Bessel beam converter based on c-cut lithium niobate crystal

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Abstract. The transformation of the 0th order Bessel beam into the 2nd order Bessel vortex beam is experimentally investigated. A c-cut lithium niobate crystal with a thickness of 514μm was used to convert the beams. It is shown that for a diffractive axicon with a period of 3.5μm illuminated by semiconductor laser (λ=639 nm), the output beam is a 2nd order Bessel vortex beam. It is shown that for a diffractive axicon with a period of 4μm illuminated by helium-neon laser (λ=632.8 nm), the output beam is a superposition of Bessel beams of the 0th and 2nd orders. The experimental results are in good accordance with mathematical modeling.

1. Introduction
The formation of higher-order Bessel beams, namely vortex Bessel beams, represents an urgent task for a number of applications, including optical manipulation tasks [1-3]. Besides, Bessel laser beams possessing non-diffractive properties [4-7] and are used as an efficient tool in various metrological [8, 9], diagnostic [10, 11] and testing [12-15] applications.

Bessel beams are also useful for investigating optical anisotropy and birefringence [16-18]. The sensitivity variation of the proposed method is achieved by changing the numerical aperture of the illuminating Bessel beam. Since the proposed method is optical and contactless, the technological purity and mechanical integrity of the samples is maintained. Thus, the method is applicable to the examination of thin films and plates, as well as soft and brittle optical materials.

In optics, anisotropic materials are widely used for transformation of beams with homogeneous polarization into cylindrical vector beams (CVBs) [19]. In the intra-cavity methods [20-22], birefringent crystals serve to discern the modes by separating them either across [20] or along [21, 22] the optical axis. In the operating principle, the method of reference [20] is similar to the extracavity method of interferometric superposition of two modes with orthogonal plane polarization [23–26]. In this case, the crystal’s optical axis is located at an angle to the cavity’s optical axis. Methods described in references [21, 22] perform the longitudinal separation of modes along the cavity’s optical axis in two foci. In this case, the crystal’s optical axis is parallel to that of the cavity. To attain a higher convergence of the beams within the crystal, an optical arrangement with adjustment of the intracavity diaphragm, radial or azimuthal polarization can be attained. This method also has extra-cavity analogs [27, 28], with a telescopic system used to obtain a converging beam in the crystal.
Gaining in popularity is the conversion of Bessel beams in the birefringent crystals to produce the required polarization [29, 30]. This enables obtaining of both radially and azimuthally polarized beams [29], along with mixed ‘spiral’ types of polarization [30]. Refractive axicons were utilized in reference [29] to generate a plane-wavefront doughnut intensity, with the radially and azimuthally polarized waves passing the crystal separated by a Wollaston polarization prism. However, it appears impossible to obtain in this way higher-order cylindrical vector beams. The higher-order cylindrical vector beams are important for reducing the focal spot [31, 32]. A most efficient and universal way to generate higher-order cylindrical vector beams can be implemented in using means of diffractive optics [33-38].

Beams with a complex polarization state are also generated by subwavelength gratings [39-46], which, like half-wave plates, provide rotation of the polarization plane and are used for linear polarization of the illuminating beam. In a converter based on subwavelength gratings, the efficiency and, consequently, the polarization contrast, varies depending on the angle of rotation of the polarization plane by the grating [42, 43, 46]. It should also be noted that this property of a change in efficiency theoretically follows from the very mechanism of the operation of subwavelength gratings and cannot be eliminated by any complication of the already complex technology of their fabrication.

For convertors assembled from half-wave plates [41] or from a polarized film [47, 48], the main factor that worsens the quality of the formed beams is the presence of sector joints. Gaps and misalignments between the sectors lead to the appearance of parasitic diffraction patterns and additionally violate the axial symmetry of the produced beams. The initial violation of the axial symmetry is determined by the limited number of sectors (usually no more than 8). The problems may be combated using low-frequency spatial filtration of the beam obtained by a telescopic system with a point diaphragm in focus. However, this technique leads to significant energy losses. The effect of sector joints can be significantly reduced by manufacturing a sector plate in the form of a single birefringent crystal, the sectors being formed by a microrelief on the crystal surface [49-52].

Note that there are polarization transformation methods that use special properties of Bessel beams. There are systems based on the conversion of conical wavefronts passing through an interference polarizing plate. Effect of nonuniform polarizations generation when the illuminating beam incidents at the Brewster angle [53-58] is used. Such systems can be both intra- [53, 54] and extracavity [55-58] ones and are based on the use of conical wavefronts formed by appropriate optical elements. Intracavity systems have the highest efficiency, because they provide a multiple passage through Brewster windows or prisms. Brewster windows [53], providing radial or azimuthal polarization, are difficult to fabricate. A simpler system is a Brewster prism [54], consisting of convex and concave conical prisms (axicons). To increase the reflectivity of azimuthal polarization, Kozawa and Sato [54] applied a multilayer dielectric coating on the conical surface of the Brewster prism. Such a system produces only a radially polarized distribution. A simplified version of the optical system, implemented in practice by Skidanov and Morozov [55], contains a diffractive axicon instead of a refractive one and a Stoletov’s pile instead of a multilayer structure (Stoletov’s pile also makes it possible to produce radial polarization). The use of the diffractive axicon increases the quality of the beam in addition to the advantages that diffraction optics provides. However, the diameter of the beam after its passage through Stoletov’s pile greatly increases because of the required large divergence angle, and collimation of the beam becomes a complex task requiring the use of high-aperture large-diameter optics. In addition, the energy efficiency of Stoletov’s pile to achieve a sufficient polarization contrast is small. Any control of the polarization state of the beam in such a system is impossible. In the papers [56-58], the optical systems are based on the transformation of conical beams in a multilayer interference structure. Such systems were effectively used to produce a two-ring radially polarized beam [56]. The suitability of this system for the formation of radially polarized Bessel beams has been experimentally shown in [57], but the control of the polarization state in it is impossible because of the large angles of incidence of light on the multilayer structure in order to obtain radial polarization. Further increase in the angles for obtaining azimuthal polarization is not possible due to technological limitations in the manufacture of diffractive optical elements and a strong decrease in energy efficiency with increasing angles of incidence. So, in the paper [58], it is proposed to form nonuniformly polarized vortex Bessel beams with a controlled polarization state by
changing the divergence of the illuminating beam incident on the diffractive axicon. It has been shown theoretically and experimentally that when the operating angles of the light incidence on an interference polarizer decrease, radial and azimuthal polarizations can be obtained with the same diffractive axicon only by replacing the lenses in the illuminating beam.

The generation of cylindrical vector beams is very efficient at sharp focusing of laser beams along the axis of birefringent crystals [59-61]. There is the radially polarized distribution in one focus and the azimuthally polarized distribution in the other focus when the incident beam has the vortex phase of the first order and circular polarization of the opposite direction. The results are extended to the generation of higher-order radially and azimuthally polarized laser beams.

Note that when the beam propagates perpendicular to the crystal axis, other transformations occur [62-64], which are close to astigmatic [17, 18].

The type of a beam is important at non-paraxial regime of a beam propagation along the crystal’s axis [65-69]. Anisotropic effects are most noticeable for Bessel beams [68, 69] because of the specific structure of their spatial spectrum.

Propagation of high-order laser modes in a highly anisotropic medium leads to complicated polarization-mode transformations connected with the angular orbital momentum of such beams [70-74]. In the case of linearly polarized radiation the energy is periodically redistributed between two transverse components, whereas with a circularly polarized beam the energy is transferred from the original beam to the vortex second-order one and back.

It was shown theoretically [68, 69] that the use of diffractive axicon makes it possible to achieve the efficiency of conversion of the 0th order Bessel beam into the 2nd order Bessel vortex beam close to 100% for small (less than 1 cm) lengths of propagation along the axis of uniaxial crystals.

Conversion of a non-paraxial circularly and linearly polarized zero-order Bessel beam into a second-order vortex beam is shown theoretically and experimentally in [71-74]. Besides static conversion [71-74] methods of dynamic conversion are developed in [75-81]. Their advantage is the possibility of pre-set partial or complete beam conversion.

This paper investigates static conversion of a zero-order Bessel beam in a thin crystal of c-cut lithium niobate. Special attention is given to the optimization of crystal thickness with the aim of saving expensive material. The influence of the optical circuit elements and interference effects on the quality of the output beam is analyzed.

2. Experimental study

To form a zero-order Bessel beam, a 40 mm-diameter amplitude diffraction axicon on a glass substrate with a ring period of 4 µm was used. An axicon amplitude mask was formed at the CLWS-200 by means of chrome thermochemical oxidation with further chemical elimination of non-masked areas. Mask exposure was performed in the vector mode, which provided an absence of topology defects and a high quality for the Bessel beam formed.

The beam transformation was studied using an optical setup shown in Figure 1. A He–Ne laser was used as a source of the linearly polarized light. The beam expander (BE) consists of a 10x objective and a positive lens with diameter 50 mm and a focal length 500 mm. A congruent uniaxial c-cut lithium niobate crystal with thickness 514 µm was used as the anisotropic medium. The c-axis of the crystal was aligned in parallel with the optical axis of the setup. An precise convergence of the ordinary and extraordinary output beams realized using a two-coordinate angle mount. To detect the output beam, its size was significantly increased by a 40x objective (MO) mounted in a three-coordinate linear mount. The intensity distribution of the output beam was recorded using a digital USB-video-camera DCM 310 with a 3 megapixel resolution and an 8-bit analogue-to-digital converter (CCD). The polarization state of the output light was identified using a film analyzer (A).

![Figure 1. Experimental setup.](image-url)
Figure 2 shows an output zero-order Bessel beam formed by a diffraction axicon with a period of 4 μm. Figure 3 presents the process of convergence of output beams. Figure 4 illustrates recombined output beams. Figures 2-4 were recorded without an analyzer.

It follows from the data obtained that the output beam represents superposition of 0th order and 2nd order beams. Figures 5-7 show computed distribution of output beam intensity for incomplete beam conversion and various analyzer orientations (corresponds to Table 2 in [59]). Figures 8-10 present experimental images of an output beams for similar positions of the analyzer.

Full transformation of the 0th order Bessel beam is also possible. This is achieved by varying the thickness of the crystal or the axicon numerical aperture. For the complete transformation of the 0th order Bessel beam into the 2nd order Bessel vortex beam, a lithium niobate crystal with a thickness of 514 μm was used. A diffractive axicon with a period of 3.5 μm and a diameter of 400 μm was produced. Axicon illuminated by a semiconductor laser with a wavelength of 639 nm. Photographs of the beams at the axicon output and crystal output are shown in figures 11, 12.

Thus, the experimental investigation confirms the validity of the mathematical model developed earlier. We also show the possibility of various converting of 0th order and 2nd order Bessel beams with
the use of thin c-cut of uniaxial crystal. Significant reduction of the crystal thickness, no more than 1 mm for full conversation instead of 15 mm in [59] was achieved and expensive material was saved.

Interference pattern of the beam is absent in the images presented, which is indicative of properly selected apertures of the forming and receiving parts of the experimental setup and sufficiently accurate angle alignment of the elements.

3. Conclusions
The transformation of a 0-th order Bessel beam into a 2-nd order Bessel beam was experimentally studied. It is shown that the conversion is effective even in a crystal with a small thickness. High optical quality of the output beam and high efficiency of conversion were noted.

The investigated effect can be used for optical measurement of the thickness of z-cut uniaxial crystals. This method is non-contact and it provides the technological purity of the crystal.

As we noted, the output beam has a vortex phase front. This phase front is resistant to significant scattering and absorption [82, 83]. So it can be used in optical data transmission over the atmospheric communication line.

4. References
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