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Local restoration of molecule orientation in a nematic liquid crystal in the microcontact–plane electrode system

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It has been experimentally shown that, in the vicinity of an electrical contact through a micropore in a dielectric film with a flat electrode (microcontact) to a layer of planar-oriented nematic liquid crystal with positive anisotropy of permittivity, the optical response in the case of applying an alternating voltage with a constant bias does not match the classical reorientation of molecules in the Fredericksz effect. Restoration of the planar molecule orientation and relevant phase retardation increase in the direction radial to the microcontact may be caused by the electric field decrease due to the influence of the bulk electric charge accumulated as a result of injection from the microcontact.

Keywords: Fredericksz effect, ion injection, phase retardation, wavefront.

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Liquid crystals (LC) are widely used in devices for displaying and processing optical information because they possess such a property as electrically controlled birefringence. However, the problem of changing the light wavefront direction by controlling phase retardation between ordinary and extraordinary rays in LC devices remains relevant since capabilities of the known methods for creating a continuous spatial phase retardation profile have a number of disadvantages. Thus, spatial light modulators fabricated according to the LCOS technology [1] are hardly suitable for creating simple, miniature and low-cost optical LC elements with minimal external control, while special methods for processing LC surfaces or bulk [2–4], which rigidly fix the reoriented LC molecules, almost fully exclude employing such LC devices under changing conditions.

The goal of this work was to study the electro-optical response in the vicinity of a planar-oriented LC microcontact in a cell whose flat electrodes are fed with constant-bias AC voltage, and to establish the possibility of the light wavefront spatial modulation in the LC layer plane near the microcontact by using phase retardation.

The experiments were performed using LC cells whose structure is shown schematically in Fig. 1: the lower substrate is a single-crystal *n* silicon wafer with the resistivity of $4.5\,\Omega\cdot$cm, which has been passivated by a thermally grown silicon oxide film about $0.4\,\mu$m thick; the upper one is a glass plate with an electrically conductive film of indium-tin oxide (ITO). Planar orientation of the nematic LC 4-n-pentyl-4'-cyanobiphenyl (5CB) was ensured by rubbing the polyimide films deposited on the surfaces of the silicon oxide film and transparent electrode. The LC layer thickness was adjusted to $10\,\mu$m by using fluoroplastic gaskets. The control voltage was a superposition of AC components U_{ac} with frequencies $f_1 \approx 75$ Hz and $f_2 \approx 1.5\cdot 10^3$ Hz (selected assuming that for f_1 the drift mode of current is predominant, while for f_2 predominant is the dielectric mode; this is consistent with the characteristic relaxation time of the nematic space charge [5]) and negative-polarity DC voltage on the Si substrate U_{dc} whose value was not so as to induce electroconvective processes in LC. The experiments were performed at room temperature ($\sim 22\,^\circ$C).

As the electrical microcontact to the LC layer from the side of the lower substrate, there was used a fragment of the non-oxidized silicon surface which was limited by the pore size of $\sim 10\,\mu$m in the silicon oxide film (Fig. 1).

Observation was performed by using a polarizing microscope with crossed polarizers in the reflection mode. The cell was positioned on the microscope stage so that the easy-orientation axis of the nematic LC molecules determined

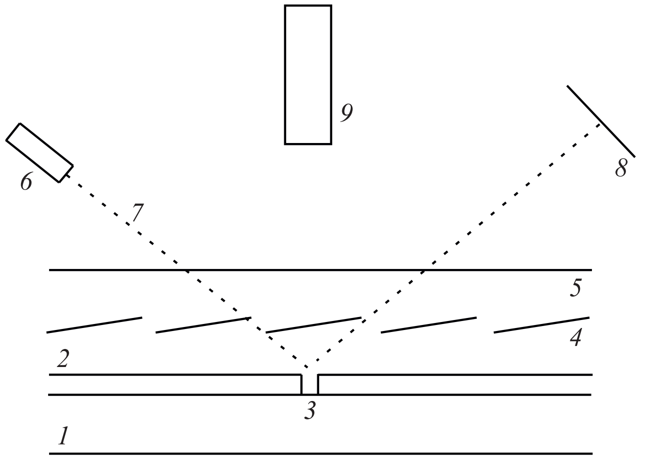

Figure 1. Schematic diagram of the LC cell and experimental setup components. *1* — Si substrate, *2* — SiO_2 film, *3* — SiO_2 film pore, *4* — LC, *5* — transparent electrode, *6* — He–Ne laser, *7* — laser beam, *8* — observation screen mounted at ~ 21 cm from the LC cell, *9* — polarizing microscope.

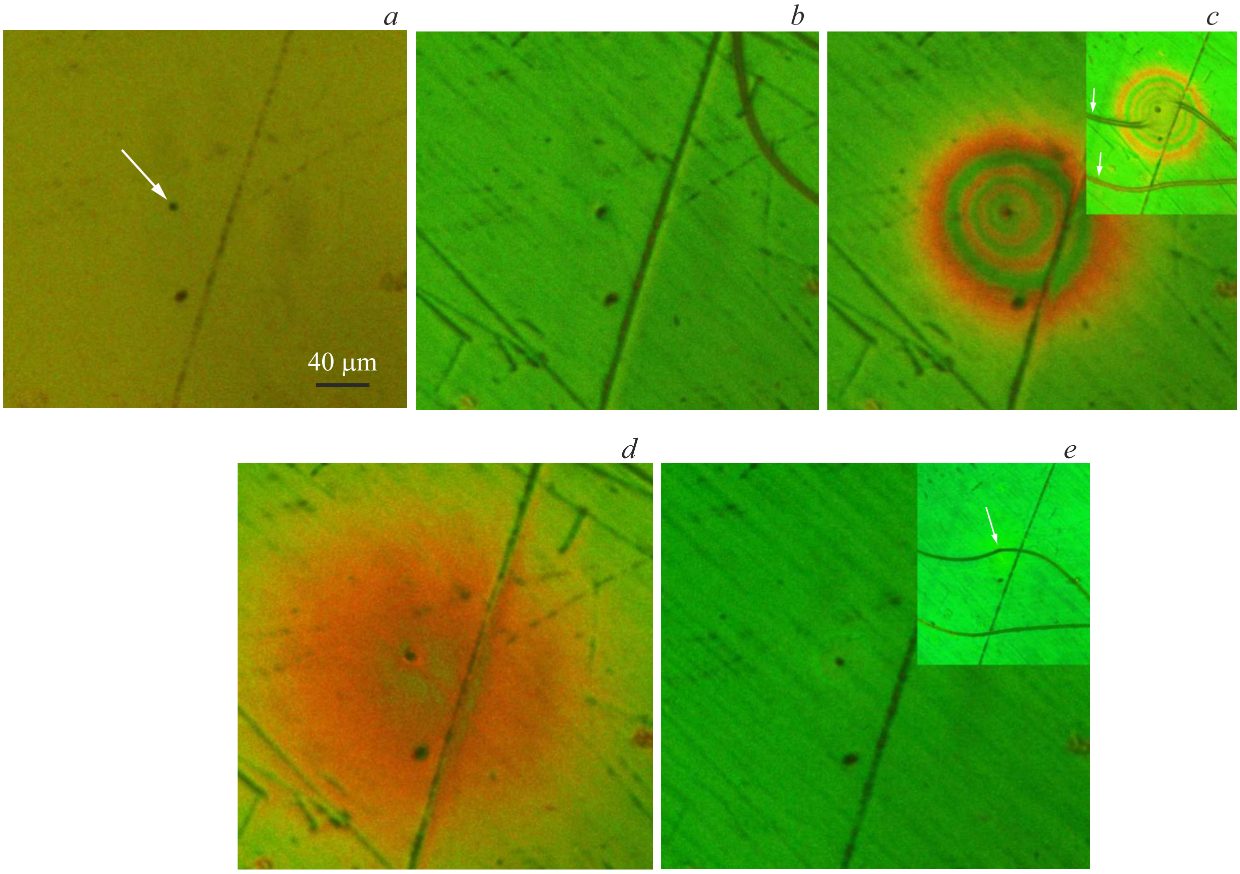

Figure 2. Electro-optical variations in LC in the vicinity of microcontact. *a* — initial planar texture ($U_{\mathrm{ac}} = U_{\mathrm{dc}} = 0$); *b* — texture of reoriented LC in the Fredericksz effect ($U_{\mathrm{ac}} = 10\,\mathrm{V}$, $U_{\mathrm{dc}} = 0$, f_1); *c* — fragment of the IR-region formation ($U_{\mathrm{ac}} = 9.6\,\mathrm{V}$, $U_{\mathrm{dc}} = 4\,\mathrm{V}$, f_1), the inset presents the „wall“ defects (marked with arrows) at $U_{\mathrm{ac}} = 6.2\,\mathrm{V}$, $U_{\mathrm{dc}} = 4\,\mathrm{V}$, f_1; *d* — fragment of the IR-region relaxation ($U_{\mathrm{ac}} = 10\,\mathrm{V}$, $U_{\mathrm{dc}} = 0$, f_1); *e* — texture of reoriented LC in the Fredericksz effect ($U_{\mathrm{ac}} = 5.5\,\mathrm{V}$, $U_{\mathrm{dc}} = 4\,\mathrm{V}$, f_2), in the inset, the „wall“ defect passes through the center of the IR-free LC region near the microcontact marked with the arrow ($U_{\mathrm{ac}} = 5.5\,\mathrm{V}$, $U_{\mathrm{dc}} = 4\,\mathrm{V}$, f_2).

by the direction of rubbing the orienting layer was at the angle of 45° to the polarization plane of the polarizer or analyzer. This cell arrangement ensured the maximally light microscope's field of view. Fig. 2, *a* presents an image of a cell fragment in the vicinity of the pore (pointed at with an arrow), which corresponds to the initial state of the LC molecules orientation.

When AC voltage U_{ac} is applied to the cell, the LC molecules get reoriented (Fredericksz effect), and the observation area becomes uniformly pseudo-colored due to the polarized light interference. It is known that the dependence of the LC layer transmittance on the applied voltage in the Fredericksz effect is of oscillatory character [5]; among the sequence of the selected color intensity maxima, the last maximum is the broadest and is well separated in voltage from the previous one. Therefore, in order to obtain the maximum contrast of optical response, amplitudes of AC voltage U_{ac} with frequencies f_1 and f_2 were selected so as to match the last maximum in the sequence of green color emergence (Fig. 2, *b*, *e*).

After adding to AC component U_{ac} DC voltage U_{dc}, the green observation field begins changing in the microcontact vicinity, namely, there emerges a region in the form of a different-color spot which expands and then transforms into a ring. This process repeats several times. As a result, an axially symmetric pattern of interference rings (IR) gets established (Fig. 2, *c*).

When voltage U_{ac} decreases to the value at which the previous maximum of the observation field green color arises outside the region with IR, this region itself increases in size and a new ring appears (the IR-region in the inset to Fig. 2, *c*). With a further decrease in voltage U_{ac}, the emerged central spot increases in size, and its color becomes indistinguishable from that of the initial LC planar texture (Fig. 2, *a*). From the moment of the nonvanishing central spot emergence, the number of rings, including the central spot, does not exceed the number of the cell transmission oscillations (outside the IR-region) which occur when the voltage increases from the Fredericksz effect threshold to U_{ac} corresponding to the last green color maximum. After DC voltage U_{dc} is switched off, relaxation of the IR-region begins, in which expansion of this region and sequential disappearance of internal IRs take place simultaneously. Over time, the

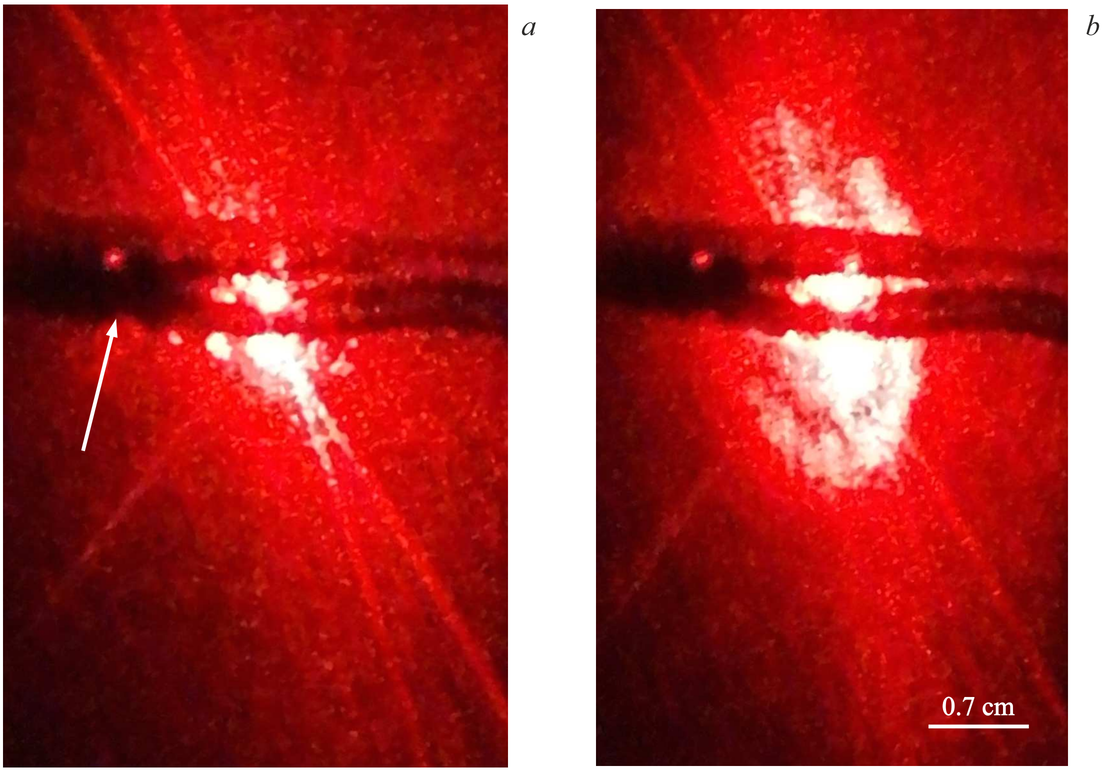

Figure 3. Radiation intensity distribution on the observation screen of the laser beam that has passed through the LC region without IR(*a*) and with IR (*b*). Frequency, Hz: *a* — $1.5 \cdot 10^3$, *b* — 75. AC voltage U_{ac}, V: *a* — 5.5, *b* — 6.2. DC voltage U_{dc}, V: *a*, *b* — 4. The arrow points to the shadow of the mask that blocks the laser beams: the first one is reflected from the glass plate, the other is reflected from the Si substrate and has not changed in passing through LC.

region reaches certain maximum dimensions and becomes uniformly pseudo-colored (see, e. g., Fig. 2, *d*). After reaching the maximum, there occurs a long-term (several tens of minutes) relaxation of sizes accompanied by gradual changing of the relaxing region pseudo-color to green.

The experiments have shown a significant influence of the AC voltage frequency on the IR-region optical response. Switching over the AC voltage frequency from f_1 to f_2 (under U_{ac} and U_{dc} or with U_{dc} switched off during relaxation) makes LC passing to the state of uniform orientation which is identical to the case of action of only the AC voltage component U_{ac} without any residual traces (Fig. 2, *e*). After the AC voltage is switched back to frequency f_1, the entire region returns to the same orientation state (Fig. 2, *c, d*) where it was before switching to AC voltage frequency f_2.

The IR-containing LC region was probed with an unfocused laser beam (Fig. 1). The radiation beam was directed to the cell at the angle of $\sim 45^\circ$ and, being reflected from the silicon substrate, hit the observation screen (Fig. 1). Fig. 3 presents the observation screen images illustrating the light intensity distribution patterns for the AC voltage with frequencies f_2 (*a*) and f_1 (*b*). Note that, in the absence of control voltage, the light intensity distribution is identical to that shown in Fig. 3, *a*, which demonstrates the absence of the wavefront deviation under the LC molecules reorientation in the Fredericksz effect. And only in the presence of IR at the AC voltage frequency of f_1 there takes place a deviation of the laser beam wavefront fragments from the initial direction, which is estimated as $\sim 4^\circ$. Selective probing of the IR-region with a focused laser beam showed that internal IR-regions are responsible for the wavefront deviation at larger angles, while peripheral annular zones deviate the wavefront at smaller angles.

Continuous change in the molecule orientation in the IR-region causes a gradual decrease in the phase retardation (PR) from the maximum in the region center to the periphery. Then relative PR may be determined at any observation point assuming that PR over the first interference ring width increases by $\sim 2\pi$ with respect to PR outside the IR-region, PR on the next adjacent ring increases by another $\sim 2\pi$ with respect to the previous ring, etc. The PR increase in the radial direction in the LC layer plane is a source of the laser beam front deflection (Fig. 3, *a*).

The obtained results were interpreted based on the assumption that the LC orientation in the IR-region gets restored due to screening the f_1-frequency electric field by the bulk electric charge accumulated due to the injection from the microcontact, which was axially symmetric in the microcontact–plane electrode system [6–9]. Therefore, the influence of orienting surfaces on LC molecules will increase, while the electric field will decrease in the radial direction to the axis. Then the interference pattern in the form of rings (Fig. 2) with axial symmetry is nothing but a scan in the cell plane of distribution of the LC-layer polarized light transmission versus the electric field.

The decrease in the f_1-frequency electric field towards the IR-region center (to at least the Fredericksz-effect threshold values) was indirectly confirmed by the following experimental facts. After a short interruption of the AC voltage action, „wall"-type defects may arise in the LC layer [5]. Defects of this type get formed in nematics at voltages above the Fredericksz effect threshold, the „wall" width being the same along its entire length (see, e. g., the lower „wall" in the inset to Fig. 2, *c*). However, width of the upper „wall" formed in the IR-region increases towards its center, while in the very center the „wall" does not form (see the insert to Fig. 2, *c*). When AC volage is switched over to frequency f_2, the same „wall" in the microcontact vicinity has no break, and its width at any LC layer point is the same (see the insert to Fig. 2, *e*).

Thus, the paper demonstrates a new method for creating a continuous axially symmetric spatial profile of phase retardation in the LC layer plane. After the region with restored LC molecule orientation is formed, it becomes possible to change PR in the LC layer in the zone of an arbitrarily selected interference ring by a value multiple of $\sim 2\pi$ by switching over the AC voltage frequency and amplitude; this seems important for electro-optical applications.

Conflict of interests

The authors declare that they have no conflict of interests.

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