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We investigated optical properties of a polymer dispersed liquid crystal (PDLC) film in-plane switched by a periodic pattern of interdigitated electrodes. Such a system acts as a thin optical phase grating which diffraction efficiency strongly depends on polarization state of the incident light. The intensity and dynamic response of various diffraction orders were analyzed as a function of the applied voltage amplitude. Our results demonstrate that by using a PDLC very effective phase gratings with response times below 10 ms can be achieved at the expense of slightly higher driving fields than needed for the similar bulk nematic liquid crystal gratings.

Keywords: in-plane switching; optical diffraction gratings; polymer dispersed liquid crystals

INTRODUCTION

Switchable optical diffraction elements are one of the key issues in the rapidly expanding field of optical data processing and communication. Accordingly the research of new materials with intriguing diffractive

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properties is a topic that strongly gains in attention. The large dielectric and optical anisotropy of liquid crystals (LC) makes these media promising for applications in switchable diffraction gratings. Two complementary routes can be used to construct grating structures in thin layers of the LCs. In the first one, periodic boundary conditions are applied to form a periodic orientational pattern, while a homogeneous electric field is used to reduce the inhomogeneity and hence weaken the diffraction effects [1–5]. In the second principle, uniform boundary conditions provide a homogeneous intrinsic LC state and a periodic distortion of the director field is achieved by applying an external electric field with a periodic spatial profile [6–10].

Most of the investigations reported in the literature consider bulk nematic phases sandwiched between the two substrates. In such a configuration a typical driving field necessary to produce a phase retardation $\Delta\Phi = \pi$ in the LC layer with the thickness of only a few optical wavelengths is of the order of $1\,V/\mu m$, which is very low compared to solid state electro-optic media. On the other hand, the use of a bulk LC material is associated with some general features that may be inconvenient for many applications. For example, due to the orientational coupling of the LC molecules in various sample regions the spatial profile of the molecular reorientation is always very smooth compared the profile of the electric field. Additionally, at high field amplitudes orientational domains are commonly formed in the course of the switching process, which results in the formation of defect walls and disclination lines. These properties result in a relatively slow dynamic response with switching-off times in the range of 10–100 ms.

Some of the above mentioned problems might be solved by adding a polymer network to the nematic LC phase. By using a polymer-dispersed liquid crystal (PDLC) instead of a bulk LC material the spatial profile of the reorientational structure as well as its dynamic response are governed by the LC droplet size rather than by the bulk electric coherence length. This provides a possibility to optimize the material properties for a selected application by controlling the morphology of the sample. In the literature relatively few reports can be found on investigations of the periodic PDLC structures. Experimental results are reported for PDLC gratings assembled by illumination of a photopolymer-LC mixture through an appropriate periodic photo mask [11–13], while to our knowledge PDLC gratings based on a periodic electric field has been studied only theoretically [14]. The latest route is, however, very attractive, as the electrode addressing schemes fabricated by nowadays electron-beam lithography techniques can be extremely fine and complex and hence provide a possibility to construct various complicated diffractive structures.

In this contribution we discuss the diffractive properties of a PDLC film sandwiched between an ordinary glass plate and a glass plate with interdigitated electrodes. Our measurements focus on optical grating effects in PDLC. Our results demonstrate that by in-plane electrode configuration a very effective optical phase modulation with response times considerably below 10 ms can be achieved at the expense of slightly higher driving fields than needed for the bulk nematic LC gratings.

EXPERIMENTAL

The prepolymer mixture used to make our PDLC samples was prepared from commercially available constituents. It was composed from: 50 wt% TL203 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, Sigma-Aldrich). Similar formulations have also been reported in the literature [15]. A drop of the mixture was placed between a clean glass plate and a glass plate 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 pitch of the corresponding grating structure was $\Lambda = 50\,\mu m$ (Figs. 1 and 2). The glass plates were separated by 5 μm glass spacers to set the thickness L. Photopolymerization was activated by exposing the sample to UV laser radiation at 351 nm. The recording lasted for 60 s with a light intensity

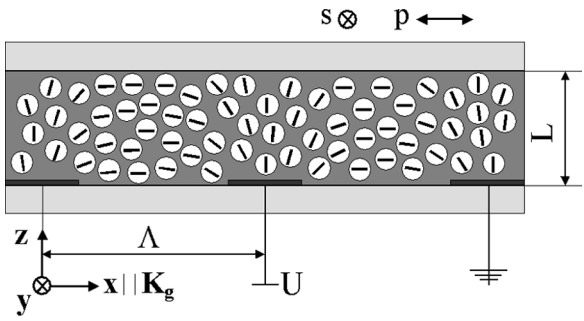

FIGURE 1 Schematic drawing of the PDLC optical phase grating of thickness L and grating spacing Λ. At high enough voltages the average nematic director field within a single droplet is parallel to the electric field lines. The directions of s and p polarizations of incident optical beam are also denoted.

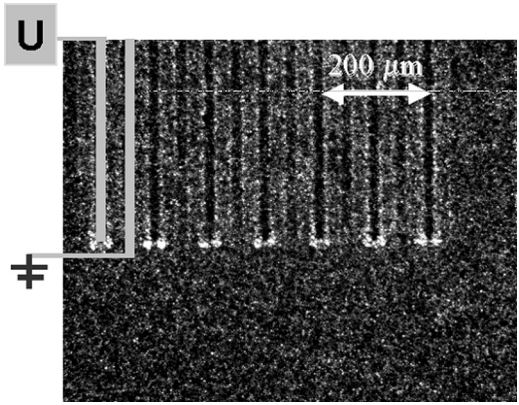

FIGURE 2 Optical polarization microscopy image of our in-plane switched PDLC sample. The position of two neighboring electrodes is marked.

of about 22 mW. After this the gratings were postcured for 300 s under a broadband UV lamp to stabilize any unreacted funtional groups from further photoreactions. The morphology of the samples was analysed by scanning electron microscopy (SEM), which revealed that photopolymerization resulted in formation of the phase-separated LC domains with diameters of 100–300 nm (Fig. 3). Due to the relatively small LC droplet size of our PDLC samples their transmittance in the absence of external voltage was relatively high, i.e., about 55%.

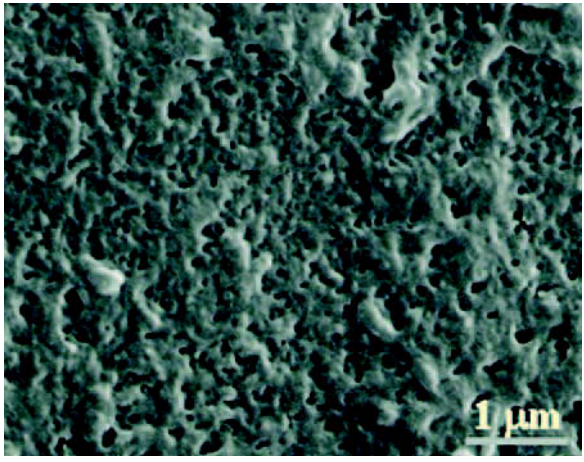

FIGURE 3 Scanning electron microscopy (SEM) image of the sample.

Reorientation of the nematic director field in the LC droplets was induced by applying a 10 kHz square-wave voltage to the finger electrodes. The resulting diffraction effects were probed by illuminating the sample with a linearly polarized He-Ne laser beam ($\lambda = 632.8$ nm) nm) impinging on the sample at normal incidence. The beam waist diameter in the PDLC layer was around 1 mm. The intensity of diffracted beams in various diffraction orders was measured by photodiodes connected to the digital oscilloscope.

DIFFRACTIVE PROPERTIES

Application of an external voltage to a PDLC in general causes an increase of the sample transmitivity as it reduces the randomness of molecular directors of the LC droplets [16]. The droplet directors align in direction of the local electric field, which in our configuration means orthogonal to the glass plates in the regions above the electrodes, and parallel to the glass plates in the regions between the electrodes (Fig. 1). The reorientation results in a periodic spatial modulation of the refractive index for *p*-polarized optical radiation, while *s*-polarized radiation should not experience any grating effects at high enough voltages.

Figure 4 shows the intensities of the 0th and the 1st diffraction orders for *p*-polarized incident light as functions of the applied voltage amplitude. The intensity is given relatively with respect to the intensity of the incident beam. Although the opacity of the material decreases with increasing field, the intensity of the 0th diffraction order (transmitted beam) decreases. This is because the diffraction

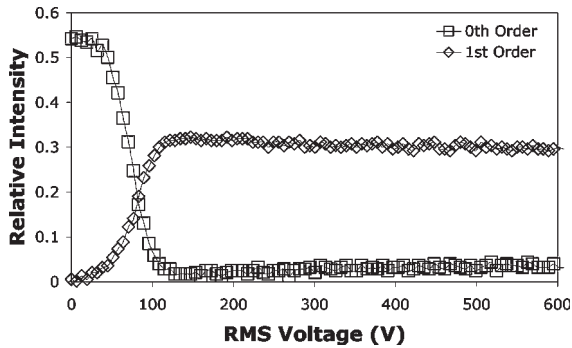

FIGURE 4 Relative intensity of the 0th and the 1st diffraction orders for *p*-polarized incident beam as a function of applied voltage amplitude. Lines are guide to the eye.

effects prevail random light scattering and more and more light is diffracted to higher diffraction orders. The intensity of the 0th diffraction order drops almost to zero at $U \approx 150\,\mathrm{V}$, while afterwards it slightly increases with increasing voltage. The intensity of the 1st diffraction order initially increases with increasing voltage, then it reaches a maximum at $U \approx 120\,\mathrm{V}$, and afterwards a bit decreases with increasing voltage. It is interesting that the ratio $(I_{1,max}/I_{0,max}) \approx 0.6$ (where indices denote the diffraction order) is much larger from the theoretical limit of 34% known for thin (Raman–Nath) optical phase gratings [17]. This unusual feature is a consequence of the reduced opacity of the material at $U \approx 120\,\mathrm{V}$.

Figure 5 shows the dependencies of the intensities of the 2nd–4th diffraction orders for *p*-polarized incident light on applied voltage amplitude. The 3rd and the 4th orders have relative intensities of only a few %, but otherwise exhibit properties very similar to the 1st order, while the behavior of the 2nd order is more exceptional. This diffraction order has a significant intensity even in the absence of external voltage. Additionally, by increasing the applied voltage amplitude its intensity increases more slowly than for other diffraction orders so that modifications take place up to $U \approx 400\,\mathrm{V}$. We relate this unusual behaviour to irreversible material modifications at the edges of the finger electrodes. In this region the magnitude of the field is very high and probably causes not only reorientation of the LC droplets, but also rearrangement of the polymer matrix. Examination of the samples by optical polarization microscopy revealed that these sample regions remained biaxial also after the voltage had been removed from the electrodes. In our electrode arrangement, in which the interelectrode

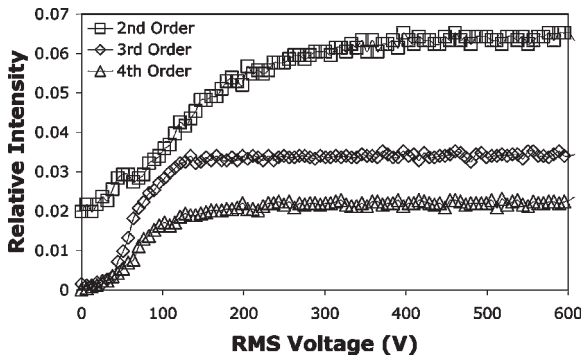

FIGURE 5 Relative intensity of the 2nd–4th diffraction orders for *p*-polarized incident beam as a function of applied voltage amplitude. Lines are guide to the eye.

spacing is twice the electrode size, structural modifications in the vicinity of the electrode edges affect mainly the 2nd diffraction order.

The unusual features of the 2nd diffraction order are pronounced also for *s*-polarized incident radiation. The intensity of various diffraction orders as a function of external voltage for *s* polarized beam is given in Figure 6. Also in this case the 2nd diffraction order has a significant intensity even in the absence of the external voltage. The intensity first increases with increasing voltage, then it reaches a maximum at $U \approx 50\,\mathrm{V}$, and afterwards it rapidly decreases to a very low value observed for $U > 150\,\mathrm{V}$. The intensities of the 1st and the 3rd diffraction orders are very low and also nearly vanish for high voltage amplitudes. This is because for $U > 150\,\mathrm{V}$ in the whole sample region the droplet directors align in the direction of local field and consequently the *s*-polarized beam represents an ordinary ray for all the droplets (Fig. 1). For $U < 150\,\mathrm{V}$ the alignment take place primarily in the regions of the highest field amplitude, i.e., near edges of the electrodes, so that also *s*-polarized beam experiences some phase as well as amplitude modulation. Contrary to the *p*-polarization case, for *s*-polarized beam the intensity of the 0th diffraction order increases with increasing voltage (see inset of Fig. 6). This is because the diffraction for *s*-polarization is in general very low, so that $I_0(U)$ in this case reveals a usual dependence of the PDLC transmittance on the external field [16].

DYNAMIC PROPERTIES

The second part of our study considered the time response of the gratings. To measure the switching times of various diffraction orders

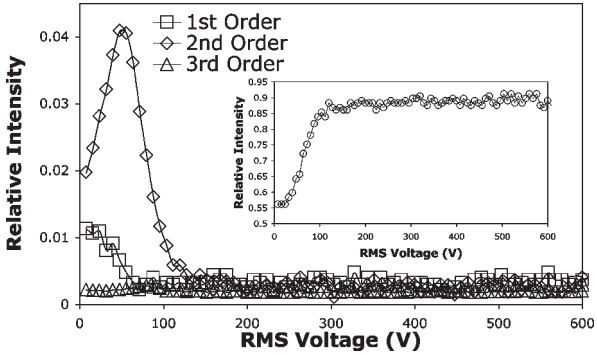

FIGURE 6 Relative intensity of various diffraction orders for *s*-polarized incident beam as a function of applied voltage amplitude. Lines are guide to the eye.

the basic 10 kHz driving voltage was amplitude modulated with the square waveform at the frequency of 10 Hz. Two different arrangements were analyzed: the modulation amplitude of $U = 800\,\mathrm{V}$ at modulation depth of 100%, and the modulation amplitude of $U = 150\,\mathrm{V}$ at modulation depth of 50%. The results are shown in Figures 7–9. The higher voltage was present on the sample from $-0.1\,\mathrm{s} < t < -0.05\,\mathrm{s}$ and $0 < t < 0.05\,\mathrm{s}$. The results for the 0th and the 1st diffraction order are given for *p*-polarized light, while for the 2nd diffraction order they are for *s*-polarized light. The behaviour of the 2nd diffraction order is again quite specific. For instance, it exhibits very slow switching-off dynamics for the 50% modulation depth. This observation supports the above given hypothesis that the corresponding structural changes in the regions close to the electron edges involve not only the LC material but also the surrounding polymer matrix.

The values of the switching -on and -off time associated with the diffracted beam intensity variation from 10–90% of the full modification are given in the Table 1. The values of the switching-on time depend on the voltage amplitude and are always significantly below 10 ms, while the values of switching-off time are around 10 ms. However, analyzing the dynamic response (Fig. 7–9) in more detail one can notice that in most cases the switching process is composed of a fast initial modification accompanied by a long slowly relaxing "tail". Such a behaviour is characteristic for practically all kinds of confined LC structures and was investigated in detail by dynamic light scattering (DLS) studies of PDLCs and other systems. The fast relaxation is due to intradroplet or intrapore orientational relaxation, while the slow decay is attributed to orientational diffusion of the preferential

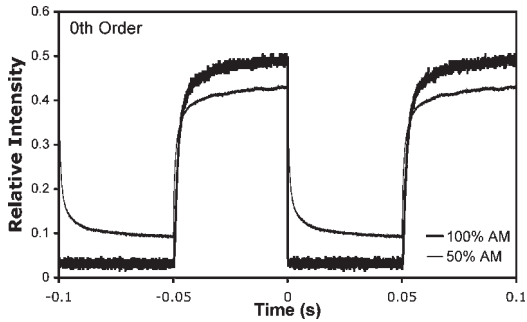

FIGURE 7 Time dependencies of the intensity of the 0th diffraction order for *p*-polarized incident beam during switching with the square waveform amplitude modulated voltage.

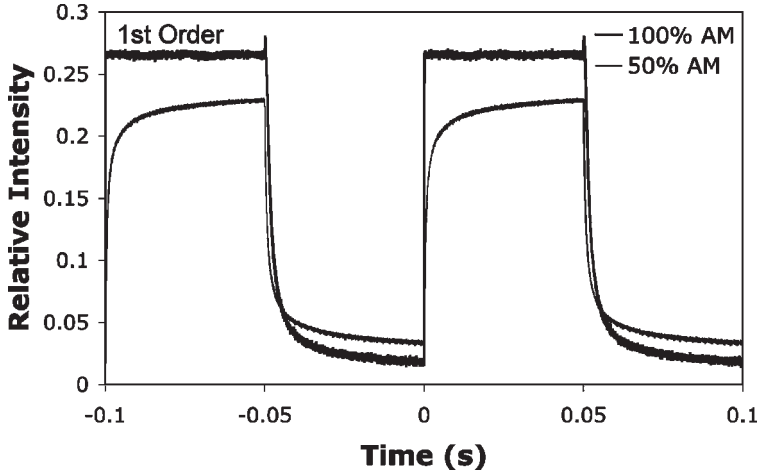

FIGURE 8 Time dependencies of the intensity of the 1st diffraction order for *p*-polarized incident beam during switching with the square waveform amplitude modulated voltage.

director orientation due to randomness and irregularities of the polymer-LC interface [18–21]. It is known that the slow process can be suppressed by application of some additional structural fields, as

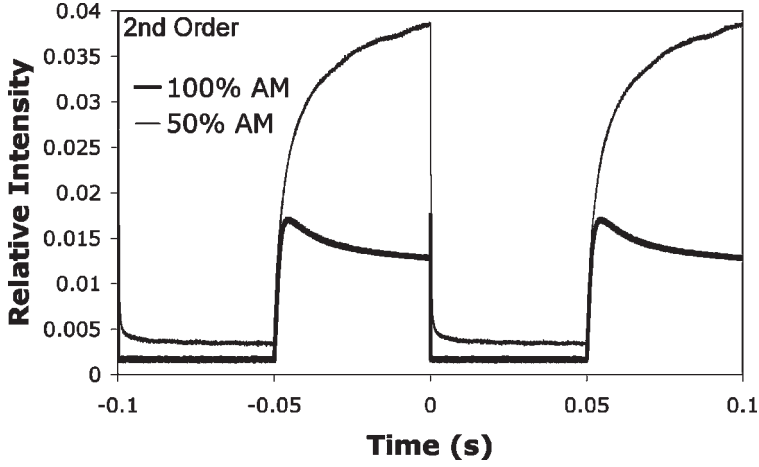

FIGURE 9 Time dependencies of the intensity of the 2nd diffraction order for *s*-polarized incident beam during switching with the square waveform amplitude modulated voltage.

TABLE 1 Switching -on and -off Times for Various Diffraction Orders Measured at two Different Amplitude Modulation Depths of the Driving Voltage

Diffraction order	Modulation depth (%)	Switching-on time (ms)	Switching-off time (ms)
0th	100	0.04	10.63
0th	50	6.94	10.10
1st	100	0.04	8.38
1st	50	7.55	7.64
2nd	100	0.04	2.26
2nd	50	0.61	23.07
3rd	100	0.05	3.45
3rd	50	5.51	5.58

for instance the one associated with LC domains of a highly anisotropic shape [21,22]. Consequently, PDLC gratings with a structure similar to our samples, but with elongated LC droplets, are expected to exhibit response times considerably below the values found in our experiments.

CONCLUSIONS

Our results show that PDLCs in-plane switched by interdigitated electrodes exhibit very similar optical diffraction properties as bulk LC materials. Both of them can be made to work either as a phase or amplitude grating, depending on whether the switchable layer is placed between crossed polarizers or not. However, in contrast to LC gratings PDLC gratings have no correlation between the LC orientation in various sample regions, so the smoothing effects are reduced and can be controlled by varying the size of the droplets. The response time of the PDLC gratings is also governed by the size and the shape of the droplets and can be tailored in accordance with the requirements for a specific application. So we believe that, when combined by electrode addressing schemes fabricated by electron-beam lithography techniques, in-plane switched PDLCs can be very appropriate materials for switchable optical diffraction elements.

REFERENCES

[1] Prost, J. & Pershan, P. S. (1976). *J. Appl. Phys*., *47*, 2298.
[2] Gibbons, W. M. & Sun, S. T. (1994). *Appl. Phys. Lett*., *65*, 2542.
[3] He, W. T., Nose, T., & Sato, S. (1998). *Jpn. J. Appl. Phys. Part 1*, *37*, 4066.

[4] Sakata, H. & Nishimura, M. (2000). *Jpn. J. Appl. Phys*., *Part 1*, *39*, 1516.
[5] Wang, X., Wilson, D., Muller, R., Maker, P., & Psaltis, D. (2000). *Appl. Opt*., *39*, 6545.
[6] Lindquist, R. G., Kulick, J. H., Nordin, G. P., Jarem, J. M., Kowel, S. T., Friends, M., & Leslie, T. M. (1994). *Opt. Lett*., *19*, 670.
[7] Titus, C. M., Kelly, J. R., Gartland, E. C., Shiyanovskii, S. V., Anderson, J. A., & Bos, P. J. (2001). *Opt. Lett*., *26*, 1188.
[8] Fujieda, I. (2001). *Appl. Opt*., *34*, 6252.
[9] Liu, W. M. & Kelly, J. (2001). *Mol. Cryst. Liq. Cryst*., *358*, 199–208.
[10] Brown, C. V., Kriezis, Em. E., & Elston, S. J. (2002). *J. Appl. Phys*., *91*, 3495.
[11] De Filpo, G., Nicoletta, F. P., Macchione, M., Cupelli, D., & Chidichimo, G. (2001). *Adv. Funct. Mater*., *11*, 457.
[12] Ren, H. & Wu, S. T. (2002). *Appl. Phys. Lett*., *81*, 3537.
[13] Ren, H., Fan, Y. H., & Wu, S. T. (2003). *Appl. Phys. Lett*., *83*, 1515.
[14] Vicari, L. (1998). *Phys. Rev. E*, *58*, 3280.
[15] De Sarkar, M., Qi, J., & Crawford, G. P. (2002). *Polymer*, *43*, 7335.
[16] Drzaic, P. S. (1995). *Liquid Crystal Dispersions*, *Liquid Crystals Series*, World Scientific: Singapore, Vol. 1.
[17] Hariharan, P. (1996). *Optical Holography – Principles, techniques and applications*, Cambridge Univ. Press.
[18] Bellini, T., Clark, N. A., & Schaefer, D. W. (1995). *Phys. Rev. Lett*., *74*, 2740.
[19] Mertelj, A. & Čopič, M. (1997). *Phys. Rev. E*, *55*, 504.
[20] Čopič, M. & Mertelj, A. (1998). *Phys. Rev. Lett*., *80*, 1449.
[21] Drevenšek-Olenik, I., Jazbinšek, M., Sousa, M., Fontecchio, A. K., Crawford, G. P., & Čopič, M. (2004). *Phys. Rev. E*, *69*, 051703.
[22] Wu, B. G., Erdmann, J. H., & Doane, J. W. (1989). *Liq. Cryst*., *5*, 1453.