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Optimization of dye mixing for achromatic transmittance control with a dye-doped cholesteric liquid crystal cell

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ABSTRACT

Transmittance-control liquid crystal (LC) devices require a high transmittance difference between their transparent and opaque states. Dye-doped cholesteric LC (CLC) cells have been widely used for transmittance control because they provide the highest transmittance difference among LC modes. However, the color of a CLC cell is different from that of a homogeneously-aligned LC cell. In this paper, we present a systematic approach to find the optimal dye concentrations for the desired black color in a dye-doped CLC cell. To achieve the desired black color in a dye-doped CLC cell, we consider its transmission spectrum in our numerical calculations. The optimal concentration for each individual dye is found through an iterative process. We demonstrate that a dye-doped CLC cell designed by considering its transmission spectrum can provide a true black color in the CIE 1931 color space.

1. Introduction

Recently, transmittance-control devices have been studied for smart windows, eyewear, and automotive applications. Transmittance-control devices, such as a suspended particle device (SPD) [1–4], electrochromic device (ECD) [3,5–13], or dye-doped liquid crystal (LC) device [14–27], can be utilized to control transmitted light intensity through the absorption of incident light. These devices allow people to see through them. However, ECDs and SPDs can suffer from various issues in terms of color neutrality, durability, manufacturing cost, and switching speed. In particular, the slow switching speed of these devices can make their eyewear and automotive applications, which require fast response times for safety, very impractical. For such applications, dye-doped LC devices are widely used because their operation is much faster than that of other types of devices.

A twisted structure, such as that of a cholesteric LC (CLC) [15,21–27], is required to achieve a high transmittance difference between the transparent and opaque states in a dye-doped LC cell. However, because of the difference in their transmission spectra, a CLC cell does not show the same color as a homogeneously-aligned (HA) cell when fabricated utilizing a commercial black dye. Therefore, to achieve the desired color, we must find a proper concentration for each individual dye by considering the transmission spectrum of each LC mode.

In this paper, we present a systematic approach to find the optimal dye concentrations for the desired the black color in the opaque state of a dye-doped CLC cell. We confirm that a dye-doped CLC cell with the optimal dye concentrations shows a true black color in the CIE 1931 color space. Additionally, the color difference between the calculated and measured results is negligible. Therefore, we expect that the proposed approach can be a useful tool in the fabrication of dye-doped LC cells for achromatic transmittance control.

2. Optimization of color-dye mixing

The color and transmittance of a dye-doped LC cell are determined by the characteristics of the dichroic dye utilized for absorption of the incident light. Therefore, it is important to find the optimal dye concentrations to achieve the desired black color in a dye-doped LC cell. The optimal dye concentrations can be found through an iterative process, known as the Newton–Raphson method [28,29], as follows:

$$\begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix}_{n+1} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix}_n - \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix}^{-1} \left(\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_n - \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_a \right) \tag{1}$$

where $[c_1\ c_2\ c_3]^T_{n+1}$ represents the dye concentrations after an iteration of Eq. (1) for the given current dye concentrations $[c_1\ c_2\ c_3]^T_n$, $[X\ Y\ Z]^T_n$ represents the tristimulus values for the given $[c_1\ c_2\ c_3]^T_n$, and $[X\ Y\ Z]^T_a$ represents the tristimulus values for the desired color. $[D]_{ij}$ represents the partial derivatives $[D]_{1j} = \frac{\partial X}{\partial c_j}$, $[D]_{2j} = \frac{\partial Y}{\partial c_j}$, and $[D]_{3j} = \frac{\partial Z}{\partial c_j}$ evaluated for the given $[c]_n$. $\overline{x_j}$, $\overline{y_j}$, and $\overline{z_j}$ are the color-matching functions defined by the Commission Internationale de l'Eclairage (CIE). One can find the

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dye concentrations for the desired color if $[X\ Y\ Z]_a^T$, $[X\ Y\ Z]_n^T$, and $[c_1\ c_2\ c_3]_n^T$ are known. The tristimulus values of each color are defined as follows:

$$X = 100 \int \overline{x_j}(\lambda)S(\lambda)T(\lambda)d\lambda / \int \overline{y}(\lambda)S(\lambda)d\lambda \quad \text{(2-a)}$$

$$Y = 100 \int \overline{y_j}(\lambda)S(\lambda)T(\lambda)d\lambda / \int \overline{y}(\lambda)S(\lambda)d\lambda \quad \text{(2-b)}$$

$$Z = 100 \int \overline{z_j}(\lambda)S(\lambda)T(\lambda)d\lambda / \int \overline{y}(\lambda)S(\lambda)d\lambda \quad \text{(2-c)}$$

where *X, Y,* and *Z* are tristimulus values that can be conceptualized as the levels of the three primary colors in the trichromatic system. λ is the wavelength of the incident light, ranging from 380 to 780 nm. *S*(λ) is the spectral power distribution of the light source. *T*(λ) is the spectral transmission of a dye-doped LC cell. Because Eq. (2) includes the transmission spectrum of an LC cell, the color of a dye-doped LC cell is dependent on the transmission spectrum of that cell. Therefore, it is necessary to consider the transmission spectrum of a dye-doped LC cell, which is dependent on the LC mode.

The transmission spectrum of a dye-doped HA cell can be calculated by invoking the Beer-Lambert law as follows [28–30]:

$$T_\perp(\lambda) = T_0(\lambda)e^{-\alpha_\perp(\lambda)cd} \quad \text{(3-a)}$$

$$T_\parallel(\lambda) = T_0(\lambda)e^{-\alpha_\parallel(\lambda)cd} \quad \text{(3-b)}$$

where $T_\perp$ [$T_\parallel$] and $\alpha_\perp$ [$\alpha_\parallel$] represent the transmittance and absorption coefficients of a dye-doped LC cell, respectively, for the polarization perpendicular [parallel] to the absorption axis of the dye molecules. *c* and *d* are the dye concentration and cell gap, respectively. T_O is the transmission spectrum of an HA cell without dye doping. Because the light incident to a transmittance-control device is unpolarized, one must calculate the transmittance of an LC cell for unpolarized light.

Unpolarized light can be represented by two linearly polarized lights perpendicular to each other. The transmittance of a dye-doped HA cell for unpolarized incident light can be calculated as the average of $T_\perp$ and $T_\parallel$ as follows:

$$T(\lambda) = \frac{T_\parallel(\lambda) + T_\perp(\lambda)}{2} = \frac{T_0(\lambda)(e^{-\alpha_\parallel(\lambda)cd} + e^{-\alpha_\perp(\lambda)cd})}{2} \quad (4)$$

As mentioned above, a dye-doped CLC cell is suitable for achieving a high transmittance difference. However, unlike an HA cell, the effective absorption coefficient of a dye is calculated as the average of $\alpha_\parallel$ and $\alpha_\perp$ because a CLC cell has a twisted structure of LCs and dye molecules. Therefore, the formula for the transmittance of a dye-doped CLC cell should be modified as follows:

$$\mathrm{T}(\lambda) = T_0(\lambda)\left(e^{-\frac{(\alpha_\parallel(\lambda)+\alpha_\perp(\lambda))}{2}cd}\right) \quad (5)$$

To determine if Eq. (5) is reliable, we compare the calculated results to the measured results in the next section. We confirm that the transmission spectrum of a dye-doped CLC cell is different from that of a dye-doped HA cell, which results in the apparent color difference. Therefore, it is essential to consider the LC mode for finding the optimal dye concentrations for a dye-doped LC cell.

To determine if the color difference occurs generally, we fabricated HA and CLC cells with a commercial black dye (S-428, Mitsui) under the same experimental conditions. As shown in Fig. 1, the transmission spectrum of a CLC cell is different from that of an HA cell. The color of the HA cell is gray, but that of the CLC cell is purple. From these results, one can see that it is necessary to find the optimal dye concentrations for each LC mode.

3. Experiments

To confirm the color difference, we fabricated dye-doped HA and CLC cells. To achieve the black color for an HA cell, we combined a positive LC (Δn: 0.077) with a dye mixture, whose dye composition was calculated utilizing Eq. (1) for the light source D65. To produce the black color, we selected cyan, magenta, and yellow dyes, whose absorption spectra are presented in Fig. 2. For a CLC cell, we added 6.7 wt % of chiral dopant to an LC mixture that was the same as that used for an HA cell. The pitch of the CLC cell was set to reflect infrared light with a wavelength of 2000 nm to avoid visible Bragg reflection.

Glass coated with indium tin oxide was utilized as a substrate. The top and bottom substrates were coated with a homogeneous alignment polyimide and the rubbing direction was anti-parallel. The cell gap was maintained at 10 μm utilizing silica-ball spacers. The LC mixture was injected into an empty cell via capillary action at room temperature.

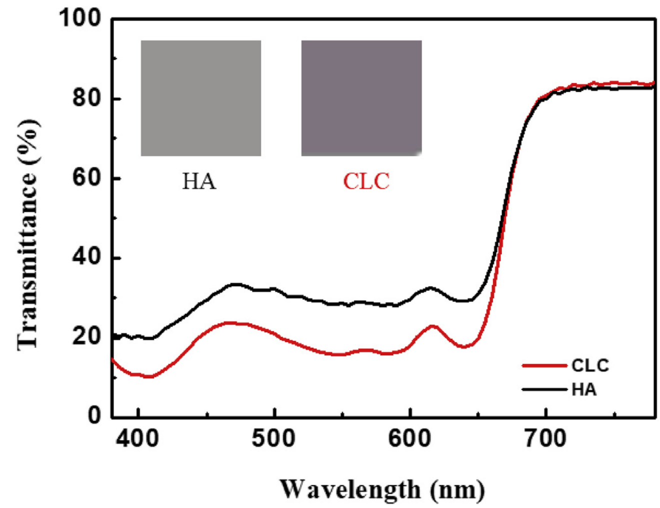

Fig. 1. The transmission spectra of black-dye-doped HA and CLC cells.

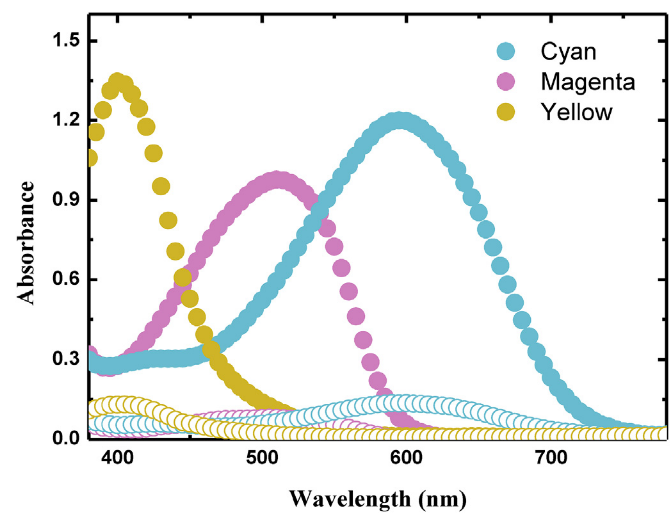

Fig. 2. The absorbance of polarizations parallel (filled circle) and perpendicular (empty circle) to the absorption axis of dye molecules.

4. Experimental results and discussion

Fig. 3 presents the calculated tristimulus values, color points in CIE 1931 color coordinates, and color change through the iterative process. We calculated dye concentrations utilizing Eqs. (1) and (4) for the black color in a dye-doped HA cell. The black color point utilized for the design of the HA cell was (0.313, 0.329), which is the black color point of a D65 light source. The tristimulus values converged to (20.90, 21.98, 23.76) and the dye concentrations converged to 1.67 wt%, 0.46 wt%, and 0.55 wt% for the cyan, magenta, and yellow dyes,