Normal and Reverse Mode Light Scattering Properties in Nematic Liquid Crystal Cell Using Polymer Stabilized Effect

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A coexistence with normal and reverse scattering modes is demonstrated in a single liquid crystal (LC) cell by using a polymer stabilized effect. The homogeneously oriented or twisted LC cell containing a small amount of reactive mesogen is exposed with UV light under a suitable curing voltage application. A light scattering state is obtained and it becomes clear by applying voltage. The cell fabricated without the curing voltage shows a reverse mode property, that is, a transparent voltage off-state and the light scattering on-state. A driving voltage of the normal mode is almost the same as that of the reverse mode. A domain with the normal mode property is successfully fabricated in the reverse mode LC cell by two step UV exposures through a photomask with and without the curing voltage. Scattering and transparent patterns simultaneously turns to transparent and scattering states without electrode partitions.

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

1. Introduction

The liquid crystal / polymer composite systems have been proposed as a polymer dispersed liquid crystal (PDLC) [1-3] and polymer network liquid crystal (PNLC) films [4-6] which typically show a light scattering state in the voltage off-state and a transparent state in the on-state. This switching property is called a normal mode. On the other hand, a reverse mode with a transparent off-state and a scattering on-state has also been proposed [7-12]. Hikmet [13] has been proposed the reverse mode cell using a nematic LC with positive dielectric anisotropy, which was prepared by photo-polymerizing the LC containing a diacrylate LC monomer called a reactive mesogen (RM) in a homogeneously oriented state. There are many chemical structures and physical values of LC with positive dielectric anisotropy. Therefore, it is easy to select a suitable LC material and to optimize the electro-optical property. The driving voltage has been successfully reduced lower than 4 V in the reverse mode cell [14-16]. Moreover, reverse mode cells with 90° twisted nematic (TN) [17] and 270° super twisted nematic (STN) [18] have also been proposed orientations.

The nematic LC / polymer composite system has also been applied to a polymer stabilizing and polymer-sustained technologies to enhance the cell performance [19-25]. The RM of typically less than 5 wt% is dissolved in the LC to get the polymer stabilized effect. When the cell is polymerized under the voltage application to form a proper polymer network in a bulk, the network causes a lower driving voltage and faster response [20, 22-25].

In this study, the polymer stabilized effect is applied to the reverse mode cell to produce the normal mode property. The stabilization condition is controlled by varying the applied voltage during polymerization. Both normal and reverse mode properties is successfully demonstrated in the cell using same composite materials and alignment treated substrates, which makes it possible that scattering and transparent patterns simultaneously turn to transparent and scattering patterns by
applying voltage without any electrode partitions.

2. Experimental

The reverse mode cell was fabricated by photopolymerizing the RM (UCL-017, DIC) in the LC host (MLC-2136 Merck, ”n=0.21). The RM of 5wt% or 10wt% was mixed with the LC. The mixture was in a nematic phase in room temperature and sandwiched between two ITO grass substrates which were coated with a rubbed polyimide film. Rubbing direction of the substrate was anti-parallel or orthogonal each other. The cell thickness was 10 µm. The cell was exposed with a UV light from an LED (λmax=360 nm) under a proper voltage application, that is a curing voltage $V_c$, to obtain the polymer stabilizing effect. The power of the UV light was 20 mW/cm$^2$ and the exposure time was 5 minutes.

![Diagram](image1)

Fig.1. Schematic model of molecular orientation in (a), the reverse mode and (b) the normal mode LC cells.

Figure 1 (a) shows schematic models of molecular orientation in the homogeneously aligned reverse mode cell ($V_c=0$). Ordinary and extraordinary refractive indices of the RM are close to those of the LC in the voltage off state and the cell is very clear. When the voltage is applied, LC molecules reorient parallel to the field and the polymer network keeps its initial configuration. Therefore, the cell turns to a light scattering state. On the other hand, when the cell is exposed with the UV light under the voltage application of $V_c$, RM molecules are polymerized with higher tilt angle. The incident light into the cell is scattered after $V_c$ is removed, since LCs return to the initial orientation and the refractive index mismatch occurs between re-oriented RMs and relaxed LC molecules. When the voltage is applied to the cell again, the tilt angle of the LC is close to the RM tilt angle and the cell becomes clear, as shown in Fig. 1(b). Therefore, we can get the normal mode property.

A capacitance of the cell before and after curing was measured by LCR meter (HP 4284A) and a dielectric constant was estimated as a function of applied voltage of 1 kHz. The area of the electrode was 1 cm$^2$. Electro-optical properties were measured by using a laser diode of 635 nm and a silicon photodiode. A polarization direction of the incident light was parallel to the LC direction on the entrance side of the substrate. A collection angle of scattered light was about 2°. The transmission of 100% was defined as the light intensity detected without the cell.

4. Results

Figure 2 shows the dielectric constant of in homogeneously aligned stabilized LC cells, as a function of applied voltage with a parameter of $V_c$. Before curing, the dielectric constant curve is almost the same as the curve using a pure LC of MLC-2136. The initial dielectric constant which was measured below a threshold voltage increased with $V_c$, since LCs in the bulk were stabilized with higher tilt angle by reoriented RMs still after removing $V_c$. When the voltage was applied to the stabilized cell, the dielectric constant in each cell

![Graph](image2)

Fig. 2 Dielectric constant curves as a function of applied voltage in homogeneously aligned stabilized LC cells before and after curing.
Transmittance curves, however, considerably changed by $V_c$, as shown in Fig. 3. Transmissions in the voltage off state of stabilized cells were lower than that of the cell with $V_c$ of 0 V. A peak transmittance appeared around 2 V in the cell with $V_c$ of 2.2 V. The transmittance simply increased with the voltage application in cells with $V_c$ of 6.5 V and 10 V, which shows the normal mode property. When the polarization direction of the incident light is perpendicular to the LC direction, the cell does not become hazy in normal and reverse mode because of an ordinary refractive index matching between LC and RM materials.

We roughly estimate the mean tilt angle which is defined by following equation

$$\bar{\theta} = \sin^{-1} \left( \frac{\varepsilon(V) - \varepsilon_\perp}{\Delta\varepsilon} \right),$$

where $\varepsilon_\perp$ is the dielectric constant referred to a short axis of LC director and $\Delta\varepsilon$ is the dielectric constant anisotropy. $\varepsilon(V)$ is the dielectric constant measured in reoriented LC cells under the voltage application. $\varepsilon_\perp$ and $\Delta\varepsilon$ of used LC are 3.5 and 6.4, respectively. Mean tilt angles of reoriented LCs molecules are shown in Fig. 4. Dielectric constants, that is, mean tilt angles in each cell did not change while the polymerization of RMs was progress. The angles reduced after removing the curing voltage, for example from 34° to 13° in the cell with $V_c$ of 2.2 V. It is indicates that the mean tilt angle of RMs and LCs which are fixed on the RM surface is about 34° and that of relaxed LCs is lower than 13°. Therefore, the refractive index mismatch occurs between polymerized RMs and relaxed LC molecules, and the incident light is scattered. When the voltage is applied to the cell with $V_c$ of 2.2 V, the mean tilt angle of reoriented LCs is close to that of RMs around 2 V and the transmittance becomes maximum. A difference of mean tilt angles between polymerized RMs and relaxed LCs molecules is about 27° in cells with $V_c$ of 2.2 - 7.5 V. Therefore, the transmittance in the off-state reduces to 5 - 10 %. Applying voltages which give refractive matching conditions between polymerized RMs and reoriented LCs are estimated about 8 V and 12 V in cells respectively with $V_c$ of 6.5 V and 10 V, from the results shown in Fig. 2. Therefore, transmittances in both cells monotonically increase, as shown in Fig. 3. The morphology of polymerized RMs in the cell was observed by using a scanning electron microscope (SEM) as shown in Fig. 5. A rice grain-like structures [26] was observed in both cells with $V_c$ of 0 V and 6.5 V. The seize of grain does not change by $V_c$ and the tilt of grains is also independent of $V_c$.
We applied the polymer stabilized effect to the 90° TN oriented reverse mode LC cell [17, 18]. Both normal and reverse mode properties shown in Fig. 6 can be obtained by the same manner as the homogenously oriented cell when the RM concentration is 5 wt%. The driving voltage of the normal mode is almost the same as that of the reverse mode. When the polarization direction of the incident light is perpendicular to the LC direction, we can get the light scattering state because a refractive index mismatch is generated near the exit side of the cell [18] in both modes. Increasing the concentration of the RM to 10 wt%, a threshold voltage became higher from 3V to 8V. When the $V_c$ was 10 V, the cell was kept a clear state by any voltage application. Almost LCs were strongly fixed to the electric field direction by the thicker RMs in the bulk.

![Fig. 6 Normal and reverse mode properties in stabilized cells with the 90° TN orientation.](image1)

A fabrication of normal and reverse mode cell by using same materials has already been reported by Yang et al [27]. They used cholesteric LC and monomer materials. The normal mode cell was prepared using substrates with no aligning treated surface and the reverse mode cell needs rubbed polyimide substrate surfaces. Y. -H. Fan et al [28], also fabricated both modes with nematic LC and RM materials. However, the normal mode was obtained by decreasing the concentration of RM below 1.0 wt%, comparing to the reverse mode of the RM concentration in a 3 - 10 wt% range. Therefore, it is not easy to make both modes together in the single cell by these methods. We demonstrated both modes in a single cell through the cell fabrication procedure shown in Fig. 7. The concentration of RM was 5 wt%. First, the cell was partly exposed with the UV light through a photo mask under the voltage of 6.5 V. Next, the second UV exposure was done all over the cell with no voltage application. The power of the UV light was 20 mW/cm² and the exposure time was 5 minutes in both exposing processes. The area of the first UV exposur showed the light scattering state on the transparent background in the off state. When the voltage of 5 V was applied, the scattered and transparent areas respectively changed to transparent and scattered state, as shown in Fig. 8.

![Fig. 7 Fabrication procedure of normal and reverse mode properties in a single cell.](image2)

![Fig. 8 Photographs of the stabilized normal/reverse mode TN oriented LC cell in (a) off-state and (b) on-state.](image3)

**4. Conclusions**

The polymer stabilizing effect has been investigated in reverse mode liquid crystal cells. The normal mode property was obtained by stabilized LCs with a suitable $V_c$. The driving voltage of two mode is almost the same and both mode properties are successfully demonstrated in a single cell. The scattering pattern was fabricated on the transparent background by two step UV exposures through the photomask with and without the $V_c$. The pattern can be turned to be the...
transparent state on the scattering background when the voltage is applied to a pair of ITO electrode without any partitions. More complex switching pattern will be possible to display by the combination of electrode patterning with a very simple static driving scheme.

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