Polymer dispersed nematic liquid crystal films with conical boundary conditions for electrically controllable polarizers

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Abstract

Polymer dispersed nematic liquid crystal (PDNLC) films with conical boundary conditions at the LC-polymer interface are considered. The conical surface anchoring with tilt angle 40° initiates forming the axial-bipolar director configuration inside nematic droplets. This droplet structure exhibits the strong scattering of light polarized parallel to the bipolar axis. In the initial state, the bipolar axes in all droplets are oriented randomly, and therefore PDNLC film scatters a light of any polarization. Electric field applied along the film plane orients the bipolar axes unidirectionally in the whole droplet ensemble, that results in its high polarization-dependent transmittance. Such PDNLC films can be used in the electrically controllable linear polarizers characterized by 89% value of the transmittance for the perpendicular polarized light and high extinction ratio 590:1 at the electric field 0.34 V/μm.

Keywords: `Polymer dispersed liquid crystal films`, Light polarizer, Nematic droplets, Scattering anisotropy, Electro-optics

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1. Introduction

Polymer dispersed liquid crystals (PDLC) are the polymer films containing liquid crystal (LC) droplets. This material is flexible and resistant to mechanical stresses. Owing to the optical anisotropy of LC, a light scattering by the droplet depends on the orientational ordering of the director (the unit vector characterizing the preferred orientation of the long axes of LC molecules) and polarization of incident light [1, 2, 3, 4, 5, 6]. The director configuration in the droplet is specified by the boundary conditions (surface anchoring), LC material parameters, droplet shape and size. The orientational structure changes under the influence of external factors (electric or magnetic fields, temperature, stress and so on) which affect the light scattering by LC droplets and, consequently, the light transmission of PDLC film. For example, the composite films can be switched from the light scattering state into the transparent one by the electric field, if the refractive index n_p of polymer is close to the ordinary refractive index $n_\perp$ of LC [7, 8, 9, 10, 11].

LC droplets in the composite films are of the oblate spheroid form with the minor axis aligned mainly perpendicular to the film plane [12, 13]. Because of random orientations of the droplets, the transmittance of the whole PDLC film for normally incident light is independent of its polarization despite the polarization dependence of the light scattered by the individual droplet. For instance, the oblate nematic droplets with bipolar configuration (Fig. 1a) scatter the light polarized parallel to the bipolar axis more intensely than another polarized light component. However, the uniaxially aligned ensemble of such droplets did not exhibit high scattering anisotropy [14, 15, 16]. High polarization dependence of the film transmittance can be obtained by forming an ensemble of prolate droplets by the unidirectional stretching of PDLC film [17, 18, 19, 20, 21, 22]. In this case the major axes of all droplets get oriented along the stretching. The symmetry axis of the bipolar configuration formed at the tangential (planar) boundary conditions in nematic droplets is aligned along the major axis (Fig. 1b). It results in the strong scattering of the light polarized along the stretching

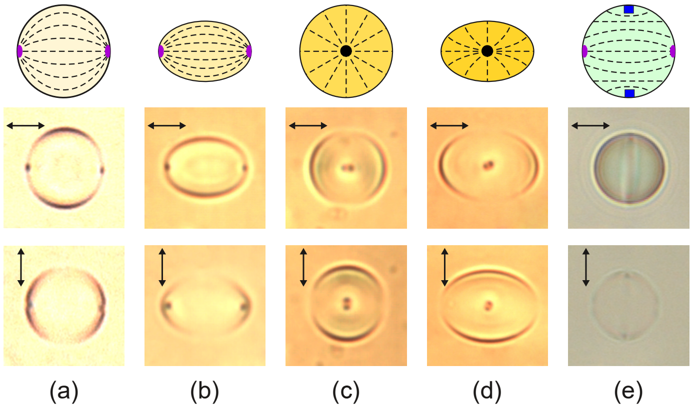

Figure 1: Photos of nematic droplets with the various director configurations taken in the polarized light when the polarizer is oriented along (middle row) and perpendicular (bottom row) to the symmetric axes of the droplets. The bipolar (a) and elongated bipolar (b) configurations under tangential boundary conditions, the radial (c) and elongated radial (d) structures under homeotropic boundary conditions, the axial-bipolar configuration (e) under conical boundary conditions. The schemes of appropriate orientational structures are presented in the top row. The polarizer's directions are indicated by the double arrows.

while the PDNLC film is transparent for the light polarized perpendicular to the stretching if the above-mentioned condition $n_p \cong n_\perp$ is valid. Nevertheless, small areas of the droplet interface near of the point defects (boojums) still scatter the perpendicular polarized light component (Fig. 1b, bottom row) decreasing its transmittance. For example, the extinction ratio (ratio $T_\perp/T_\|$ of the transmittances for the light polarized perpendicular and parallel to the stretching, respectively) 420:1 was reached at $T_\perp = 0.49$ [17]. The similar effect, but with less transmittance anisotropy, was observed in PDNLC films with the droplet radial configuration at the homeotropic (perpendicular) surface anchoring (Fig. 1c) after their stretching (Fig. 1d) [23].

The electric field applied in PDNLC film plane orients the LC director along the field. This makes the light polarized along the electric field scatter stronger than the light with orthogonal polarization [24, 25, 26]. Therefore, the transmittances of light polarized perpendicular and parallel to the applied field as well as their ratio depend on the voltage. It enables to produce polarizers with the electrically controlled light transmission and polarization degree. Ideally, a homogeneous director alignment in the unidirectionally oriented LC droplets is necessary to achieve high polarizer performance.

In PDNLC films with the conical boundary conditions at the LC-polymer interface, the unique axial-bipolar director configuration is formed inside the nematic droplets with a diameter less than 10 μm (Fig. 1e) [27, 28, 29]. The director distribution in such droplets is much closer to homogeneous one than the bipolar configuration within the droplets with tangential anchoring (Fig. 1a). As a result, the significant difference of the droplet textures can be observed in the light polarized parallel or perpendicular to the bipolar axis (middle and bottom rows, respectively, in Fig. 1e). In the middle row the droplet looks like a dark circle with sharp borders due to mismatching of LC and polymer refractive indices. Consequently, such a droplet strongly scatters the light polarized parallel to the bipolar axis. In contrast, the droplet is almost invisible in the perpendicular polarized light (bottom row) due to the refractive indices matching. In this case the polarized light is not practically scattered by this droplet.

In this paper we study the electrically controllable transmission of polarized light by PDNLC films with conical boundary conditions, in which the axial-bipolar droplets get oriented by an in-plane applied electric field.

2. Experimental approach

PDNLC films based on the nematic mixture LN-396 (Belarusian State Technological University) dispersed in poly(isobutyl methacrylate) (PiBMA) (Sigma Aldrich) have been studied [27]. For the used composition, the conical surface anchoring of LC is formed with the tilt angle 40°. The samples were prepared by TIPS technology [12] with the weight ratio LN-396 : PiBMA $= 60 : 40$. During this process the mixture of LC and polymer was heated to 70 °C followed by cooling to the room temperature for 5 minutes. In the process of phase separation, a part of the LC remains in the polymer matrix, that leads to a change of the polymer refractive index. The phase separation and droplet formation does not yet occur at the weight ratio LN-396 : PiBMA = 30 : 70. The refractive index of such a polymer matrix is $n_p = 1.518$. Refractive indices of LC are $n_\perp = 1.52$ and $n_\| = 1.69$. The electrooptical cells were assembled using the glass substrates with two ITO electrodes separated by the gap of 650 μm on each substrate (Fig. 2). Such a layout allows applying 1 kHz AC electric field in the plane of PDNLC film. The PDNLC films of 15 and 25 μm-thick were investigated.

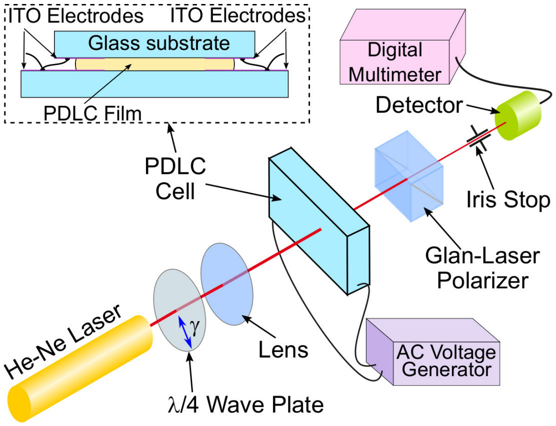

Figure 2: Schemes of the optical setup and PDNLC cell to measure polarization characteristics of the light passed through PDNLC film.

The light transmission was measured by using the optical setup shown in Fig. 2. The circularly polarized light of He-Ne laser ($\lambda = 632.8$ nm) (Lasos) focused by the lens with focal distance 75 mm was incident normally on the sample. The diameter of laser beam at the sample is measured by the Laser Beam Profiler LBP-1 (Newport) and was 320 μm at 13,5% level. The focused laser beam passed between ITO electrodes through PDNLC film and further through the Glan-Laser polarizer oriented parallel or perpendicular to the direction of the applied electric field. The silicon detector with amplifier PDA100A-EC (ThorLabs) was used to measure the intensity of transmitted light. The detector was equipped by the iris stop with angular size 45 minutes corresponding to the

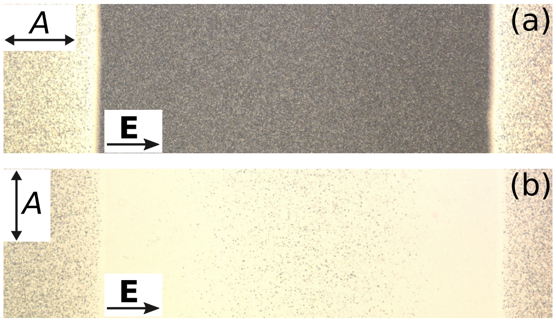

Figure 3: Microphotos of PDNLC film taken for two analyzer (A) orientations: parallel (a) and perpendicular (b) to the in-plane applied electric field $\mathbf{E}$. Microscope polarizer is switched-off. The gap between ITO electrodes is 650 μm.

angular size of laser beam without PDNLC cell. The digital multimeter 34465A (Keysight) was used to measure the signal from the detector.

3. Results and discussion

Typical patterns of the studied PDNLC films under the action of in-plane applied electric field $\mathbf{E}$ are shown in Fig. 3. When the analyzer is parallel to $\mathbf{E}$, the film area between electrodes looks as a dark rectangle due to the strong scattering of the light polarized along the analyzer because the bipolar droplet's axes are oriented along the electric field (Fig. 3a). Conversely, the same area of the film is a bright rectangle if the analyzer is orthogonal to $\mathbf{E}$ (Fig. 3b). Here. this occurs because the refractive indices of both film components are matched, and consequently the light polarized perpendicularly to $\mathbf{E}$ does not scatter.

The dependences of PDNLC cells transmittances $T_{\|,\perp}$ on the applied voltage are given in Fig. 4a. The transmittances were determined as $T_{\|,\perp} = I_{\|,\perp}/I_0$, respectively, where I_0 is light intensity after the Glan polarizer without the sample, $I_{\|,\perp}$ are the light intensities after the sample and Glan polarizer for the parallel ($\|$) or perpendicular ($\perp$) orientation of the polarizer to the applied electric field. AC voltage varies the transmittance of polarized light components. The optical response of PDNLC cells is not threshold. The 15 μm-thick PDNLC film shows considerable changes of light transmission in the range of the applied voltage up to 100 V ($E \cong 0.15$ V/μm), when $T_\perp$ increases to 80% and $T_\parallel$ decreases to 0,5%, at that the extinction ratio $ER = T_\perp/T_\parallel = 160 : 1$ (Fig. 4b). Further voltage increase leads to the smooth growing of $T_\perp$ to 89% and ER to 590:1 at 220 V ($E \cong 0.34$ V/μm). The transmittances of both polarized components are less than 1% in the initial state for the cell with PDNLC film of 25 μm thickness. The maximum variation is observed in the 100-200 V range, in which $T_\perp$ increases from 7% to 62%, at that the extinction ratio ER grows up to 2581:1. Further increase of voltage results in the growth of $T_\perp$ up to 67% and the slight decrease of ER to 2300:1 at 260 V ($E \cong 0.4$ V/μm).

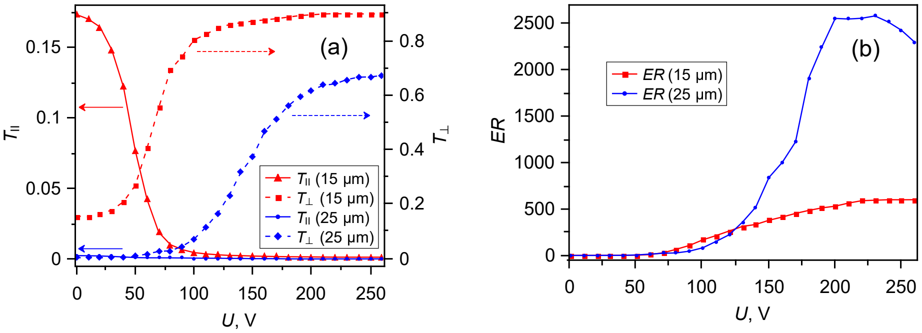

Figure 4: Transmittances of the polarized light components $T_{\parallel,\perp}$ (a) and their extinction ratio $ER = T_\perp/T_\parallel$ (b) depending on the applied voltage U for two cells with PDNLC films of 15 and 25 μm thickness. The gap between electrodes is 650 μm.

4. Conclusion

The polarization-dependent light transmission of PDNLC cells with the axial-bipolar director configuration in LC droplets caused by the in-plane applied voltage has been studied. The electric field decreases the transmittance $T_\parallel$ of light polarized parallel to its direction and simultaneously increases $T_\perp$ component as the voltage rises. The cells exhibit the high extinction ratio ER and perpendicular component of transmittance at low values of the control electric field (less than 0.4 V/μm). For instance, the transmittance 89% for the perpendicular polarized light and high extinction ratio 590:1 have been obtained for the

15 μm-thick PDNLC film at the electric field 0.34 V/μm. These are record values for the electrically controllable linear polarizers based on the light scattering anisotropy. It should be noted that *ER* value can be significantly increased if the thicker films to be used, but then the transmittance $T_{\perp}$ be reduced.

Thus, PDNLC films with the conical boundary conditions can be effectively used for the low-voltage controlled linear polarizers and polarization-sensitive optical switches.

Acknowledgments

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