Cell Thickness Dependence on Electric Optical Property of Reverse Mode Liquid Crystal Display

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Electro-optical properties have been investigated as a function of cell thickness in a reverse mode cell which shows a transparent off-state and a light scattering on-state. The cell is prepared by using a nematic liquid crystal (LC) and a photo-reactive mesogen. A driving voltage and a contrast ratio of this device strongly depend on a cell thickness and there is a trade-off relationship between them. We have reported that the cell thickness dependence in the reverse mode LC cell is different from that in a normal scattering mode polymer dispersed LC with normal scattering mode. The turbidity in voltage on-state is investigated as a function of cell thickness and a simple model with polymer rich and poor layers in the cell is proposed to analyze scattering properties. The low driving voltage is compatible with the high contrast ratio by control the cell thickness and the morphology of polymer network.

Keywords: liquid crystal, reverse mode, twisted nematic orientation, reactive mesogen

1. Introduction

A polymer dispersed liquid crystal (PDLC) has been studied intensively in recent years for their potential in display and window applications [1-3]. The PDLC shows a light scattering state in a zero field (off-state) and a transparent state when the voltage is applied (on-state), which is called “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. Typical reverse mode LC cells are prepared by using a cholesteric LC [4] and a nematic LC with negative dielectric anisotropy ($\Delta\varepsilon<0$) [5]. Those driving voltages are relatively high because of a short chiral pitch of LC and a poor dielectric anisotropy, respectively.

Another type of reverse mode cell has been proposed by Hikmet [6]. It consisted of the homogeneously oriented nematic LC with positive dielectric anisotropy ($\Delta\varepsilon>0$) and a reactive mesogen (RM). The ability to use nematic LC with positive dielectric anisotropy opens access to a large class of LC materials with large dielectric and optical anisotropies, which makes it possible to easily optimize display properties. The cell based on homogeneously orientation needs a sheet polarizer to get a high contrast ratio, since the incident light polarized perpendicular to the optical axis of the cell is not scattered by applying the voltage.

To eliminate the dependence of light scattering on the polarization direction of the incident light, we have proposed to use a 90° twisted nematic (TN) [7, 8] and 270° super twisted nematic (STN) [9] oriented configurations of LC/RM composites. When higher contrast ratio is needed, a simple method is to increase a cell thickness since the scattering exponentially becomes stronger with cell thickness. However, it is known that the driving voltage also increases with the cell thickness [10,11]. In this study, the dependence of cell thickness on electric optical properties has been investigated in the reverse mode LC cell.

2. Experimental

We used the RM of ARLM-002 (Osaka Organic Chemical Industry) and nematic LCs of MLC-2136 ($\Delta n=0.212$, $\Delta\varepsilon=6.1$, Merck) and MLC-2053 ($\Delta n=0.235$, $\Delta\varepsilon=42.6$, Merck). The RM with a small amount of photoinitiator of Irg-907 was dissolved in the nematic LC at concentration of 5wt%. The mixture was sandwiched between
two ITO glass substrates which were coated with a rubbed polyimide film. The cell thickness was 5–25 μm. The cell was exposed with UV light (λ_{\text{max}}=360 nm) of 20 mW/cm² for 5 minutes at room temperature.

An electro-optical property was measured using an unpolarized light of a laser diode (635 nm) and a silicon photodiode. The frequency of the applied voltage was 1 kHz. A collection angle of scattered light was about 2°. The transmittance of 100% was defined as the light intensity detected without the cell. The polymer network structure was observed by using a scanning electron microscope (SEM). This configuration is basically maintained during photo-polymerization of the RM.

Figure 1 shows a schematic model of the reverse mode twisted nematic LC cell. In the zero field state (off-state), the polarization plane of the incident light rotates along the molecular orientation in the cell. Since the refractive indices of LC and RM are very close (n_{oLC} \approx n_{oRM} and n_{eLC} \approx n_{eRM}), index matching is achieved for both e- and o-waves traveling in the cell and thus the cell is very clear in Fig. 1(a). Upon voltage application to the cell, the LC reorients parallel to the field, while polymer network keeps its configuration. The polarization plane of the incident light does not rotate. Therefore, refractive index mismatch occurs between RM and LC molecules and the cell is opaque in the on-state.

**3. Results**

Figure 2(a) and (b) show SEM photos of the polymer network in cells prepared using MLC-2136 and MLC-2053. Morphologies of rice grain-like structures and smooth polymer strands are shown in Fig. 2(a) and 2(b), respectively.

![Fig. 1. Schematic model of molecular orientation in 90° twisted reverse mode TN cell](image)

![Fig. 2 SEM photographs of the polymer network in reverse mode cells using (a) MLC-2136 and (b) MLC-2053.](image)

![Fig. 3 Transmittance vs. voltage curves in reverse mode cells with different cell thickness. LCs used in cells are (a) MLC-2136 and (b) MLC-2053.](image)
Figure 3(a) and 3(b) show transmittance vs. voltage curves. The incident light is unpolarized. The transmittance decreases with increasing voltage. The threshold voltage of the cell using MLC-2136 is lower than that of using MLC-2053, even if $\Delta \varepsilon$ of MLC-2136 is smaller than that of MLC-2053. A similar relationship between threshold voltage and polymer morphology has been reported when using different RM materials [10].

Figure 4 and 5 show transmittance vs. voltage curves. The incident light is unpolarized. The transmittance decreases with increasing voltage. The threshold voltage of the cell using MLC-2136 is lower than that of using MLC-2053, even if $\Delta \varepsilon$ of MLC-2136 is smaller than that of MLC-2053. A similar relationship between threshold voltage and polymer morphology has been reported when using different RM materials [10].

A polymer sustained alignment technology has been proposed for a multi vertical alignment mode [13] and the RM of 0.1 ~ 1wt% is typically mixed with the nematic LC. In this case, almost RM is polymerized on the substrate, not in the LC bulk [14]. A similar phenomenon might occur in the reverse mode cell and we assume polymer rich and poor layers in the cell and propose a simple model of two layers structure as shown in Fig. 6. The turbidity $\tau$ which is given by

$$\tau = -\log(T)/d$$  \hspace{1cm} (1)

where $T$ is transmittance and $d$ is cell thickness, is rewrote as a function of $d (=d_1+d_2)$

$$\tau(d) = \tau_1 \quad (d < d_1)$$  \hspace{1cm} (2)

$$\tau(d) = d_1(\tau_1-\tau_2)/d + \tau_2 \quad (d > d_1),$$  \hspace{1cm} (3)

where $\tau_1$ and $\tau_2$ are turbidities of polymer rich and poor layers in the on-state, respectively. Thickness of the polymer rich layer $d_1$ is constant in the thicker cell.

Fig. 4 Threshold voltage as a function of applied voltage.

Fig. 5 Contrast ratio as a function of applied voltage.

Fig. 6 Two layers model of the reverse mode cell.
Figure 7 shows the calculated relationship $\tau$ and $1/d$ with parameters of $\tau_1$, $\tau_2$ and $d_1$. Figure 8 shows measured $\tau$ of reverse mode cells in the on-state as a function of $1/d$. Next we draw fitting lines and estimate $\tau_1$, $\tau_2$ and $d_1$ as shown in Table 1. $d_1$ of the cell using MLC-2136 is thicker than that of the cell using MLC-2053. In addition $\tau_1$ using MLC-2136 is smaller than that using MLC-2053. It suggests that the polymer concentration in the polymer rich layer using MLC-2136 is lower than that using MLC-2053. The size of voids within polymer networks in the cell using MLC-2136 is larger than that in the cell using MLC-2053 as shown in Fig. 2. These photos also support the difference of the polymer concentration in the polymer rich layer of the cell using MLC-2136 and MLC-2053.

![Figure 7](image1.png)

**Fig. 7** Contrast ratio as a function of applied voltage.

![Figure 8](image2.png)

**Fig. 8** Contrast ratio as a function of applied voltage.

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<thead>
<tr>
<th></th>
<th>$\tau_1$</th>
<th>$\tau_2$</th>
<th>$d_1$</th>
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<tr>
<td>MLC-2136</td>
<td>0.14</td>
<td>0.03</td>
<td>7.0</td>
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<tr>
<td>MLC-2053</td>
<td>0.23</td>
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Table 1 Fitting parameters

4. Conclusions

Cell thickness dependences in the reverse mode cell have been investigated on the threshold voltage and the contrast ratio. The threshold voltage increases with cell thickness according to the theory which is analyzed in the PDLC cell. However, the contrast ratio does not proportionally increase since the turbidity in the on state depends on the cell thickness. We propose the simple model with polymer rich and poor layers in the reverse mode cell and estimate the thickness and the turbidity of each layer. The cell can be designed with considering the trade-off relation between driving voltage and contrast ratio.

References