P-184: Optical Compensation for High Contrast Ratio in Reflective Horizontal Switching LC Cell

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Abstract
We propose an optical configuration for the reflective liquid crystal (LC) cell with a single polarizer that can show excellent contrast ratio by effectively eliminating phase dispersion. The proposed configuration consists of a half-wave retarder, an A-plate, a quarter-wave LC cell, and a reflector. We designed this optical configuration on a Poincaré sphere with the trigonometric method. From the calculation, we confirm that the proposed configuration provides high contrast ratio over twice compared to the conventional configuration.

1. Introduction
Reflective liquid crystal displays (LCDs) are considered as suitable display devices because of their small weight and low power consumption. It provides high brightness compared with the double polarizer mode [1-5]. On the other hand, there is a problem of the polarizer mode that has low contrast ratio in comparison with the double polarizer mode due to the light leakage in the dark state. However, the former has a low contrast ratio in comparison to that of the latter because of light leakage in the dark state.

To reduce the leakage, a previous paper proposed an optical configuration that consists of a polarizer, half-wave retarder, and quarter-wave LC cell in addition to a reflector as shown later [6-7]. The previous single-polarizer LC cell used in that study can reduce the light leakage by eliminating phase dispersion in the dark state. Therefore, it showed a comparatively good contrast ratio by compensating the phase dispersion at the designed wavelength, for example, at the green wavelength. However, light leakage in the conventional optical configuration continues to exist at the red and blue wavelengths because the phase dispersion at these wavelengths cannot be completely eliminated.

Therefore, in this paper, we propose a novel optical configuration for the reflective LCD with a single polarizer, which provides an excellent dark state along the entire visual wavelength range so that it can induce a very high contrast ratio.

2. The principal of the compensation film
In the reflective LC cell, the most important condition for obtaining a high contrast ratio is that the polarization state in the entire visible wavelength of the traveling light in front of the reflector becomes circular polarization state, whose position is $S_3$ on the Poincaré sphere [8-11]. Figure 1 shows the conventional optical configuration of the reflective LC mode for a single polarizer and its optical principle on the Poincaré sphere in the dark state. The conventional reflective LC cell consists of a polarizer, half-wave retarder, and quarter-wave LC cell in addition to a reflector. A previous paper reported an optical configuration that could successfully compensate the phase dispersion in the entire visible wavelength range during the passage of light through the half-wave retarder and quarter-wave LC cell so that the light could be circularly polarized in front of the reflector.

In Fig. 1 (a), the axis of the polarizer is set to 0° and the optic axes of the half-wave retarder and quarter-wave LC cell are set to $\theta$ and $\theta + 45^\circ$, respectively. Further, the optimized value of $\theta$ is 15° [6]. Figure 1(b) shows the polarization state of the light passing through the reflective LC cell in the previous paper on the Poincaré sphere in red (■), green (●), and blue (▲) wavelength lights. Positions $P$, $H$, and $Q$ represent the position of the polarizer, the optic axis of the half-wave retarder, and the optic axis of the quarter-wave retarder. The circular path $P_H$ is the polarization path of the light passing through the half-wave retarder, which has a centering position $H$. The circular paths $P_{0G}$, $P_{0B}$, and $P_{0R}$ represent the polarization paths of the red, green, and blue wavelength lights passing through the quarter-wave LC.
layer; these paths are centered at $Q$ by the optic axis of LC layer. After passing through the half-wave retarder, phase dispersion occurs because of the different phase retardations of the red, green, and blue wavelengths. However, the optical phase dispersion can be effectively reduced by passing the lights through the quarter-wave LC cell.

However, the optical path of the light passing through the quarter-wave LC cell and proceeding toward $S_2$ can vary for lights with different wavelengths, as shown in Figure 1(b). After passing through the half-wave retarder and quarter-wave LC cell, the polarization state of the green wavelength light arrives alone at $S_2$ in front of the reflector. However, the polarization state of the light in red and blue wavelengths can be deviated to the goal position $S_3$, and this causes light leakage in the dark state. Therefore, in order to obtain a perfect dark state, we need to gather the polarization state of the light in the entire visible wavelength in front of the reflector on the circular polarization position $S_3$.

We used ML-0249 for the quarter-wave LC cell ($\Lambda_{\text{red}} = 158.25$ nm, $\Lambda_{\text{green}} = 164.7$ nm, and $\Lambda_{\text{blue}} = 178.75$ nm). In practice, we do not change the material properties of the LC, which implies that the positions $A, A_G,$ and $A_B$ are fixed because they depend on the LC material. The starting point for designing the half-wave retarder is that the condition $\Delta H_G = A_G, A_A = A_B$ should be satisfied; $\overline{AH_G}$ and $\overline{AA_G}$ are the radii of the polarization paths of the green wavelength light and $\overline{AH_B}$ and $\overline{AA_B}$ are the radii of the polarization paths of the blue wavelength light due to the positive $A$-plate. From this, $\overline{AH_G}, \overline{AH_B}, A_A$, and $A_B$ can be easily calculated using the equations given below:

$$\overline{AH_G} = A_G = \frac{\Gamma_G^b}{\Lambda_{\text{red}}} - \frac{\Gamma_G^g}{\Lambda_{\text{green}}}$$

$$\overline{AH_B} = A_B = \frac{\Gamma_B^b}{\Lambda_{\text{blue}}} - \frac{\Gamma_B^g}{\Lambda_{\text{green}}}$$

$\Gamma_G^b, \Gamma_G^g, \Gamma_B^b,$ and $\Gamma_B^g$ are the phase retardations of the red, green, and blue wavelength lights in the quarter-wave LC cell, respectively. From this, we can calculate the optimized polarization positions of a light on the circular path $P_Q$.

Figure 3 shows the calculation of the retardation of the green and blue wavelength lights caused by the half-wave retarder. From the triangles $HAH_G$ and $HAH_B$, we can obtain the retardation.
of the green and blue wavelength lights, respectively.

$$\Gamma_{\lambda/2}^{G} = \pi + \angle AHH_{G} , \Gamma_{\lambda/2}^{B} = \pi + \angle AHH_{B}$$  \hspace{1cm} (2)

$$\angle AHH_{G} = \cos^{-1}\left[ \frac{\cos AH_{G} - \cos HH_{G} \cos HA}{\sin HH_{G} \sin HA} \right]$$  \hspace{1cm} (3)

$$\angle AHH_{B} = \cos^{-1}\left[ \frac{\cos DH_{B} - \cos HH_{B} \cos HA}{\sin HH_{B} \sin HA} \right]$$  \hspace{1cm} (4)

where $\Gamma_{\lambda/2}^{G}$ and $\Gamma_{\lambda/2}^{B}$ represent the calculated retardations of the green and blue wavelength lights by the half-wave retarder, respectively.

The optimized retardation value of the positive $A$-plate can also be obtained by using the following simple trigonometric equation that employs $\angle HAH_{G}$ and $\angle HAH_{B}$:

$$\Gamma_{A}^{G} = \pi / 2 - \angle HAH_{G} , \Gamma_{A}^{B} = \pi / 2 - \angle HAH_{B}$$  \hspace{1cm} (5)

$$\angle HAH_{G} = \cos^{-1}\left[ \frac{\cos HH_{G} - \cos AH_{G} \cos HA}{\sin AH_{G} \sin HA} \right]$$  \hspace{1cm} (6)

$$\angle HAH_{B} = \cos^{-1}\left[ \frac{\cos HH_{B} - \cos AH_{B} \cos HA}{\sin AH_{B} \sin HA} \right]$$  \hspace{1cm} (7)

$\Gamma_{A}^{G}$ and $\Gamma_{A}^{B}$ represent the calculated retardations of the green and blue wavelength lights by the $A$-plate, respectively.

### 3. Result

By using the abovementioned equations and Cauchy’s formula [12], we could obtain the optimized retardation values for the half-wave retarder and positive $A$-plate. We verified the improved dark state of the reflective cell by using the helpful LC software DiMOS (developed by Autronic-Melchers, Germany) instead of performing experiments because each optimized film requires very long time to be supported. Figure 4 shows a comparison of the calculated reflection spectra between the conventional and the proposed reflective LC cells in the dark state when $\theta = 15^\circ$. From this figure, we confirm that light leakage still occurs for blue wavelength because we find that no optimized condition exists for blue light.

On the several performance of the different conditions respectively, we observed the normal dispersion characteristics in both the $A$-plate and half-wave retarder if we use the condition $\theta = 20^\circ$. Table 1 shows the calculated optimized retardations for the $A$-plate and half-wave retarder for each wavelength for a single polarizer reflective LC cell using ML-0249.

Figure 5 shows a comparison of the calculated reflection spectra between the conventional and the proposed reflective LC cells in the dark state. From this figure, we confirm that an excellent dark state can be achieved by using the proposed optical configuration for $\theta = 20^\circ$; the configuration can permit a high contrast ratio that is greater than two times the calculated conventional optical configuration.
4. Conclusion

We have proposed an optical configuration for the reflective LC cell with a single polarizer that provides an excellent contrast ratio. By applying and optimizing the $A$-plate and half-wave retarder, we have simultaneously achieved an excellent wideband property. We confirm that the proposed configuration provides an excellent contrast ratio in comparison to the conventional reflective LC cell by effectively eliminating phase dispersion.

5. Acknowledgements

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6. References


<table>
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<th>$\frac{\Delta n}{\Delta n}$ (546 nm)</th>
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<td>$400$ nm</td>
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<td>$633$ nm</td>
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<tr>
<td>Half-wave retarder</td>
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<td>$1.058$</td>
</tr>
<tr>
<td>Positive A-plate</td>
<td>$1.130$</td>
<td>$1.085$</td>
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Table 1. Calculated retardations of the half-wave retarder and positive $A$-plate ($\theta=20^\circ$)