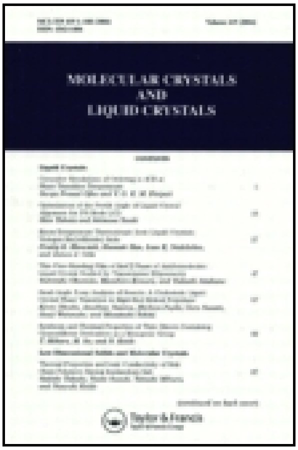

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In-Plane Switching of Holographic Polymer-Dispersed Liquid Crystal Transmission Gratings

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Electric field-induced reorientation of liquid crystal droplets in holographic polymer-dispersed liquid crystal (HPDLC) transmission gratings was investigated. In-plane reorientation of the droplet directors was attained by the use of interdigitated ITO electrodes. Samples with different angles between the directions of the grating vector and the electrodes were analyzed. The results show that intrinsic alignment of the droplets induced by the structural field is similar to the alignment induced by an external field of 6E7 V/m, i.e., the droplet directors are strongly trapped along the direction of the grating vector.

Keywords: holographic patterning; optical diffraction; polymer-dispersed liquid crystals

INTRODUCTION

Holographic polymer-dispersed liquid crystals (HPDLCs) are composite photonic media with large potential for applications in devices such as reflective displays, optical switches and interconnects, mirrorless lasers, tunable photonic crystals, etc. [1,2]. They are fabricated by photopolymerization of a mixture of photosensitive monomers and liquid crystals (LC) in the interference field of the two or more laser beams. Due to photopolymerization-induced phase separation of the constituent compounds LC molecules congregate in the dark regions of the interference pattern, while polymer material is accumulated in the bright regions. The final holographic structure is

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typically composed of LC-rich planes full of small droplets separated by planes of a more or less pure polymer. Structures with very high refractive-index contrast can be achieved [3,4].

One of the main advantages of photonic structures made from HPDLCs is that their diffractive properties are electrically switchable by relatively low external voltages. Application of an external field reorients the optical axis within the birefringent LC domains and thus modifies the refractive-index mismatch between the LC regions and the polymer network. Understanding of field-induced structural modifications is very important for further development of the HPDLC media. In view of applications one of the most important parameters is the magnitude of the critical field needed to modify the droplet orientation. This is determined by the structural anisotropy of the system that is, through shape and surface anchoring of the cavities and the associated local hindrance of the droplet directors.

It is well known that diffraction efficiency of H-PDLC gratings strongly depends on the polarization state of the incident light and is typically much larger for polarization perpendicular to the liquid crystal (LC) rich planes (*p* polarization) than for polarization along the LC rich planes (*s* polarization) [5,6]. This property is presumably related to the elongated shape of the LC droplets, which in combination with appropriate surface anchoring leads to the nematic director field with preferred direction perpendicular to the holographic planes [3,7,8].

To probe the intrinsic level of orientational order of the LC droplets within the polymer matrix we studied field-induced reorientation of the in-plane switched (IPS) HPDLC transmission gratings made from commercially available constituents. Optical diffraction of the gratings with different angles between the grating vector and the applied field was analyzed. Our findings clearly demonstrate that the intrinsic alignment induced by a local structural field and the one induced by external electric field are of the same order of magnitude.

EXPERIMENT

The prepolymer mixture used to make our HPDLC samples was prepared from commercially available constituents. It was composed from: 50 wt% TL205 nematic LC (EM Industries), 30 wt% 2-ethylhexyl acrylate (Sigma-Aldrich), 5.625 wt% aliphatic urethane acrylate oligomer 8301 (Ebecryl (Radcure)), 1.875 wt% trimethylolpropanetriacrylate (Sigma-Aldrich) and 12.5 wt% 1,1,1,3,3,3-Hexafluoroisopropyl acrylate (HFIPA, Chem Service). A drop of the mixture was placed between a clean glass plate and a glass plate covered with interdigitated indium-tin-oxide (ITO) electrodes. The electrodes were formed by the conventional photolithographic method and were 16.7 μm wide, while the interelectrode separation was 33.3 μm, so that the periodicity of the corresponding electrode structure was 50 μm. The glass plates were separated by 5 μm glass spacers to set the thickness. Photopolymerization was activated by exposing the sample to the interference field of the two UV laser beams at $\lambda_{UV} = 351$ nm. The recording lasted for 60 s with a light intensity of 22 mW. An unslanted transmission grating with a grating spacing $\Lambda = 1$ μm was fabricated (Fig. 1). After holographic recording the grating was postcured for 300 s by a broadband incoherent UV lamp to assure complete polymerization of the material.

Before the recording process a glass cell was rotated for some selected angle θ with respect to the modulation direction of the interference pattern. This way we obtained gratings with different angles between the in-plane applied field $\boldsymbol{E}$ and the holographic grating vector $\boldsymbol{K}_g$ (Fig. 2). Samples with $\theta = 0°$, 30°, 45°, 60° and 90° were prepared.

In-plane reorientation of the LC droplets was induced by applying a 10 kHz square-wave voltage to the finger electrodes. The resulting modification of the diffraction properties was probed by illuminating the sample with a linearly polarized He-Ne laser beam ($\lambda_{HN} =$ 632.8 nm) impinging on the grating at the Bragg angle (–12°) with respect to the sample normal. The beam was tightly focused onto the sample, so that the beam waist in the HPDLC layer has a diameter

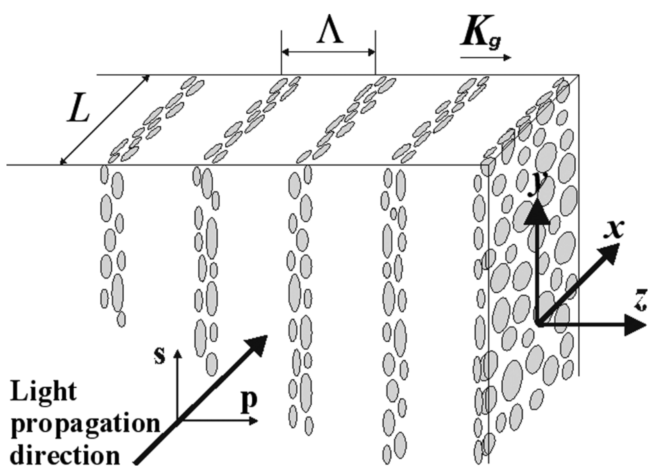

FIGURE 1 Schematic drawing of the HPDLC transmission grating.

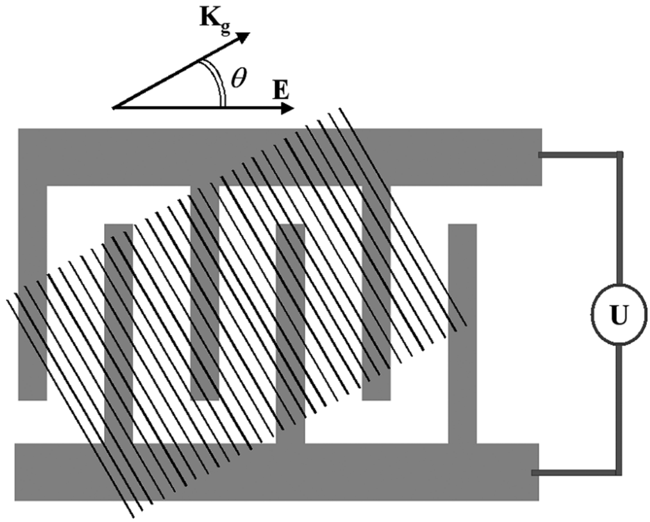

FIGURE 2 Orientation of the holographic grating planes (thin parallel lines) with respect to the interdigitated electrodes.

of 7 μm, i.e., considerably below the interelectrode spacing. This enabled us to probe the lateral variations of the structure with respect to the distance from the finger electrodes and consequently precisely focus the beam in the central region between the two electrodes. Two silicon photodiodes were used to simultaneously detect the intensity of the transmitted beam (0th diffraction order, I_0) and the intensity of the diffracted beam (1st diffraction order, I_1). The polarization direction of the incident beam was set to be either s or p polarization (Fig. 1).

RESULTS AND DISCUSSION

A typical characteristics of PDLCs and HPDLCs is their translucent appearance, which is a consequence of the refractive index mismatch between the neighboring LC droplets and between the LC material and the polymer host. The later is usually selected so that its refractive index coincides with the ordinary refractive index of the LC. In the absence of external electric field droplet directors $\boldsymbol{N}_\mathbf{d}$ of the bipolar LC droplets, which define local direction of the optical axis, point in direction determined by the structural field of the system. The structure of PDLCs is isotropic and hence droplet directors point in random directions. In HPDLCs the symmetry is broken and consequently the structure might impose some preferential direction of the $\boldsymbol{N}_{\mathbf{d}}$. The main aim of our experiments was to confirm the existence of this preferential direction and to determine the magnitude of the corresponding alignment effect.

Figure 3 shows diffraction intensities as a function of RMS applied voltage U obtained for the sample with $\theta = 0^{\circ}$ (Fig. 2). This means that the applied field $\boldsymbol{E}$ was parallel to the grating vector $\boldsymbol{K}_{\mathbf{g}}$. The intensities of the 0th and the 1st diffraction orders are given relatively with

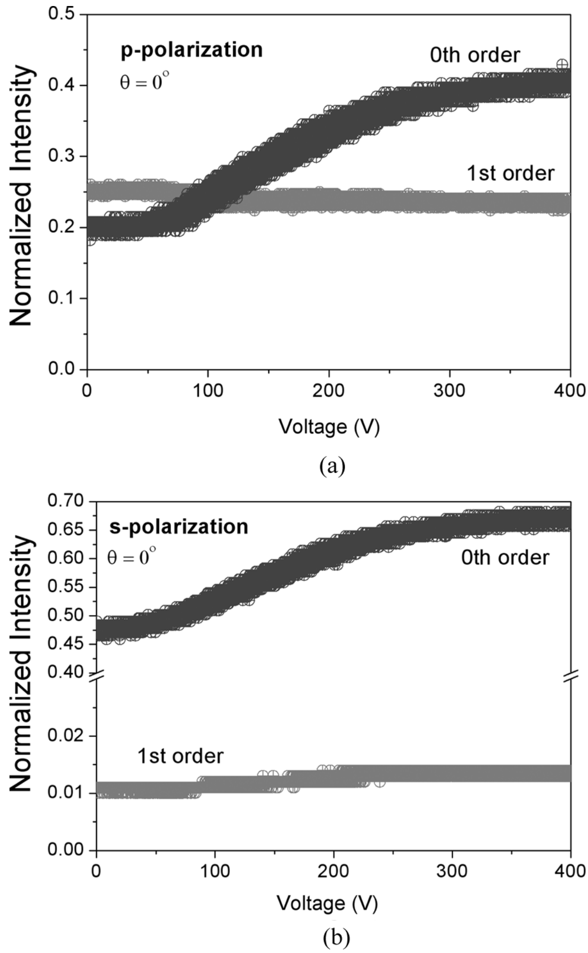

FIGURE 3 Intensities of the 0th and the 1st diffraction orders for grating structure tilted for 0° with respect to the intercalated electrodes: response for p-polarized beam (a) and for s-polarized beam (b).

respect to the incident intensity. The 1st order diffraction intensity for *p*-polarized beam is initialy (for $U = 0$) 25 times larger than for *s*-polarized beam. This can be explained by strong alignment of the droplet directors $\boldsymbol{N}_\mathbf{d}$ along the direction of $\boldsymbol{K}_\mathbf{g}$. The optical axis of the LC-droplet rich planes is consequently also parallel to the $\boldsymbol{K}_\mathbf{g}$. In such a configuration *p*-polarized beam corresponds to an extraordinary ray, which refractive index is larger than the refractive index of the surrounding polymer-rich planes. Therefore a strong modulation of the refractive index is perceived by the *p*-polarized beam. On the contrary, the *s*-polarized beam corresponds to the ordinary ray of the LC-rich planes, which refractive index is more or less matched with the refractive index of the polymer planes. As a result only a weak refractive index modulation is detected by the *s*-polarized light.

Application of external voltage of the magnitudes up to $U = 400\,\mathrm{V}$ ($E = 80\,\mathrm{V}/\mu\mathrm{m}$) induces only relatively minor perturbations of the 1st order diffraction intensities. This behaviour indicates that already at $U = 0$ the droplet directors are aligned more or less to the maximum possible level, so that external field cannot further improve their alignment and consequently refractive index modulation is practically unaffected by the field. In contrast to the 1st order diffraction, the 0th order diffraction intensities significantly increase with increasing voltage for both polarizations. This effect is consequence of the reduced optical loss associated with the reduced incoherent light scattering within the sample. Our observations indicate that the incoherent and the coherent optical effects in HPDLCs are quite differently affected by external field.

Figure 4 shows the results achieved for $\theta = 60^\circ$. For $\theta \neq 0^\circ$ electric field tends to align the droplet directors along the direction of the field and consequently optical axis of the LC-droplet rich planes is rotated from the direction of the $\boldsymbol{K}_\mathbf{g}$ towards the direction of the field. The *p*-polarized beam, which for $U = 0$ corresponds to the optical eigen-wave, is after reorientation not the eigen-wave anymore. It is hence transformed to the elliptically polarized beam and consequently its refractive index modulation decreases. The situation for *s*-polarized beam is similar, but produces an increase of the refractive index modulation.

The reorientation effect is even more profound for the sample with $\theta = 90^\circ$ (Fig. 5). There one can clearly notice an opposite behaviour of the 1st order diffraction intensities for *p* and for *s* polarized beams. For $U = 0$ the normalized value of the $I_{1\mathrm{p}}$ is around 0.3, while the value of $I_{1\mathrm{s}}$ is very low. For $U \sim 300\,\mathrm{V}$ $I_{1\mathrm{p}}$ becomes very low, while $I_{1\mathrm{s}} \sim 0.3$. This means that external field of $U \sim 300\,\mathrm{V}$ ($E = 60\,\mathrm{V}/\mu\mathrm{m}$) causes rotation of the $\boldsymbol{N}_\mathbf{d}$ for 90° with respect to the initial direction. It also induces more or less the same level of orientational order than the

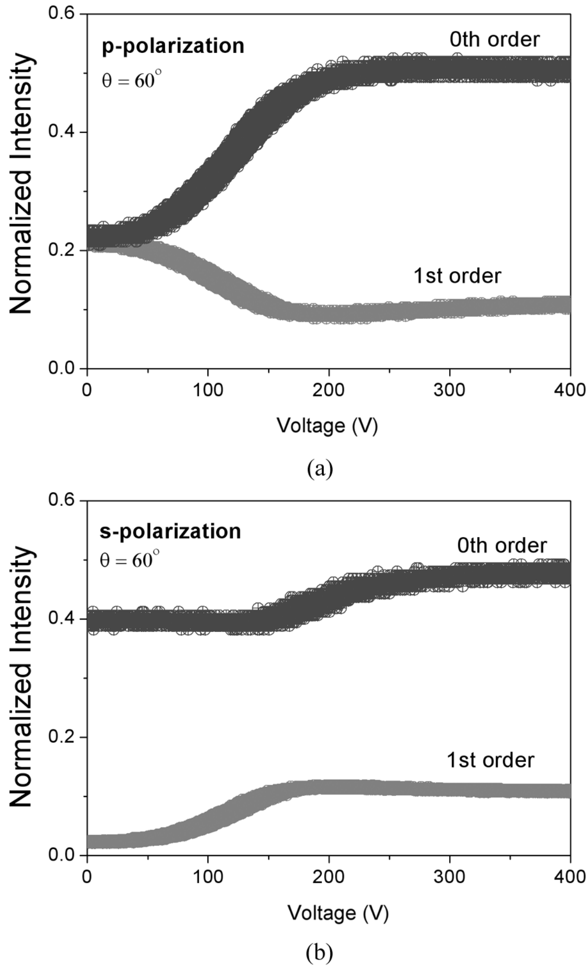

FIGURE 4 Intensities of the 0th and the 1st diffraction orders for grating structure tilted for 60° with respect to the intercalated electrodes: response for p-polarized beam (a) and for s-polarized beam (b).

intrinsic structural field. These findings signify that an external electric field of 60 V/μm acting in the presence of the intrinsic structural field is large enaugh to overcome the alignment effect of the structural field and cause a saturation of the droplet alignment.

In Figures 3–5 one can notice that diffraction intensities of different samples ($\theta = 0^\circ$, 60°, 90°) measured at $U = 0$ are similar, but not exactly the same. This problem is typical for HPDLC gratings, because their

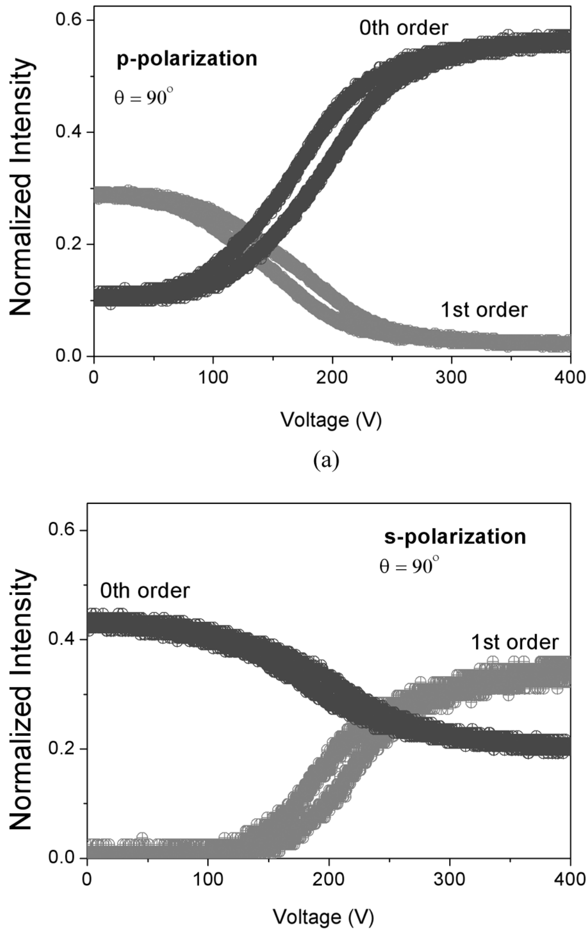

FIGURE 5 Intensities of the 0th and the 1st diffraction orders for grating structure tilted for 90° with respect to the intercalated electrodes: response for p-polarized beam (a) and for s-polarized beam (b).

properties very strongly depend on minor differences in the sample preparation procedure. For that reason any more detailed quantitative comparison between different samples would be quite speculative. Nevertheless, the above-described observations clearly demonstrate the existence of a strong structural field-induced alignment of the LC droplets in the HPDLC gratings.

CONCLUSIONS

Our results show that in-plane switching provides a very convenient configuration to study field-induced reorientation of the LC droplets in HPDLC transmission gratings. We found that the intrinsic alignment of the droplets is very large, namely that droplet directors are strongly trapped along the direction of the grating vector. The alignment effect of the structural field is equivalent to the alignment effect of an external field of 60 V/μm. Our experiments also demonstrate that by appropriate arrangement of the finger electrodes fine-tuning of optical diffraction can be achieved, which is difficult to realize in the conventional out-of-plane switching geometry.

REFERENCES

[1] Crawford, G. P. (2003). *Optics and Photonics News*, *14*, 54.
[2] Sutherland, R. L., Tondiglia, V. P., Natarajan, L. V., Bunning, T. J., & Adams, W. W. (1994). *Appl. Phys. Lett.*, *64*, 1074.
[3] Bowley, C. C. & Crawford, G. P. (2000). *Appl. Phys. Lett.*, *76*, 2235.
[4] Bunning, T. J., Natarjan, L. V., Tondiglia, V. P., & Sutherland, R. L. (2000). *Ann. Rev. Mater. Sci.*, *30*, 83.
[5] Jazbinšek, M., Olenik, I. D., Zgonik, M., Fontecchio, A. K., & Crawford, G. P. (2001). *J. Appl. Phys.*, *90*, 3831.
[6] Drevenšek-Olenik, I., Fally, M., Ellabban, M. A. (2006). *Phys. Rev E*, *74*, 021707.
[7] Sutherland, R. L., Tondiglia, V. P., Natarajan, L. V., & Bunning, T. J. (2001). *Appl. Phys. Lett.*, *79*, 1420.
[8] Sutherland, R. L. (2002). *J. Opt. Soc. Am. B*, *19*, 2995.