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Dual Structure of Cholesteric Liquid Crystal Device for High Reflectance

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The structure of cholesteric liquid crystal (CLC) undergoes a helical distortion which is left-handed or right-handed. By the right-hand CLC layer, Left-handed polarized light is reflected and vice versa. The color reflected by the selective reflection depends on the chiral pitch and the anisotropy of the refractive index. However, the reflectance of the single CLC layer is theoretically limited to 50% because only one of right- or left-handed circularly polarized light is reflected. In this paper, we demonstrate the enhanced reflectance of a dual-CLC device which can reflect both right- and left-handed circularly polarized light.

Keywords: liquid crystals, cholesteric, reflective mode, high reflectance

1. INTRODUCTION

Recently, there have been many studies regarding electronic paper due to its bistability and low power consumption.[1-8] One promising approach to electronic paper is the cholesteric liquid crystal (CLC) device.[9] When unpolarized light is incident to the CLC layer with the right-hand sense, only the left-handed circularly polarized light, which depends on the chiral pitch and the anisotropy of the refractive index, is reflected.[10-12] Therefore, the reflectance is theoretically limited to 50%. However, for device application, high light efficiency and high brightness are required.[13,14] To improve the reflectance, both the left-handed and right-hand circularly polarized light should be reflected. In this paper, for high reflectance, we propose a CLC device using two layers, including the right-handed and left-handed CLC layers. We fabricated test cells which reflect red, green, and blue. Enhanced reflectance of the fabricated dual structure is also demonstrated.

2. OPTICAL SIMULATION

For the right-handed CLC layer, left-handed circularly polarized light is reflected. By using coupled mode analysis, the optical properties of the CLC layer can be calculated.[12] Assuming that the light propagates along the z-axis, the direction of the electric field of the light is located on the xy plane. The dielectric tensor of the right-handed CLC layer can be written as

$$\varepsilon(z) = \varepsilon\begin{pmatrix}\beta & 0\\ 0 & \beta\end{pmatrix} + \varepsilon_0\alpha\begin{pmatrix}\cos 2qz & \sin 2qz\\ \sin 2qz & -\cos 2qz\end{pmatrix} \tag{1}$$

where

$$\beta = \frac{1}{2}(n_e^2 + n_0^2) \tag{2}$$

$$\alpha = \frac{1}{2}(n_e^2 - n_0^2) \tag{3}$$

and q is related to the chiral pitch by $q = 2\pi/P_0$. The total electric field is represented by the sum of the field of the incident light and reflected light:

$$\mathbf{E} = A(z)\begin{pmatrix}1\\ i\end{pmatrix}e^{i(\omega t - kz)} + B(z)\begin{pmatrix}1\\ -i\end{pmatrix}e^{i(\omega t + kz)} \tag{4}$$

where $A(z)$ denotes the amplitudes of the incident light, and $B(z)$ is that of reflected light. This satisfies the following wave equation:

$$\frac{d^2}{dz^2}\mathbf{E} + \omega^2\mu\varepsilon\mathbf{E} = 0\,. \tag{5}$$

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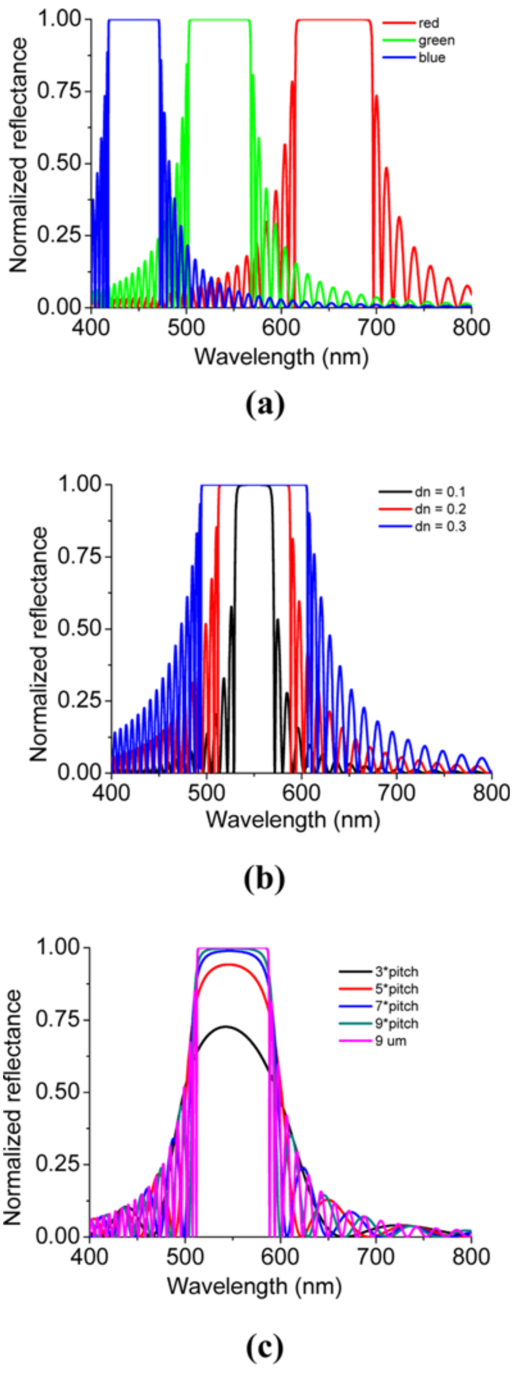

Fig. 1. Calculated reflectance with respect to (a) various chiral pitch lengths, (b) various anisotropy values of reflective index, and (c) the various numbers of the chiral pitch.

Table 1. Parameters of the CLC device used in the simulation.

Parameter	Value
Center of wavelength	550 nm
Average reflectance index	1.5
Cell gap	9 um

Substituting Eq. (4) for the electric field into the wave Eq. (5) and by using Eq. (1) for the dielectric tensor for the CLC layer, the relation between A and B is obtained. Then, after trivial calculation, the expression for reflectance is obtained:

$$R = |r|^2 = \frac{\kappa^2 \sinh^2 sL}{s^2 \cosh^2 sL + \left(\frac{\Delta k}{2}\right)^2 \sinh^2 sL} \qquad (6)$$

where

$$s^2 = \kappa^2 - \left(\frac{\Delta k}{2}\right)^2 = \kappa^2 - (k-q)^2 . \qquad (7)$$

From the Eq. (7), reflectance depends on the chiral pitch, the anisotropy of the reflective index, and the thickness of the CLC layer. The calculated spectroscopic characteristics of the selective reflection in terms of various parameters are shown in Fig. 1. The parameters used in the calculation are listed in Table 1. The center of the wavelength for reflected light is determined by the chiral pitch length of the CLC layer. The reflectance with various chiral pitch lengths is shown in Fig. 1(a). The centers of the wavelength are 455 nm, 535 nm, and 655 nm. The bandwidth of the reflected light is also related to the anisotropy of the reflective index. As the anisotropy of the reflective index is increased, a larger bandwidth is obtained as shown in Fig. 1(b). The number of the chiral pitch also has an effect on the reflectance. As the number of the chiral pitch increases, the reflectance also increases as shown in Fig. 1(c).

For the left-handed CLC layer, the reflectance for right-handed polarized light can be similarly calculated. From Eq. 6, we can expect that there would be no difference in the reflectance from the CLC layer with the left-handed sense if the two CLC layers have the same chiral pitch. By stacking the CLC layers with opposite chiral senses, the reflectance can be maximized because the CLC layers reflect both the right- and left-handed circularly polarized light. We have calculated the reflectance from each CLC layer with the opposite chiral sense and that from the stacking CLC layer with the opposite chiral sense, and the results are shown in Fig. 2.

The parameters used in the numerical calculation were the following: liquid crystal MLC-6650; optical anisotropy $\Delta n = 0.1498$, $n_e = 1.6495$, $n_o = 1.4997$, and chiral pitch = 365.2 nm. While the reflectance of the single CLC layer was 50%, the reflectance of 100% was obtained with the dual structure as shown in Fig. 3. When unpolarized light is incident to the single CLC layer, only one of the right- or left-handed circularly polarized lights is reflected. On the other hand, both the right- and left-handed circularly polarized light can be reflected by the two CLC layers with the opposite chiral sense.

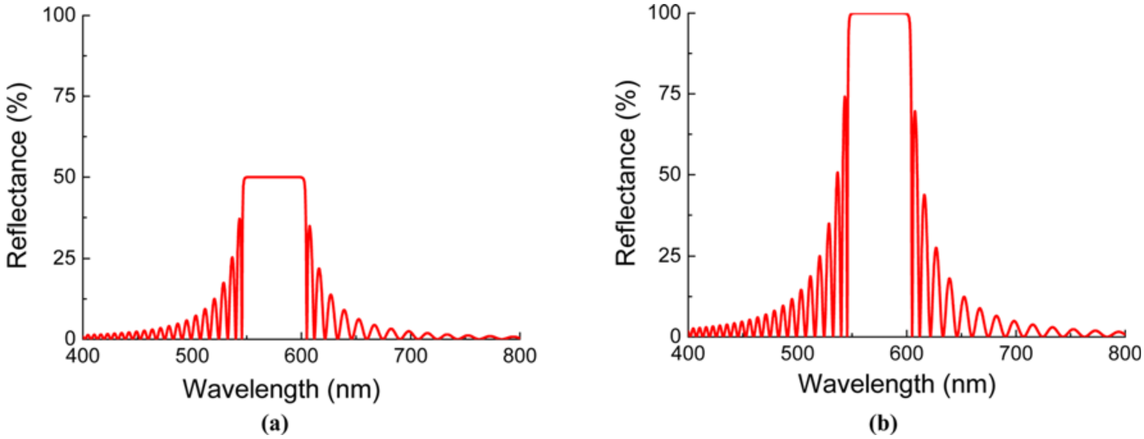

Fig. 2. Calculated reflectance with (a) a single CLC layer and (b) the proposed dual CLC layer.

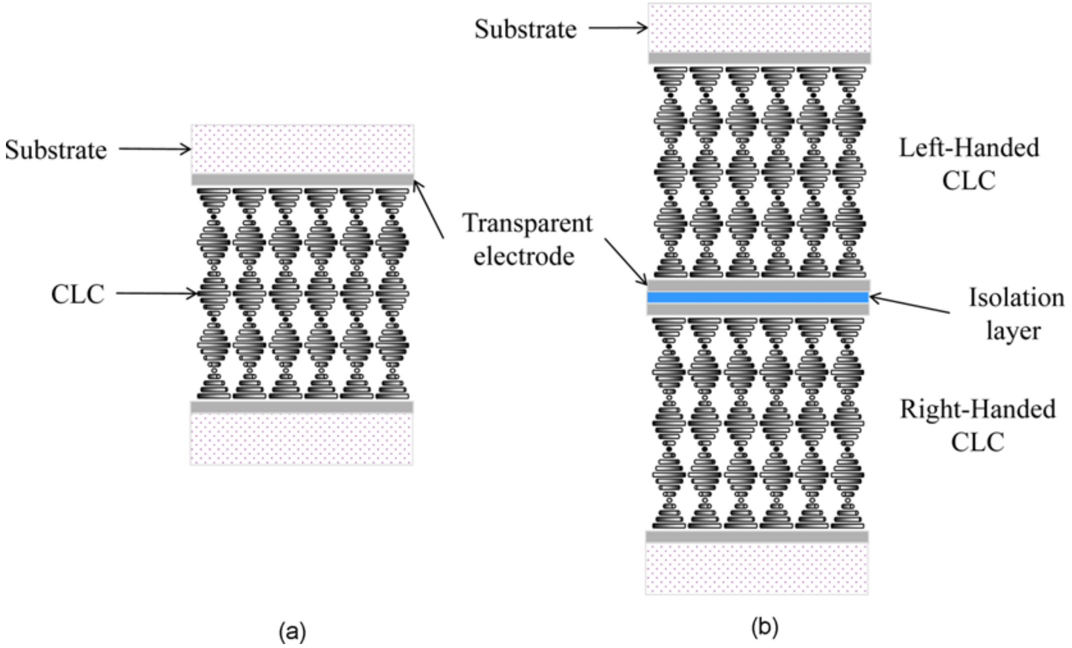

Fig. 3. The CLC device structure with (a) a single layer and (b) the proposed dual layer.

3. RESULTS AND DISCUSSION

To clarify the effects of the dual structure, we fabricated several test cells. The process of fabricating the dual CLC cell is shown in Fig. 4. Two substrates were separated by a spacer with the diameter of 9 um. Each test cell was filled with the LC material MLC-6650 whose optical anisotropy is 0.1498 as previously mentioned. For the dual structure, we used an isolation layer in which the transparent electrode was coated on both surfaces. Figure 5 shows the fabricated CLC cells with the dual structures, which reflect red, green, and blue.

The schematic diagram of the measuring system is described in Fig. 6. A halogen lamp was used as a white light source. The light source was incident to the cell in the normal direction. A detector was located behind the cell in the normal direction. Transmittance was measured by a spectrometer, and the equivalent reflectance was derived from the transmittance, which is the difference between the maximum transmittance and the measured transmittance.[15] This is simply represented by (100 – measured transmittance) %. With the single CLC layer, the equivalent reflectances of the red, green, and blue cells were 46%, 43%, 40%, respectively, as shown in Fig. 7(a). The equivalent reflectances of the dual red, green, and blue cells were 71%, 64%, and 63% as shown in Fig. 7(b).

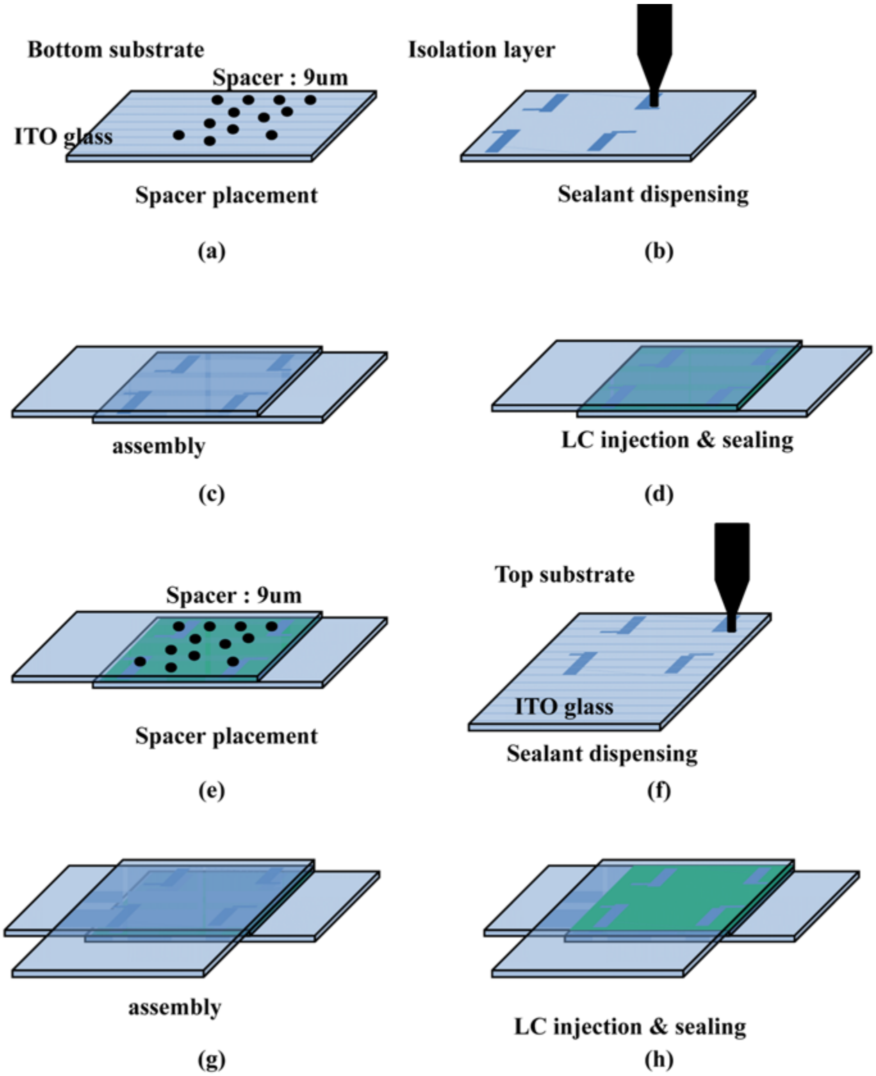

Fig. 4. Fabrication process: (a) spacer placement on the bottom substrate, (b) sealant dispensing on the isolation layer, (c) assembly between the bottom substrate and the isolation layer, (d) LC injection and sealing of the bottom cell, (e) spacer placement on the bottom cell, (f) sealant dispensing on the top substrate, (g) assembly between the bottom cell and top substrate, and (h) LC injection and sealing of the top cell.

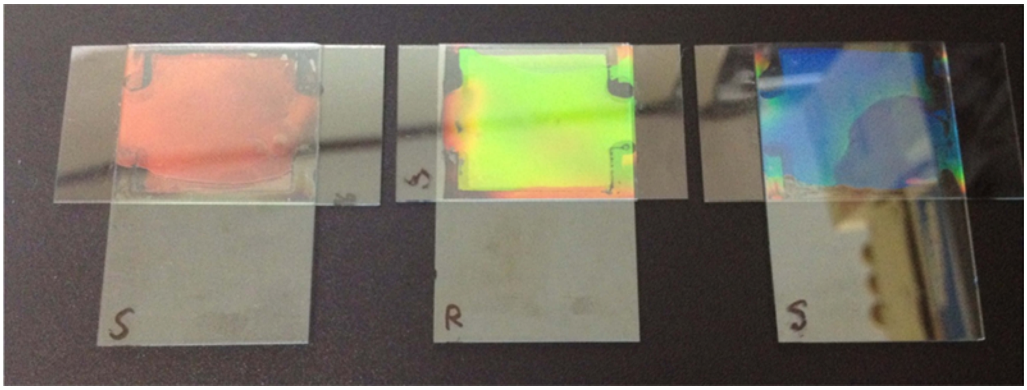

Fig. 5. Fabricated dual CLC Cells which reflect red, green, and blue.

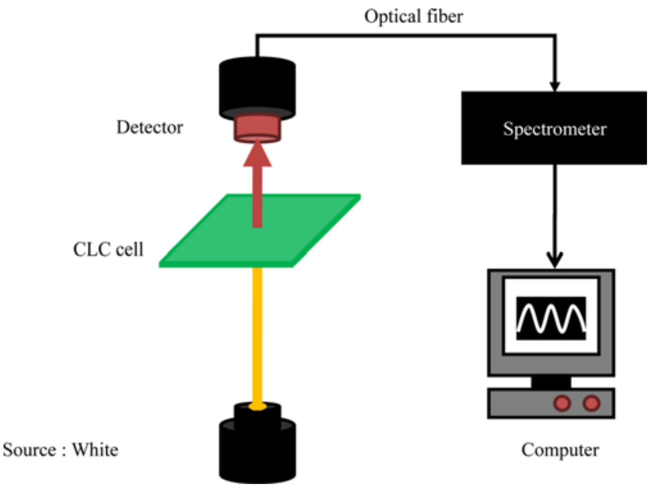

Fig. 6. Schematic diagram of the measuring system.

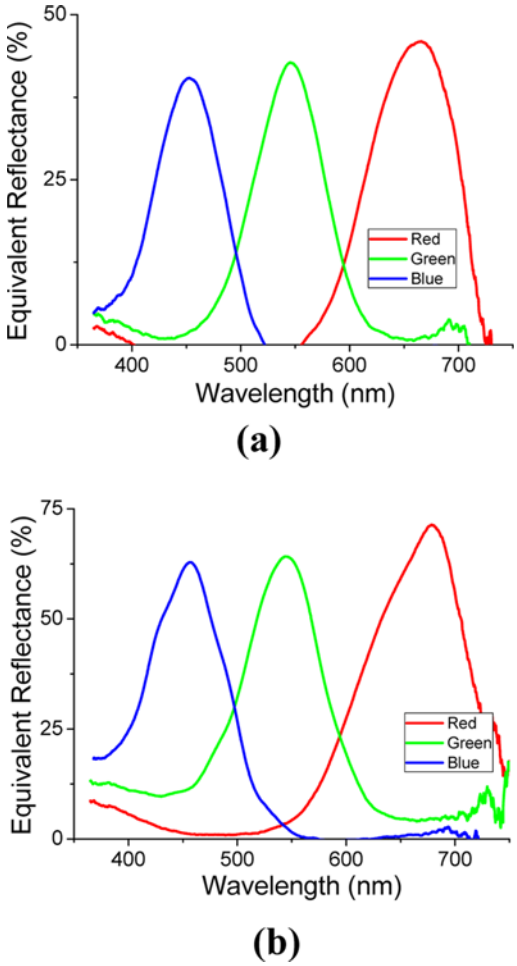

Fig. 7. Equivalent reflectance of CLC cell with (a) a single structure and (b) the proposed dual structure.

The measured reflectances shown in Fig. 7 were lower than the calculated values. The major source of device performance degradation is the order parameter of liquid crystal materials, which is the amount of orientational order (S). For a completely random and isotropic sample, S = 0; however, for a perfectly aligned sample, S = 1. For the simple calculation, we assumed that liquid crystal molecules are perfectly aligned; thus, in this case, the order parameter S is 1. However, for liquid crystal materials in the nematic phase, the order parameter is between 0.3 and 0.8 due to thermal fluctuation, which affects the reflective index anisotropy, the elastic constants, and the chiral pitch. Therefore, the measured reflectance is lower than that of the calculated results.

4. CONCLUSIONS

The reflectance in the single CLC layer is theoretically limited to 50% because, by the right-hand CLC layer, left-handed polarized light is reflected and vice versa. To improve the reflectance, we propose the dual CLC device which includes an isolation layer. With our proposed device, not only the right-handed circularly polarized light, but also the left-handed circularly polarized light is simultaneously reflected. Thus, we can obtain reflectances of about 71%, 64%, and 63% for red, green, and blue, respectively.

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