Improvement of Color Shift and Viewing Angle in a Vertically-Aligned Liquid Crystal Cell

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In this paper, we propose an optical configuration for a vertical alignment (VA) liquid crystal (LC) cell that can improve the viewing angle and the color shift. In order to achieve the improved optical performance, we add two negative C-plates and a single negative A-plate to a LC cell. We optimize the VA liquid-crystal-display (LCD) by using the Muller matrix method. The calculated optical characteristics of the proposed VA LCD are compared to those of a conventional VA LCD for verification.

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I. INTRODUCTION

With the rapid growth of information technology, many efforts have been concentrated on improving the image quality in the liquid-crystal-display (LCD) industry. In terms of large-sized thin-film transistor (TFT)-LCD monitor and TV applications, current technology requires a wide viewing performance and a fast response time simultaneously. Therefore, various approaches using the electro-optical effects of liquid crystal (LC) modes, such as in-plane switching (IPS) [1], fringe field switching (FFS) [2], patterned vertical alignment (PVA) mode [3], and multi-domain vertical alignment (MVA) mode [4], have been proposed to improve the viewing angle properties. In particular, the PVA and MVA modes show an excellent contrast ratio in the normal direction. Therefore, many LCD manufacturers use vertically aligned (VA) LC cells in TV applications. However, the VA LC needs to add compensation films to the LC cell in crossed polarizers, which has the advantage not to disturb the existing manufacturing lines, for improving the viewing angle. Previous papers presented the optical configurations of the VA LC cell with optical compensation films for wide viewing angle. Hong et al. proposed an optical configuration VA LCD with a wide viewing angle by using two A-plates and two C-plates [5]. Lin showed a high-transmittance circular polarizertype MVA-LCD with a wide viewing angle by using a combination of two A-plates, a C-plates, and two λ/4 plates [6]. In addition, Chen et al. showed an optical configuration using two biaxial films in order to improve the optical characteristics [7]. However, all the papers introduced here consider the optical characteristics at a single wavelength for optimization. Generally, we need to consider the optical characteristics over the entire visible wavelength range to determine the dependence of the material properties on the dispersion of the refractive index. In previous papers, consideration has been given to the compensation of the retardation in the visible wavelength range for improving the viewing angle [8], and this optical configuration exhibited a good the viewing angle. However, we found that the color shift as a function of the incident angle deteriorated, especially in the blue wavelength range. In this paper, we propose another optical configuration for the VA LC cell that can improve the color shift and the optical viewing angle over the entire visible range. The configuration uses two negative C-plates and a single negative A-plate.

II. LIGHT LEAKAGE IN THE CONVENTIONAL VA LC CELL IN THE OBLIQUE DIRECTION
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The optical performance of the VA LC cell alone in an oblique direction deteriorates with viewing angle, which can increase the light leakage in the dark state. In general, one of the reasons for the off-axis light leakage is a shift of the principle axis of the optical components. The effective principle axis of the optical components deviates from the principle axis in normal incidence by the deviation angle $\delta$ [9]. The change in the retardation value of the compensation film for oblique incidence may also be another factor. The effective retardation $\Gamma$ of the optical layers at oblique incident angles as a function of the polar $\theta$ and the azimuth angle $\phi$ of the incident light can be easily calculated by using the extended $2 \times 2$ Jones matrix method [10–12]. The last reason for light leakage is the dispersion of the refractive index of the optical components along the wavelength [13,14].

A conventional VA LC cell has a VA LC layer and two crossed polarizers. Fig. 1(a) presents the polarization state of the light on the Poincaré sphere when the light passes through the cell in the normal direction [15]. The symbols $\bullet$, $\blacksquare$, and $\blacklozenge$ represent the polarization state of the light with red ($R = 630$ nm), green ($G = 550$ nm), and blue wavelengths ($B = 450$ nm), respectively. In this paper, we assume that the optical axis of the vertically-aligned LC layer in the absence of an electric field is the same as the optical axis of the positive C-plate. The normally-incident light passes through the polarizer and the VA LC layer without any deviated angle $\delta$ and phase retardation $\Gamma$. Therefore, the polarization state of the light after passing through them is still $S_1$, which is not only the polarization state of the polarizer but also the absorption axis of the analyzer in the normal direction. This means the VA LC cell shows a perfect dark property at normal incidence.

Figure 1(b) shows the polarization state of the light when the light obliquely passes through the cell in a diagonal direction. In the dark state, the obliquely-incident light experiences a deviated angle $\delta$ compared to normal incidence when it passes the polarizer. Therefore, the position of the polarization axis of the polarizer will deviate by $2\delta$ from $S_1$. The start polarization position for oblique incidence becomes position $A$. The polarization positions of the light for $R$, $G$, and $B$ wavelengths after passing through the VA LC layer with fast axis $Q$ are rotated to the polarization positions $Br$, $Bg$, and $Bb$, respectively, due to the phase dispersion of the LC cell along the circle path $P_1$, which is centered at $OQ$. The subscript of the letter represents $R$, $G$, and $B$ wavelengths. Here, the polarization positions $Br$, $Bg$, $Bb$ are quite different from the polarization position $H$, which is the perfect opposing position of the polarization axis of the analyzer in the oblique incidence. Here, we can assume that the large deviation between positions $Br$, $Bg$, and $Bb$ and position $H$ will induce a serious off-axis light leakage in the dark state.

III. OPTICAL CONFIGURATION FOR REDUCING THE COLOR SHIFT AND THE LIGHT LEAKAGE IN THE OBLIQUE INCIDENCE

Optical compensation can be achieved by applying optical compensation films to the conventional LC cell. Fig. 2(a) shows the proposed configuration of the VA LC cell with two negative C-plates ($nx = ny > nz$) and a negative A-plate ($nx < ny = nz$). The optical axis of the negative A-plate is aligned with the absorption axis of the incident polarizer. An improved optical polarization path of the proposed LC cell is described on the Poincaré sphere, as shown in Fig. 2(b). The start position is at position $A$ when the light passes through the polarizer obliquely. Then, the polarization state of the light passing through the negative A-plate with position $K$ on the optical axis moves to position $B$ along the circle path $P_1$. The polarization position moves to positions $C$ and $D$ along the paths $P_2$ and $P_3$ on the circle $j$ after passing through the lower negative C-plate and VA LC layer, re-
\[
S' = R(-2\theta) \cdot M(\Gamma) \cdot R(2\theta) \cdot S(P)
\]

where \(R(2\theta)\) and \(R(-2\theta)\) are the rotating matrix and reverse rotating matrix to the principle axis. \(M(\Gamma)\) represents the Muller matrix for the rotated polarizing components with phase retardation \(\Gamma\). \(S(P)\) is the Stokes vector of the incident light after passing through the polarizer, and \(S'\) represents the Stokes vector of the output light. \(S_{0,P}, S_{1,P}, S_{2,P}\), and \(S_{3,P}\) are the Stokes polarization parameters of the Stokes vector \(S(P)\). In the proposed configuration, the angle of rotation for the negative \(A\)-plate is \(90^\circ + \delta\), and \(S_{2,P}\) values in each \(R, G, B\) wavelength are \(-0.2441\) [rad]. By using the calculated value, we can calculate the retardation value \(\Gamma\) of the negative \(A\)-plate for each wavelength in order to move the polarization state of the light passing through the negative \(A\)-plate on the Poincaré sphere.

The second condition for optimization is to determine the retardation of the upper negative \(C\)-plate. For the calculation, we assume that the lower negative \(C\)-plate has normal wavelength dispersion in which retardation decreases in proportion to the increase in wavelength. A practical example of the dispersion of the refractive index of the lower negative \(C\)-plate is shown in Table 1.
Table 1. Optical constants of thin films of the materials.

<table>
<thead>
<tr>
<th></th>
<th>(\lambda = 450) nm</th>
<th>(\lambda = 550) nm</th>
<th>(\lambda = 630) nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative A-Plate</td>
<td>-113.54</td>
<td>-138.80</td>
<td>-159.06</td>
</tr>
<tr>
<td>Lower negative C-plate</td>
<td>-237.60</td>
<td>-223.30</td>
<td>-217.27</td>
</tr>
<tr>
<td>Upper negative C-plate</td>
<td>-136.70</td>
<td>-160.44</td>
<td>-176.64</td>
</tr>
</tbody>
</table>

Fig. 3. Color shift for \(R,G,B\) wavelength light in the horizontal and the diagonal directions (a) for a conventional structure and (b) for the proposed structure. Symbols ◯, □, and ◦ represent the \(R,G,B\) wavelength light in the horizontal direction, and symbols ●, ■, and ■ represent the \(R,G,B\) wavelength light in the diagonal direction.

Fig. 4. Calculated iso-luminance in the dark state (a) for the conventional VA LC cell and (b) for the proposed VA LC cell.

For achromatic color performance in the dark state, the polarization state of the light after passing through the upper negative \(C\)-plate must move together from \(D_r, D_g,\) and \(D_b\) to \(H\), which is the desired final destination of the tri-stimulus wavelength for the perfect dark state. The Stokes vector of point \(H\) is \((1, 0.96974, 0.24413, 0)^T\), so we can easily calculate the retardation value of the upper negative \(C\)-plate by using the Muller matrix method through Eq. (1).

Table 1 shows the calculated optimized retardation values of the three compensation films for the \(R,G,\) and \(B\) wavelengths. In this calculation, we set the dispersion property of the LC as \(\Delta n(\lambda = 450\) nm) / \(\Delta n(\lambda = 550\) nm) = 1.04 and \(\Delta n(\lambda = 630\) nm) / \(\Delta n(\lambda = 550\) nm) = 0.98. The cell gap \(d\) for the calculation was set to 4.2 \(\mu m\). From Table 1, we observe that the calculated result for the used films show that they are feasible for a practical approach to display devices. We verified the improved viewing angle of the proposed VA LC cell by using the commercial LC software TechWiz LCD provided by SANAYI System Co. in Korea.
IV. CONCLUSIONS

In conclusion, we have proposed an optical configuration of a VA LC cell with two negative C-plates and a single negative A-plate. In order to achieve an excellent dark state by compensating for the off-axis light leakage overall visible wavelengths, we optimized the retardation value of the compensation films for each wavelength by using the Stokes vector and the Muller matrix on the Poincaré sphere. Numerical calculations show that the proposed structure not only exhibits wide viewing-angle characteristics but also a reduced color shift by compensating for the light leakage in the visible wavelength range.

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REFERENCES