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Gradient microscale PDLC single layers for light control[♣]

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The electro-optical (EO) light-switching properties of wedge-formed microscale droplet-gradient single layers of polymer-dispersed liquid crystals (PDLC) are examined. Related to the wedge dimension, the liquid-crystal droplets in the layers reach several tens of micrometers. Being precisely controlled by the layer thickness, the variable droplet size can be of use for EO light control.

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1. Introduction

Polymer-dispersed liquid crystals (PDLCs), consisting of liquid crystal (LC) droplets dispersed in an optically transparent solid polymer matrix, are special types of advanced electro-optical (EO) materials [1–4]. Based on the electric field-dependent refractive index, the EO light-switching properties of these systems are widely applied. Particularly, the gradient PDLCs are very efficient in a number of high-tech applications, such as light switches and tunable light filters, switchable lenses, etc. [5,6].

In previous work, we reported on stable microscale PDLC single layers [7]. Formed in a wedge cell by nanosecond laser photopolymerization, these layers have a regular and controllable droplet gradient. It is further of interest to examine the EO light-switching properties of such PDLC wedge thin films.

2. Experimental

The preparation of the PDLC wedge film is described in detail in [7]. Briefly, a 50:50 wt. % mixture of UV-curable NOA-65 (Norland) and E7 nematic LC (BDH) was filled in a wedge-like cell. The cell was constructed from a 25μm-thick Mylar spacer and two 1mm-thick 17.5mm-long glass substrates, with inner surfaces coated with conductive indium-tin-oxide (ITO) (Fig. 1). The monomer/LC mixture was subjected to very slow UV polymerization-induced phase separation (PIPS), performed at room temperature with high-power nanosecond UV laser pulses.

The EO light-switching properties of the prepared PDLC film were characterized at room temperature, by measurements of the voltage dependence of the transmittance of a circularly polarized diode laser beam (λ = 635 nm, 1 mW, 1 mm beam diameter). The PDLC wedge cell was mounted on a translating stage and illuminated at a 0° angle of incidence. The light beam was chopped at 90 Hz. The light that passed through the PDLC film was registered by a photodiode and computer-controlled lock-in amplifier (SR830, Stanford Research Systems). The output of the lock-in in-built function generator was amplified and a sweep of a sinusoidal voltage with amplitude 0 – 30 V_{rms} at 350 Hz was applied to the ITO electrodes of the wedge cell.

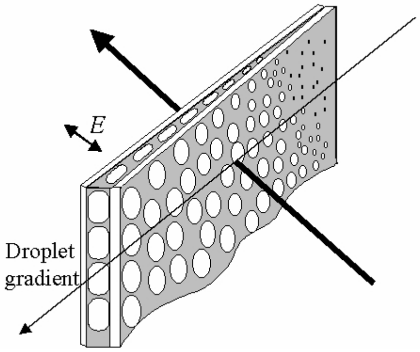

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Fig. 1. Schematic illustration of a gradient single-layer PDLC wedge film. The arrow indicates the direction of the incident light beam.

For the response time measurements, the photodiode output was acquired by a Tektronix 2336 oscilloscope synchronized with the driving voltage packets from the lock-in instrument supplied to the PDLC cell. The repetition rate of the packets of frequency 1 KHz and amplitude 10 V_{rms} was 20 Hz. From the digitized temporal traces, the time values were taken for the light intensity to fall (or rise) to 90 % of its final value, i.e. the baseline of full response.

3. Results and discussion

Fig. 2 presents the voltage-dependent light transmittance recorded for various layer thicknesses δ, when the examined PDLC wedge cell is translated across the incident light beam. The PDLC film exhibits light switching from scattering (off-state) to transparent (on-state) modes with a relatively low switching voltage (V_{switch}) and low driving voltage, as expected for microscale droplets with a size of 10 – 50 μm. It is known that the mechanism responsible for the electrical switching is the change in the effective (average) refraction index of the dispersed LC molecules (n_{eff}) with the applied electric field (E) [1–3]. In the off-state, the local average orientation of the rodlike nematic molecules in the dispersed LC microdroplets is random, leading to a mismatch between n_{eff} and the index of the polymer (n_p), thus resulting in strong scattering of the incident light. A sufficiently high E aligns the nematic director parallel to the electric field (and to the direction of the light propagation as well), and, if n_{eff} of the aligned LC matches n_p, then the bulk PDLC material appears transparent.

The value of the switching electric field (E_{switch}) of a PDLC film can be related to microscopic parameters [8,9]:

$$E_{switch} \approx [(R_2/R_1)^2 - 1]^{1/2} \left(4\pi K/\Delta\varepsilon\right)^{1/2}/cR, \quad (1)$$

where R_2 is the major droplet radius, R_1 the minor radius (in our case $R_2/R_1 \approx 2$), K is a Frank elastic constant for distortion and $\Delta\varepsilon \approx 12$ is the dielectric anisotropy of the nematic [10], R is the characteristic droplet radius, and c is expressed as [8]

$$c = 3\varepsilon_p/(\varepsilon_{eff} + 2\varepsilon_p), \quad (2)$$

where ε_p and ε_{eff} are the dielectric constants of the cured polymer and LC, respectively.

The voltage shift observed for the light-switching curves in Fig. 2 results from the electric field gradient of magnitude $E = V/\delta$, linearly descending with δ. Indeed, such a shift in the corresponding transmittance-field dependencies is strongly reduced (Fig. 2 b). The values of E_{switch} are comparable to those reported for similar microscale UV-cured PDLCs, like E7/Epoxy [11] and E7/NOA-65 (50:50 wt. %) [12] at room temperature.

A negligible hysteresis was found for the transmittance-voltage curves. The hysteresis effect following from the droplet size dispersion (<D>) is known for micrometer-sized PDLCs [2,13]. Also, the sharpness of the switching behavior depends on <D> [2]. In our case, the light-switching behaviors imply that <D> in the studied PDLC layer is relatively low. The results obtained by optical microscopy and coherent light diffraction confirms the narrow size distribution of the droplets organized in a single layer. Furthermore, the investigation of the droplet organization in the PDLC film reveals a well-ordered structure that approaches a two-dimensional array.

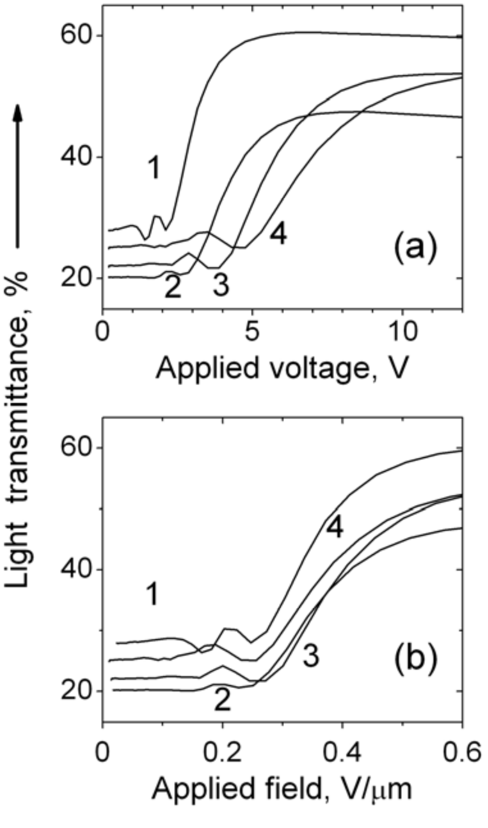

Fig. 2. (a) Voltage-dependent light transmittance (λ = 635 nm) of a single-layer PDLC film measured at 20º C. Film thickness: 8.5 μm (curve 1); 11.4 μm (curve 2); 14.3 μm (curve 3) and 18.6 μm (curve 4). Panel (b) presents the same data versus the applied electric field

Fig. 2 shows that the switching characteristics of the PDLC wedge film, such as the switching voltage (V_{switch}), transparency level (on-state) and the on/off contrast ratio, depend significantly on the film thickness δ. This is reasonable, since n_{eff} is a function of the LC droplet size [2,3,14]. As reported elsewhere [7], the droplet sizes in the examined wedge-confined PDLC single layer increase linearly with δ. The droplet gradient is echoed in the refractive index distribution which is electrically commanded by the opposite gradient of the electric field $E = V/\delta$. This results in a change in the switching characteristics (Fig. 3) which can be controlled by δ. Most important for practical use is the tunability of V_{switch}. The tuning for the present PDLC wedge film was in the range 2 – 3 V (Fig. 3 c). Also, Fig. 3 (b) illustrates that the on/off contrast of the PDLC wedge film can be simply optimized by tuning of δ.

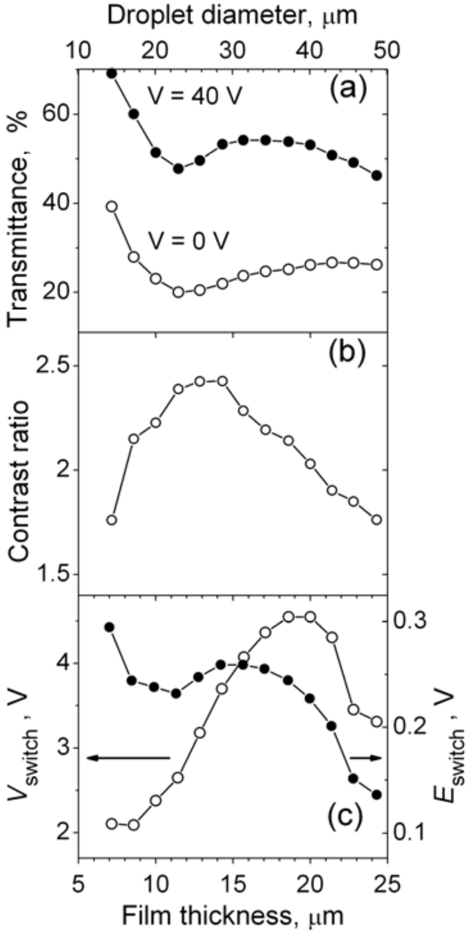

Fig. 3. (a) Variation of the light transmittance in the ON and OFF states; (b) on/off contrast ratio; (c) switching voltage V_{switch} and switching field E_{switch} of a single-layer PDLC film of thickness λ = 635 nm, the temperature is 20° C.

The electric-field switching value $E_{\text{switch}} = V_{\text{switch}}/\delta$ decreases for larger droplets (Fig. 3 c). This dependence agrees reasonably with the theoretical one (Eq. 1), well established for microscale PDLCs [8,9,12,13].

The response time for switching was in the range usual for such a type of microscale PDLC device [4,8,9,13,15]. Depending on the droplet size, the rise time (τ_{ON}) was measured to be 1 – 10 ms, and the turn-off time (τ_{OFF}) was between 10 and 30 ms (Fig. 4). Their values can be expressed as [12]:

$$\tau_{ON} = \frac{\gamma_1}{\dfrac{\Delta\varepsilon E^2}{4\pi} - \dfrac{[(R_2/R_1)^2 - 1]K}{R^2}} \tag{3}$$

$$\tau_{OFF} = \frac{\gamma_1 R^2}{[(R_2/R_1)^2 - 1]K} \tag{4}$$

where γ_1 is a rotational viscosity coefficient.

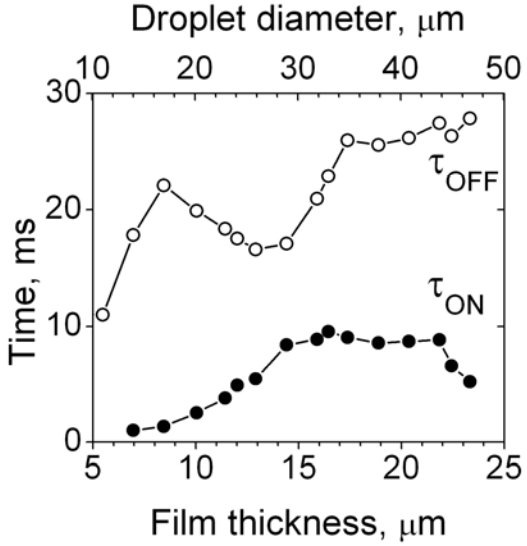

Fig. 4. Rise time (τ_{ON}) and turn-off time (τ_{OFF}) versus the PDLC film thickness. Time accuracy ± 0.2 ms. The applied AC voltage is 10 V, the temperature is 20° C.

In contrast to E_{switch}, the dependencies of the response times τ_{ON} and τ_{OFF} on δ (or the droplet mean diameter *D*) do not match the theoretical predictions (Eqs. 3 and 4). Especially, the measured τ_{OFF} does not scale quadratically with *D*. Also, an unexpected declination takes place for τ_{OFF} (Fig. 4). As indicated by our supplementary measurements, this discrepancy can be attributed to optical interference effects in the single PDLC layer. Well-resolved oscillations in the field-dependent transmittance curves, observed at $E < E_{\text{switch}}$ (Fig. 2), and other experimental evidence support the above assumption. Indeed, the light intensity is modulated by the optical phase shift (Δ) induced by the light propagation through the PDLC film with a variable optical path length, $\Delta \propto [n_{\text{eff}}(E) - n_{\text{p}}]\,\delta$. As analyzed and explained in [16], the optical interference in a PDLC film may result in an effective decrease of τ_{OFF}. Our experimental results reveal that the optical interference is most pronounced when δ is in the range 15 to 20 μm. Further analysis is necessary to elucidate the resultant phase retardation effect on the light-switching characteristics of the wedge-formed PDLC single layer.

4. Conclusions

We examined the EO functionality of a wedge-confined microscale PDLC single layer with a linear droplet gradient. The PDLC film is dual operating, by both electric field and thickness control. Utilizing LC microdroplets with a controlled size, the EO properties of the PDLC wedge film can be simply tuned by translation of this device across the incident light beam. The proposed EO PDLC wedge can be applied as a tunable light filter/shutter (light modulator/discriminator) and tunable prism. Depending on the LC/monomer mixtures used for PDLC preparation, various behaviors for the EO light-switching characteristics can be obtained, thus extending the potential applicability of such a PDLC device.

Acknowledgements

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References

[1] J. W. Doane, in Liquid Crystals – Applications and Uses, ed. B. Bahadur, World Scientific Publishing Co. Pte. Ltd, Singapore (1990), Vol. **1**, p. 361.
[2] P. S. Drzaic, Liquid Crystal Dispersions, World Scientific Publishing Co. Pte. Ltd, Singapore (1995).
[3] G. R. Crawford, S. Zumer (eds), Liquid Crystals in Complex Geometries Formed by Polymer and Porous Networks, Taylor & Francis Ltd, London (1996).
[4] P. Drzaic, Liq. Cryst. **33**, 1281 (2006).
[5] H. Ren, S. T. Wu, Appl. Phys. Lett. **81**, 3537 (2002).
[6] H. Ren, S. T. Wu, Appl. Phys. Lett. **82**, 22 (2003).
[7] Y. Marinov, G. B. Hadjichristov, A. G. Petrov, J. Optoelectron. Adv. Mater. **9**, 417 (2007).
[8] B. G. Wu, J. H. Erdmann, J. W. Doane, Liq. Cryst. **5**, 1453 (1989).
[9] P. S. Drzaic, A. Muller, Liq. Cryst. **5**, 1467 (1989).
[10] H. Wang, T. X. Wu, S. Gauza, J. R. Wu, S. T. Wu, Liq. Cryst. **33**, 91 (2006).
[11] J. Y. Kim, P. Palffy-Muhoray, J. Appl. Phys. **66**, 362 (1989).
[12] K. Amundson, Phys. Rev. E **53**, 2412 (1996).
[13] P. Drzaic, Liq. Cryst. **33**, 1286 (2006).
[14] J. H. Ryu, S. G. Lee, K. D. Suh, Liq. Cryst. **31**, 1587 (2004).
[15] D. Coates, J. Mater. Chem. **5**, 2063 (1995).
[16] D. Rudhardt, A. Fernandez-Nieves, D. R. Link, D. A. Weitz, Appl. Phys. Lett. **82**, 2610 (2003).

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