Experimantal oberving of transformation Bessel beam spreading along axis of crystal during wavelength changes

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Abstract

In paper decribe experimental observing transform bessel beam, formed by diffraction axicon in moment propagation through anisortopic birefringence crystal. This observation covers large range wavelength changes (from 520 nm to 534 nm). Theoretical explain effect is given.

Keywords: laser with changing wavelength; diffraction axicon; birefringent crystal; bessel beams

1. Introduction

It is well-known the usage of anisotrophic elements to convert beams with the homogeneous polarization into cylindrical vector beams [1-6]. At the same time, it is necessary to implement the separation of the longitudinal modes along the optical axis of the system, which is parallel to the axis of the crystal. To improve convergence of the beams in the crystal, it is possible to use telescopic system or to form beams with high numerical aperture. Polarization and mode conversion during propagation along the axis of the crystal were considered for both Bessel and Gaussian beams [7-16].

It has been shown in the studies [17, 18] that during the propagation along the crystal axis neuraxial Bessel beams have other properties than Gaussian beams, namely, experiencing a uniform periodic change of intensity. In this case, the Bessel beam of zero order and second-order are periodically converted from one to another [7-9, 17, 18]. The oscillation period is directly proportional to the wavelength of the laser radiation and inversely proportional to the square of the spatial frequency of the laser beam and the difference of the dielectric capacitivity, which is corresponding to the ordinary and extraordinary rays. This dependence allows control occurring transformation in the crystal due to changes of the characteristics in either Bessel beam or crystal. In particular, the spatial frequency of the beam depends on the numerical aperture of the axicon [19-22] which shapes the beam, also it is possible to adjust characteristics of the beam by changing the beam divergence [23]. To change the parameters of the crystal, it can be heated [24] or effected by electro-optic [25]. However, the most convenient way of adjustment is to change the wavelength of the laser radiation which has a direct linear relationship from the period of transformation [26].

It was experimentally demonstrated the ability [26] to manage the transformation of the Bessel beam at the output of the CaCO3 crystal by changing the wavelength of the radiation illuminating the diffractive axicon. It was achieved almost complete transformation of the Bessel beam of zero order beam to the second order using the axicon period of 2 μm and the wavelength at $\Delta\lambda$ =1.5 of the initial value of λ = 637.5. The variation of the wavelength within a small range was achieved by changing the temperature of the laser. In contrast to this method, the usage of a laser with variable wavelength provides a wide range of $\Delta\lambda$, and therefore the possibility of achieving complete conversion using the axicon with a large period, i.e., a smaller numerical aperture. Note that the usage of axicons with high numerical aperture is limited not only with technological possibilities of production [27] and reduction of non-diffraction distribution cut [20], but with the limiting numerical aperture [28], in which propagating waves occur in the considered optical medium.

This paper shows the results of experimental observation of the mode conversion of Bessel beam formed by the axicon amplitude with a period of 3 μm with the output of a deuterated potassium dihydrogen phosphate crystal when the wavelength of the laser EKSPLA NT 200 radiation is changed.

2. Theoretical analysis

Consider an anisotrophic crystal whose axis is oriented along the optical axis.

The intensity distribution I(x,y,z) in the propagation of Bessel beam along the axis of the crystal is as follows [9, 11, 17, 18]:

$$I(x,y,z) \approx \frac{1}{2}\left[|C(z)|^2 J_0^2\left(k\alpha\sqrt{x^2+y^2}\right) + |S(z)|^2 J_2^2\left(k\alpha\sqrt{x^2+y^2}\right)\right], \quad (1)$$

where $J_0(\cdot)$ и $J_2(\cdot)$ - Bessel functions of zero and second order, respectively,

$$C(z) = \exp(ikz\gamma_o) + \exp(ikz\gamma_e),$$
$$S(z) = \exp(ikz\gamma_o) - \exp(ikz\gamma_e), \quad (2)$$

where α – numerical aperture of the beam, z – is the distance traveled; γo, γe - are the values which are determining the direction of propagation of the ordinary and extraordinary rays:

$$\gamma_o = \sqrt{n_o^2 - \alpha^2},$$
$$\gamma_e = \sqrt{n_o^2 - \alpha^2 n_o^2 / n_e^2}, \quad (3)$$

where no, ne – ordinary and extraordinary refractive indices of the crystal.

A complete transformation of the Bessel beam of zero order to the beam of second order will periodically occur at distances that are multiples of the value:

$$z_p = \frac{\lambda}{\gamma_o - \gamma_e} \approx \frac{2\lambda n_o n_e^2}{\alpha^2 \left(n_o^2 - n_e^2\right)}. \quad (4)$$

Full transformation period depends on the refractive indices of the crystal and the numerical aperture of the axicon, as well as on the wave length of radiation. Moreover, the wavelength dependence is direct and linear, i.e. the most convenient to dynamically change the value of period so that the output of the crystal is formed the desired pattern.

3. Experimental results

3.1. Method of experiment

In this paper experiments were conducted using the optical arrangement shown in the fig.1, where 1 – laser with changing wavelength EKSPLA NT 200, 2 – diaphragm, 3 – collimator, 4 – diaphragm, 5 - DOE, 6 – anisotropic crystal, 7 – 20x microobjective, 8 – digital USB camera TOUPCAM UCMOS05100KPA.

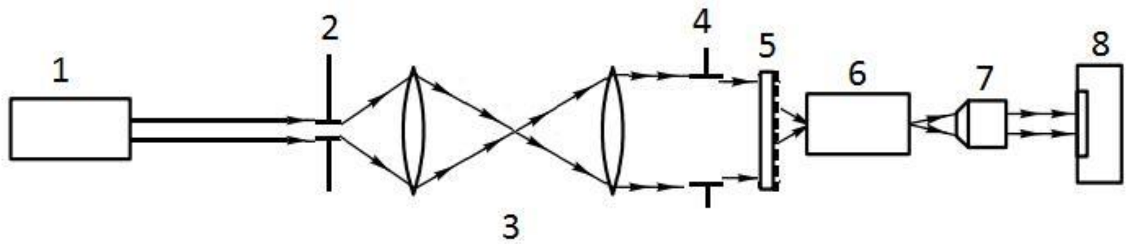


Fig. 1. Optical setup of the experiment.

A laser with variable wavelength was used as a radiation source EKSPLA NT 200. In the considered range of wavelength variation (520 – 534 nm), the laser beam has a horizontal X-polarization. The energy of the laser radiation obtained in the range of the visible spectrum wavelength is variable from 610 microjoule (450 nm) to 45 microjoule (700 nm) . The extension of the beam is done by the collimator. Owing to the fact that the beam emerging from the laser has a Gaussian intensity distribution, it has become necessary to select a part of the beam with a small change of intensity. This problem can be solved by introduction of a diaphragm 2. Septum 4 allows to limit the numerical aperture and to enable formation of the propagating waves. The intensity distribution of the output beam was recorded with a digital USB camera with a resolution of 5 mega pixels and ADC digit capacity of 12 bits.

The Bessel beam of zero order is formed by using a diffraction amplitude of the axicon with period which operates with nearly the same effectiveness in the considered wavelength range. The Bessel beam was directed along the axis of a crystal with cross-sectional dimension and length 20 mm. As a result of Bessel beams transformation there were formed interference pattern intensity distribution for different wavelengths and it was recorded with the microscope objective and digital cameras (table 1). To highlight different X and Y components of the transformed beams a rotating analyzer was installed in front of the digital camera.

3.2. Results and discussion

As you can see in the images, when the wavelength changes by $\Delta\lambda$=14 nm there is a complete transformation of the Bessel beam of the first order to the second, which is caused by the reaction of doubly refracting crystal. The observed phenomenon is explained by the formula (4), where λ is in the numerator. At the same time, change of wavelength is similar to the changes of the propagation length of the beam, as if it had been changed the dimensions of the crystal. To verify the observed phenomenon in the described conversion model it was carried out an additional numerical calculation for the wavelength of 520 nm and 532 nm. Intensity distributions of the Bessel beams images which were converted by electro-optic crystal for given experimental conditions obtained by numerical calculation are presented in table 2.

Based on the simulation results, we can conclude that the observed experimental results are very similarity with the mathematical description for the Bessel beams conversion in the considered wavelength range.

Table 1. Distribution of intensity bessel beams tranformed in birefringent crystal.

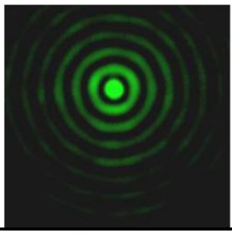
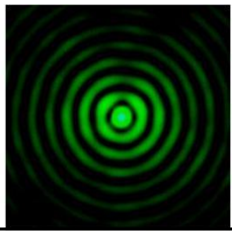
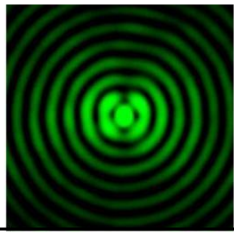
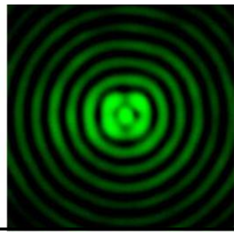
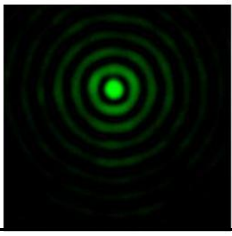
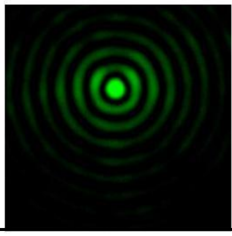
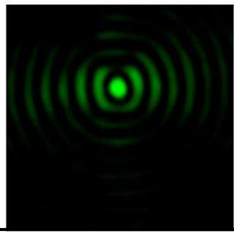
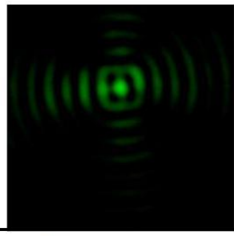
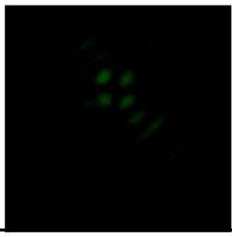
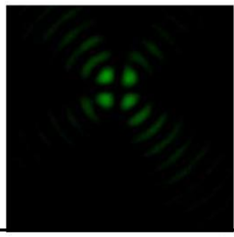
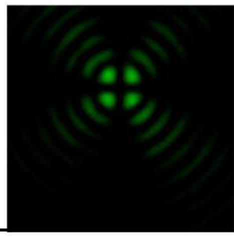
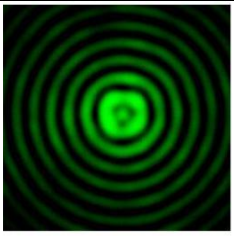
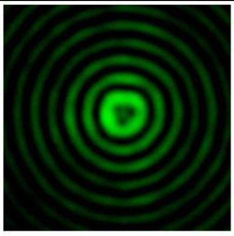
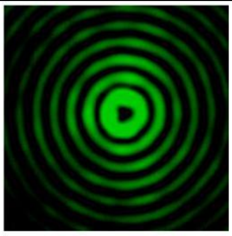
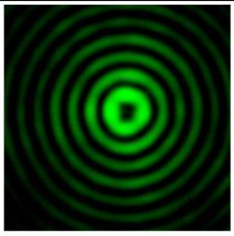
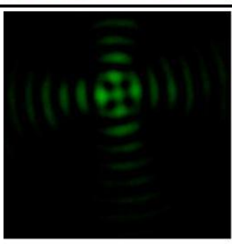
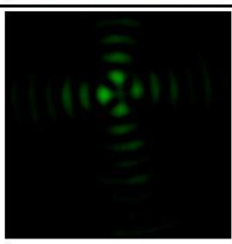
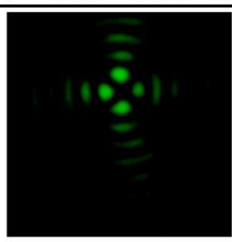
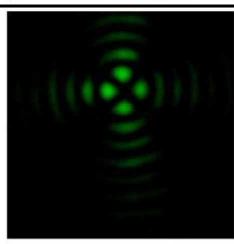
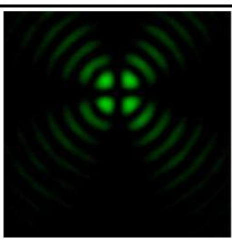
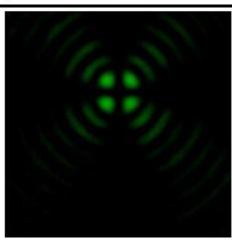
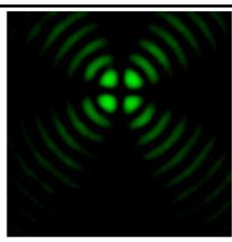
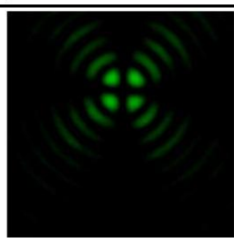
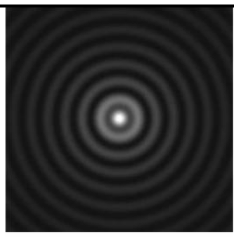
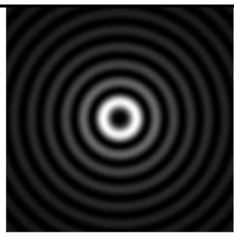
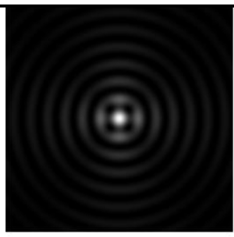
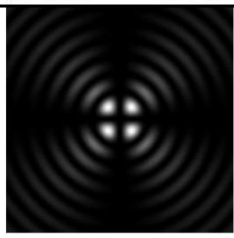
Wavelength	**520**	**522**	**524**	**526**
				
X component				
Y component				
Wavelength	**528**	**530**	**532**	**534**
				
X component				
Y component				

Table 2. Modeling distribution of intensity bessel beams transformed in birefringent crystal.

Wavelength	**520**	**532**
		
X component		
Y component		

4. Conclusion

It was experimentally demonstrated the conversion of Bessel beams of zero order, generated by the axicon with period in birefringence crystal, depending on the change of the wavelength of the laser radiation in the range of λ = 520-534 nm to the Bessel beams of the second order, which has an annular intensity distribution. Further increase of the wavelength has showed a recurrent re-transformation into a Bessel beam of zero order. Comparative analysis of experimental images of full intensity and their components with images obtained by the numerical simulation has showed their similarity.

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