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Optical switch based on the electrically controlled liquid crystal interface

ANDREI A. KOMAR,[1,*] ALEXEI L. TOLSTIK,[1] ELENA A. MELNIKOVA,[1] AND ALEXANDER A. MURAVSKY[2]

[1]Physics Department, Belarusian State University, Nezavisimosti avenue 4, 220030 Minsk, Belarus
[2]Institute of Chemistry of New Materials, National Academy of Sciences, Fr. Skaryna Street 36, 220141 Minsk, Belarus
*Corresponding author: komar.andrei@gmail.com

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The peculiarities of the linearly polarized light beam reflection at the interface within the bulk of a nematic liquid crystal (NLC) cell with different orientations of the director are analyzed. Two methods to create the interface are considered. Combination of the planar and homeotropic orientations of the NLC director is realized by means of a spatially structured electrode under the applied voltage. In-plane patterned azimuthal alignment of the NLC director is created by the patterned rubbing alignment technique. All possible orthogonal orientations of the LC director are considered; the configurations for realization of total internal reflection are determined. The revealed relationship between the propagation of optical beams in a liquid crystal material and polarization of laser radiation has enabled realization of the spatial separation for the orthogonally polarized light beams at the interface between two regions of NLC with different director orientations (domains). Owing to variations in the applied voltage and, hence, in the refractive index gradient, the light beam propagation directions may be controlled electrically.

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1. INTRODUCTION

Extensive use of optical methods to transmit and control information bytes facilitates the development of compact optoelectronic switches for optical signals [1–3]. Nematic liquid crystals (NLC) featuring high anisotropy of the refractive index (~0.1 – 0.25) and offering the possibility for its variation under the effect of external electric fields look most promising as electro-optical materials. In a standard scheme using a planar cell, comprising two glass substrates and a LC layer between them, light beams are directed perpendicular to the substrates. With such a scheme, transmission of the LC cell is, as a rule, electrically controlled. New possibilities are associated with diffraction of radiation from the spatially modulated LC structures [4–7] and also with the use of LC cells for the transformation of linearly polarized light beams into beams with radial or azimuthal polarizations and for the generation of optical vortices [8].

In the last few years, another optical geometry when laser radiation is propagating within an LC layer along the glass substrates has become widespread. It is shown that the milliwatt power of laser radiation is sufficient for observation of the self-focusing effects and formation of the soliton-type propagation of light beams due to reorientation of the NLC director under an electromagnetic field of an optical wave [9–11]. Such soliton beams form waveguide channels, where (similar to the ordinary waveguides), the modes of different orders can exist [12]. The schemes offering the creation of interfaces between two LC modes differing in orientations of the director are of particular interest. At the interface of two director orientational domains, one can realize reflection, refraction, and polarizational separation of light beams [13–16]; with the use of several interfaces, the waveguided propagation of laser radiation can be attained [17–19].

This work presents analysis of the reflection features for the linearly polarized light beams at the interface of two regions of NLC with different combinations of the director orientations. Two methods to create the interface between such orientational domains are considered: (1) with the spatially structured electrode used for the generation of two regions having the orthogonal (planar and homeotropic) director orientation; (2) with a special patterned alignment technique used to create an orthogonal (planar) orientation of the director in two regions of NLC in the cell plane.

2. LC CELL WITH INTERFACE BETWEEN TWO ORIENTATIONAL DOMAINS

An experimental setup is shown in Fig. 1. Radiation of a He–Ne laser was injected into the cell by means of a lens, enabling the formation of the light beam 50 μm in diameter. The light

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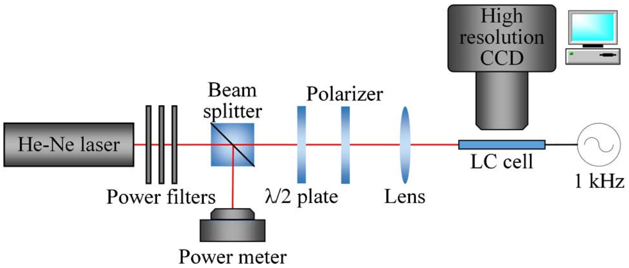

Fig. 1. Experimental setup.

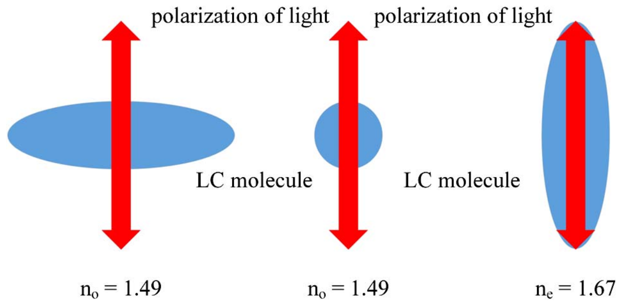

Fig. 2. Possible orientations of the NLC molecule and light polarizations.

beam power was 100 μW; the beam divergence after focusing was about 100 mrad. AC voltage with a frequency of 1 kHz was applied to the cell. The light beam propagation within the LC cell was recorded by a high-resolution CCD camera. The cell includes two glass substrates with the deposited layer of a transparent electrode (usually ITO) and a planar alignment layer specifying the initial NLC director orientation. Thickness of the cell is determined by the spacers and is about 200 μm. A great thickness of the LC cell was selected to ease the light beam input and to demonstrate the total internal reflection effect for different combinations of the LC director orientations. Within the cell, the interface between two LC regions with the orthogonal director orientations has been created. To this end, we have used the spatially structured electrodes on which the voltage was impressed or a special photopolymeric alignment material exposed to orthogonally polarized radiation. In the process, the light beam is directed within LC along the substrates and at an angle to the interface between the two regions rather than perpendicular to the substrates. In this way, one can realize the light beam interactions with the interface between two domains having the orthogonal director orientations.

It is known that the elongated NLC molecules are schematically represented as an ellipsoid of refractive indices of the optically uniaxial crystal determining the optical axis orientation that, for a positive nematic liquid crystal ($n_e > n_o$), is coincident with the director orientation. There are two limiting cases for the interaction between the linearly polarized light and the oriented NLC layer: with the light polarization vector (1) parallel and (2) perpendicular to the LC director when an extraordinary or an ordinary wave is excited, respectively.

We have used 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. The refractive index at the probing radiation wavelength 632 nm for an extraordinary wave was $n_e = 1.67$ and, for an ordinary wave, it was $n_o = 1.49$.

In the general case, molecules may be oriented at any angle with respect to the light polarization. However, to attain a maximal effect, we consider the limiting cases of the mutually orthogonal orientations. As seen in Fig. 2, three limiting combinations of the LC director orientation with respect to the light polarization vector are possible. In the first two cases, we consider propagation of an ordinary wave and, in the third case, of an extraordinary wave.

For the nematic liquid crystal used during the experiments, the total reflection angle is calculated by Snell law as follows:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2, \quad (1)$$

where $n_{1,2}$ are the effective refractive indices and $\theta_{1,2}$ are the corresponding angles with the normal to the interface.

From Eq. (1), we can find that, in the limiting case when $n_1 = n_e = 1.67$ and $n_2 = n_o = 1.49$, the total internal reflection ($\theta_2 = 90°$) is observed for the incidence angle exceeding $\theta_1 = 63°$ As a consequence, a maximal angle for the radiation input relative to the interface between two regions associated with the total internal reflection effect is equal to 27°.

As three limiting orientations of the NLC director relative to the incident radiation polarization vector are possible, in the general case we have nine combinations of the mutual NLC director orientations. Figure 3 gives possible geometry of the LC director orientations; peculiarities in propagation of the linearly polarized light are analyzed depending on the polarization state. As seen in Fig. 3, three cases should be considered:

(a) when the refractive index values in both regions of an LC cell are identical and the light propagation is rectilinear;

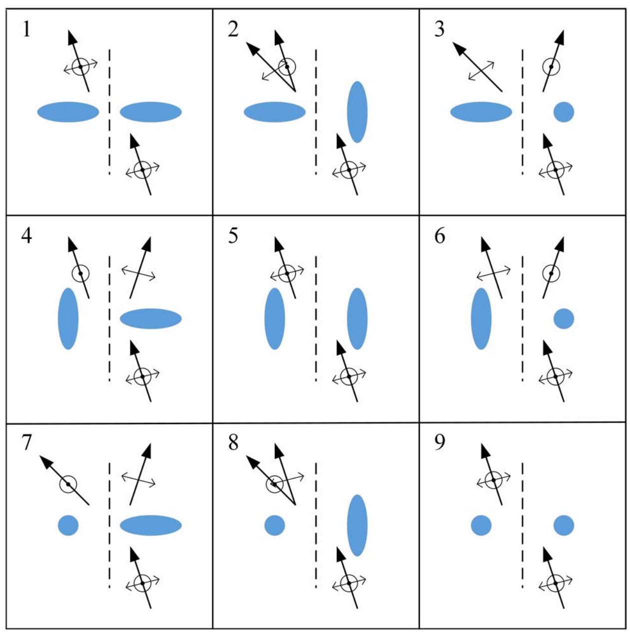

Fig. 3. Variants of the NLC director orientations in two regions of the cell; schemes describing the propagation of the orthogonally polarized light beams.

(b) when a light wave goes from the region with a higher refractive index to that with the lower one and the total internal reflection effect is possible;
(c) when a light wave goes from the optically less dense medium to that with a greater density and the optical refraction effect is observed.

Variants 1, 5, and 9 are associated with a homogeneous orientation of the LC director over the whole volume of the cell when there is no interface and the propagation of light is linear for both polarizations. For variants 2 and 8, the birefringence effect is realized when a wave with one polarization is propagating linearly and, with the other polarization, is subjected to refraction. At the incidence angle 63°, an angle of refraction is equal to 53° in accordance with the propagation direction changed by 10°. Variants 3 and 6, when the total internal reflection is experienced by the vertical component of light polarization, and variants 4 and 7, when the total internal reflection is realized for a horizontal polarization, are of the greatest interest.

To realize the NLC director orientation, as shown in Fig. 3, the interface between the domains was formed by two methods. The planar spatially structured director orientation was created using a special patterned rubbing technology. A homeotropic orientation arises as an external electric field is applied, and the director orientations may be continuously controlled due to changes in the field strength. Variants 3, 6, 7, and 8 in Fig. 3 are associated with the case of two regions having the orthogonal (planar and homeotropic) director orientations. Variants 2 and 4 correspond to the orthogonal director orientations in the two cell regions with the planar oriented nematic liquid crystal.

3. PARTIAL ELECTRODE ETCHING METHOD

Let us consider a method to create within the cell two regions with orthogonal (planar and homeotropic) orientations of the NLC director. The interface of two domains is obtained by forming on one of the substrates the patterned electrode occupying only a certain area of the substrate, as shown in Fig. 4. With the applied voltage to the electrodes, LC molecules are homeotropically oriented under the effect of an external electric field. As a result, the interface is formed. In the region, where one of the electrodes is lacking, the LC orientation remains planar, whereas between the electrodes the NLC director orientation is homeotropic.

The structured electrode was produced using aluminum as a current-conducting material. The electrode was formed by the lift-off lithography method. A positive photoresist layer was preliminary coated on the glass surface and illuminated by UV radiation through a mask. The nonilluminated photoresist was removed in the process of development. This procedure results in the formation of two regions on the glass substrate: with photoresist and without photoresist. Next, aluminum was sputtered on top of the sample. Then, the remaining photoresist was etched together with the above sputtered aluminum. And, at the places without the photoresist, aluminum was retained at the substrate surface. This method is used to form the patterned electrode occupying only a part of one of the substrates in the LC cell. A transparent ITO electrode on top of the second substrate allows one to observe the light beam propagation within the LC cell. Figure 5 presents a photograph of the cell produced by this method.

The initial uniform planar orientation of NLC in the cell was provided in a standard way by rubbing of a special alignment polymer applied above the electrodes. Without an external electric field, LC has a planar orientation over the whole cell volume, as shown in Fig. 3, variant 5. An electric field, AC voltage 5 V AC 1 kHz, leads to a homeotropic orientation of LC between the electrodes (variant 6). When light is input from the side of a homeotropic orientation of LC, for the vertical light-polarization component an extraordinary wave is excited, whereas, in the region with planar orientation, an ordinary wave is excited.

Figure 6 presents photographs of the light beam propagating within an LC cell at different voltages. The interface between homeotropic and planar orientations of the LC director is given by a thin horizontal line. It is seen that, without the applied voltage, the light propagation is rectilinear, whereas the reflected light beam is observed even at a voltage of 5 V. Intensity of the reflected beam increases with the voltage, running into saturation at voltages on the order of 30 V. It should be noted that the voltage increase leads to shifting of the reflecting interface and to widening of the reoriented LC crystal region involved in the reflection process. Such a situation is associated with a structure of the cell having one of the substrates with a continuous electrode (Fig. 4). As the applied voltage is increased, a threshold value of the voltage required for molecular reorientation is attained in the increasingly growing LC region neighboring

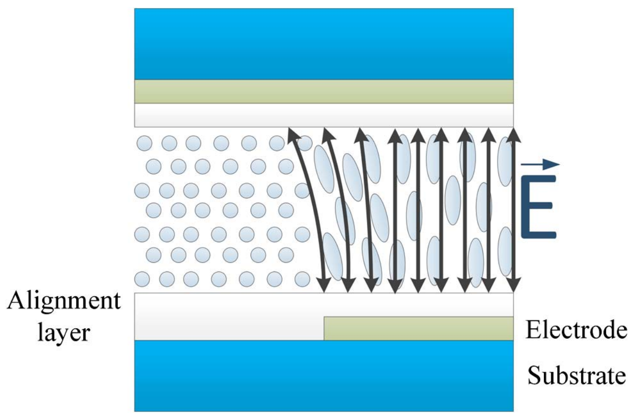

Fig. 4. Schematic of the cell with a partially etched electrode.

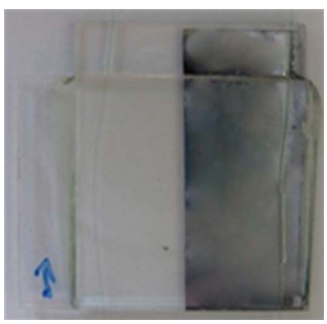

Fig. 5. Photograph of the cell with a partially etched electrode.

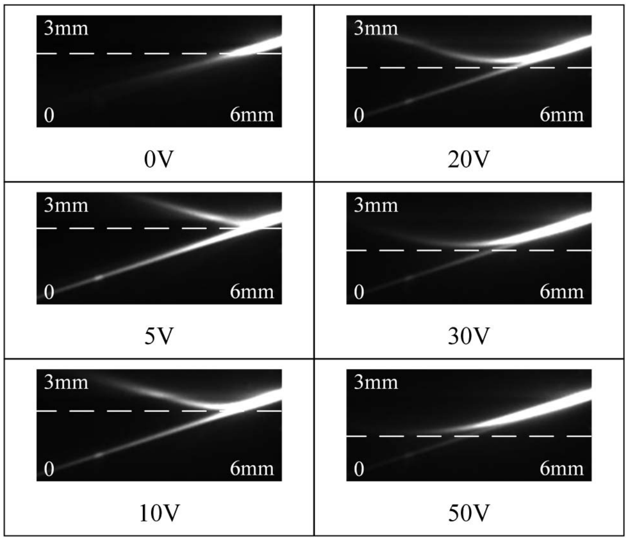

Fig. 6. Photographs of the transmitted and reflected light beams within an LC cell with a partially etched electrode for the vertically polarized light beam at the voltages: 0, 5, 10, 20, 30, and 50 V.

the interface. The interface is shifted by several micrometers (comparable with the cell thickness). Widening of the region near the interface, in turn, results in delocalization of the reflection process. As shown in Fig. 6, reflection at 5 V is realized in a local region (comparable with the light beam size), whereas at higher voltages (20, 30, and 50 V) the beam path is smoothly curved over a fairly wide region neighboring the interface and coming to several hundreds of micrometers. A penetration depth of radiation into the LC cell is about 5 mm, being determined by light scattering (hence, we can observe the light beam) and, to a greater extent, by the LC cell production technology or by the ordering degree of LC molecules.

Note that the effect of reflection from the interface between two mesophases associated with reorientation of the LC director was observed even at low voltages (~10 V), despite a great thickness of the cell (200 μm). This is due to the fact that the Fredericks transition becomes apparent at the center of the cell at the external voltages in excess of the threshold value. The threshold voltage is independent of the cell thickness, being determined by the well-known formula [20]:

$$U_t = \pi(4\pi K_{11}/\Delta\varepsilon)^{\frac{1}{2}}, \tag{2}$$

where $\Delta\varepsilon$ (anisotropy of the LC permittivity) is the elastic modulus for the S effect. For a nematic liquid crystal (NLC), the threshold voltage comes to 1–2 V. In this case, the LC molecular reorientation occurs at the cell center, whereas, close to the substrates, the molecules are strongly bonded to the surface and the LC orientation is nearly planar. A size of the LC region exhibiting the Fredericks transition is dependent on the LC layer thickness and on the voltage applied. A size of the LC region, where the molecular orientation is close to homeotropic ($\theta \approx \pi/2$), was estimated using the approximate function of the NLC director rotation angle on the applied field [21]:

$$\theta(z) = 2\mathrm{arctg}(\exp(\pi E z/U_t)) - \pi/2. \tag{3}$$

As demonstrated by the computations, for the LC layer 200 μm thick and for the twice exceeded threshold, the homeotropically oriented LC region has a thickness of 40 μm. When the threshold voltage is exceeded thrice, the rotation angle $\theta \approx \pi/2$ is attained in the LC layer 80 μm thick, and, when the threshold is exceeded by a factor of five, thickness of the reoriented layer is 140 μm. This feature has been taken into consideration when a laser beam was coupled into the LC cell 50 μm in diameter.

In this way, for particular incidence angles on the interface, between two domains, one can realize the total internal reflection effect for the vertical light beam polarization. As this takes place, the horizontally polarized radiation is propagating rectilinear because an ordinary wave is excited in both domains of the cell.

This is illustrated by Fig. 7, which shows photographs of the light beam propagation within an LC cell for different polarizations of laser radiation at the cell entrance (an angle of 0° is associated with a horizontal polarization and an angle of 90° with vertical polarization). As previously noted, the interface of two LC regions with orthogonal orientations of the director

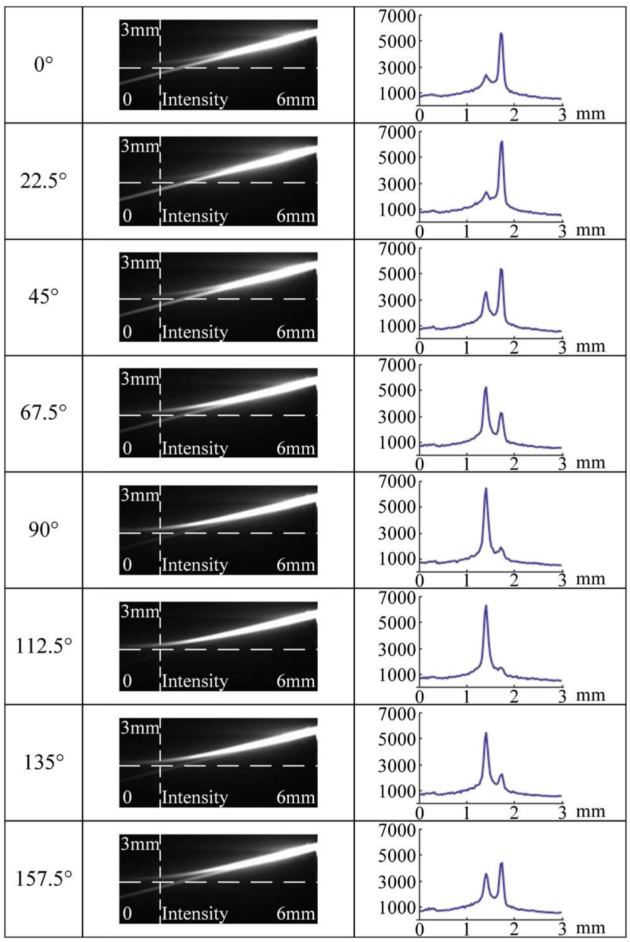

Fig. 7. Photographs of the transmitted and reflected light beams and also spatial intensity distributions over their cross sections within an LC cell with a partially etched electrode for different laser radiation polarizations at the voltage 50 V.

is given by a thin horizontal line. The right-hand side of the figure presents the spatial intensity distribution over the section depicted in Fig. 7 by a dashed line. Based on the data given, we estimate a degree of the laser radiation redistribution between the reflected and transmitted beams. As expected, in the case of a horizontal polarization (an angle of 0°), the main part of radiation is transmitted through the interface between the two domains, whereas, for a vertical polarization (an angle of 90°), one can observe redistribution of the power into the reflected beam.

4. METHOD USED TO OBTAIN THE PATTERNED PLANAR ORIENTATION OF NLC

To realize variants 2 and 4 in Fig. 3, it is required to create the planar mutually orthogonal orientations of the LC director. This is realized using the special patterned rubbing alignment technology to create the planar LC orientational domains shown in Fig. 8 [22]. The experimental substrates have transparent electrodes whose surface is coated with a photosensitive alignment polymer. The alignment layer is rubbed in the required direction and exposed to nonpolarized UV light. Next, the second layer of the photopolymer is deposited, rubbed in the orthogonal direction, and illuminated by nonpolarized UV radiation through a photomask. Then the surface is wet processed to remove the material from the nonilluminated areas.

Figure 9 shows a photograph of the experimental cell in crossed polarizers. The observed bright line is associated with the intermediate region at the interface of two domains, where the twist structure is formed.

Variant 4 in Fig. 3 is used to separate the polarization components of laser radiation. In this case, we expect that the vertically polarized radiation is transmitted through the interface between the two domains and the horizontally polarized radiation is reflected from the interface. Photographs of the light beam propagation in an LC cell for different polarizations of laser radiation at the cell entrance are demonstrated in Fig. 10. A thin horizontal line represents the interface between two LC regions with orthogonal orientations of the director. On the right-hand side, the spatial intensity distributions over the beam cross section may be observed. As seen, just the

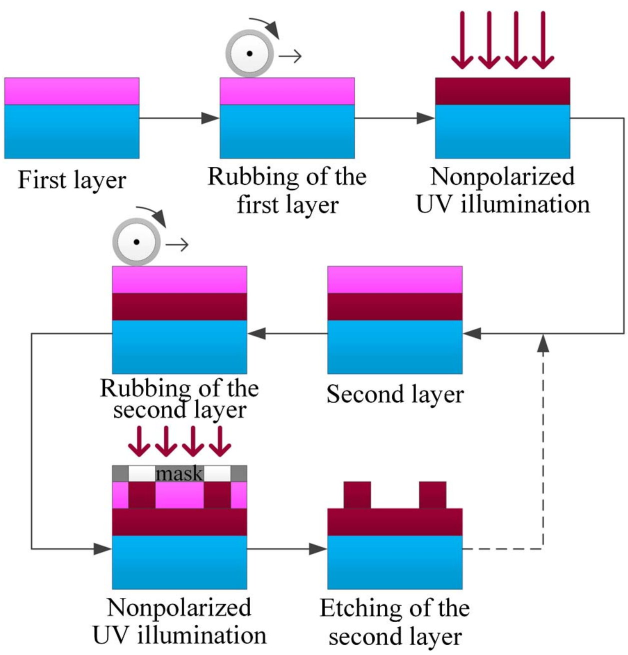

Fig. 8. Technology used to obtain the textured planar orientation of LC.

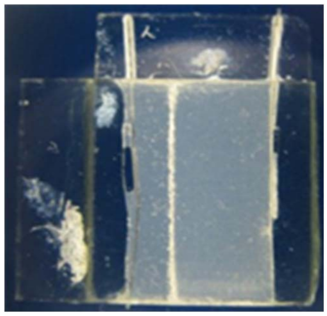

Fig. 9. Photograph of the cell with the orthogonal planar director orientation in crossed polarizers.

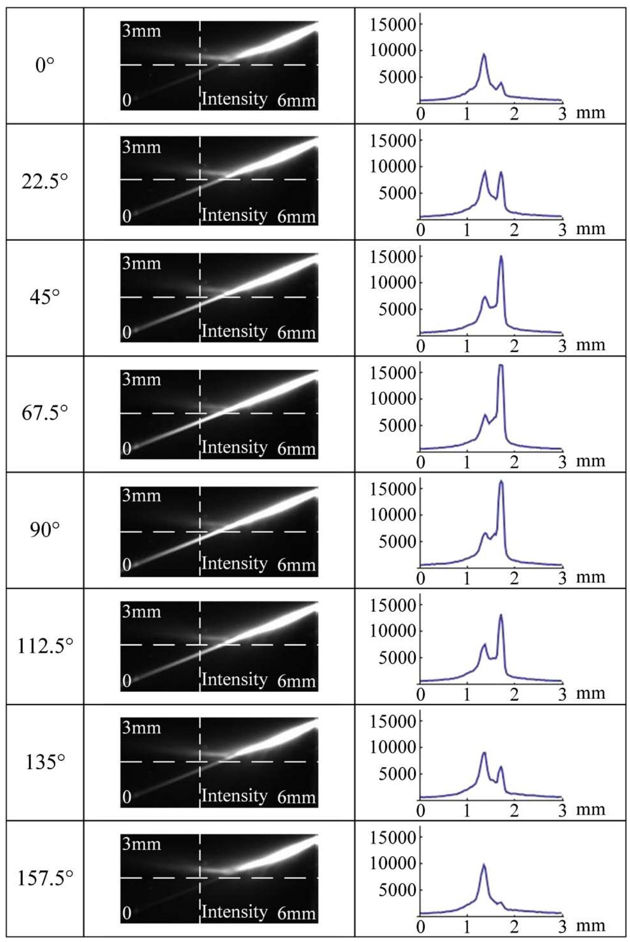

Fig. 10. Photographs of the light beams and spatial intensity distributions over their cross sections in a cell with the orthogonal planar LC director orientation for different polarizations of laser radiation.

horizontally polarized radiation (an angle of 0°) is subjected to reflection from the interface, as the corresponding extraordinary wave is excited exactly in that direction when radiation is input into the cell, whereas the vertically polarized radiation (an angle of 90°) is propagating rectilinear.

Note that, as distinct from the previous method using a partial etching of the electrode, for realization of the orthogonal planar NLC director orientation by the proposed method no electric field is required to form the interface between two domains. At the same time, application of an external electric field leads to the director reorientation and to the formation of homeotropic mode of NLC, too. In this case, the interface between two domains and, hence, the refractive index gradient disappears; thus, radiation with both orthogonal polarizations will be propagating rectilinear within the LC cell.

5. CONCLUSION

The propagation features of light beams within planar spatially structured LC cells containing the interface between two domains with the orthogonal director orientations are presented. All possible orthogonal orientations of the LC director are considered, and the configurations for realization of the total internal reflection effect are determined. It is demonstrated that, in the cases studied, a light beam with an arbitrary polarization is split into two beams representing an ordinary and extraordinary wave.

The created experimental samples of LC elements (polarization switches) demonstrate the possibility for polarization separation of the light beams. It is shown that the introduction of two principally different technologies used to create the interface between two domains with the orthogonal director orientations enables reflection of horizontal and vertical polarizations. It should be noted that the relationship between the NLC refractive index and the applied voltage makes it possible to realize the electric control over light beams. When using the partial electrode etching method, an external electric field is required to switch the LC interface. On the contrary, in the case of the orthogonal planar LC director orientation, the interface exists without such a field; application of voltage results in smoothing of the refractive index gradient. Combining different topologies of LC orientation, one can develop the controlled optical spatial and polarization switches for optical signals over the whole visible spectral range at any polarization. Such combination offers the creation of new liquid-crystal photonic devices, which comprise active and passive refractive interfaces, to guide light and to control the light propagation direction by means of refraction and total internal reflection at the gradient refractive index interfaces, low-voltage switchable.

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