Optimization of Color and Transmittance in a Dye-doped Chiral-nematic Liquid Crystal Cell

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ABSTRACT

Among various dye-doped liquid crystal (LC) devices, a chiral-nematic LC cell provides the highest transmittance difference between its transparent and opaque states. We propose a systematic approach to find the optimal dye mixing for black color in the opaque state and optimization method in the parameter space for the maximum transmittance difference.

1 INTRODUCTION

Transmittance-control devices allow users to control the transmitted light intensity through the absorption of the incident light. These devices have been widely studied for switchable sunglasses, smart windows, and automotive applications. For switchable sunglasses and automotive applications, the transmittance-control device requires a fast response time for safety. An electro-chromic device, suspended particle device, and dye-doped liquid crystal (DDLC) device have been developed for transmittance control. Among various devices, a DDLC device shows faster response time (< 1s) than other devices [1-3].

A dye-doped chiral-nematic LC (DDCNLC) device shows the high transmittance difference between the transparent and opaque states. Thanks to its twisted structure, a DDCNLC cell absorbs the incident light regardless of the polarization direction in the planar (opaque) state [4-6]. However, because of its twisted structure, a DDCNLC cell does not show the black color when fabricated utilizing a commercial black dye. Moreover, the trial-and-error method has been used to find the condition for a DDCNLC cell with the desired performance because there is no systematic design process for a DDCNLC cell.

In this paper, we propose a systematic approach to find the optimal dye mixing for true black color in the opaque state of a DDCNLC cell and the condition for the maximum transmittance difference between the transparent and opaque states. To find the optimal dye concentration for the desired black color, we use the iterative process with the transmission spectrum of a DDCNLC cell. Additionally, by excluding the conditions that cannot satisfy the desired performance within the calculated constant transmittance-difference contour map, we can easily obtain the condition for the desired performance in a DDCNLC cell without any trial-and-error process. We believe that the proposed systematic approach can be very useful for designing a transmittance-control device using a DDCNLC cell.

2 THE TRANSMITTANCE OF DYE-DOPED CHIRAL NEMEATIC LIQUID CRYSTAL CELL

The transmittance of a homogeneously-aligned LC cell for polarization parallel and perpendicular to the absorption axis of the dye molecules can be described as

$$T_{\parallel} = T_0 exp(-\alpha_{\parallel} cd) \qquad (1\text{-a}),$$

$$T_{\perp} = T_0 exp(-\alpha_{\perp} cd) \qquad (1\text{-b}),$$

where $T_{\parallel}$ and $T\perp$ are transmittances of a DDLC cell for polarization parallel and perpendicular to the absorption axis of the dye molecules, respectively. T_0 is the transmittance of a homogeneously aligned LC cell without a dye. $\alpha_{\parallel}[\alpha_{\perp}]$ is the absorption coefficient, c is the dye concentration, and d is the cell gap [7,8].

In the homeotropic state, dye molecules are aligned perpendicular to the substrates so that the cell is transparent. In the twisted state, dye molecules absorb the incident light regardless of the polarization direction. The transmittance in the homeotropic and twisted states can be expressed as

$$T_{homeo} = T_0 exp(-\alpha_{\perp} cd) \qquad (2\text{-a}),$$

$$T_{twist} = \frac{T_0}{2} exp[exp(-\alpha_{\parallel} cd) + (-\alpha_{\perp} cd)] \qquad (2\text{-b}),$$

where T_{homeo} and T_{twist} represent the transmittances of the homeotropic and twisted states. By using these transmittances of a DDCNLC cell, we can design a DDCNLC cell systematically for transmittance control.

3 OPTIMAIZATION OF DYE MIXING FOR DESIRED BLACK COLOR

The color and transmittance of a DDLC cell are determined from the characteristics of the dichroic dye used for absorption of the incident light. Therefore, it is important to mix the black dye to achieve the desired black color in a DDLC cell by considering the transmittance of each LC mode. Due to the twisted structure of a DDCNLC cell, it does not show the black color when fabricated using a commercial black dye. Therefore, to achieve the desired black color in the opaque state of a DDCNLC cell, we should find a proper concentration of each single dye considering the twisted structure of a DDCNLC cell. The optimal dye concentrations can be found through an iterative process, known as the Newton-Raphson method [8,9] with Eq. (2-b), which represents the transmittance in the opaque state of a DDNCLC cell. To produce the black color, we selected cyan, magenta, and yellow dyes, whose absorption spectra are presented in Fig. 1. As the iterative process was repeated, the color of a DDCNLC cell became closer to target black color (Fig. 2). To confirm the reliability of our calculation, we compared the transmission spectra between the calculated and measured results, as shown in Fig. 3. The results confirm that the calculated results are reliable.

4 DESIGN PROCESS TO FIND THE CONDITION FFOR THE MAXIMUM TRANSMITTANCE DIFFERENCE

Thus far, the trial-and-error method has been used to find the condition for a DDCNLC cell with desired performance. To find the condition for the maximum transmittance-difference while satisfying the desired performance, we calculated the transmittance difference as we varied the cell gap and dye concentration by using Eqs. (2-a) and (2-b). We plotted the constant transmittance-difference contour map on the parameter space of the cell gap and dye concentration (Fig. 4) using the calculated transmittance. By using the calculated constant transmittance-difference contour maps, we introduce how to design a DDCNLC cell with the desired performance. The design process is as follows: i) exclude the condition that cannot satisfies the minimum transmittance in the transparent state. ii) determine the maximum cell gap considering the response time or driving voltage and the maximum dye concentration, considering the saturation concentration of the dye to be mixed with the used LCs. iii) select the condition for the maximum transmittance difference (Fig. 5). In the proposed process, we can determine the cell gap and dye concentration with the desired performance, such as the transmittance in the transparent state, response time, and driving voltage. Therefore, by using the proposed process, we can systematically obtain the condition for the desired DDCNLC cell before cell fabrication.

5 SUMMARY

In this study, we demonstrated a systematic approach for designing a DDCNLC cell with the desired characteristics, such as a specific transmittance difference, transmittance in the transparent state, driving voltage, response time, and color in the opaque state. Once the transmittance formulas of a DDCNLC cell are given, the design of a DDCNLC cell with the desired black color and performance can be achieved. By using the proposed iterative process, we can find the dye concentration for true black color in the opaque state of a DDCNLC cell. Moreover, by confining regions in a constant transmittance-difference contour map, we can also find the condition for a DDCNLC cell with the desired performance. For the confirmation of the proposed approaches, we fabricated DDCNLC cells with proposed processes, and we found that the experimental results satisfied the desired performance.

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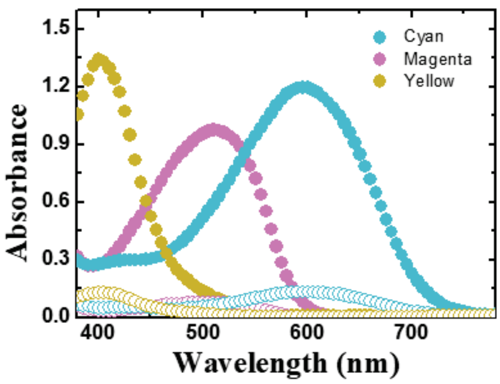

Fig. 1 The absorbance of polarizations parallel (filled circle) and perpendicular (empty circle) to the absorption axis of dye molecules.

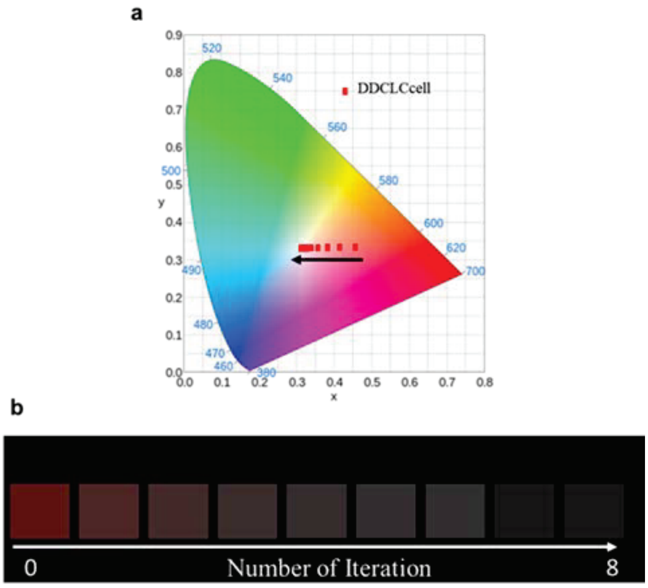

Fig. 2 (a) Movement of color point (red squares) for a DDCNLC cell over multiple iterations. (b) Color change of the DDCNLC cell over multiple iterations.

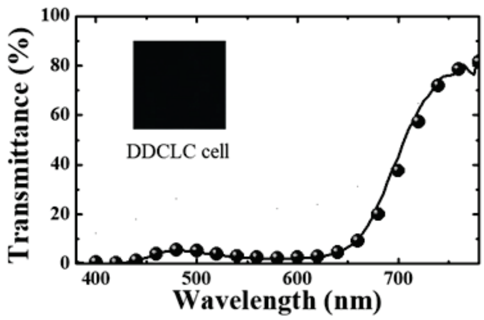

Fig. 3 Calculated (line) and measured (circle) transmission spectra of the DDCNLC cell when dye concentrations were optimized for the black color in a DDCNLC cell.

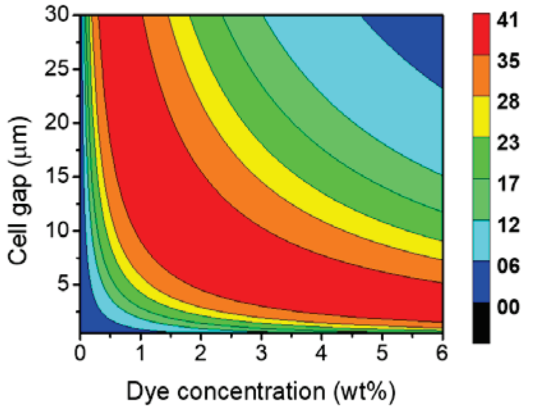

Fig. 4 Constant transmittance-difference contour maps of DDCNLC cell on the parameter space of the cell gap and dye concentration

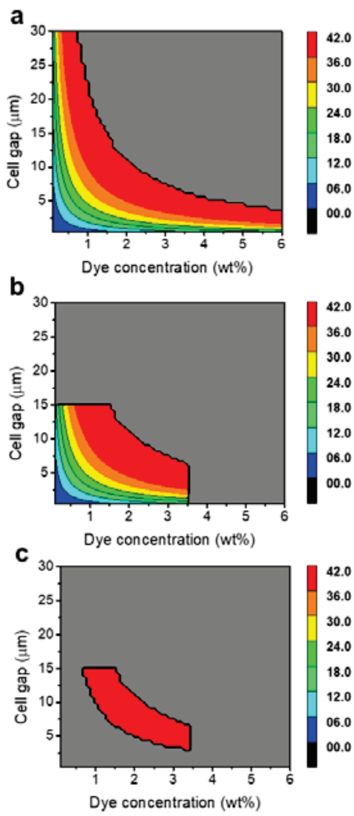

Fig. 5 Example of the proposed design process for a DDCNLC cell on a constant transmittance-difference contour map. (a) The region that does not satisfy the minimum transmittance in the transparent state is excluded. (b) The regions that do not satisfy the conditions of the cell gap and dye concentration are excluded. (c) The regions that do not satisfy the minimum transmittance difference are excluded.