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Single-Layered Microscale PDLC Films for Electro-Optical Modulation of Laser Radiation*

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Abstract. We report on low-voltage, high-contrast amplitude/phase modulators of laser radiation on the basis of microscale polymer-dispersed liquid crystal (PDLC) single layers providing interference contrast enhancement. The modulators were prepared from liquid crystal (LC) E7 in the solid matrix of UV-cured polymer NOA65. Operating at low voltages, E7/NOA65 single-layered PDLC films of thickness 10–25 μm and mean diameter of LC droplets up to 50 μm are capable of producing a large phase shift up to $\pi/2$ for the propagating laser light. This property is very attractive for linear and non-linear optical applications. The precise spatial control of droplet size along the film thickness allows the linear droplet-size gradient single-layered PDLC films to be used for tunable spatial light modulators and other devices for active control of laser radiation.

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1 Introduction

In optoelectronics, the materials of microscale liquid crystals (LCs) dispersed in optically transparent polymeric binders (polymer-dispersed liquid crystals, PDLC) are widely used. They permit construction of portable systems to record, process and display information, as well as for control and modulation of light beams [1-3]. The search and development of new materials with low control voltage operated by integrated circuits with low-power consumption are still needed.

Operating through an electrically-controllable dielectric reorientation of the LC molecules in droplets, the electro-optical (EO) properties of PDLC composites are suitable for efficient modulation of light. Advanced applications have been

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demonstrated by use of microscale PDLC phase modulators [3-8]. It is of importance that unlike the nano-PDLCs, the microscale PDLC devices exhibit considerably lower operating voltages and other valuable properties.

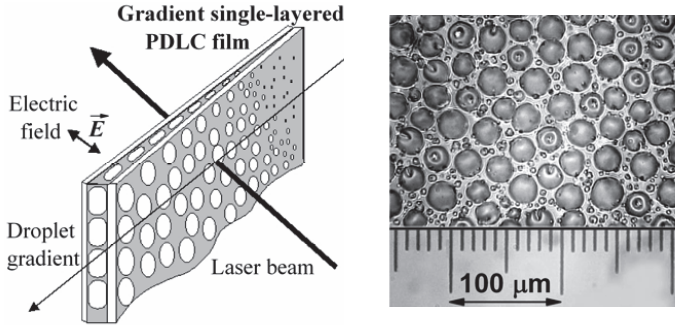
The problem of PDLC films is their poor contrast [9]. Various approaches that have been used to solve this problem require high control voltages to be supplied. Here we propose low-voltage microscale single-layered PDLCs to increase the contrast by interference quenching effect of transmitted light, aiming their possible applications as tunable modulators of laser light in the transmission mode. Nematic droplet dispersion of LC E7 in optically isotropic and transparent polymer matrix of UV-cured NOA65 is examined by employing a He-Ne laser. The variable cell gap, namely a wedge-formed PDLC cell of thickness ranging from a few to several tens of micrometers, allows to be characterized the EO switching, the response time and electrically-produced optical phase shift by single-layered PDLC as a function of the layer thickness and the LC droplet size.

2 Experimental

The preparation of microscale PDLC single-layered films of variable thickness, the experiment set-up and apparatus employed for the measurements were described in details elsewhere [10,11]. Briefly, two 1-mm-thick plane-parallel glass plates with inner surfaces coated with a thin conductive layer of indium-tin-oxide (ITO) were used to make the PDLC cell. The PDLC films were prepared from a homogeneous mixture of 50:50 wt% LC E7 and NOA65 monomer by photopolymerization-induced phase separation [12]. Formed in 17.5 mm long wedge cell with a 25 μm thick Mylar spacer, the PDLC single layers had a continuously varying thickness from 3 to 25 μm (Figure 1a). The EO experiments were performed at room temperature at which E7 is in a nematic phase. The EO response of the PDLC films was probed by linearly polarized He-Ne laser beam (wavelength $\lambda = 632.8$ nm). An AC signal from lock-in instrument (SR830) was amplified and used to drive the PDLC. To characterize the optical phase change, the transmittance of the single-layered PDLC films was measured under parallel- and crossed-polarizer conditions.

3 Results and Discussion

A detailed study on the morphology of the micrometer-sized single-layered E7/NOA65 PDLC material was presented in [10,13]. It should be emphasized that highly regular and well-dispersed planar-aligned bipolar LC droplets with a very defined and constant shape take place for the prepared PDLC films (Figure 1b). The LC droplets exhibit double-truncated spherical shapes whose mean diameter varies as twice the cell gap [10]. Having a linear gradient along the film length, the droplet size for the examined PDLC film varies from 5–6 μm to



(a) (b)

Figure 1. (a) Schematic illustration of the prepared gradient-droplet size single-layer PDLC wedge-formed film and the orientation of both incident laser beam and AC electric field applied; (b) Optical micrograph of a sector on PDLC single-layer film with the mean diameter of LC droplets 24 μm.

~ 50 μm. Thus, by simple translation of the PDLC film across the light beam (Figure 1a), one can use a layer region of desirable droplet size.

Figure 2 presents voltage-dependent light transmittance of the PDLC single layer. As seen, a considerably low operating voltage takes place, as compared to the usual 'thick' bulk PDLCs, in which the droplet sizes are smaller than the film thickness. This peculiarity is advantageous for the practical applications of PDLCs. Further, a relatively low level of scattered light is observed in the switching curves at zero applied field. This feature results mainly from the lack of multiple scattering in the single PDLC layer. Due to the single-layer arrangement of the droplets, a well pronounced optical interference effect occurs that leads to a deep minimum of transmittance, and hence, to an enhanced PDLC contrast.

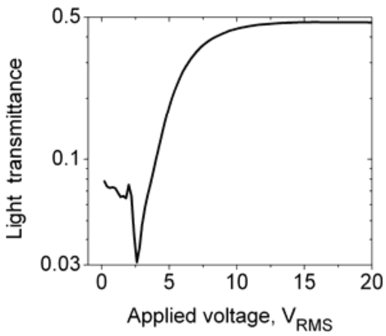


Figure 2. AC voltage-dependent light transmittance ($\lambda = 632.8$ nm from He-Ne laser) through a microscale PDLC single-layered film measured at the film thickness 24 μm.

As expected, the examined PDLC with large LC droplets exhibited a relatively slow EO response and relaxation dynamics, both dependent on the LC droplet size (film thickness, respectively). By increasing film thickness, the rise time (turn-on, τ_{on}) of EO switching increases too, being also dependent on the applied voltage. At 10 V, τ_{on} varies from ~ 15 ms (at film thickness 10 μm – the smaller droplets) to ~ 35 ms (at film thickness 25 μm – the larger droplets). At the same voltage, the turn-off time (τ_{off}) is about 10 ms and does not considerably change with the film thickness. Considering the application of single-layered PDLC films for light modulation, the switching can be accelerated by use of higher operating voltage up to the optimum one [14]. Thus, at 30 V τ_{on} varies from ~ 0.5 ms (at film thickness 10 μm) to ~ 4 ms (at film thickness 25 μm), but τ_{off} also increases (from ~ 2.5 ms to ~ 35 ms, respectively). Such behavior qualitatively agree with the well developed theory for LC electric-field reorientation molecular dynamics [15-18].

The electrically-induced phase retardation (Δ) by microscale PDLC single layer was measured following the approach [8]. Figure 3(a) depicts Δ at a film thickness of 24 μm. As seen, Δ can be well commanded by the field-induced change in the effective refraction index, $n_{\text{eff}}(E)$, of the dispersed nematic LC. The experimental results indicate, that Δ is higher for the bigger LC droplets and at a low voltage (Figure 3), in agreement with data reported for microscale PDLC phase modulators [5-8,19,20]. Reasonably, because of larger droplet size, the phase retardation obtained by microscale PDLC is much larger than that by nano-PDLCs [19,20]. As demonstrated in [8], such an efficiency of the electrically-commanded phase modulation is enough to be practically applied in PDLC-based microdevices for adaptive optics (e.g., for tunable-focus microlens arrays). It should be noted that the EO modulation by such PDLC films can be also highly selective within a certain frequency range [21]. The selective band-pass filtering may be useful for applications based on various schemes by

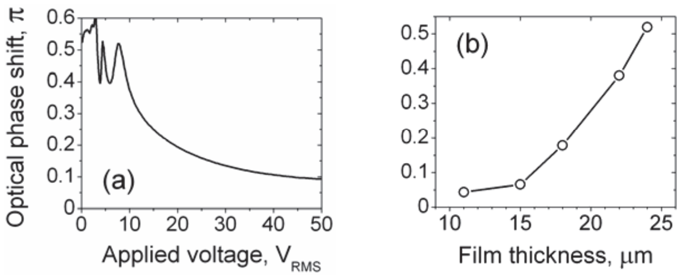


Figure 3. The electrically-induced optical phase shift (Δ) by linear droplet-gradient microscale single-layered PDLC film ($\lambda = 632.8$ nm from He-Ne laser) *vs.*: (a) the AC voltage applied, the film thickness was 24 μm (the corresponding mean diameter of LC droplets was 48 μm); (b) the film thickness, the applied voltage was kept 10 V_{RMS}.

exploiting efficient EO modulation by PDLC in the infrasound frequency range which are of interest for military, geo-acoustic and bio-medical monitoring.

4 Conclusions

Linear-gradient single-layered microscale PDLC films are examined for tunable modulation of laser radiation. The single-layered PDLC films of E7/NOA65 with relatively large LC droplets, we have produced, exhibit a rather low switching voltage, a reduced light scattering, a high contrast ratio for amplitude modulation, as well as an efficient electrically-commanded phase modulation, additionally controllable through LC droplet size gradient. These properties may be useful for tunable PDLC-based light modulators, adaptive-optic and other practical devices and sensors.

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