

INVESTIGATION OF BRAGG GRATINGS RECORDED IN POLYMER-DISPERSED LIQUID CRYSTALS

K. Beev^{a*}, S. Sainov^a, T. Angelov^b, A. G. Petrov^b

^aCentral Laboratory of Optical Storage and Processing of Information, BAS,
1113 Sofia, Acad. G. Bonchev Str., bl. 101, Bulgaria

^bInstitute of Solid State Physics, BAS, 72 Tsarigradsko Chausse Blvd, 1784 Sofia, Bulgaria

Bragg gratings, holographically formed in polymer-dispersed liquid crystals (H-PDLCs) are studied. Mixture of the commercially available E7 liquid crystal and NOA65 polymer in ration 1:1 are employed. Polymerisation in presence of electric field is produced. A significant increase of the diffraction efficiency in the case of field-applied recording is observed. The exposure characteristics, electric field switching behaviour, polarization and Bragg angle dependences are examined.

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1. Introduction

The increased attention paid to holographic polymer-dispersed liquid crystals (H-PDLC) during the recent years is based on the widespread possibilities that they provide switchable optical elements. The low cost and the different specific characteristics obtained by varying the initial components and curing set-up confirm the interest in that material. Since the first description [1], large efforts have been exerted in order to optimize, to gain better understanding of the fundamental properties of H-PDLC and to apply and integrate them in different optical devices.

The formation of the gratings follows the next described mechanism. Phase separation of PDLC occurs during illumination with spatially modulated light distribution (interference pattern), initiating a counter diffusion of the pre-polymer to the bright regions of the interference pattern where polymerization takes place. The liquid crystal is forced and set in the dark regions of the optical field. As a result, a refractive index modulation occurs fixing the light distribution. The structure consists of alternating polymer rich and liquid crystal (LC) rich layers. An important feature of these gratings is the reversible electrical switching of the diffraction efficiency (DE). The application of strong enough electric field aligns the LC inside the droplets in which it is confined allowing the switching of the grating.

Dye molecules are added in the pre-polymer mixture in order to shift the absorption maximum in the visible spectrum. To start the free-radical polymerization processes, a co-initiator is required to generate radicals initiating the polymer curing.

The thorough H-PDLC review [2] with 63 citations was published in year 2000. It is important to note that this attractive composite recording material has a serious high voltage control drawback, connected with the strong anchoring of the nanoscale LC droplets, which is still an unsolved problem restricting many practical applications. For example, multiplexed switchable gratings [3, 4] and variable-wavelength Bragg grating [5] operate at 20-28 V/ μm , tunable Fresnel lenses [6] – at 12 V/ μm . In [7], a tunable face-centered-cubic photonic crystal operates at 15-50 V/ μm . Recently reported, dye lasing using PDLC as angle-dependant narrow spectral-band

* Corresponding author: kbeev@optics.bas.bg

feedback element [8] requires $15 \text{ V}/\mu\text{m}$. This underlines the importance of further optimization of H-PDLC electro-optical properties in order to decrease the controlling voltage.

In the present work the characteristics of Eosine dye-doped H-PDLC are examined. For the first time, to our best knowledge, H-PDLC grating formation is performed in the presence of applied AC voltages. This, to a certain extent, is similar to the applied electric field techniques, used for polymer stabilized liquid crystals. The electro-optical switching characteristics, the angular sensitivity and polarization behaviour of the gratings are studied.

2. Experimental results and discussion

The pre-polymer syrup consists of a homogeneous mixture of 49% NOA65 (Norland Optical Adhesive 65), 49% E7 liquid crystal, 0.5% Eosin dye and 1.5% Triethylamin. The sample is spread between two indium tin oxide-coated glass substrates, separated with $30\mu\text{m}$ spacers.

The transmittance visible spectra of this recording medium are investigated with Cary 5E spectrophotometer in $400 - 600 \text{ nm}$ region. Fig. 1-a demonstrates the spectra for the both polarizations at 0V electric field. In this case s- and p-polarization correspond to electric field vector parallel and perpendicular to the slit, respectively.

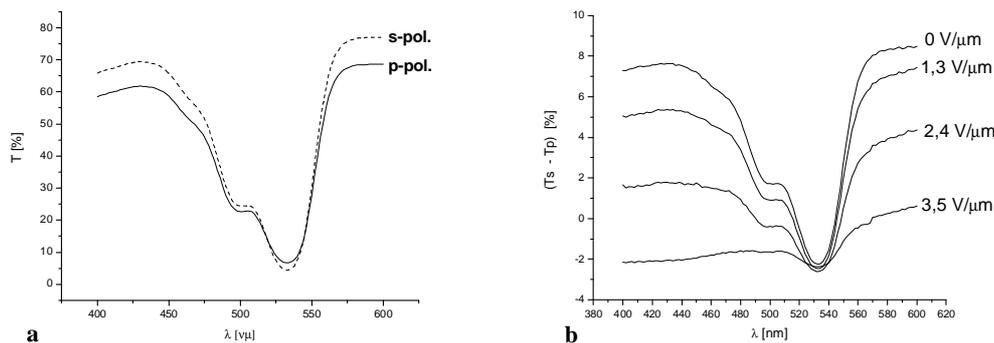


Fig. 1. Spectral transmittance of the uncured PDLC sample. a – polarization characteristics; b – transmittance differences for s- and p-polarization at different applied electric fields.

The p-polarization remains almost constant when AC voltage is applied. Conversely, voltage induced changes in the transmittance spectra for s-polarization are observed. The polarization difference $T_s - T_p$ is shown in Fig. 1-b. The experimental error is less than 0.5% [9, 10]. The observed changes are due to the dye-molecule reorientation caused by the LC rotation.

The above described samples are used for holographic gratings recording. Fig. 2 illustrates the optical set-up.

The PDLC cell is connected to AC generator working in the range of $0-105 \text{ V rms}$ at 2 kHz frequency. The beam splitter (BS) and the mirrors M_1 , M_2 provide an interference pattern from the Ar^{2+} laser irradiation at 514 nm with $1250 \text{ lines per mm}$ on the sample. The grating spacing Λ is $0.8 \mu\text{m}$. The polarization of the recording beams is s- (perpendicular to the incidence plane in this case). Simultaneously, a He-Ne laser is applied for investigation of the grating formation and DE dynamic. With the rotator R the monitoring beam polarization is changed.

In the present work different electric fields E_r are applied during grating formation in H-PDLC. Different values of the diffraction efficiency are obtained depending on E_r . At $E_r = 0 \text{ V}/\mu\text{m}$ and low applied electric field (Fig. 3-a, $E_r = 1.3 \text{ V}/\mu\text{m}$) the grating formation starts almost immediately after the laser illumination. The DE is low and even decrease at $1.3 \text{ V}/\mu\text{m}$. Fig. 3-b illustrates the higher field application leading to a rapid DE increase combined with induction period appearance. The threshold exposure ($\sim 30 \text{ mJ}/\text{cm}^2$) is relatively low – at least an order of magnitude smaller compared to [11].

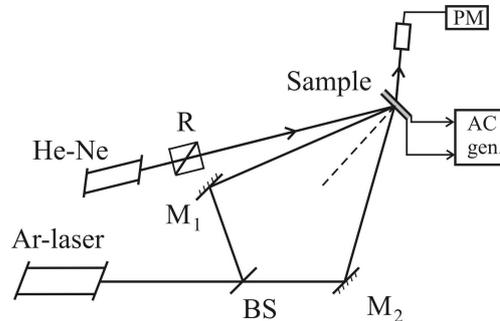


Fig. 2. Optical set-up sketch: BS – beam splitter, M_1 , M_2 – mirrors, R – polarization rotator, PM – power meter, AC gen. – AC generator.

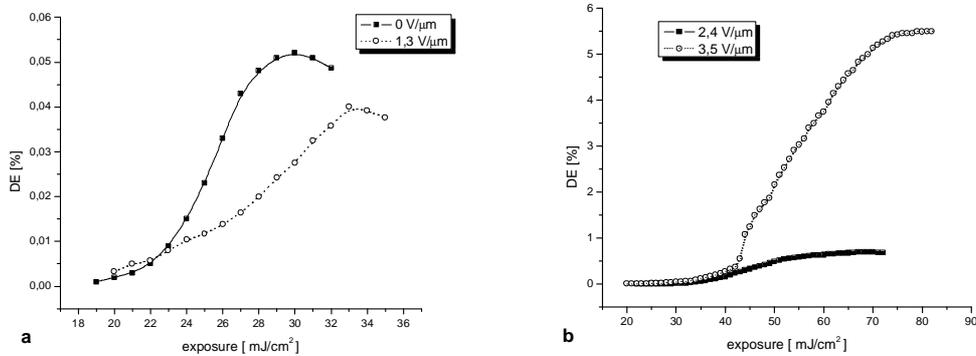


Fig. 3. The diffraction efficiency dependence on the applied voltage E_r during grating formation.

The DE increase could be related to the mass-transfer facilitation during the grating formation. The applied voltages are relatively low compared to the values necessary for total reorientation of the LC in the pre-polymer syrup. In that sense only the bulk of the LC droplet is affected. This looks as a layer to layer diffusion processes of the mesophase requiring insignificant force for their initiation.

We have investigated the DE behaviour of our Bragg grating, recorded at $E_r = 0$ and $E_r = 3.5 \text{ V}/\mu\text{m}$ as a function of root-mean-square applied voltage. The measurement results are shown in Fig. 4. The obtained threshold field is near to zero for the s-polarization when $E_r = 3.5 \text{ V}/\mu\text{m}$ is applied during recording (Fig. 4-b). For all other cases the threshold value is $\sim 2 \text{ V}/\mu\text{m}$. The increase of the applied field is coupled with electrical shorting [7]. If we extrapolate the switching curves, the DE would decrease to zero at 13-15 $\text{V}/\mu\text{m}$ for $E_r = 0$ and 4.5-6 $\text{V}/\mu\text{m}$ for $E_r = 3.5 \text{ V}/\mu\text{m}$, respectively. It is interesting to note that $\sim 11 \text{ V}/\mu\text{m}$ switching field obtained in other studies employing similar pre-polymer syrup [12].

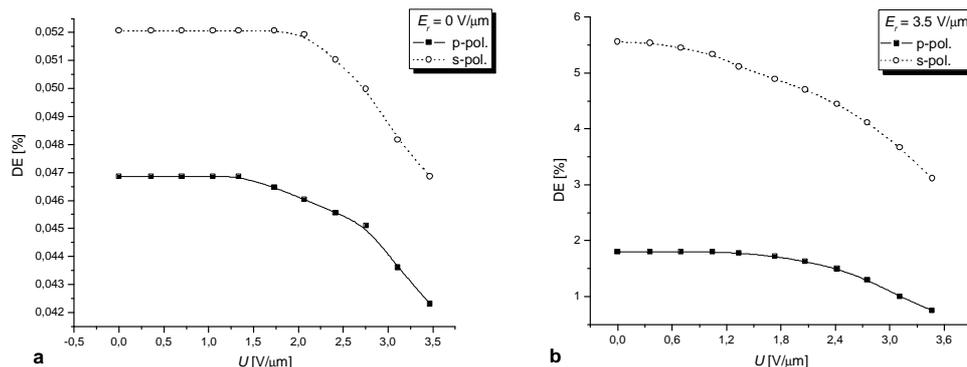


Fig. 4. Diffraction efficiency dependence on the applied electric field. (a) – $E_r = 0$; (b) – $E_r = 3.5 \text{ V}/\mu\text{m}$.

The angular sensitivity is investigated with s- and p-polarized laser beam at 633 nm with 5% accuracy. The normalized intensity dependence on the reconstruction angle is illustrated on Fig. 5. We have observed that the intensity full width at half-maximum (FWHM) shows weak polarization dependence. This result is in agreement with similar investigations [13] showing no differences. The broader FWHM in the present work is probably due to the small thickness of our Bragg gratings, recorded in relatively thin layers of 30 μm pre-polymer syrup. It could be calculated that the grating thickness is $\sim 3 \mu\text{m}$ for the lowest value $Q = 10$ of the Klein parameter, $\Lambda = 0.8 \mu\text{m}$, average refractive index $\bar{n} = 1.55$ and $\lambda = 0.514 \mu\text{m}$. For Bragg gratings, recorded in 5.3 μm thick emulsion [14], the obtained FWHM is $\sim 5.6^\circ$, i.e. very close to the obtained by us value of 6° .

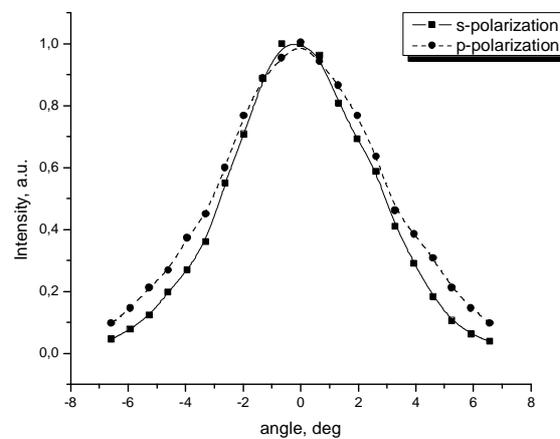


Fig. 5. Normalized DE (intensity of the diffracted beam) Bragg dependence for s- and p-polarization.

The polarization dependence on the diffracted intensity I is investigated. The polarization azimuth θ is changed by the rotator R (Fig. 2) during reconstruction. The theoretical treatment made by Gasvik [15] gives the following relation:

$$I(\theta) / I_s = (1 - B) \cos^2 \theta + B \quad (1)$$

Where the parameter B is defined as a ratio between diffracted intensities for p- and s-polarization: $B = I_p / I_s$. According to Gasvik's theory $B = 0.05$, while from Kogelnik [16] $B = 0$. In the case of Bragg grating, recorded in H-PDLC $B \sim 0.5$ [1]. From our measurements $B = 0.3$. One possible explanation of the obtained results is that theoretically only pure phase gratings are considered. Our recording medium is a composite material and for p-polarization we can expect higher light scattering.

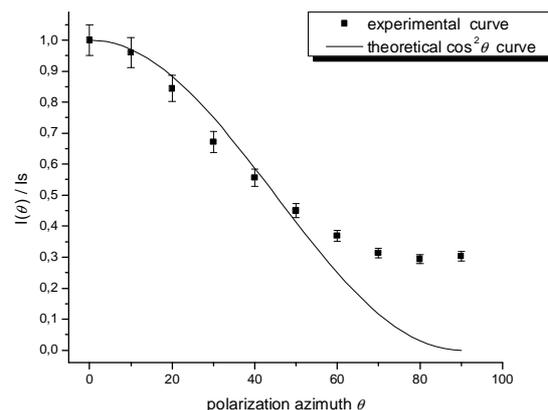


Fig. 6. The normalized diffraction efficiency dependence on the polarization azimuth.

3. Conclusion

In conclusion, we have demonstrated that by applying voltage during the holographic grating recording, it is possible to change the electric switching characteristics of H-PDLC optical elements along with substantial DE increasing. In our opinion, it is one of the ways to overcome the high voltage problem of H-PDLC optical elements. We shall report soon further studies connected with low frequency voltage that is applied on H-PDLC during recording.

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