Improvement of Light Scattering in Reverse Mode Liquid Crystals using Micro-Lens Array Effect

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A reverse mode liquid crystal (LC) characteristic which shows a transparent voltage off-state and a light scattering on-state can be obtained by two light scattering mechanisms. One is using an index mismatching between LC and polymer matrix and another is using a micro-lens array with a short focal length. Here, we combine two reverse mode technologies in one LC cell. We investigate relations between the cell thickness and the lens diameter of a hole array patterned electrode and successfully obtained the stronger light scattering with low driving voltage. Not only an extraordinary ray but an ordinary ray can also be scattered by non-uniform electric field which is caused by using hole patterned electrodes on both side of the substrates.

Keywords: Nematic liquid crystal, Reverse mode, Micro-lens array, Light scattering, Smart window

1. Introduction

A liquid crystal / polymer composite system called as a polymer dispersed liquid crystal (PDLC) [1-3] has been studied intensively in recent years for their potential in display and window applications. Such devices show a light scattering state in a zero field (off-state) and a transparent state when the voltage is applied (on-state), which is called a “normal mode”. On the other hand, a reverse mode LC cell showing the transparent off-state and the light scattering on-state has also been proposed due to saving power consumption and a fail-safe procedure [4−11]. The light scattering causes by refractive index mismatching between LC and polymer matrix in these PDLCs.

Light scattering reverse mode devices using nematic LC, not cholesteric LC, have been proposed by using other mechanisms. From a historical point of view in LC display technologies, a dynamic scattering mode (DSM) is one of the first reverse mode LC display since a turbulence of LCs was induced by an ionic flow [12,13]. However, the DSM requires a considerable current to flow for the operation, which causes a short life time and a power consumption. Another is by using a micro-lens array system using LC refractive index distributions [14−17]. A non-uniform electric field is produced by the hole patterned electrode structure. The lens effect with the short focal length can be switched and the light scattering properties have been controlled [14,15].

In this paper, we propose the reverse mode LC cell prepared by combining the index mismatching and the micro-lens array systems. The light scattering is successfully enhanced and the contribution of each light scattering mechanism is discussed under the voltage application.

2. Cell Structures

Figure 1 shows schematic models of reverse mode cells in the on-state. TYPE A shown in Fig. 1(a) is the LC / polymer composite cell. A reactive mesogen (RM) in the LC bulk is oriented parallel to the RM axis and then polymerized. The cell is hazy in the on-state, because the reoriented LC axis is perpendicular to the RM axis and refractive index
mismatch occurs between RM and LC molecules. TYPE B shown in Fig. 1(b) is the LC micro-lens cell. The hole-patterned electrode causes a suitable non-uniform electric field and the refractive index distribution generates the lens effect. TYPE C is the combination of TYPE A and B and both light scattering mechanisms perform, as shown in Fig. 1(c).

3. Experimental

In TYPE A and C, we used a LC of MLC2136 ($\Delta n=0.21$, $\Delta \varepsilon=6.7$, from Merck) and a diacrylate monomer RM (UCL-017, from DIC) mixture. The monomer of 5 wt% was dissolved in the LC. The polymerization was carried out with the UV light (365 nm) of 20 mW/cm$^2$ for 300 s. The LC in TYPE B did not include the RM. In TYPE B and C, a randomly or hexagonally arranged hole patterned electrode was prepared. The holes occupy 50% of the electrode area. The LC was aligned parallel to the rubbing direction homogeneously in all cells. An electro-optical property of the cell was measured with a laser diode of 635 nm and a silicon photodiode. The polarization direction of the laser was parallel to the alignment direction of LCs. The transmittance of 100% was defined as the light intensity detected without the cell. A collection angle of the scattered light was set to about 2°.

4. Results

Figure 2 shows voltage vs. transmittance (VT) curves in TYPE A cells with different cell thickness. The light scattering rightly becomes stronger with the thickness of the media as clearly shown in inserted figure with log scale y axis. Stronger light scattering by lower driving voltage is desired. However, it has been well known that the driving...
voltage of PDLC increases with cell thickness [18-20]. These two requests are always in a trade-off relation in TYPE A.

Figure 3 shows VT curves in TYPE B cells with different cell thickness. The randomly arranged hole patterned electrode was used. The diameter of the hole $\phi$ was 30 $\mu$m. The threshold and driving voltages are independent of the cell thickness and the transmittance becomes minimum around 2 volts. Next, VT curves with the parameter of the hole diameter were measured in TYPE B and are shown in Fig. 4. The cell thickness is about 5 $\mu$m. It has been reported that the lens diameter affects to the focal length and the strong light scattering can be obtained when the ratio of the diameter to the thickness is around 1 to 5 [14,15].

We prepared TYPE C cell with the cell thickness of 5 $\mu$m and the hole diameter of 20 $\mu$m. Figure 5 shows VT curves in TYPE A, B and C cells. The cell thickness in TYPE A and B cells is also 5 $\mu$m. The hole diameter in TYPE B is 20 $\mu$m. The lowest transmittance in the on-state can be obtained in TYPE C. Therefore, the contrast ratio increases from 4.3 in TYPE A to 23 in TYPE C. It is considered that the stronger light scattering is obtained by the synergy with the index mismatching of LC / polymer and the lens effect of short focal length.

Figure 6 shows contour plots of far-field scattering patterns of the cell under the voltage application of $V_{10}$ and $V_{90}$, which refer to the applied voltage required to achieve 10% and 90% variations of the transmission. $V_{10}$ and $V_{90}$ denote the corresponding threshold and driving voltages. We used the hexagonal arranged hole patterned electrode in TYPE B and C cells here. In TYPE A shown in Figs. 6(a) and 6(d), the light mainly diffused perpendicular to the polarization direction of incident light, that is LC alignment direction. It indicates that the polarized scattering light propagates in the bulk of LC layer. On the other hand, the light circularly diffused in TYPE B as shown in Figs. 6(b) and 6(e). If an ideal refractive index profile is formed inside the hole patterned electrode, the shortest focal length $f$ of the LC lens is expressed using Fresnel’s approximation (Eq. 1),

\[ f = \frac{r^2}{2\Delta nd} \]

where $r$ is the lens radius ($=\phi/2$) and $d$ is the cell thickness $\Delta n$ is refractive index anisotropy. In this case, $f$ is estimated as about 50 $\mu$m and the focus point should be inside the glass substrate. Therefore, the diffusing light direction is independent of the polarization direction on the incident light.

The light diffused area in TYPE C is larger than those of TYPE A and B, as shown in Figs. 6(c) and 6(f). Moreover, the contour shape indicates that the index mismatching and the lens property effectively

![Fig. 5. Voltage vs. transmittance curves in TYPE A, B and C cells. The cell thickness is 5 $\mu$m and the hole diameter is 20 $\mu$m.](image)

![Fig. 6. Far-field scattering patterns of cells under the voltage application.](image)

![Fig. 7. Birefringence color images at the minimum transmittance states in (a) TYPE B and (b) TYPE C cells.](image)
contribute to the light scattering and lower transmittance. Figure 7 shows birefringence color images of TYPE B and C cells at the minimum transmittance states by the voltages application of 2.5 and 4.0 volts, respectively. The birefringence color shift from red at the center to blue at the edge of the hole electrode in TYPE B cell. Almost the same color distribution from red to blue can be seen in TYPE C cell. The color shift corresponds to the index shift of about 0.08, which results in the estimated focal length of about 125 μm. The incident laser beam is scattered and the beam not parallel light anymore in the bulk of the LC layer of TYPE C cell, therefore, the light scattering which is caused by the lens effect should be enhanced more.

In TYPE A, the ordinary lay does not induce the index mismatching and is not scattered. However, it has been reported that the ordinary lay can be scattered in the micro-lens array LC cell [15] and the scattering is not so strong that the transmittance is about 60% in TYPE B cell (d=5 μm, φ=20 μm). Therefore we used the hole patterned electrode substrate on both sides of the substrate to increase the ordinary ray scattering, as shown in Fig. 8. The cell thickness is 20 μm and the hole diameter is 30 μm. The LC refractive index anisotropy Δn is 0.29. We successfully reduce the transmittance of ordinary ray to 20%. This cell structure can also be adopted to TYPE C and the strong light scattering of both ordinary and extraordinary rays should be expected more.

5. Conclusion
We have investigated the reverse mode cells using two light scattering mechanisms; the index mismatching the micro-lens array effect. These two mechanisms incorporate into the LC cell and stronger light scattering can be obtained with suitable lens diameter and the cell thickness by low driving voltage application. Both of the ordinary and extraordinary incident ray light can be scattered by using the hole patterned electrode on both sides of the substrate.

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References
1. J. W. Doane, A. Golemme, J. L. West, J. B. Whitehead Jr., and B.-G. Wu, *Mol. Cryst. Liquid Cryst.*, 165 (1988) 511.
2. P. S. Drzaic, *Liq. Cryst.*, 3 (1988) 1543.
3. C. G. Paul Montgomery Jr. and N. A. Vaz, *Appl. Opt.*, 26 (1987) 738.
4. D.-K. Yang, L.-C. Chien, and J. W. Doane, *Appl. Phys. Lett.*, 60 (1992) 3102.
5. F. P. Nicoletta, G. D. Filpo, J. Lanzo, and G. Chidichimo, *Appl. Phys. Lett.*, 74 (1999) 3945.
6. R. A. Hikmet, *J. Appl. Phys.*, 68 (1990) 4406.
7. R. Yamaguchi, Y. Waki, and S. Sato, *Jpn. J. Appl. Phys.*, 36 (1997) 2771.
8. R. Yamaguchi, Y. Waki, and S. Sato, *J. Photopolym. Sci. Technol.*, 10 (1997) 19.
9. R. Yamaguchi and L. Xiong, *Jpn. J. Appl. Phys.*, 49 (2010) 06023-1-32.
10. I. Dierking, L. L. Kosbar, A. Afzali-Ardakani, A. C. Lowe, and G. A. Held, *Appl. Phys. Lett.*, 71 (1997) 2454.
11. R. Yamaguchi and S. Sato, *Jpn. J. Appl. Phys.*, 33 (1994) 4007.
12. G. H. Heilmeier, L. A. Zanoni, and J. A. Castellano, *Appl. Phys. Lett.*, 13 (1968) 46.
13. G. H. Heilmeier, J. A. Castellano, and L. A. Zanoni, *Mol. Cryst. Liq. Cryst.*, 8 (1969) 293.
14. T. Nose and S. Sato, *Liq. Cryst.*, 5 (1989) 1425.
15. T. Nose and S. Sato, *ITE Technical Report*, IDY90-153 (1990) 78.
16. M. Ye, S. Hayasaka, and S. Sato, *Jpn. J. Appl. Phys.*, 43 (2004) 6108.
17. J. F. Algorri, N. Bennis, V. Urruchi, P. Morawiak, J. M. Sánchez-Pena, and L. R. Jaroszewicz, *Sci. Rep.*, 7 (2017) 17818.
18. R. Yamaguchi and S. Sato, *Jpn. J. Appl. Phys.*, 33 (1994) 4007.
19. P. S. Drzic, “Liquid Crystal Dispersions”, World Scientific, London, 1995.
20. R. Yamaguchi and S. Sakurai, *J. Photopolym. Sci. Technol.*, 27 (2014) 28.