Phase diffraction patterns optically induced by laser Bessel-like beams in photorefractive lithium niobate with a doped surface layer

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Abstract. The evolution of the characteristics of one-dimensional phase diffraction structures during their optical induction by bessel-like monochromatic beams in photorefractive samples of lithium niobate is studied experimentally. Both, one-dimensional (1D) and two-dimensional (2D) Bessel-like beams with different topology of 2D beam cross-sections are formed from Gaussian laser beams using the amplitude masks with rectangular and annular apertures. Also, the property of reconstructing the formed bessel-like laser beams after they have passed through an obstacle has been experimentally verified. These almost diffraction-free light fields with wavelengths of 457 and 532 nm can change the refractive indices of photorefractive lithium niobate samples and form within them the nonlinear photonic diffraction structures.

1. Introduction

In the most cases, any laser source generates Gaussian-shaped light beam, which may be tightly focused with beam waist region in longitudinal direction depending on the light wavelength and minimal transverse waist size. However, some applications require not conventional shapes of light beams, which demonstrate some properties distinct of Gaussian laser beams. These are diffraction-free beams including Bessel-like ones [1], Airy beams [2] and some other non-diffracting shape-preserving light beams [3]. The Bessel-like beams are close to theoretical diffraction-free fields which are not limited in the transverse directions. The real Bessel beams cannot exist because of the infinite optical power they should carry. However, there are some configurations that may form Bessel-like beams in the bounded space area.

The usual ways to form two-dimensional almost diffraction-free light fields exploit so called axicon lenses, annular apertures or optical fiber elements [1]. However, in some cases not only two-dimensional light fields are required but also one-dimensional ones. Strictly speaking they are quasi-one-dimensional Bessel-like beams because in the second transverse dimension these fields display the Gaussian-like profiles if they are formed by laser beams.

The main aim of this study is formation of one-dimensional and two-dimensional Bessel-like fields with different shapes of transverse light patterns using diffraction grating-like amplitude transparencies. The obtained longitudinally homogeneous light patterns generate photonic structures, e.g. waveguide or diffraction systems in photorefractive lithium niobate (LiNbO$_3$) samples [4-6]. We use for this purpose of amplitude masks including their couples rotated with respect to each other at some angles. Every mask contains the metal screen with two rectangular slits in it. Amplitude masks with an annular aperture were also used.
2. Experimental conditions and experimental results

The solid-state YAG:Nd³⁺ laser with light wavelength of \( \lambda = 532 \) nm and semiconductor laser (\( \lambda = 457 \) nm) are used as CW light sources in experiments. The near to parallel laser beam illuminates the amplitude mask that is located in the focal plane of a lens (cylindrical or spherical, depending on one-dimensional or two-dimensional light field is formed). The longitudinally uniform interference pattern appears after this lens which may be used to generate the photonic phase structures in the photosensitive material [6]. In the scheme with amplitude mask two light beams produced by the slits in a screen interfere in an area after lens (Figure 1). To form two-dimensional Bessel-like field, we use two amplitude masks with required angle between directions of their slits. For the formation photonic structures we use the photorefractive samples LiNbO₃:Fe and LiNbO₃:Cu. To test properties of the phase photonic structure generated within the sample, we use laser radiation with \( \lambda = 532 \) nm and \( \lambda = 457 \) nm. The near field and far field diffraction patterns are studied with a CCD camera at this stage. The formed patterns were also studied with the help of a microscope.

2.1. Bessel-like light beam formation with amplitude masks

As the particular results, images in Figure 2 show 1D (\( \lambda = 457 \) nm) and 2D light patterns (\( \lambda = 532 \) nm) near the back focal plane of a cylindrical lens with focal length 100 mm (a), and spherical lenses (b - c) with focal length of 180 mm at different dimensions of slits and different slit orientation with respect to each other. To form 1D beam, we use the metal mask with two parallel rectangular slits. The slit cross-section measures 0.1×1.5 \( \text{mm}^2 \) with a distance between slit centers of 0.6 mm. Similar masks are used to form 2D Bessel-like beams with slit width 0.2 mm and their length 2 mm. The distances between their centers range from 0.5 to 1 mm.

To obtain interference patterns with longitudinal displacement, amplitude masks with an annular aperture with a slit width of 0.05 mm and a diameter of 0.5 mm It is illustrated by images in Figure 3 with dependences of intensity cross-sections of Gaussian beam and 2D interference field on position of CCD camera along the light propagation direction measured in centimeters. Figure 4 demonstrates corresponding dependences of Gaussian beam diameter at half maximum intensity level and the width of interference field central maximum for the case when they are comparable in dimensions. It is clearly seen that variation of transverse dimensions of this Bessel-like beam is much less when compared with that for the usual Gaussian beam.
2.2. Formation of photonic structures by Bessel-like beams in photorefractive lithium niobate

Bessel-like 1D and 2D beams are used to generate phase diffraction patterns in photorefractive samples of copper-doped plate LiNbO₃:Cu (0.05 wt%). The near-surface region is doped with Cu ions by thermal diffusion at a temperature of 900 °C from a film deposited on the surface of the sample by sputtering in a vacuum. The thickness of the doped layer is about 100 μm. The dimensions of this plate are 10×6×3 mm³ along X, Y, and Z axes. The presence of copper does not lead to a significant increase in the dark conductivity of LiNbO₃, which ensures the long-term storage of optically induced elements in such a material. The light polarization at phase structure induction corresponds to the crystal extraordinary or ordinary waves. At the structure readout we use the extraordinarily polarized light waves of YAG or semiconductor lasers. The light pattern in Figure 5a illustrates near-field diffraction of light (λ=532 nm) on the 1D few-element phase grating with spatial period 180 μm induced within the LiNbO₃:Cu plate. The optical power and exposure time at this grating creation are 1 mW and 3 minutes. Image in figure 5b shows cross-section of 2D interference pattern obtained with two amplitude masks 90° rotated with respect to each other in the same crystal plate. Figure 5c shows the generated two-dimensional diffraction structure on the output plane of the crystal with an increase of 80x. It should be noted that exposure time to induce this 2D structure makes up 30 minutes at the same light power as it was used at 1D grating formation.
Figure 5. Light diffraction patterns at the output facet of LiNbO$_3$:Cu plate (a), 2d Bessel-like field (b), formed diffraction pattern by light Bessel-like field two-dimensional (perpendicularly superimposed masks are located at an angle of 45° to the optical axis) (c)

Images in Figure 6 demonstrate the change of 1D diffraction grating profile in time during its generation in photorefractive plate LiNbO$_3$:Cu. They are obtained with amplitude mask scheme. The spatial period of phase gratings in this case is 100 μm. At the initial stage of the grating formation (less than 10 seconds) the near field diffraction image and its intensity profile are practically the same as in the light field. However, at the exposure time increase (t=80 s) the arising of maximal intensity within side lobes of near field diffraction image as well as in intensity profile of that image are observed. Indeed, the photorefractive optical nonlinearity is saturable and that results in possible creation of phase diffraction and waveguide elements with required profiles in photorefractive lithium niobate. Image in Figure 7 demonstrate light picture in the far zone during optical probe on the formed phase structure with a spatial period of 190 μm.

Figure 6. Near field diffraction images at the exit surface of LiNbO$_3$:Cu plate (left) and their intensity profiles (right) for exposure times less than 10 s (upper line) and 80 s (lower line).

The time evolution of the grating diffraction efficiency (the ratio of the intensities of the diffraction maxima of the first and zero orders) for light with a wavelength of 532 nm (Figure 8) made it possible to estimate the magnitude of the change in the refractive index of the material in the lattice region. At a measured value of the diffraction efficiency at an exposure time of about 100 s, the change in the refractive index is 0.000103.
Figure 7. Light picture in the far zone during optical probe of the phase structure in the crystal (the spatial period of the phase structure is 190 μm)

Figure 8. The graph of the dependence of the diffraction efficiency on the exposure time.

3. Conclusion
In conclusion, our experimental results confirm the possibility creation of few-element phase diffraction structures and more complicated photonic waveguide circuits with required profiles within photosensitive materials like photorefractive crystals by light fields with Bessel-like shapes. Variation of parameters of optical schemes gives the additional degree of freedom to create Bessel-like light beams with needed characteristics. Experimentally demonstrated the change in the refractive index profile of one-dimensional phase diffraction structures during their optical induction in crystal photorefractive lithium niobate samples by one-dimensional Bessel-like beams.

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