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Formation of Singular and Bessel Light Beams using Electrically Controlled Liquid Crystal Diffractive Elements

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A new method for formation of singular and Bessel light beams of different orders with the use of electrically controlled liquid crystal (LC) diffractive optical elements has been proposed and experimentally implemented. Formed elements are able to change the polarization and phase structure of an initial incident plane wave due to anisotropic modulation of the refractive index inside the layer of nematic LC. The orientation of LC molecules is defined by previously illuminated photopolymeric layers on the substrates of LC cell.

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1. Introduction

Unique possibility of using LC elements for controlling light fluxes attracted attention of many research organizations and industrial firms [1–3]. This increased interest is due to the properties of LC elements (thin optical layers, low operating voltage, low cost of production). One of the most promising applications of liquid crystals is to create a controlled diffractive elements and spatially inhomogeneous anisotropic structures forming light fields with the desired properties, including the generation of optical vortices [4–8]. Using the interface between two domains with different orientations of LC director allows controlling the direction of the light beams propagation based on the effect of total internal reflection [9–12], as well as creating a waveguide structure [13, 14].

This paper describes the method for creation of diffraction LC elements, that allows forming vortex and Bessel light beams. The increased interest in such beams is due to their unusual properties: the preservation of the topological structure of propagating vortex beam, quasi-diffraction-free structure of Bessel beams, etc, which allows using them to capture microscopic objects [15], to form waveguide structures and optical signal transmission systems [16, 17], to analyze the media with phase inhomogeneities and with a high degree of chaotization [18], to investigate the microstructure of cylindrical objects [19], as well as for such unusual applications as searching and study of planets outside the solar system [20].

2. Diffractive optical elements based on liquid crystal structures

Currently, various types of controlled LC elements and methods of forming the diffraction gratings have developed. In the first papers (e.g. [21]), the optoelectronic structure on the basis of relief grating, which produced by mechanical rubbing a layer of polyvinyl alcohol to provide initial orientation of the LC director were used to control the diffraction. An alternative method is to use a special form of the electrodes, allowing to generate a spatially modulated orientation of the LC director [22]. In recent papers, for orientation of LC molecules were used photopolymers, which change their properties when illuminated by UV

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radiation [5], [23].

The polymers used in the work, were synthesized at the Department of Physical Optics of the Belarusian State University [23]. Photopolymers include benzaldehyde fragments as side groups. Photoanisotropy of such polymers is stable since it is associated with the formation of cross-links between macromolecules oriented under the influence of polarized UV radiation. As a result, in the volume of polymeric material and on its surface an optical anisotropy is induced and surface acquires properties LC orientant.

Schematic diagram of the developed LC element and the resulting diffraction pattern are shown in Fig.1. LC cell consists of two glass plates with transparent electrodes made of indium oxide. The thickness of the LC layer was 20 micrometers. A positive nematic liquid crystal VIN9 on the basis of cyanobiphenyls and Demuth esters developed at the Research Institute of Applied Physical Problems of the Belarusian State University has been used. The refractive index at the probing radiation wavelength $\lambda = 632nm$ for an extraordinary wave was $n_e = 1.67$ and for an ordinary wave it was $n_o = 1.49$.

To create a spatially structured LC cell photosensitive polymer layer with thickness of about 0.1 micrometer were applied to the surface of the electrode by centrifugation of a 2 percents solution of the polymer in ethyl acetate. The illumination of the first layer was carried out through a specially designed mask to form the diffraction structure that produces the light field with desired properties. The exposure time was chosen so that the conversion of the photosensitive component is at least 90 percents. For creation of an orientated layer on the second glass plate we used the photopolymer uniformly illuminated by radiation with polarization orthogonal with respect to the radiation, which illuminates the first layer. Thus, the orthogonal orientations of the LC director on the illuminated areas of the opposite substrates are formed, which corresponds to the formation of spatially modulated twisted structure in the volume of the LC layer. The values of the diffraction efficiency in the first order obtained with this method of forming the LC elements are close to the limit value for thin phase holograms [5].

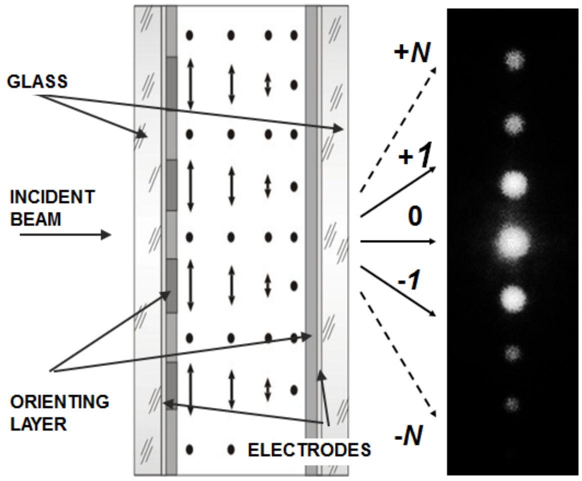

FIG. 1. Optical scheme of electrically controlled LC element.

3. Diffractive optical elements for generating vortex and Bessel light beams

To create elements that form the singular and Bessel optical beam it is necessary to create an appropriate diffractive structure of the liquid crystal, which implies a formation of corresponding anisotropy in a layer of orienting material. To solve this problem, we proposed the use of amplitude masks on quartz glass, which is used then to exposure one of orientation layers.Profile of transparency was calculated in advance and represents intensity distribution obtained by the interference of a plane wave with a vortex or Bessel optical beam. For example, to calculate the mask for the vortex beams the total intensity of the interference of the light field in the vicinity of a screw dislocation can be written as:

$$I\left(x,y\right)\sim\ A_1^2+A_2^2\left(\frac{x^2+y^2}{r_0^2}\right)^{|l|}+2A_1A_2\left(\frac{x^2+y^2}{r_0^2}\right)^{\frac{|l|}{2}}\cos\left[\frac{2\pi x}{L}-l\times arctg\left(\frac{y}{x}\right)\right] \tag{1}$$

wherein A_1, A_2 are the amplitudes of the plane wave and vortex beam respectively, r_0 is a radius of the vortex beam, L is a period of the interference pattern defined by the angle of convergence of the light beams.

To restore holographic transparencies we used a single-mode radiation of a He-Ne laser, so the resulting spatial distribution of the intensity of the interference field was calculated in the approximation of a Gaussian reference wave. Similarly, the masks for formation of Bessel-like beams of different order have been calculated. The examples of interference patterns for formation of vortex (a, b) and Bessel-like (c, d) beams are presented on Fig.2.

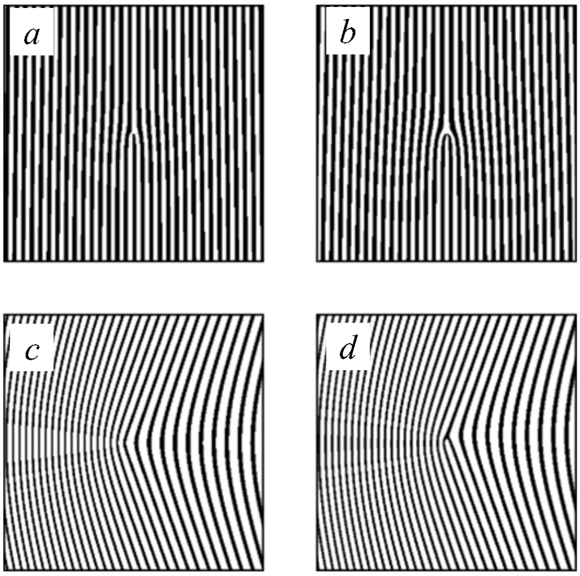

FIG. 2. Amplitude masks to form: singular light beam of first (a) and second (b) order, Bessel light beam of zeroth (c) and first (d) order.

Calculated masks were used to create diffractive elements forming Bessel and singular light beams. The diffraction efficiency was about 20 percents (Fig.3). Control of the transmission of LC optoelectronic elements have been implemented using an electric field applied to the cell that leads to reorientation of the LC molecules. An alternating electric field at a frequency of 1 kHz was applied to eliminate the effect of screening. It is seen that when applied voltage is exceed the value of $5V$ almost complete reorientation of the LC director takes place and the light beam propagates along the axis of the birefringent crystal, almost non-diffracting. In this way, one can realize the operation of "switching-off"for this diffraction element.

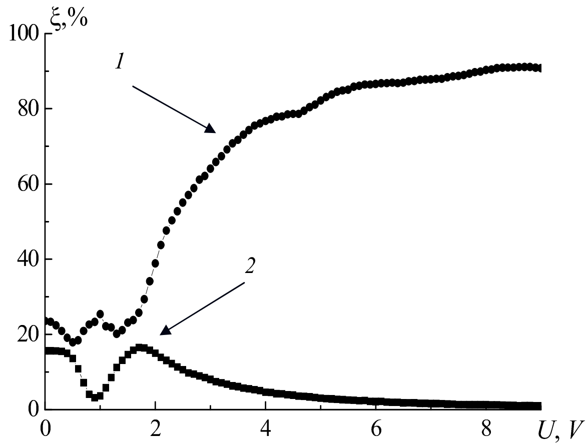

FIG. 3. Dependence of diffraction efficiency on applied voltage: 1 – zeroth order, 2 – first order.

Fig.4 shows the characteristic structure of the light fields obtained at the output of the LC element in the different orders of diffraction. The beams diffracted in the $+N$ and $-N$ diffraction orders, have an opposite sign of topological charge. The transition from the first to higher orders of diffraction leads to a multiplication of the topological charge. This is illustrated in Fig. 5, which shows the interference pattern of the diffracted beams with a plane, and a spherical wave. One can see the formation of a characteristic fork, and the number of branches determines the value of the topological charge (Fig.5a, a unit charge for the first-order diffraction). Fig.5b shows an interference pattern with a spherical reference wave. It is seen that the interference of singular beam with a spherical wave formed spiral twist direction which determines the sign of the topological charge (positive - clockwise, and negative - counterclockwise).

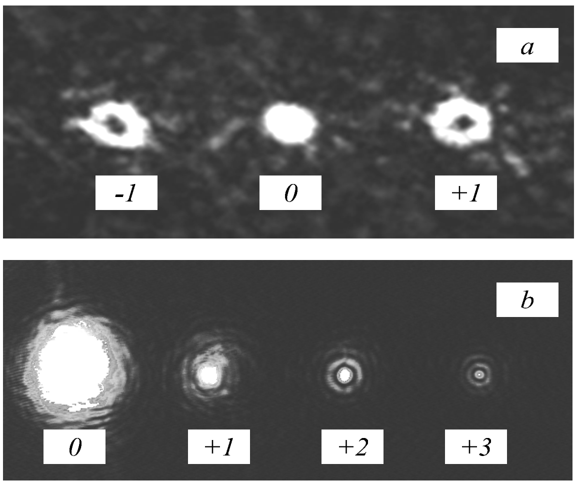

FIG. 4. Diffraction pattern and beam profile of singular (a) and Bessel (b) light beams.

4. Conclusions

Thus, in the present study we demonstrated a method of forming optical vortices and Bessel beams through an electrically controlled LC diffractive elements. The technique for creating a spatially modulated phase structures based on

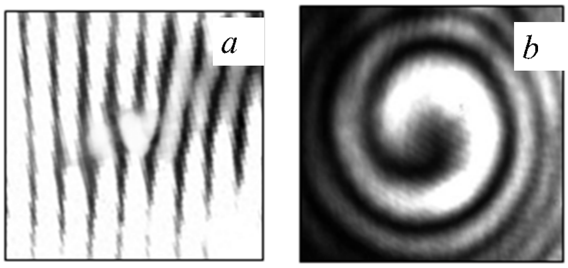

FIG. 5. Interference patterns of vortex beam with plane (a) and spherical (b) wave.

nematic liquid crystals with polymeric photo-alignment has been developed. The performance of electrical control of LC cell, which allows to create vortex and Bessel light beams with different topological charges, has been demonstrated, and the dependence of the diffraction efficiency of the applied voltage has been studied. The results can be of practical interest in development of a variety of laser-optical devices such as laser tweezers, control of phase inhomogeneities diagnostics turbulence, etc.

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