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Operation with Laser Radiation by Using of Liquid Crystal Elements

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A new method of creation the electrically controlled diffraction elements has been proposed and experimentally implemented , which is based on a nematic liquid crystal and orienting photopolymer material. These elements were developed to form singular optical beams with a given topological charge and to transform a linearly polarized light beam into a beam with radial or azimuthal polarization. Also, was investigated the propagation of laser radiation in a spatially structured layers of nematic liquid crystal with an anomalously high value of birefringence and the laws of reflection of light beams at the boundary between the two mesophases were founded. The conditions for total internal reflection, waveguide propagation and polarization separation of light beams were identified.

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1. Introduction

One of the problems in modern optics is the development of advanced inexpensive devices capable of controlling the spatial propagation direction of light beams. Such elements will be useful in fiber-optic communication lines, in designing of integrated circuits with the use of optical methods for luminous transmission and data processing, etc. The liquid-crystal (LC) media characterized by high birefringence and offering the possibility for its low-voltage (about several volts) electrical variations look promising for the creation of devices intended to control the light beams.

At the same time, the studies are in progress for the development within a media of waveguide structures using a special configuration of the propagating optical field. In particular the structures of this type are created with the help of singular light beams. Because of this, the problem of creating the controlled optical elements which make it possible to form an optical field with the desired structure receives much attention.

This paper presents the experimentally analyzed techniques to control laser radiation by the controlled LC elements. The method to form a singular light beam using the controlled diffraction optical element is studied; the schemes designed to control the propagation direction of laser beams with the use of LC elements based on the total internal reflection effect are considered.

2. Diffraction elements based on LC structures

At the present time different types of the controlled diffraction LC elements are available and various grating-formation methods are known [1-6]. In the early works the control of diffraction was realized by means of the optoelectronic structures “relief grating – liquid crystal”. The initial orientation of the LC director was specified by a mechanically rubbed layer of polyvinyl alcohol. An alternative method is the use of the special-form electrodes enabling the spatially modulated LC director orientation. In the recent works the LC orientation is specified by means of orienting photopolymers. The polymers under study in this paper which include benzaldehyde fragments as side groups and are similar in their structure reveal photosensitivity, specifically, demonstrating the photoinduced birefringence. Their photoanisotropy is stable as it is associated with the formation of the oriented cross-links between the macromolecules under the effect of polarized UV radiation. The results obtained demonstrate that, due to the effect of polarized UV radiation, anisotropy is induced both within the bulk of a polymeric material and on its surface to give this surface the properties of the LC orientant.

Figure 1 shows a schematic diagram of the designed LC element. The LC cell includes two glass plates with transparent electrodes of indium oxide. A layer of the light-sensitive polymer with a thickness of about 0.1 μm was applied to the electrode surface by centrifugation from a 2% solution of the polymer in ethyl acetate. Exposure was realized by the collimated UV radiation polarized due to Brewster reflection from a silicon plate. The first layer was illuminated through the specially-developed mask to produce the diffraction structure forming an optical field with the required properties. Exposure time was selected so that a degree of the photosensitive component transformation can be no less than 90%. To this end, the similar-thickness film applied to the quartz substrate was preliminary exposed to the same conditions and the material phototransformation process was followed by means of the electronic absorption spectra.

The orienting layer of the second plate was represented by a polymer uniformly illuminated by the radiation polarized orthogonally to the radiation illuminating the first layer. The optical cell was filled with LC within the vacuum chamber. The LC layer was 20 μm thick. Optical anisotropy of the nematic 1289 LC used was 0.17. A light beam was directed to the face of the LC cell with the orienting grating. In this case an orthogonal orientation of LC occurs for the diffraction elements on both substrates to form the twist-structure. A choice of this geometry was motivated by a considerable dependence of the diffraction efficiency on the LC structure type. With identical directions of the LC director in the

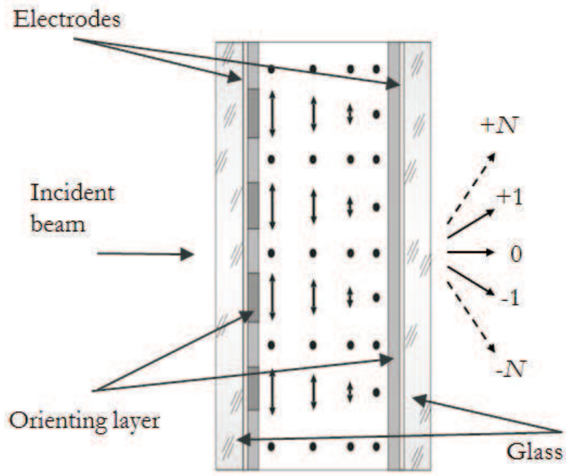

FIG. 1: Schematic diagram of LC element.

illuminated photopolymeric area at the grooves of the orienting grating and at the surface of the second substrate, intermolecular interactions result in partial orientation of the LC molecules and in the intergroove gaps. The partially oriented LC structure with a minor spatial modulation of the LC layer director is formed within the medium volume. But when the twist-structure is formed, concurrent effects of both substrates on the LC orientants lead to the formation within the medium of the spatially modulated twist-structure that is associated with a much deeper modulation of the refractive index for the LC layer.

As demonstrated in previous studies of the controlled diffraction gratings [18], with this variant of forming the diffraction LC elements the first-order diffraction efficiencies were close to the limiting value for thin phase holograms and hence the use of the T-deformation and of photopolymeric orienting layers is a preferable solution. To create the elements forming singular light beams, one should form the adequate diffraction structure of LC that is associated with induction of the corresponding anisotropy within the layer of orienting material. It is proposed to use the amplitude transparent mask on silica glass for exposure of one of the orientant layers. A profile of the transparent mask computed in advance represents the interference pattern for a coherent plane wave with a vortex optical beam.

During the experiments the holographic transparencies were reconstructed by radiation of a single-mode helium-neon (He-Ne) laser. Because of this, the final spatial intensity distribution of the interference field has been computed in the approximation of a Gaussian reference wave.

The developed computational program has made it possible, based on the graphical files and with the use of the adequate equipment, to produce the required amplitude transparent masks with the characteristic "pitchfork", the number of the teeth of which determines the topological charge value. The diffraction efficiency of these elements is below 10% indicating the necessity to create more effective structures on the basis of LC and photopolymers.

The control of photoelectronic LC elements was realized with the use of an electric field applied to the cell and leading to reorientation of the molecules in LC. To exclude the screening effect, the variable electric field was applied at a frequency of 1 kHz.

As demonstrated by analysis of the diffraction efficiency depending on the voltage applied, which is shown on Figure 2 where 1 is for the zero-order and 2 is for first-order of diffraction, for the element representing the phase LC structure forming a singular beam there is an optimum voltage of 1.7 V and in this case the diffraction efficiency is close to 20%.

A value of the diffraction efficiency was not maximal, being conditioned by the manufacturing method and quality of the initial amplitude transparent mask – with the use of a pulsed laser to burn nickel on the substrate. As expected, using of photolithographic methods offers the possibilities for better quality of the transparencies and hence of the formed diffraction structures to provide increase in the efficiency to a level approaching the limiting level for thin phase holograms (30%), and also to offer higher diffraction orders, similar to those considered in the early works.

At voltages above 5 V, the LC director

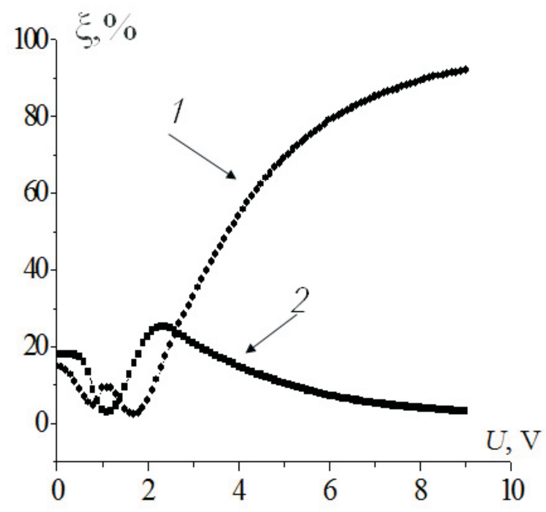

FIG. 2: Graph of diffraction efficiency dependence.

is almost completely reoriented (LC molecules are positioned orthogonally with respect to the electrodes) and the light beam is propagating along the axis of a birefringent crystal, practically without diffraction.

To explain the polarization state of diffracted waves with the use of even and odd diffraction orders at a thin diffraction grating, we consider a model for an anisotropic transparency. This model is a diffraction grating with the nodes containing microphase anisotropic plates permitting rotation of the polarization plane. In this way we can demonstrate the method to form vortex optical beams with the use of LC diffraction elements. In the process of work different modulation procedures for the refractive index of LC have been analyzed; the technique for the formation of the electrically-controlled spatially modulated phase structures on the basis of a nematic liquid crystal and with the use of an orienting photopolymer have been developed; analysis of the diffraction efficiency as a function of the applied voltage has been performed. Operation of the electric-control scheme for a LC cell has been demonstrated with the simultaneous formation of singular beams having different topological charges that offers much promise for the development of various laser and optical devices.

The other method of forming the waveguide structures is based on the phenomenon of total internal reflection.

The interface of two LV volumes differing in the director orientation direction is created within a LC cell. The propagation of laser radiation is controlled by means of an external electric field applied to the liquid-crystal cell.

3. Control of laser radiation by LC waveguides

This paper presents the specially developed and experimentally realized technique to create the interface of two different topologies for the nematic LC director orientation that is based on etching of the electrode from the LC cell substrate surface and on forming of the interface with the use of an external electric field. To realize the effect of total internal reflection, it is required to create within the LC cell two regions with the refractive indices corresponding to ordinary and extraordinary waves. The experimental positive birefringent nematic liquid crystal was characterized by the refractive indices: $n_o = 1,49$ for ordinary wave and $n_e = 1,67$ for extraordinary wave. For a maximal difference between the refractive indices in LC, the total internal reflection angle was $\theta_c \approx 63°$ to conform to the entrance angle of radiation into the cell that is equal to $27\,^\circ$.

Figure 3 presents a scheme of the developed LC cell. On glass substrates – e the electrically conductive layer – d is sputtered to provide for the voltage application to the substrate. If a transparent electrode is required, one can use the substrates with a layer of ITO, representing the conductive layer of indium (III) (In_2O_3) and tin oxide (IV) (SnO_2), deposited on glass. In some of the experiments aluminum was deposited instead. The orienting material – special polymer (layer c) – was applied to the substrate with a conductor. The orientation was specified with the use of the polymer rubbing process or by the polarized light effect (photoalignment), both methods have been tried in the process of work. A thickness of the cell and hence of the LC layer (a) was varied from 2–5 to 200–300 μm, by using of spacers (d), depending on the experimental objectives.

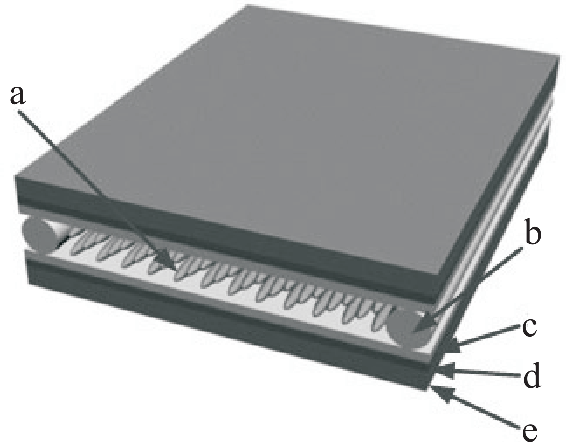

FIG. 3: Schematic of a liquid-crystal cell.

Figure 4 shows the experimental setup. The radiation source is a He-Ne laser operating at the wavelength 633 nm. Rotation of the polarization plane of the output beam was performed with the help of $\lambda/2$ plate. For the effective radiation input, the selected lens had the focusing length 5 cm, optimal in this case. The light propagation within the LC layer was recorded by the CCD camera positioned above the cell. The experimental LC cells had a thickness of 135 μm in order that the radiation input into the cell be complete and that within the LC cell the scattered radiation be observed, and this is possible for thick cell only. All the experiments have been conducted at the laser power 200 μW.

4. Textured LC orientation

First, to obtain the textured orientation of LC within the cell, the electrode was partially etched on the surface of one of the substartes

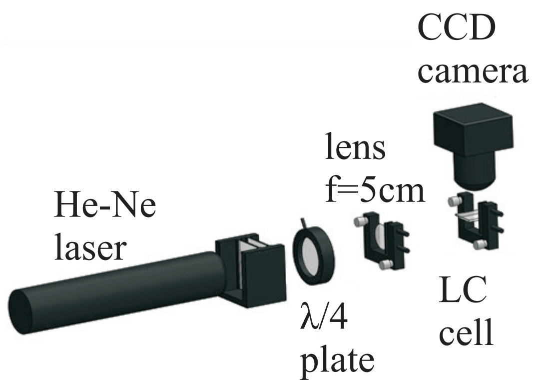

FIG. 4: Schematic of experimental setup.

as reffered ot Figure 5. The curves for reflection from the LC boundary depending on the heigh of radition input into the cell (by system tuning) and on the applied voltage have been constructed.

To obtaine the refractive index interface, the electrode was etched from a half of the lower sunstarte. With the voltage applied, under the effect of an external electric field, LC was aligned homeotropically in the region between the electrodes and the refractive index gradient was formed within the cell. Aluminum was used as a conductive material inducing the textured orientation. The electrode was etched by the lift-off lithography method when a positive photoresist was applied to the glass surface and subjected to the effect of UV radiation through the mask with subsequent etching. Aluminum was sputtered over the obtained sample, whereas the remaining photoresist was etched together with the above-sputtered electrode. By this method the conducting layer was retained only at the place without the photoresist. Using this technique, the authors have obtained the textured electrode on the lower substrate of the LC cell. Because of the necessity to observe the scattered radiation within the crystal, the conducting layer on the upper substrate was a film of transparent ITO.

The initial orientation of LC in the developed cell was specified by the standard procedure – by rubbing of a special polymer. Figure 6 demonstrates the operation principle of the interface. Without the external electric field, LC was oriented planar over the whole cell, along the refractive index interface, both components of the polarized light propagating rectilinearly. This case is shown on Figure 5a. With the applied voltage, the electric field was formed only in the region between the electrodes, where LC was oriented hoemotropically. When light was introduced from the side with the homeotropic orientation of LC, for the vertical light polarization component an extraordinary wave was excited, whereas in the region of the planar orientation an ordinary wave was excited. In this way at certain incidence angles of light one can obtain the effect of total internal reflection. The horizontal light polarization component in this case has a rectilinear propagation as it is associated with excitation of an ordinary wave in both regions of the LC orientation. By this technique of creating the controlled LC interface the state of switching-on is realized when an external electric field is applied to the cell.

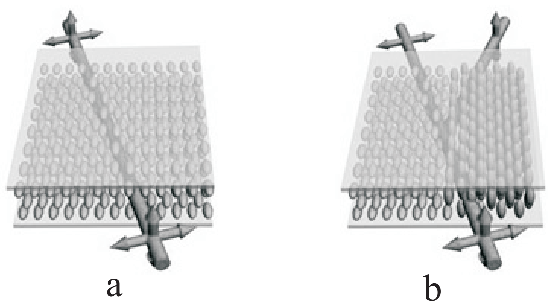

FIG. 5. The principle of light reflection from the LC interface based on the textured electrode.

Since the interface reflects the vertical polarization component of laser radiation, on polarization rotation at the entrance to the cell the common logarithm of the intensity ratio $\frac{I_r}{I_t}$ for the reflected and for transmitted beams must represent nothing else but the squared tangent of the tilt angle α of polarization at the cell entrance, and we have that

$$\lg \frac{I_r}{I_t} = \tan^2 \alpha.$$

The curve is given in Figure 6. In the case of the total internal reflection of light from the interface or total light transmission the intensity ratios tend to $+\infty$ and $-\infty$, respectively. In the real experimental conditions the polarization angle, for which a maximum of this function is observed, conforms to the best reflection from the LC interface.

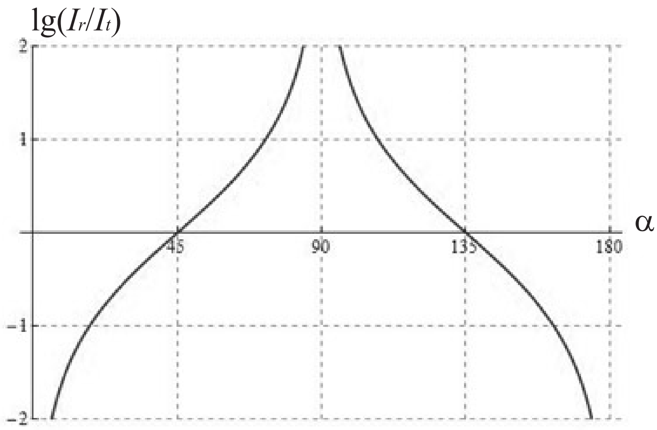

FIG. 6. Theoretically predicted relationship between reflection and light polarization at the cell entrance.

Based on the experimental dependencies, the curve for the common logarithm of the intensity ratio for the reflected and transmitted beams was constructed as shown in Figure 7. Points of the curve comply with the experimental data. As seen, the best reflection is observed not for the vertical polarization at the cell entrance but in the case when the polarization plane is rotated by an angle of 20° with the cell. This effect is due to the influence of a meniscus on the beam incoming to the cell as the LC molecules at the interface "air – liquid crystal" are affected not only by the intermolecular interaction forces and by the electric field applied to the cell but also by the surface tension forces. So, at the cell entrance the twist structure is formed that rotates the light polarization vector.

To verify the assumption concerning the radiation polarization-plane rotation on the entrance to the LC cell, a cell has been manufactured with a sticked glass plate at the (radiation introduction) end of the cell. The plate was covered by the orienting layer,

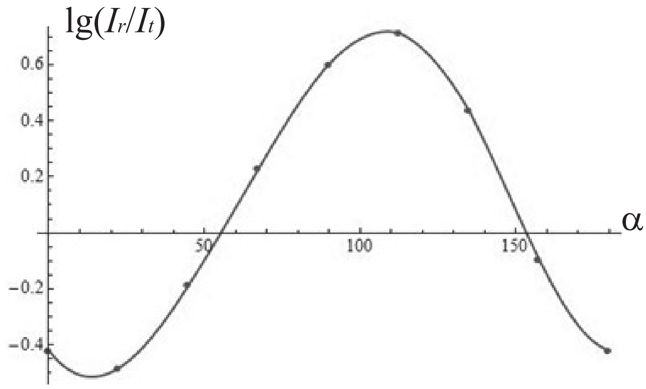

FIG. 7. Reflection from the interface depending on the polarization of laser radiation.

rubbed preliminary in accordance with the homeotropic alignment of LC within the cell. It was found, that input of radiation through the glass plate eliminates the effect associated with the polarization plane rotation of laser radiation. As expected, the total internal relection effect was obsrved at the angle 90°, corresponding to the vertical radiation polarization in the scheme shown in Figure 5, b. In the case of horizontal polarization at the angle 0° or 180° the propagation of light within the cell is practically without reflection.

5. Conclusion

Thus, in the process of work the authors have studied experimentally and optimized the conditions for the creation of the controlled liquid-crystal elements enabling the effective control of laser radiation by variations in its spatial, polarization, and phase structure according to the experimental targets. The control of such elements with the use of the external electric field has been realized experimentally. The optimum modes for operation of the controlled diffraction elements in the available optical schemes have been established. Besides, the encouraging results have been obtained in the development of waveguide structures in a nematic LC layer

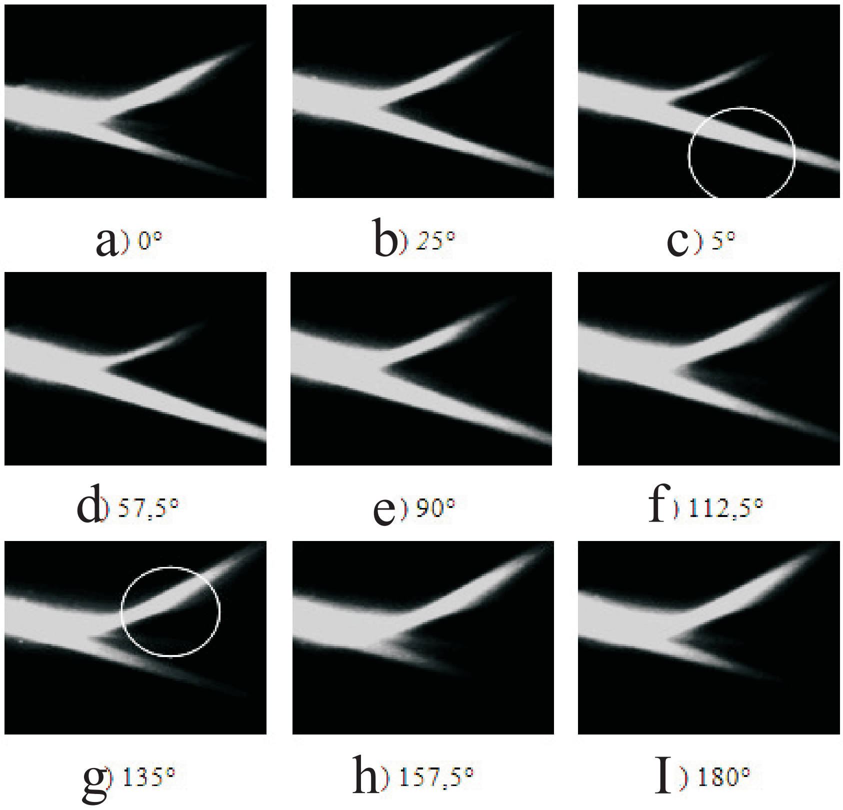

FIG. 8. Photographs of the laser beam input into LC cell through the end glass plate for different polarizations of laser radiation.

which offer the possibility for the maximum light-beam reflection effect from the interface of two LC volumes differing in orientations of the director. Of particular interest was the experimental realization of switching the laser beam propagation direction by means of the director reorientation under the effect of the applied electric field.

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