Electric field control of diffraction and noise in dye-doped liquid crystals

M. KACZMAREK, R. S. CUDNEY[a] , S. A. TATARKOVA
School of Physics, University of Exeter, Exeter EX4 4QL, United Kingdom.
[a] División de Física Aplicada, CICESE, Apdo. Postal 2732, Ensenada, B.C, Mexico.

ABSTRACT

We present results on permanent gratings in highly dye-doped liquid crystal cells without polymer coatings of the cells' surfaces. The surface-mediated gratings remain in cells for months without degradation of their quality. The peak diffraction efficiency can be controlled, enhanced or decreased, by applying low voltage AC field. At low frequencies, below 1 Hz, the diffracted signal can modulated by the AC field, but the time development of the signal shows a complex response. The enhancement of diffraction can be, however, observed at all frequencies we tested (0.1 Hz – 300 kHz). The permanent gratings cannot be removed by heating above the liquid crystal phase transition temperature as on cooling the diffraction efficiency is restored.

Keywords: reorientation, permanent grating, dye doped liquid crystals, surface anchoring

INTRODUCTION

One of the most efficient optical nonlinear materials developed so far are photorefractive-like liquid crystals [1]. Their thin film format (typically between 10-25 μm), ideal for integrated optics applications, is accompanied by large diffraction efficiencies and high coupling coefficients [2,3].

There have been several reports on the performance of photorefractive liquid crystals [4,5,6,7]. Photorefractive liquid crystals are based on liquid crystals mixed with either dye or fullerene or with photosensitive polymer layers added to the cell's surfaces. Liquid crystals, sensitised with dopants, are also excellent materials to write strong optical patterns [8,9]. The reorientation process that liquid crystal molecules undergo can be significantly influenced by surface-mediated effects and anchoring, which can ultimately lead to permanent fixing of gratings [10].

Gibbons and co-workers studied liquid crystals with dyes added either to the liquid crystal mixture [11] or to a polymer layer on the surface of a substrate [12]. They showed that after prolonged illumination (several minutes to hours) the liquid crystal molecules re-orient and remain in that state even after light was switched off. They also investigated the electro-optical properties of the optically generated gratings[13]. Chen and co-workers [14] also demonstrated that azo-dye doped nematic liquid crystals can work well as a holographic storage medium. Khoo and co-workers [4] showed that with the application of a dc field prior and then during light illumination, persistent refractive index changes can be created. Recently, Simoni and co-workers demonstrated successful holographic grating storage in dye doped liquid crystals [15] and permanent reorientation of the director [16].

In this paper we present the results on creating permanent patterns in dye doped liquid crystals using high concentration of the dye with no special polymer layers and short writing time. We show that diffraction efficiency and scattered noise can be adjusted by applying small AC voltage.

EXPERIMENT

We investigated transient and permanent gratings in a 12 μm thick film of 5CB liquid crystal doped with a relatively high concentration (above 1%) of a methyl red dye. The gratings were written by two linearly polarised (p-polarisation) intersecting beams (488 nm), both incident at approximately 30° with respect to the normal of the sample's surface. We recorded permanent gratings with spacings of either 10 or 11 μm. The diffraction efficiency of these gratings was determined by monitoring the power of the diffracted beam derived from a linearly polarised (p-polarisation) He-Ne laser.

We observed that permanent gratings can be created in such samples

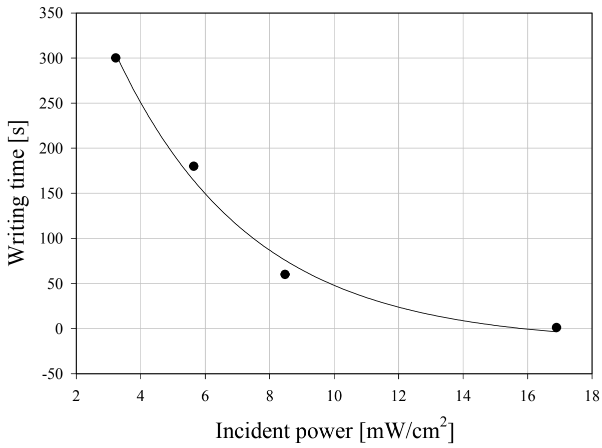


FIGURE 1 Approximate time to write a permanent grating

without any special coating of the cell surfaces, provided that the product of the illumination time and the incident intensity exposure is above a threshold (fig 1). Our cells had high absorption coefficient, namely 416 cm^{-1} at 488 nm. For relatively low incident intensities, such as 16 mW/cm^2, the threshold illuminating time was approximately a second.

Diffraction from permanent gratings was measured with either a p-polarised or circularly polarised probe beam. No diffraction was observed for an s-polarised probe beam. No grating was observed if the writing beams were s-polarised, irrespective of the probe polarisation. The permanent gratings, both one and two-dimensional, persist for months when kept at room temperature.

RESULTS AND DISCUSSION

If the liquid crystal sample is heated above the phase transition temperature, the diffraction efficiency decays (fig. 2); however, some residual diffraction is observed even in this phase. We believe this is

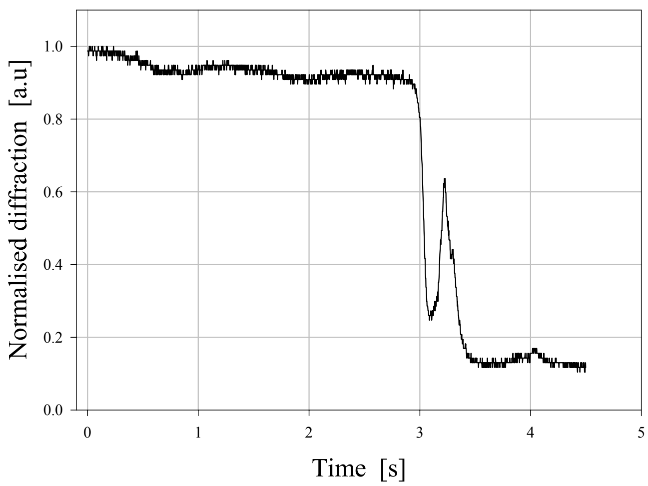
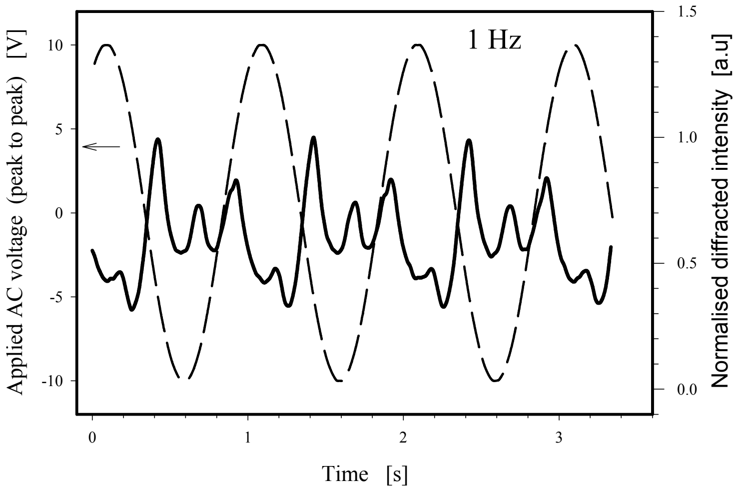


FIGURE 2 Dynamics of diffraction at phase transition at 35.2°C.

due to a strong anchoring of the liquid crystal to the surface. On cooling the liquid crystal to room temperature, the diffraction slowly recovers to its original value.

The diffraction pattern we observed for one dimensional grating

(a)



(b)

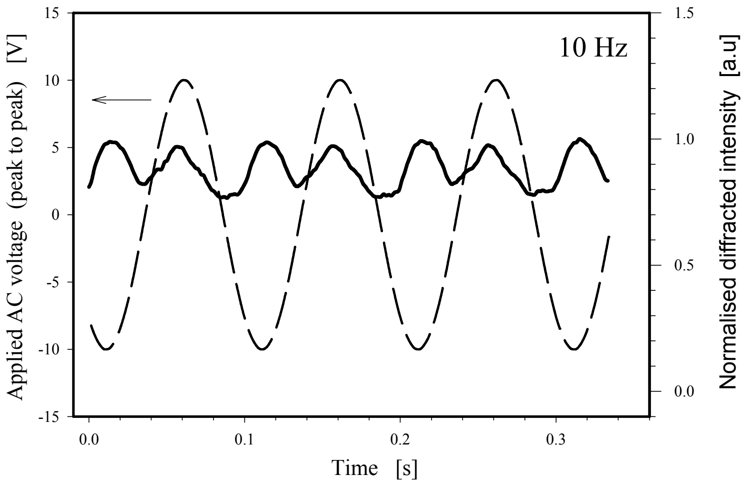


FIGURE 3 Time evolution of diffracted signal at 20 V applied AC field for diffrent frequencies: 1 Hz (a) and 10 Hz (b)

consisted of several diffracted orders.

We explored ways of adapting the diffraction and found that application of AC field can strongly influence the grating. Figure 3 shows two examples of time development of diffracted signal. For low frequencies, such as 1 Hz and below, the strong modulation of diffracted signal suggests that liquid crystal molecules can follow the direction of perturbing electric field. However, increasing the frequency to approximately 10 Hz and above, decreased significantly the modulation of the diffracted signal, as expected because of the relatively long time scale of reorientation processes of liquid crystal molecules.

Applying AC field not only caused the realignment of molecules, but also influenced the magnitude of diffraction from these permanent gratings. The necessary voltage that had to be applied was relatively low, namely below 20 V (peak to peak).

We observed that diffraction efficiency could be increased by over factor of 3. We investigated the details of the dependence of diffracted signal and speckle noise level on the magnitude and frequency of applied AC field. Figure 4 presents a typical dependence of the peak

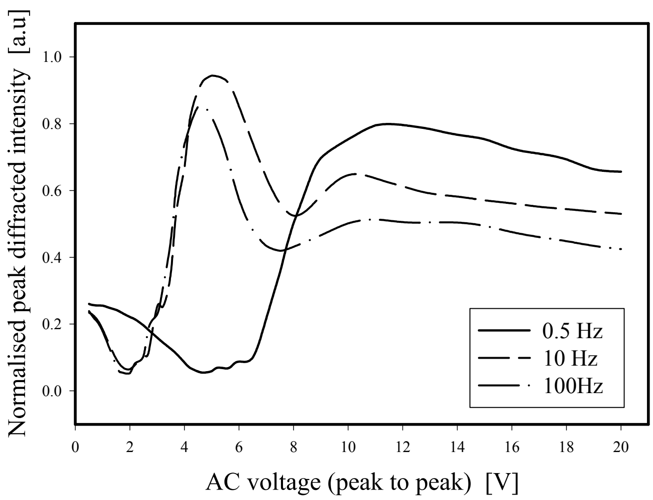


FIGURE 4 Peak diffracted intensity versus AC voltage

intensity of the first diffracted order on the applied AC field. As can be seen, the grating can be practically temporarily removed by applying 2V sine-wave AC field. The diffraction is then negligible. However, applying approximately 5V of AC field can enhance diffraction significantly. This strong dependence on the voltage enables a flexible control of diffraction. The results also indicate that there exists an optimum field frequency, around 10 Hz, that gives the strongest modulation of the grating and hence the strongest diffraction.

We carefully separated the diffraction spot from the scattered light by positioning a detector several meters from the liquid crystal cell. The aim of such configuration was to monitor carefully the noise (scattered light) dependence on the applied field and its frequency. A section of scattered light, close but separate from the first order, was sent on a detector. Figure 5 presents a few examples of the effect we observed.

The level of scattered light increases with applied voltage although it

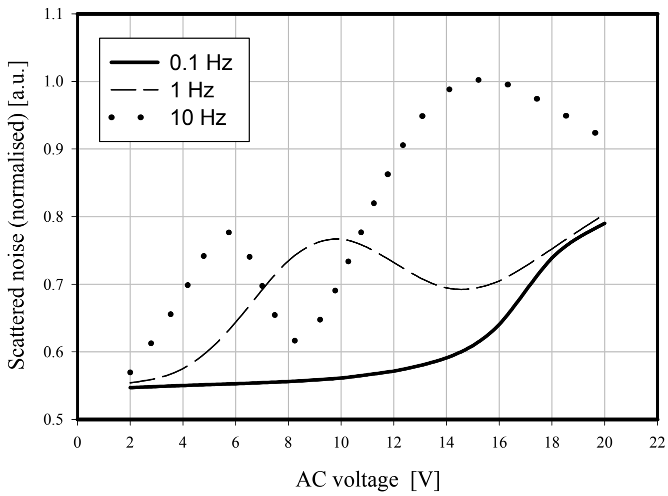


FIGURE 5 Noise (scattered light) dependence on AC field

can be adjusted. Only for very low frequencies (below 1 Hz) and voltages up to 12 V, its level remained low.

Although the exact, microscopic mechanism of forming and then adapting of the alignment of molecules is not clear yet, their macroscopic behaviour suggest that its is both light-induced bulk and surface mediated effects that play a role. Simoni and co-workers [16,17] demonstrated the interplay between the light-induced reorientation of dye molecules that exerts a bulk torque on the director, aligning it in the direction perpendicular to the incident light polarisation, and dye molecules phototransformation and adsorption on the cell surfaces, that imposes a surface torque aligning the director in the direction parallel to the incident polarisation.

Our gratings inspected under a polarising microscope indeed showed a structure of unperturbed homeotropic alignment and reoriented, planar-like alignment of molecules. It indicates that even with the initial, strong homeotropic anchoring on both surfaces of the cells, a new orientation (planar-like) can be formed in the illuminated regions of the sample. Large dye concentration in our samples and therefore significant adsorption on the surfaces is most likely to be responsible for the strength of light-induced alignment. The final configuration of molecules was stable and showed no changes in time. It is possible the light-induced modulation of alignment we observed is related to electric charges trapped at the surfaces, as discussed recently by Zhang and co-workers [18].

CONCLUSIONS

We have demonstrated that in strongly dye doped nematic liquid crystals permanent patterns can be written with relatively short illumination time and intensity. Diffraction from such permanent gratings can be changed by low voltage AC field and a factor of 3 enhancement of diffracted signal can be achieved. For low frequencies, signal's modulation can be strong with the response time in the range of milliseconds. The effect of the applied field on the efficiency of permanent gratings creates promising possibility for their external control and their potential use in new devices.

ACKNOWLEDGMENTS

We are grateful to Ben Hodder for his technical help with the liquid crystal samples. We would also like to thank Sergei Slussarenko and Andrzej Miniewicz for their valuable advice and useful discussions. The authors gratefully acknowledge the financial support of the Engineering and Physical Sciences Research Council (EPSRC) under grant number GR/M/11844 and of the Royal Society under their research fellowship scheme.

REFERENCES:

1. E. V. Rudenko, A. V. Sukhov, Sov. Phys. JETP, **105**, 1621 (1994) and Mol. Cryst. Liq. Cryst. Science & Techn. A, **282**, 125, (1996)
2. I.C.Khoo, B.D.Guenther, M.V.Wood, P.Chen, Min-Yi Shih, Opt. Lett. 22, 1229 (1997).
3. S.Bartkiewicz, A.Miniewicz, F.Kajzar, M.Zagorska, Appl. Opt. **37**, 6871 (1998).
4. I.C. Khoo, IEEE J. Quant. Electron. **32**, 525, **(**1996)
5. I.C.Khoo, S.Slussarenko, B.D.Guenther, Min-Yi Shih, P.Chen, and M.V.Wood, Opt.Lett. **23**, 253 (1998).
6. G. Cipparone, A. Mazulla, Fi. Simoni, Opt. Lett. **23**, 1505 (1998).
7. S.Bartkiewicz, A.Miniewicz, F.Kajzar, M.Zagorska, Mol. Cryst. Liq. Cryst. 322, 9 (1998).
8. I. Janossy, T. Kosa, Opt. Lett. **17**, 1183 (1992).
9. D. Voloshchenko, A. Khyzhnyak, Y. Reznikov, V. Reshetnyak, Jpn. J. Appl. Phys. **34**, 566 (1995)

10. F. Simoni, O. Francescangeli, Y. Reznikov, S. Slussarenko, Opt. Lett. **22**, 549 (1997).

11. S-T. Sun, W.M. Gibbons, P.J. Shannon, Liquid Crystals **12**, 869 (1992).

12. W.M. Gibbons, P.J. Shannon, S.-T. Sun, B. J. Swetlin, Nature (London) **351**, 49 (1991)

13. S-T. Sun, W.M. Gibbons, Appl. Phys. Lett. **65**, 2542 (1994)

14. A. G. Chen, D. J. Brady, Opt. Lett. **17**, 441 (1992)

15. L.Lucchetti, F.Simoni and Y.Resnikov, Opt.Lett. **24**, 1062 (1999).

16. O. Francescangeli, S. Slussarenko, F. Simoni, D. Andrienko, V.Reshetnyak, Y.Reznikov, Phys.Rev.Lett. **82**, 1855 (1999).

17. F. Simoni, O. Francescangeli, J. Phys: Condens. Mat. 11, R439 (1999).

18. J. Zhang, V. Ostroverkhov, K. D. Singer, V. Reshetnyak, Yu. Reznikov, Opt. Lett. 25, 414 (2000).