

Formation of Photonic Structures in Photorefractive Lithium Niobate by 1D and 2D Bessel-like Optical Fields

A Inyushov, P Safronova, I Trushnikov, A Sarkyt, and V Shandarov

Tomsk State University of Control Systems and Radioelectronics, Lenin Prospect 40,
Tomsk, 634050, Russia

E-mail: shandarovvm@svch.rk.tusur.ru

Abstract. 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 and Fresnel biprisms. These almost diffraction-free light fields with wavelengths of 532 and 633 nm can change the refractive indices of photorefractive lithium niobate samples and form within them the nonlinear photonic diffraction structures. The characteristics of photonic structures induced in this way are studied by diffraction of monochromatic light with wavelengths of 633 and 532 nm.

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, 5]. 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 and Fresnel biprisms. The obtained longitudinally homogeneous light patterns generate photonic structures, e.g. waveguide or diffraction systems in photorefractive lithium niobate (LiNbO_3) samples [6, 7]. 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.



2. Experimental conditions and experimental results

The solid-state YAG:Nd³⁺ laser with light wavelength of $\lambda=532$ nm and He-Ne laser ($\lambda=633$ nm) are used as CW light sources in experiments. The near to parallel laser beam illuminates the biprism or amplitude mask. The amplitude mask 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 immediately after biprism due to interference of Gaussian beam halves passed through the prism (Figure 1 a). In the scheme with amplitude mask two light beams produced by the slits in a screen interfere in an area after lens (Figure 1 b). To form two-dimensional Bessel-like field, we use two amplitude masks with required angle between directions of their slits. Formed interference patterns generate photonic lattices or phase diffraction gratings in the photosensitive material. We use for this purpose 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 $\lambda=633$ nm and $\lambda=532$ nm. The near field and far field diffraction patterns are studied with a CCD camera at this stage using as the unfocused as the tightly focused laser beams.

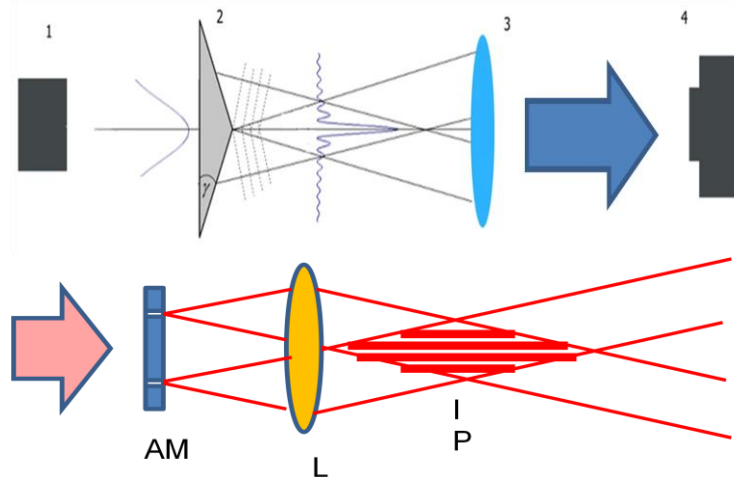


Figure 1. Experimental setups for formation of Bessel-like beams with Fresnel biprism (a), and with amplitude masks (b). 1 – laser source, 2 – biprism, 3 – image lens, 4 – beam analyser, AM – amplitude mask, L – lens.

2.1. Bessel-like light beam formation with amplitude masks

As the particular results, images in Figure 2 show 1D ($\lambda=633$ nm) and 2D light patterns ($\lambda=532$ nm) near the back focal plane of a cylindrical lens with focal length 80 mm (a), and spherical lenses (b - d) with focal length of 190 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 mm² 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.

The interference nature of formed light fields in the experiments provides their much better longitudinal homogeneity compared with 2D Gaussian beam. 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.

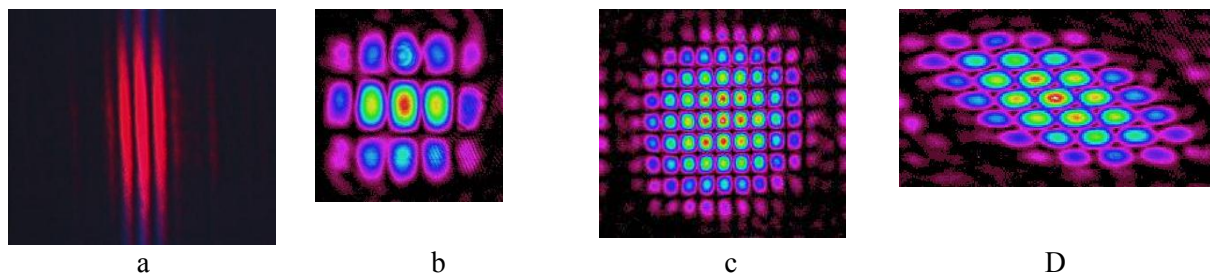


Figure 2. Light cross-sections of 1D and 2D Bessel-like fields for horizontal widths of central maxima: a – 20 μm; b – 230 μm (90° angle between slit directions); c – 60 μm (the same angle); d – 90 μm (45° angle between slit directions).

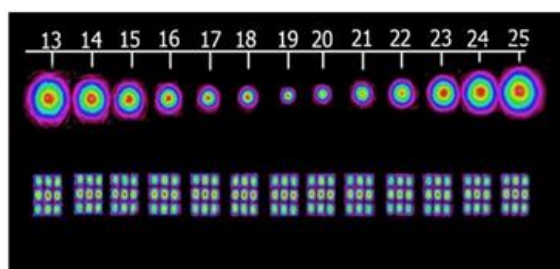


Figure 3. Intensity cross-sections of Gaussian beam (a) and 2D interference field (b) at different positions along light propagation direction.

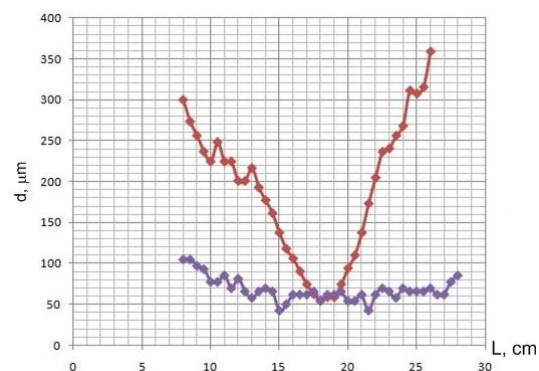


Figure 4. Gaussian beam diameter (red) and the central maximum diameter of interference pattern (blue) along light propagation direction.

2.2. Bessel-like light beam formation with Fresnel biprisms

Two-dimensional Bessel-like beams are formed in usual cases with laser beam passed through conical lenses, so-called «axicons» [1]. To form quasi-one-dimensional Bessel-like beams it is possible to exploit Fresnel biprisms [1] which can be considered as 1D analog of axicon lens. A laser beam with Gaussian profile is separated by a prism into two parts which interfere with each other in a space after the prism. The transverse profile of interference pattern in this case is close to that for Bessel beam.

The spatial “period” of interference image Λ is determined in this case by expression

$$\Lambda = \frac{\lambda}{2 \sin((n-1)\gamma)} \quad (1),$$

where λ is the light wavelength, n is the refractive index of prism material, and γ is the angle of the prism (Figure 1 a).

We use biprisms with these angles 4° and 12° in experiments. Images in Figure 5 illustrate light pictures in cross/sections of laser beam ($\lambda=532$ nm) passing through the prism with 4° angle in different positions. Picture a shows beam before prism, pictures b and c demonstrate cross-sections of light beams passed through the prism after the interference region, and picture d shows interference light pattern immediately after prism. It should be noted that light field is strongly scattered at diffraction on the apex line of the prism [8] and the scattering band is seen between light beam halves (Figure 5 b). To suppress this scattering, the prism apex is screened by black paper band and scattering disappears. It increases the contrast of interference pattern (Figure 5 d).

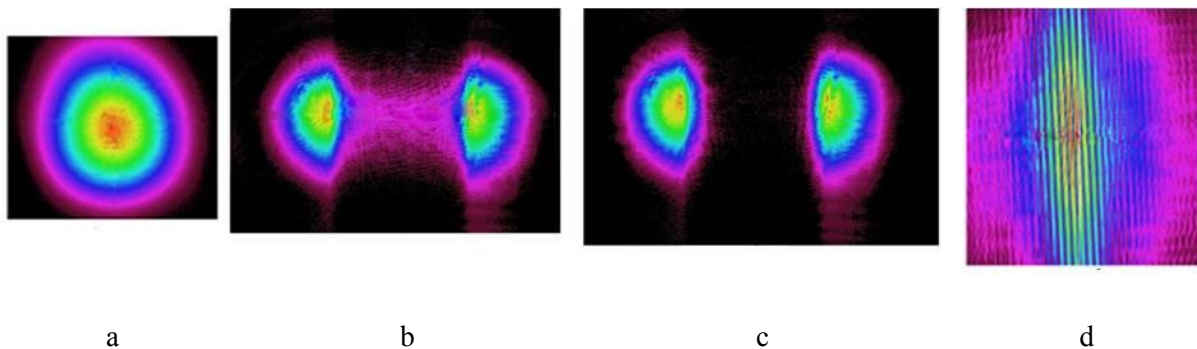


Figure 5. Cross-sections of laser beam ($\lambda=532$ nm) passing through biprism. Initial laser beam (a), light picture outside the interference area with scattering at the prism apex (b), the same image with apex screened (c), and interference pattern immediately after prism (d).

2.3. Formation of photonic structures by Bessel-like beams in photorefractive lithium niobate

Bessel-like 1D and 2D beams are used to generate phase diffraction structures in photorefractive samples of copper-doped plate $\text{LiNbO}_3\text{:Cu}$ (0.05 wt%). The dimensions of this plate are $10 \times 2 \times 15 \text{ mm}^3$ along X, Y, and Z axes. It is doped with Cu while crystal growth. 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 He-Ne lasers. The light pattern in Figure 6 a illustrates near-field diffraction of light ($\lambda=532$ nm) on the 1D few-element phase grating with spatial period $180 \text{ }\mu\text{m}$ induced within the $\text{LiNbO}_3\text{:Cu}$ plate. The optical power and exposure time at this grating creation are 1 mW and 3 minutes. Image in figure 6b shows cross-section of 2D interference pattern obtained with two amplitude masks 90° rotated with respect to each other in the same crystal plate. And image in Figure 6c demonstrates near field diffraction pattern at the exit facet of that plate obtained with laser beam ($\lambda=532$ nm) diffraction at the phase grating induced in $\text{LiNbO}_3\text{:Cu}$ plate. 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.

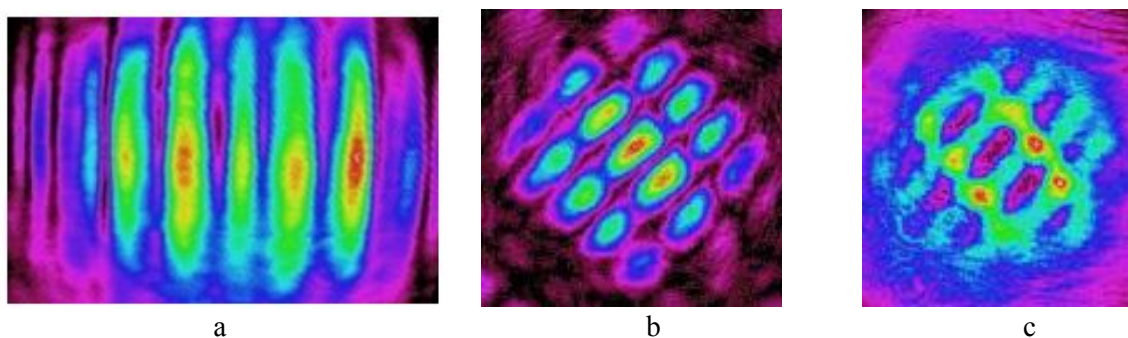


Figure 6. Cross-sections of laser beam ($\lambda=532$ nm) passing through biprism. Initial laser beam (a), light picture outside the interference area with scattering at the prism apex (b), the same image with apex screened (c), and interference pattern immediately after prism (d).

Images in Figure 7 demonstrate the change of 1D diffraction grating profile in time during its generation in photorefractive plate $\text{LiNbO}_3\text{:Cu}$. They are obtained with amplitude mask scheme. The spatial period of phase grating in this case is $100 \text{ }\mu\text{m}$. 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.

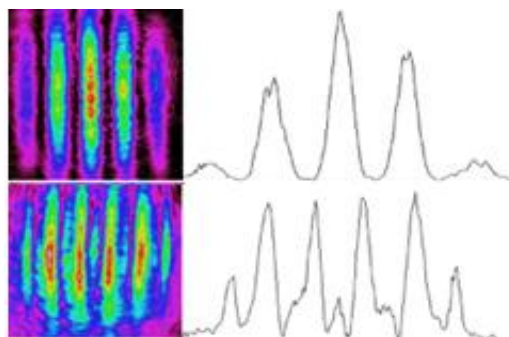


Figure 7. Near field diffraction images at the exit surface of $\text{LiNbO}_3\text{:Cu}$ plate (left) and their intensity profiles (right) for exposure times less than 10 s (upper line) and 80 s (lower line).

3. Conclusion

In conclusion, our experimental results confirm the possible 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.

Acknowledgments

This study was carried out with the financial support of Ministry of Education and Science of Russia (within the task N 3.1110.2017/PCh of the project part).

References

- [1] Duocastella M and Arnold C B 2012 *Laser Photonics Rev.* **6** 607
- [2] Siviloglou G A and Christodoulides D N 2007 *Optics Letters* **32** 979
- [3] Bandres M A and Rodriguez-Lara B M 2013 *New Journal of Physics* **15** 013054
- [4] Henderson D M and Abrams R L 1970 *Optics Communications* **5** 223
- [5] Zhu X, Schülzgen A, Li L, and Peyghambarian N 2009 *Applied Physics Letters* **94** 01102
- [6] Kip D 1998 *Appl. Phys. B* **67** 131
- [7] Petrov M P, Stepanov S I and Khomenko A V 1991 *Photorefractive Crystals in Coherent Optical Systems* (Berlin: Springer-Verlag)
- [8] Lei M, Yao B 2004 *Optics Communications* **239** 367