessel beams or diffraction-free beams are new type of coherent beams [10]. Bessel beams have a feature of conserving their transverse intensity distribution, expressed by the zeroth-order Bessel function, while they propagate in free space. The simplest diffraction-free beams can be formed by superposition of plane waves whose wave vectors lie on the cone. One of the ways for the creation of Bessel beams is the use of an optical element- axicon [10].

The scheme of the Bessel beam formation from Gaussian beam at 633 nm wavelength by an axicon with aperture cone angle $175^\circ$ is shown in figure 1. The convergence angle of the beams behind the axicon was adjusted by moving the output lens of the beam expander back or forth, thus varying the convergence angle within ~ 3-4°, which, in turn, changes the spacing between the concentric rings in the range of 10 - 25 μm. An ideal Bessel beam has no intensity gradient along the propagation axis and can be schematically represented as a set of co-axial hollow light cylinders surrounding the central light rod. The profile of Bessel beam is a set of concentric rings (figure 2). Bessel beam becomes divergent behind the overlapping zone and forms a ring pattern in the far field (figure 1).

![Figure 1. Experimental scheme illustrating the formation of Bessel beam by axicon.](image)

![Figure 2. Fragment of radial intensity distribution of Bessel beam formed by axicon with aperture cone angle 175° in the overlapping zone of the beams.](image)

The spacing between the concentric rings, measured by beam profiler, shows their equidistant disposition, except for few central rings. The period of annular structure shown in the figure equals
~10 μm for certain position of output lens of the beam expander. The number of rings reaches up to 1000. The annular ring pattern is two-dimensional, however, as an annular grating this structure is one-dimensional with the period determined by the spacing between rings.

2.2. Recording of annular photonic lattice by Bessel beam technique in LN:Fe crystal

The experimental scheme of recording of annular photonic lattice is shown in figure 3. The laser source was single-mode second harmonic of cw YAG:Nd laser at 532 nm wavelength with linear polarization and 100 mW power. Bessel beam obtained by scheme illustrated in figure 1 illuminated LN:Fe crystal which was placed in the overlapping zone of the axicon. Optical C-axis of the crystal was oriented along the crystal surfaces (Y-orientation). The laser beam polarization was directed along the C-axis. LN crystal doped with 0.05wt% Fe had 15mmx10mmx2mm dimensions.

2.3. Testing of recorded refractive photonic lattice

The recorded annular photonic lattice was tested using red laser beam by observing the diffraction pattern from the photonic lattices in the far field. Figure 4 shows the readout scheme for testing of lattice recorded inside the crystal. The testing was performed by red beam to avoid the erasure of the grating during readout [4, 6].

Figure 5 shows the result of testing by Gaussian beam of photonic lattice recorded in Y-cut LN:Fe. The far field transmitted diffraction pattern consists of two opposite disposed segments of a ring. Thus the diffraction pattern from photonic lattice has pronounced azimuthal dependence of intensity.
distribution with higher diffracted intensity along the C-axis of the crystal. To investigate the azimuthal dependence of intensity distribution of diffraction pattern the direct observation of photonic lattices by phase microscope was also performed.

Figure 5. Far field transmitted diffraction pattern from photonic lattice recorded in Y-cut LN:Fe during 60 min, for nearly orthogonal incidence of the probe Gaussian beam at 633 nm to the crystal surface.

Figure 6. Phase microscope image of the annular photonic lattice inside the LN:Fe crystal. Vertical arrow shows the direction of optical C-axis of the crystal. Circular arrow shows the direction of azimuthal angle $\phi$.

Figure 6 shows phase microscope image of the photonic lattice inside the LN:Fe crystal. The white dashed lines mark the areas where the grating is recorded with high contrast (upper and lower sectors) and is not recorded at all (right and left sectors).

3. Discussion
The physical mechanism of the formation of holographic lattices in photorefractive materials is based on the electro-optic effect [6-9]. Fe ions occur in LN crystal in different valence states: Fe$^{2+}$ and Fe$^{3+}$. The corresponding band diagram is shown in figure 7. The green light excites the electrons from Fe$^{2+}$ to conduction band. Electrons migrate in the conduction band and finally are trapped by Fe$^{3+}$.

Figure 7. Band diagram of lithium niobate doped with iron. CB is the conduction band, VB is the valence band.
The redistribution of the charges builds up an internal electric field $E$ and so changes the refractive index. Thus, the inhomogeneous illumination of photorefractive materials leads to the modulation of refractive index. Two main mechanisms – photovoltaic effect and diffusion of photo-induced carriers are responsible for formation of refractive lattices in photorefractive crystal [6-9,]. The diffusion effect can be neglected for lattice spatial frequencies less than $10^5$ lines/cm [8] which is in case of the present experiment. The electric field induced by photovoltaic effect is due to the charge separation taking place along the C-axis of the crystal [8].

In LN crystal the change of extraordinary index is larger than the change of ordinary index by a factor of four [7] and the induced refractive index change $\Delta n$ is mainly due to the distortion of the extraordinary index of refraction.

**Figure 8.** Schematic of space-charge field formation in photorefractive crystal during the illumination by Bessel beam. White and green circles are non-illuminated and illuminated regions of Bessel beam, respectively. Bent arrows schematically illustrate migration of electrons on periphery (1) and central part (2). Open and filled circles show schematically an electron and trap, respectively.

Figure 8 shows schematically the migration and space charge formation in different regions of annular intensity distribution of Bessel beam inside the photorefractive Y-cut crystal. The appearance of azimuthal dependence of recorded lattice is due to the predominant migration of the electrons along the C-axis of the crystal. In LiNbO$_3$:Fe crystals the displacement of the electron is 0.5 Å per one absorbed photon for $\lambda=0.53$ µm wavelength [8]. The distance between bright and dark zones along C-axis is approximately 100 times larger on periphery compared with the central part of illuminated region. The diameter of Bessel beam on the crystal surface was measured 5mm. The period of lattice is 10 µm. Thus probability of the migration and final trapping of the electrons in the dark zone is higher in the central region compared with the periphery. As a consequence, left and right sectors of the lattice will have more contrast than upper and lower sectors which lead to the azimuthal dependence of the recorded lattice (see Fig.6). The suggested model requires detailed quantitative study taking into account the recording beam power, period of grating, geometrical size of recording lattice etc. Azimuthal dependence of recorded photonic lattices can be avoided by use of Z-cut photorefractive crystal as recording medium. The recording of the 2D lattices in Y-cut crystal by
Bessel standing wave [11] with half wavelength period in axial direction will also reduce the azimuthal dependence of recorded circular structure due to switching on the diffusion mechanism of recording which takes place in all directions but with less efficiency compared with photovoltaic effect [8]. These experiments are in progress and the results will be published elsewhere.

4. Conclusion
Annular refractive photonic lattice was created by Bessel beams technique in photorefractive Y-cut LN:Fe crystal. The testing of the lattice by probe beam showed azimuthal dependence of intensity distribution of far field diffraction pattern. Further observation by phase microscope showed that recorded lattice has pronounced azimuthal dependence. The appearance of azimuthal dependence of recorded lattice is the result of the predominant migration of the electrons due to the photovoltaic effect along the C-axis of the crystal. The qualitative explanation is given.

5. References
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