

# Optomechanical control of transforming Bessel beams in a c-cut of lithium niobate

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**Abstract.** Transformation of zero-order Bessel beams into a second-order vortex beam in the process of propagation in a c-cut of lithium niobate  $\text{LiNbO}_3$  crystal has been investigated experimentally. The possibility of controlling beam transformation by means of changing the curve radius of the illuminating beam is shown. The possibility of Bessel beam transforming by compact devices on the basis of thin c-cuts of uniaxial crystals with a diffraction mask formed on their surface is proved.

## 1. Introduction

High-order Bessel laser beams are used for optical trapping and displacement of atoms [1], microparticles [2], microbiological objects [3, 4]. The use of anisotropic crystals is one of the ways of producing devices and methods of forming Bessel beams with a vortex phase. Theoretical studies [5-8] have shown that periodic transformation of zero-order Bessel beams propagating off-axis into a second-order vortex beam takes place in uniaxial crystals. Higher efficiency of transformation and reduction of the spatial period of transformation in case of increased numerical aperture of the beam and the crystal birefringence is noted in experimental studies [9, 10]. As was shown earlier [8], the beam recurrence interval in the crystal depends on the crystal refraction and the axicon numerical aperture. For axicons with the numerical aperture of 0.15-0.5 the period is tens of microns. For a beam to be formed the thickness of a crystal should be maintained with micron tolerance, which is difficult because of the production complexity.

It is implied, as a rule, that the axicon is illuminated by a plane wave. As this takes place, the greater the diameter of the beam illuminating the axicon, the longer the illuminated section being formed. In most cases the plane wave is obtained with the help of a telescopic system that increases the size of the beam emitted by the laser.

If the distances between the components of the telescopic system vary the radius of the curve of the beam wavefront at the system's output will also vary. The illumination of the axicon by the spherical wavefront is equivalent to the addition of phase functions of the axicon and the lens (the element is known as "lensicon" [11, 12]). It can be easily shown that the numerical aperture of the formed Bessel beam determining the distance between the rings will vary depending on the radius of curvature of the wavefront of the beam that illuminates the axicon. Consequently, the period of beam transformation in the crystal will also vary. This phenomenon can be used for the adjustment of the optical system to the crystal parameters. It can be adjusted both toward the production of a diverging spherical wavefront (the period will increase) and toward a converging one (the period will decrease).

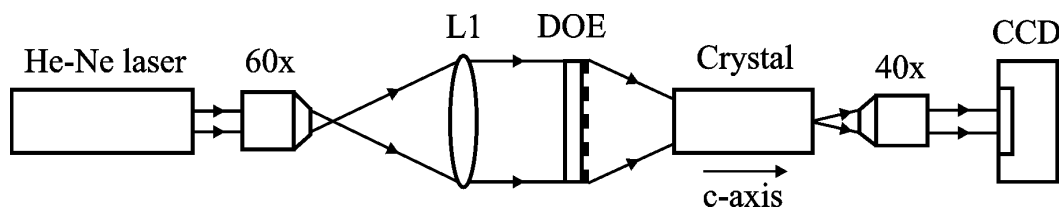
If, for some reason, it is not convenient to adjust the position of the collimator lens this can be accomplished with an additional lens mounted between the axicon and the crystal. In this case the converging wavefront can be obtained only under certain conditions of the formation of a real image  $d > 4f$ , where  $d$  is the distance between the axicon and the crystal. The magnification coefficient can be calculated by the known formulas of the geometric-optical theory of image formation.



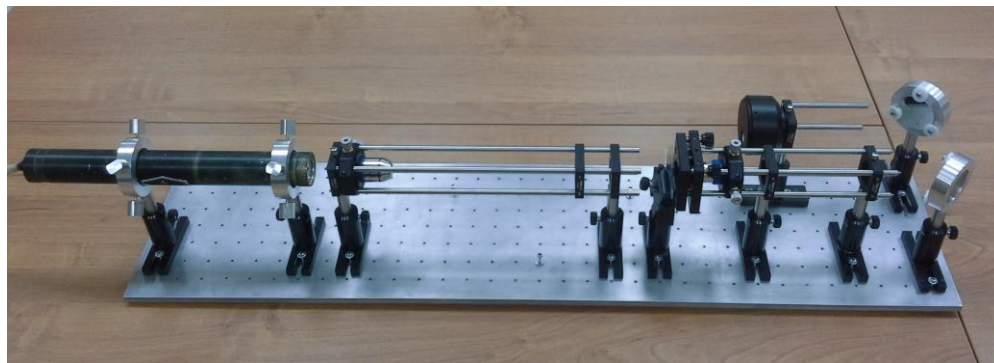
Variations in longitudinal magnification coefficient known from geometrical optics [13] is the main disadvantage of this approach (taking place as a result of using lenses as imaging systems). It leads to changes in the transformation period along the axis inside the crystal, while ring periods at the input and output of the crystal vary. An additional telescopic system is used to reduce the effect [14]. However, these phenomena are insignificant for low magnification coefficients and moderate numerical apertures. Comparing this optomechanical approach with other possible methods of optics adjustment to the crystal parameters, namely, heating the crystal or changing the wavelength we should note the undeniable advantages of the optomechanical approach, such as simplicity of implementation and a wide range of tuning.

## 2. Experimental investigation

An optical setup was assembled for the investigation of optomechanical transformation of a zero-order Bessel beam into a second-order vortex beam. The diagram and the external view of the setup are shown in figs. 1, 2. The setup comprised a source of radiation, a beam expander, a diffraction axicon, a c-cut of a crystal, a microobjective and a CCD array. The C-axis of the crystal was oriented parallel to the optical axis of the setup. Accurate bringing of the ordinary and extraordinary beams to a point was provided due to a two-dimensional angular mount.



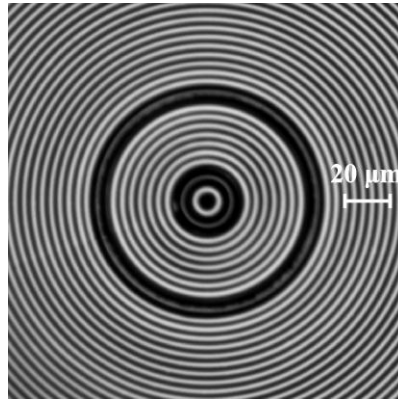
**Figure 1.** Scheme of experimental setup



**Figure 2.** Photo of the experimental setup

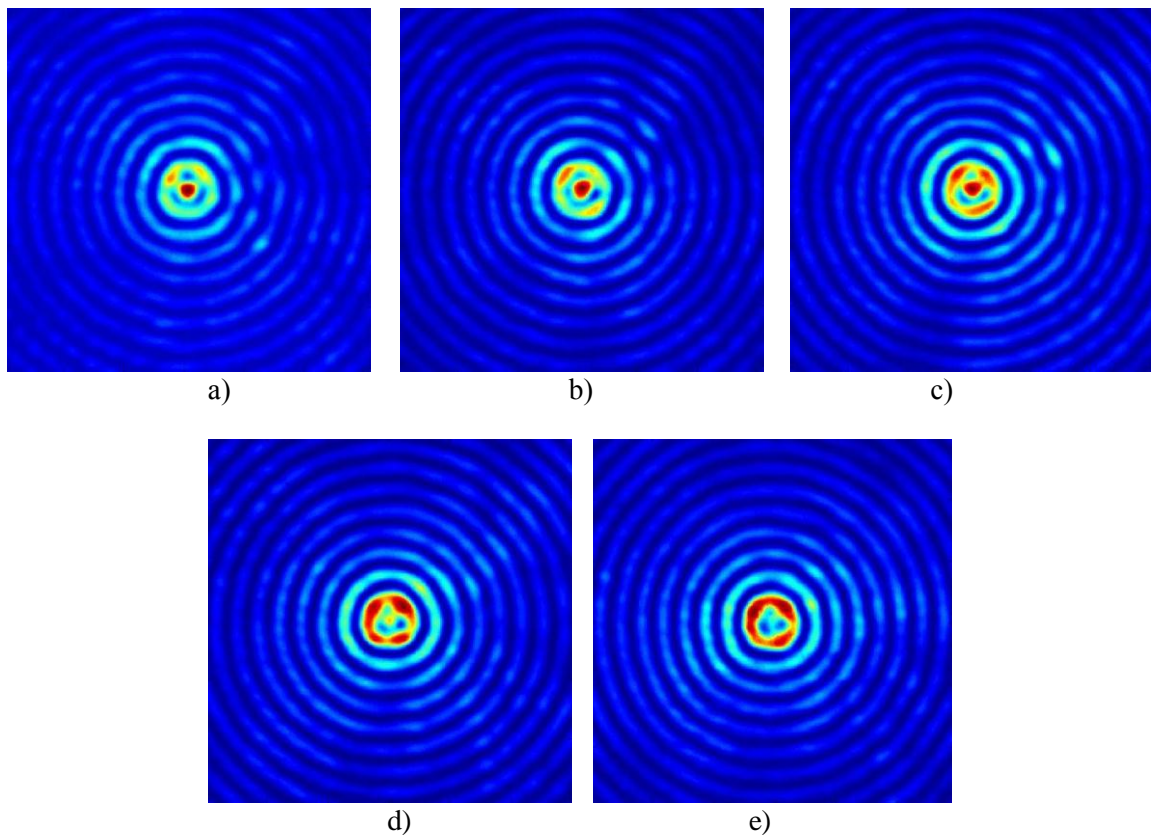
To form a zero-order Bessel beam a 40 mm-diameter amplitude diffraction axicon on a glass substrate with the ring period of 4 mkm was produced ( for  $\lambda=0,6328$  it corresponds to the numerical aperture  $\alpha=0,1582$ ). Mask exposure was performed on the CLWS-200 installation in the vector mode, which provided absence of topology defects and high quality of the Bessel beam formed. To detect the beam outside crystal its size was increased by a 40x objective with a NA=0.65 aperture in excess of the axicon numerical aperture. The image of the diffraction mask (chrome 100 nm thick) is presented in fig. 3. The width of the light and dark rings is the same and is equal to 2 microns. There are two rings of increased width, necessary for the alignment of the laser beam, in the central part of the axicon. Since the radius of the outer broad chrome ring does not exceed 50 mkm the distortion of the Bessel beam introduced by it will take place at a distance of up to 350 mkm with an numerical aperture  $\alpha=0,1582$ . As the crystal was placed at a distance of 5 mm from the axicon and the diameter

of the axicon's illuminated part was 15 mm the presence of such defects did not affect the results of the experiments.



**Figure 3.** Electron microscope image of the axicon with 4 mkm period

The laser beam was expanded by a 60x objective and an L1 plane-convex lens with a focusing distance of 20 cm. The L1 lens could be moved along the optical axis causing changes in the curvature of the vortex beam that illuminated the axicon. Fig. 4 shows the experimental results of Bessel beam transformation in a c-cut of a  $\text{LiNbO}_3$  crystal 0.5 mm thick for different positions of the L1 lens.



**Figure 4.** Transformation of Bessel beam in c-cut of lithium niobate with changing of distance from objective to lens L1: a) L=0 cm, b) L=5 cm, c) L=10 cm, d) L=15 cm, e) L=20 cm

From figure 4 it follows that the variation of the wavefront curvature by moving the illuminating lens makes it possible to transform a zero-order Bessel beam into a second-order beam. The magnitude of movement required for complete transformation is determined by the crystal length, the birefringence and the numerical aperture of the axicon.

### 3. Conclusions

In case of thin crystals considerable shifting of the lens is required, comparable with the focusing distance. This reduces the operation speed of adjustment. This drawback can be eliminated by using axicons with a greater numerical aperture formed directly on the crystal surface. The use of electrically operated lenses based on liquid crystals and electrooptical materials is a promising approach. The methods mentioned can be incorporated in a single optical element comprising control circular electrodes and a diffraction microrelief.

### Acknowledgments

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