Enhancement of absorption and haze with hybrid anchoring of dye-doped cholesteric liquid crystals

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Abstract: We demonstrated that hybrid anchoring of dye-doped cholesteric liquid crystals (ChLCs) could be used for the simultaneous control of haze and transmittance. Hybrid anchoring of ChLCs can be obtained by the vertical anchoring at one substrate surface and planar anchoring at the other substrate surface. In a ChLC cell with hybrid anchoring, the LCs near the planar alignment layer are in the planar state, while those near the vertical alignment layer are in the focal-conic state. In the initial opaque state, the incident light can be absorbed by the LC mixture in the planar state and scattered by the LCs in the focal-conic state. The ChLC cell with hybrid anchoring exhibited lower transmittance and haze value than those of a focal-conic state in a ChLC cell with vertical anchoring. The cell can be switched to the transparent state without use of a complicated drive scheme at a driving voltage significantly lower than that for a double-layered cell.

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1. Introduction

Recently, see-through displays using organic light-emitting diodes (OLEDs) have been extensively studied [1,2]. However, owing to the transparent area at each pixel of an OLED see-through display panel, it can neither provide a black color nor completely hide objects behind the panel. These problems can be overcome by placing a light shutter behind a see-through display panel [3–11].

Dye-doped liquid crystal (LC) light shutters have been intensively studied, as they can simultaneously scatter and absorb the incident light. In addition, they can be switched to the transparent state by applying an electric field [6–11]. Dye-doped LC/polymer composites can scatter and absorb the incident light; however, they can suffer from a degradation of the dichroic dyes during the ultraviolet (UV) curing process [12, 13]. To avoid this problem, cholesteric LCs (ChLCs), which scatter and absorb the incident light in the focal-conic state, have been studied [6–10, 12–15]. The focal-conic state can be obtained by applying a vertical electric field or using vertical alignment layers. A ChLC cell with vertical anchoring (VA-ChLC cell) has the advantages of a simple drive scheme and higher haze value than a ChLC cell with planar anchoring (PA-ChLC cell) [12, 13]. However, a dye-doped VA-ChLC cell exhibits a rather high transmittance in the opaque state, as the dichroic dye molecules are not oriented parallel to the substrates.

To lower the transmittance in the opaque state, a light shutter consisting of two ChLC cells, one for light scattering and the other one for light absorption, was reported [7]. Although this double-cell light shutter has a low transmittance in the opaque state, as the dye molecules are aligned parallel to the substrate, it suffers from several disadvantages, including a low transmittance in the transparent state, large thickness, and high fabrication cost. A double-layered cell containing a polymer-dispersed LC (PDLC) film was proposed for a higher transmittance in the transparent state [8]. However, it requires a high driving voltage, and it is difficult to fabricate.

In this paper, we propose a ChLC cell with hybrid anchoring (HA-ChLC cell), which contains LCs in both planar and focal-conic states. In the initial opaque state, the incident light is absorbed by dye molecules in the planar state, and backward- and forward-scattered by the randomly oriented LCs in the focal-conic state. The hybrid anchoring of ChLCs can be achieved through a vertical anchoring at one substrate surface and planar anchoring at the other substrate surface without any additional fabrication process. In an HA-ChLC cell, the LCs near the planar alignment layer are in the planar state, whereas the LCs near the vertical alignment layer are in the focal-conic state. We have shown that an HA-ChLC cell can provide a significantly higher transmittance in the transparent state than a double-cell light shutter, and can be operated at a significantly lower driving voltage than a double-layered cell containing a PDLC film.

2. Principle of operation

For absorption of the incident light, we use dichroic dyes, which are convenient for switching as they can be easily aligned by LC molecules. The incident light is strongly [weakly] absorbed when the polarization direction of the incident light is parallel [perpendicular] to the
absorption axis of the dye molecules. To absorb the incident light regardless of the polarization direction, we can use the planar state of ChLCs [6–8]. For scattering of the incident light, we can use the focal-conic state of ChLCs, which scatter the incident light owing to the refractive index mismatch between randomly oriented LC domains [12–15]. The planar state of ChLCs can be obtained by the planar anchoring, whereas their focal-conic state can be obtained by the vertical anchoring. The orientation of LC molecules away from the substrates is determined by the orientation of neighboring LC molecules [6, 13].

![Image](image_url)

**Fig. 1. Structure and operation of an HA-ChLC cell.**

The operation of an HA-ChLC cell is illustrated in Fig. 1. It is switchable between the opaque and transparent states. The opaque state can be realized using light absorption by the LC mixture in the planar state and light scattering by the LCs in the focal-conic state. In the opaque state, the incident light is absorbed by the dye molecules, and backward- and forward-scattered by the randomly oriented LCs. For the switching to the transparent state, we apply a vertical electric field between the top and bottom substrates. In the transparent state, the light scattering and absorption are minimized as the LC and dye molecules are vertically oriented [6–16].

### 3. Fabrication and measurement

To fabricate an HA-ChLC cell, we formed a vertical alignment layer (SE-5662, Nissan) on one substrate and planar alignment layer (SE-6514, Nissan) on the other substrate. The two substrates were baked for 1 h at 220 °C. We mixed the LC (E7, Merck) with a chiral dopant (S811, Merck) and dichroic dye (S428, Mitsui). The amount of the chiral dopant was chosen to reflect infrared light with a wavelength of 2,000 nm (pitch: 1.25 μm). We doped ChLCs with 1 wt% of dichroic dyes. The materials were mixed in a glass vial by stirring continuously for 24 h at room temperature. The mixture was then injected into a 10-μm-thick cell.

We measured the absorbance to compare the difference in absorption between dye-doped PA- and VA-ChLC cells. According to Beer’s law, the absorbance can be expressed as $2 - \log_{10} T$, where $T$ is the transmittance of the fabricated cell [17, 18]. We used the
transmittance ratio between ChLC cells with and without dichroic dyes to eliminate the effect of light scattering. It can be expressed as \( \log_{10}(T / T_0) \), where \( T_0 \) is the transmittance of a cell fabricated without dichroic dye.

We evaluated the optical performance of the fabricated cells using a haze meter (HW-65W, Murakami Color Research Laboratory). The specular [diffuse] transmittance, \( T_s [T_d] \), refers to the ratio of the power of the beam that emerges from a sample cell, which is parallel (within a small range of angles of 2.5°) [not parallel] to a beam entering the cell, to the power carried by the beam entering the sample. The total transmittance, \( T_t \), is the sum of the specular \( T_s \) and diffuse \( T_d \) transmittances. The haze \( H \) can be calculated as the ratio \( H = T_d / T_t \).

4. Experimental results and discussion

The planar state of a ChLC cell can be obtained by the planar anchoring of LCs. It can be switched to the focal-conic state by applying an electric field to the ChLC cell. Instead of applying an electric field, the initial focal-conic state can be realized by the vertical anchoring [13, 19–21].

![Fig. 2. Measured (a) absorbance and (b) haze values of PA- and VA-ChLC cells as a function of the pitch.](image)

We measured the absorbance and haze of a PA-ChLC cell in the planar state and VA-ChLC cell in the focal-conic state as a function of the helical pitch. As shown in Fig. 2(a), although dye-doped LCs in both planar and focal-conic states can absorb the incident light, the absorbance of the dye-doped LCs in the planar state is significantly higher than that in the focal-conic state, as the LC and dye molecules in the planar state are aligned parallel to the substrates. On the other hand, the haze value of a ChLC cell in the planar state is almost zero regardless of the pitch as it does not scatter the incident light. As shown in Fig. 2, a dye-doped VA-ChLC cell can simultaneously absorb and scatter the incident light [13, 21]. However, the absorbance of the dye-doped LCs in the focal-conic state is significantly lower than that in the planar state owing to the randomly oriented dye molecules. Therefore, it is preferable to use the planar state for a higher light absorption in a dye-doped ChLC cell.
To confirm the orientation of the LC molecules in an HA-ChLC cell, we measured the reflectance of the cell. The amount of the chiral dopant was chosen to reflect the visible light. We compared reflection spectra of a PA-ChLC cell in the planar state, VA-ChLC cell in the focal-conic state, and HA-ChLC cell. Bragg reflection was observed in the PA-ChLC cell; however, it was not observed in the VA-ChLC cell, as shown in Fig. 3. In the HA-ChLC cell, Bragg reflection was observed when the light was incident onto the substrate coated with the planar alignment material as the LC molecules were aligned parallel to the substrate. On the other hand, when the light was incident onto the substrate coated with the vertical alignment material, the reflection spectrum was similar with that of the VA-ChLC cell. Therefore, we can conclude that both planar and focal-conic states can be obtained in a single cell by the vertical anchoring at one substrate surface and planar anchoring at the other substrate surface.
The optical performance of the fabricated HA-ChLC cell was measured using a haze meter. Figure 4 shows the total transmittance, specular transmittance, and haze of the fabricated cell as a function of the applied voltage (1 kHz). The measured total transmittance, specular transmittance, and haze in the opaque state were 32.1%, 6.0%, and 81.3%, respectively. With the increase of the applied voltage, the total and specular transmittances increased, while the haze value gradually decreased. The measured total transmittance, specular transmittance, and haze in the transparent state (at an applied voltage of 45 V) were 71.8%, 71.5%, and 0.4%, respectively. The proposed ChLC cell shows the hysteresis behavior, which exists in pure ChLCs as well [22]. Although hysteresis may make the grey-scale operation difficult, we do not need to worry about this for light shutter applications which rely only on the switching between the opaque and transparent states.

![Graph showing measured switching behavior](image)

Fig. 5. Measured switching behavior of the fabricated HA-ChLC cell.

We measured the response time of the fabricated dye-doped HA-ChLC cell with 1 kHz voltage wave of 50 V, as shown in Fig. 5. The switching time from the opaque [transparent] to the transparent [opaque] state was 27.8 ms [6.80 ms]. We also measured the response time of a HA-ChLC cell without dyes. The measured switching time from the opaque [transparent] to the transparent [opaque] state was 21.8 ms [6.40 ms]. They are nearly the same as those of a dye-doped sample.

![Images showing opaque and transparent states](image)

Fig. 6. Photographs of the fabricated HA-ChLC cell in the opaque and transparent states.
Photographs of the fabricated HA-ChLC cell are shown in Fig. 6. In the opaque state, the HA-ChLC cell can provide a black color and hide the objects behind the display panel as the incident light is absorbed by dye molecules aligned parallel to the substrate in the planar state and scattered owing to the refractive index mismatch between LC domains in the focal-conic state. In the transparent state, we can clearly observe objects behind the display panel.

Table 1. Measured total transmittance, specular transmittance, haze, and the absorbance of the fabricated PA-, VA-, and HA-ChLC cells.

|     | PA planar | focal-conic | VA | HA |
|-----|-----------|-------------|----|----|
| $T_s$ | 36.4      | 40.6        | 36.9| 32.1|
| $T_v$ | 34        | 16.2        | 10 | 6  |
| Haze | 6.6       | 60.1        | 72.9| 81.3|
| Absorbance | 0.35 | 0.25 | 0.27 | 0.32 |

We compared the optical performances of the fabricated ChLC cells, as shown in Table 1. The focal-conic state of the PA-ChLC cell can be obtained by applying a vertical electric field of 20 V. The HA-ChLC cell exhibited the lowest total and specular transmittances. Although the absorbance of the HA-ChLC cell was lower than that of the PA-ChLC cell, the total transmittance of the HA-ChLC cell was lower than that of the PA-ChLC cell owing to the backward scattering. Moreover, the HA-ChLC cell exhibited the highest haze value. The more random orientation of the LC and dye molecules could be attributed to the different anchoring in the HA-ChLC cell, leading to the increased haze value. However, further studies are necessary for a better understanding of the physical mechanism. The operating voltage for the transparent state of the ChLC cells was almost the same.

We fabricated a double-layered cell containing a PDLC film [8] to compare the transmission characteristics with those of an HA-ChLC cell. To prepare a PDLC film, we mixed a positive LC (E7, $\Delta n$: 0.223, $\Delta e$: 13.5) with a UV curable monomer (NOA65, Norland Products). To prepare dye-doped ChLCs, we mixed a positive LC (E7) with a chiral dopant.
(S811, Merck). The mixing ratio was chosen to reflect infrared light of 1,640 nm. 0.7 wt% of black dichroic dye molecules (S428, Mitsui) were doped into the LC mixture.

The transmission spectra of the fabricated HA-ChLC cell and the double-layered cell were measured using a spectrometer (MCPD 3000, Photal), as shown in Fig. 7. The average specular transmittances in the opaque state of the fabricated HA-ChLC cell and the double-layered cell were 2.85% and 0.69%, respectively. The specular transmittance of the double-layered cell is lower as the incident light is strongly scattered by the PDLC film. The specular transmittances in the transparent state of the HA-ChLC cell at 45 V and double-layered cell at 200 V were 72.7% and 75.5%, respectively. Although the double-layered cell exhibits a higher transmittance than the HA-ChLC cell, it requires a significantly higher operating voltage. Moreover, the double-layered cell requires a complex fabrication process, while the HA-ChLC cell can be simply fabricated by the injection of the LC mixture into an empty cell.

5. Conclusion

We demonstrated that a dye-doped HA-ChLC cell can be used for the simultaneous control of the haze and transmittance. We confirmed that both planar and focal-conic states could be obtained in a single cell by the vertical anchoring at one substrate surface and planar anchoring at the other substrate surface. In the opaque state, the HA-ChLC cell exhibited higher haze and absorbance than the PA-ChLC cell in the focal-conic state. The specular transmittance was decreased by 63.0%, and the haze value was increased by 35.3%. Almost the same transmittance and driving voltage were observed in the transparent state. The HA-ChLC cell could be easily fabricated by filling the LC mixture into an empty cell with neither additional fabrication process nor degradation of the dichroic dyes. The HA-ChLC cell and the double-layered cell exhibited almost the same transmittance in the transparent state, while the driving voltage of the HA-ChLC cell was only one-fourth of that of the double-layered cell.

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