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Generation of TH- and TE-polarized Bessel light beams at acousto-optic interaction in anisotropic crystals

P.A. Khilo [a], N.S. Kazak [b], N.A. Khilo [b], V.N. Belyi [b,*]

[a] Gomel State Technical University, Oktyaborskaya ave., 246746 Gomel, Belarus
[b] B.I. Stepanov Institute of Physics, 68 Nezavisimosti ave., 220072, Minsk, Belarus

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A B S T R A C T

This paper lays out a theory of acousto-optic (AO) interaction of TH- and TE-polarized Bessel light beams (BLBs) for the case when incident and diffracted optical fields and plane acoustic wave propagate along the optical axis of an uniaxial crystal. We have solved a system of coupled equations and calculated the diffraction efficiency of AO interaction, which has been shown to be close to one limited case of plane–wave interaction. We look at some particular cases of isotropic and anisotropic scattering, which can or cannot be accompanied by a change of the polarization state of vector BLBs. The paper explores acousto-optic processes of transferring optical singularities onto the wave front of BLBs and considers the transformation and generation of high-order phase dislocations (optical vortices) at AO interaction of BLBs along the optic axis of uniaxial crystals. Also under examination are peculiarities of AO interaction of Bessel vortex beams in the condition of the transverse and longitudinal phase-matching for uniaxial crystals of hexagonal, tetragonal and trigonal symmetries. The acousto-optic process under study can be used as a method for generation of the TH- and TE-polarized BLBs, which allows manipulating the polarization state of the output optical field in time.

1. Introduction

An important area of Bessel light beams (BLBs) research is the elaboration of methods for controlling their wave front structure and generation of singular beams. Application for these purposes of the acousto-optic interaction is a new, imperfectly explored area of investigations. It should be noted that whereas the acousto-optic (AO) diffraction of light field in the plane–wave approximation or Gaussian light beams has received a rather good study [1–3], there are practically no papers on the AO transformation of BLBs [4,5]. As with plane waves, BLBs can be represented, to a high degree of accuracy, as rigorous solutions of Maxwell Eqs. [(6) and (7)]. This is of importance for studying the vector AO interactions because they give us the exact knowledge of the polarization states of such beams [6,7]. Among the various polarization states of BLBs, the well-known ones are the radial (ρ-) and azimuthal (φ-) polarizations. The beams with such polarization states are more effective in some applications as compared to the beams with the linear or circular polarization. For example, a number of papers are devoted to applications of such beams in laser technology (see, for example, [8–10]). Due to their non-diffractive nature and a narrow dark central region, the high-order BLBs can be used for atom guiding over extended distances [11–13], as well as for focusing cold atoms [13]. In papers [14–15] the orbital angular momentum of BLBs is calculated with the demonstration of the transfer of the orbital angular momentum to a low-index particle trapped in optical tweezers with the help of high-order BLBs. Some properties of interfering high-order BLBs and BLBs with z-dependent cone angle were examined in [16,17]. The use of such beams for controlling the rotation of microscopic particles in optical tweezers and rotators is demonstrated. The self-healing properties of interfering BLBs allow the simultaneous manipulation and rotation of particles in spatially separated sample cells [18]. Thus, the development of methods for generating and transforming Bessel vortices is of both scientific and practical interest.

It should be noted that the uniaxial crystals can also, without the AO interaction, transform simultaneously the polarization state and spatial structure of BLBs as well as the order of a dislocation of the phase front [19–23]. In other words, the polarization dynamics of BLBs is associated with the energy exchange between the circularly polarized components propagating along the optical axis of uniaxial or biaxial crystals. But the formation of TH- and TE-polarized BLBs due to AO interaction allows one, as is shown in this paper, to extend the set of BLBs which can be obtained owing to transformation of single input BLB and also to manage the transformation process.

In the present paper a successive approach is developed to describe the AO interaction in uniaxial crystals. There exists a simple way of achieving the AO interaction without distortion of the BLB structure.

* Corresponding author. Tel.: +375 17 2841068; fax: +375 17 2949002.
E-mail addresses: v.belyi@dragon.bas-net, v.adamenko@ifanbel.bas-net.by (V.N. Belyi).

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For this, it is necessary to go over to a geometry, wherein interacting waves propagate along the optical axis, because only in such geometry incident BLBs of TE and TH-polarization preserve their structure. We consider here the AO interaction of zero and high-order BLBs with a plane acoustic wave at the co- and counter- propagation. Owing to the geometry mentioned the phase velocities of TE- and TH-polarized beams do not coincide, which enables us to realize their selective interaction with the plane acoustic wave.

The specific character of mathematical description of the indicated form of the AO interaction is in the necessary fulfillment of two types of the phase-matching. Besides the usual longitudinal phase-matching realizable at the equality of the phase velocities of transmitted and diffracted waves, BLBs necessitate at the same time the so-called transversal phase-matching. The latter is related to the fact that BLBs with different cone angles have also the different spatial structures and, consequently, various values of the overlapping integral with the diffracted beam. As a result, the AO interaction can effectively be realized only at the maximum of the overlapping integral. The calculations of the appropriate integrals should be carried out and conditions should be determined when the overlap integrals are maximal. Such a description of the AO interaction supposes that the BLBs may be regarded as a whole; that is it can be assigned as an integrate field. This concept of integrity does not coincide with the well-known approaches wherein BLB is considered as a superposition of plane waves or of two conical beams.

The paper is structured as follows. In Section 2 the geometry of forward and backward AO scattering of vector BLBs is considered. In Section 3 the propagation of BLBs along the optical axis of an uniaxial crystal is presented. The tensor of the dielectric permittivity at the presence of the AO interaction in the cylindrical coordinates is presented in Section 4. In Section 5 the equations for the slowly varying amplitudes of interacting BLBs and transformation and generation of high-order phase dislocations at AO interaction of BLBs are considered. The analysis of overlap integrals and peculiarities of AO interaction of BLBs in uniaxial crystals of different symmetries will be considered in Section 6. A conclusion is given in Section 7.

2. Geometry of forward and backward AO scattering

Owing to cylindrical symmetry of BLBs, AO diffraction on the plane acoustic wave, which does not break the field symmetry, can be made only at the forward or backward scattering. For the case of an isotropic medium the phase matching is realizable only at backward scattering. In a case of uniaxial crystals the preservation of the structure of BLBs of TE- and TH-polarization is possible only when propagating along the optical axis. Here the acoustic wave should also propagate along the optical axis. Fig. 1(a and b) show the geometry of the forward and backward AO scattering when the incident field is the BLBs.

When anisotropy-influenced, the optical field excited in a crystal depends essentially on the polarization state of the incident BLBs. In the most symmetric case the circularly-polarized BLBs incident from an isotropic medium on an uniaxial crystal in the direction of the optical axis which is parallel to the z-axis (Fig. 1a). From the boundary conditions it follows that in the crystal two BLBs will be excited with equal amplitudes and circular cones of the wave vectors. The wave vectors $\boldsymbol{k}_o$ and $\boldsymbol{k}_e$ belonging to the indicated cones and lying in the plane (x, z) are presented in Fig. 1a and correspond to the well-known ordinary and extraordinary plane waves. The projections of such vectors on the boundary interface are the transverse wave numbers of BLBs, which are equal for all beams. It should be noted that in the absence of an azimuthal modulation of the phase, i.e. for zero order BLBs, the polarization of BLBs coincides with the polarization of plane waves. Therefore, BLBs of the ordinary (o-) type have the TE- or azimuthal polarization, and BLBs of the extraordinary (e-) type have the TH-polarization containing the radial and longitudinal components. For azimuthally modulated beams (BLB of higher orders) this relation is disturbed. Hereafter the relevant symbols o and e are preserved to designate TE- and TH- BLBs of any order.

3. Propagation of BLBs along the optical axis of uniaxial crystal

Let us consider the propagation of BLB along the optical axis of an uniaxial crystal. The incident BLB of an arbitrary polarization will excite in the uniaxial crystal two eigen waves, i.e. ordinary (o-) type (TE-polarization) and extraordinary (e-) type (TH-polarization) of BLBs. The electrical fields of these modes are exact solutions of the Maxwell equations and can be written as [21]

$$\vec{E}^{(o)} = A_o\left(\vec{c}_{+}J_{m-1}(q\rho)+\vec{c}_{-}J_{m+1}(q\rho)\right)\exp(im\varphi+ik_{o,z}z), \qquad (1)$$

$$\vec{E}^{(e)} = A_e\left[\vec{c}_{+}J_{m-1}(q\rho)-\vec{c}_{-}J_{m+1}(q\rho) - \frac{2iq\varepsilon_o}{k_{ez}\varepsilon_e}J_m(q\rho)\vec{e}_z\right]\exp(im\varphi+ik_{e,z}z), \qquad (2)$$

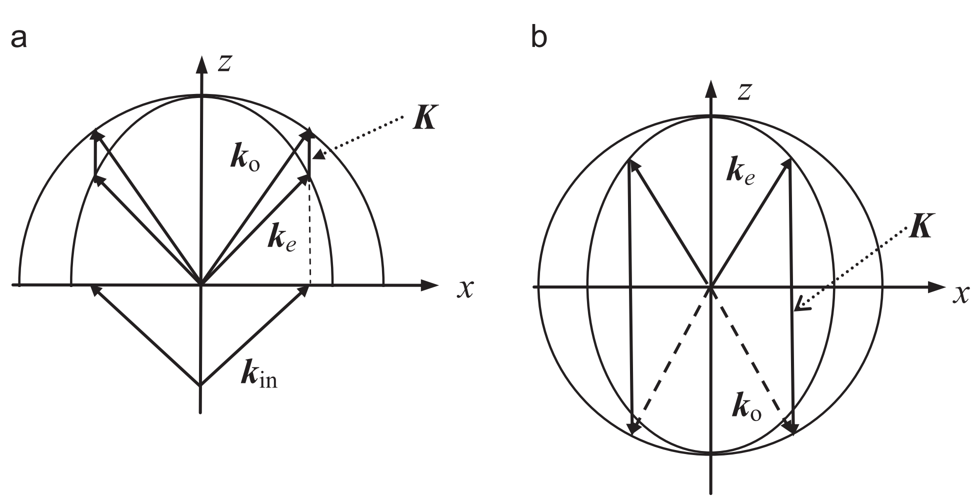

Fig. 1. Orientation of the ordinary $\boldsymbol{k_o}$ and extraordinary $\boldsymbol{k_e}$ wave vectors related to the incident BLB (wave vector $\boldsymbol{k_{in}}$), and also o- and e- BLB in a crystal (a). The scheme of back scattering of Bessel light beam with the change of polarization ($e \to o$ scattering) (b). The scheme of forward scattering with the change ($e \to o$) of polarization (a). Here $\boldsymbol{K}$ is the acoustic wavevector.