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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 polarizer-type MVA-LCD with a wide viewing angle by using a combination of two A-plates, a C-plates, and two $\lambda/4$ 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 visual 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.

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II. LIGHT LEAKAGE IN THE CONVENTIONAL VA LC CELL IN THE OBLIQUE DIRECTION

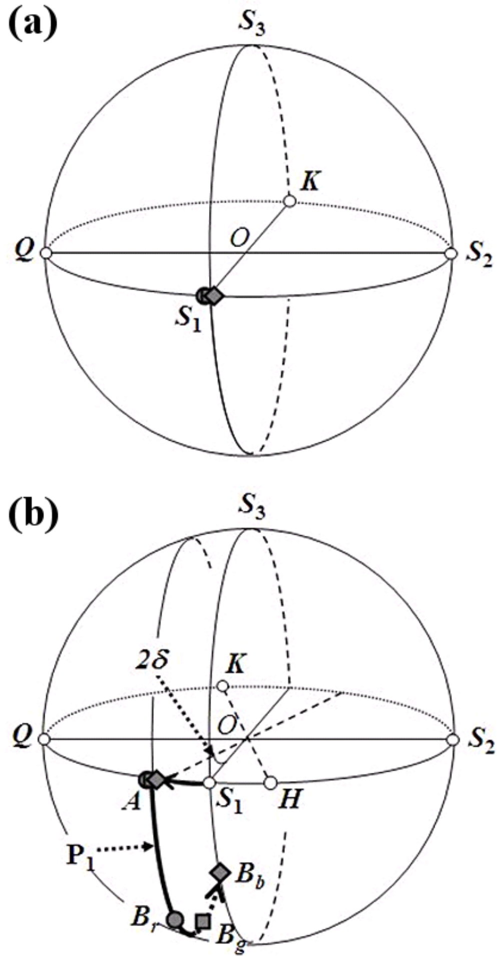

Fig. 1. Polarization states of the light by a conventional VA LC cell on a Poincaré sphere (a) in the normal direction and (b) in the diagonal direction.

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 δ [9]. The change in the retardation value of the compensation film for oblique incidence may also be another factor. The effective retardation Γ of the optical layers at oblique incident angles as a function of the polar θ and the azimuth angle ϕ of the incident light can be easily calculated by using the extended 2 × 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 •, ■, and ♦ 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 δ and phase retardation Γ. 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 δ compared to normal incidence when it passes the polarizer. Therefore, the position of the polarization axis of the polarizer will deviate by 2δ 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-

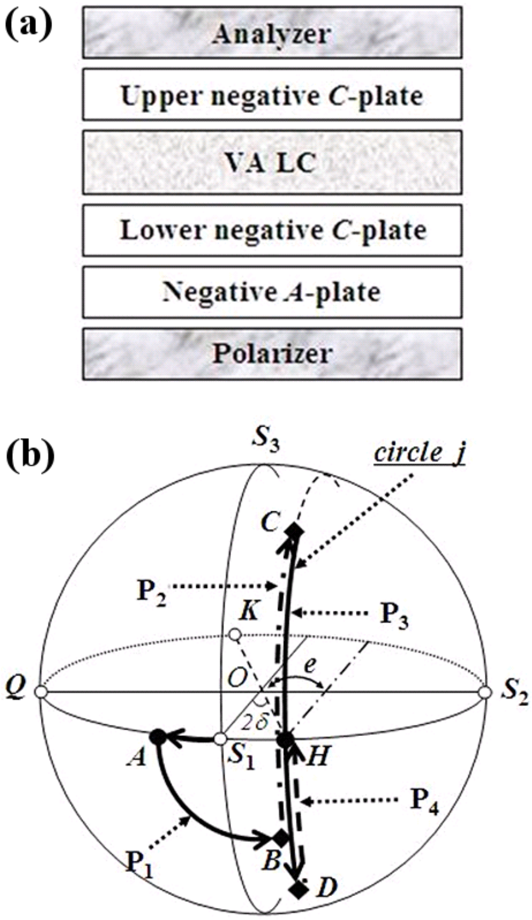

Fig. 2. Optical configuration and polarization states of the proposed VA LC cell: (a) optical configuration and (b) polarization path on the Poincaré sphere in the oblique incidence

spectively, which is centered at position Q. Finally, the polarization state of the light passing through the negative C-plate reversely rotates to position H along path P_4 on the circle j. Therefore, the process of the proposed configuration can effectively move the polarization position of the light passing through the cell to the desired position H, the opposing position of the polarization axis of the analyzer for oblique incidence so that it can clearly eliminate the off-axis light leakage in the dark state.

For the optimal dark state, it is necessary to make the polarization state of the light in the visible wavelength range move to position H in front of the analyzer with the following two conditions. In this letter, we do not handle the material property of the LC, and we optimize the optical configuration for the condition of $\theta = 70°$ and $\phi = 45°$ because the off-axis light leakage can be maximized under this condition [9]. The first condition is that the polarization positions for the R, G, and B wavelengths after passing through the negative A-plate should be on the circle j, as shown in Fig. 2(b). A numerical description of the circle j is simply given by $S_2 = e$. Once we know the S_2 value e, we can calculate the retardation value of the negative A-plate for each wavelength. The deviation angle δ is calculated as 0.1233 [rad]. In this case, the value e of the S_2 axis can be simply described as $e = \sin 2\delta$, so that we can calculate the e value as 0.2441 [rad]. From this calculated e value, we can find the optimum retardation value of the negative A-plate on the Poincaré sphere by using the Muller matrix and the Stokes vector [16,17]. The Stokes parameters of the light for the three wavelengths after passing through the negative A-plate can be described as follows:

$$
\begin{aligned}
S' &= R(-2\theta)\cdot M(\Gamma)\cdot R(2\theta)\cdot S(P)\\
&= \begin{pmatrix} 1 & 0 & 0 & 0\\ 0 & \cos^2 2\theta + \cos\Gamma \sin^2 2\theta & (1-\cos\Gamma)\sin 2\theta \cos 2\theta & \sin\Gamma \sin 2\theta\\ 0 & (1-\cos\Gamma)\sin 2\theta & \cos 2\theta \sin^2 2\theta + \cos\Gamma \sin^2 2\theta & -\sin\Gamma \sin 2\theta\\ 0 & \sin\Gamma \sin 2\theta & \sin\Gamma \cos 2\theta & \cos\Gamma \end{pmatrix} \begin{pmatrix} S_{0\_P}\\ S_{1\_P}\\ S_{2\_P}\\ S_{3\_P} \end{pmatrix} = \begin{pmatrix} S'_0\\ S'_1\\ S'_2\\ S'_3 \end{pmatrix}
\end{aligned} \quad (1)
$$

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 Γ. $S(P)$ 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 $90° + \delta$, 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 Γ 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 circle j 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.

	Δnd (nm)		
	(λ = 450 nm)	(λ = 550 nm)	(λ = 630 nm)
Negative *A*-Plate	–113.54	–138.80	–159.06
Lower negative *C*-plate	–237.60	–223.30	–217.27
Upper negative *C*-plate	–136.70	–160.44	–176.64

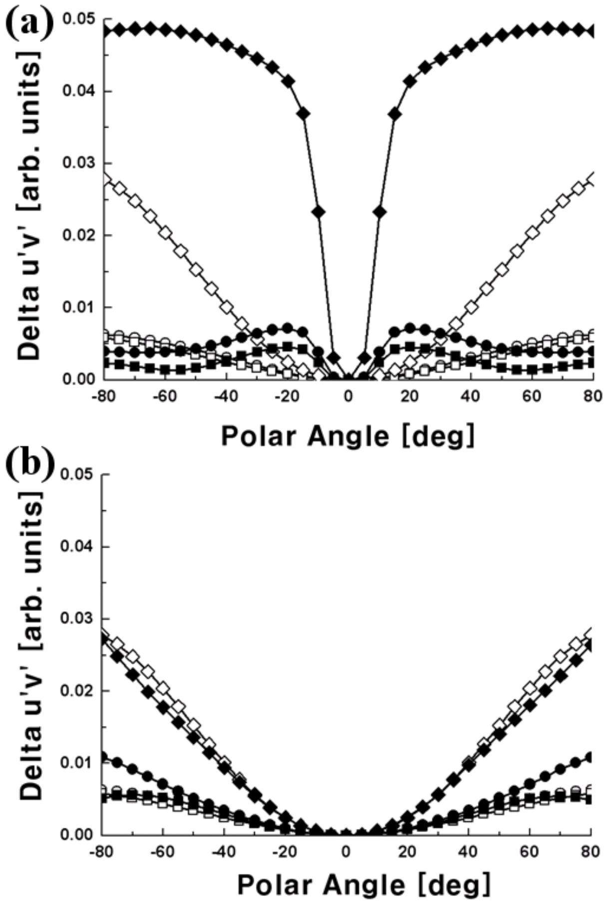

Fig. 3. Color shift for R, G, B wavelength light in the horizontal and the diagonal directions (a) for a conventional structure and (b) for the proposed structure. Symbols ∘, □, and ◇ represent the R, G, B wavelength light in the horizontal direction, and symbols •, ■, and ■ represent the R, G, B wavelength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

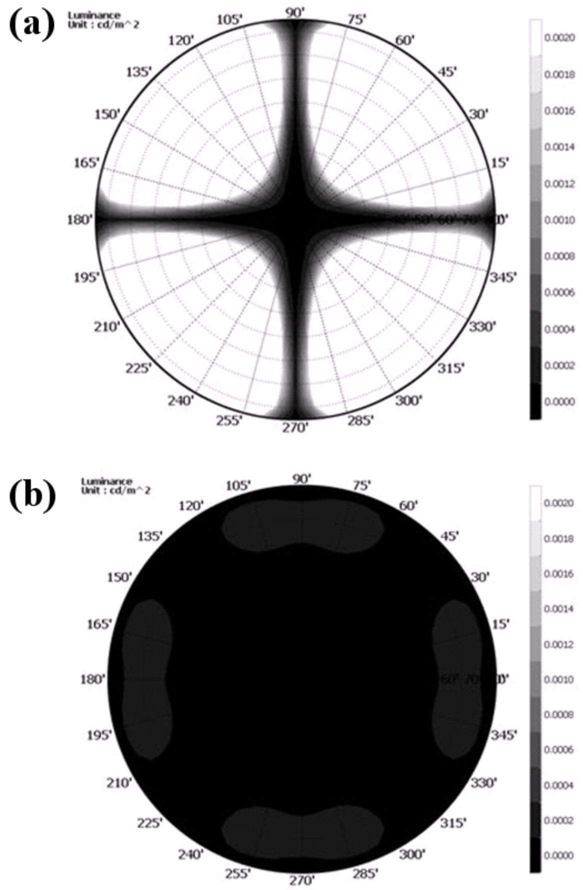

Fig. 4. Calculated iso-luminance in the dark state (a) for the conventional VA LC cell and (b) for the proposed VA LC cell.

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 Dr, Dg, and Db 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 μm. 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.

Figure 3 presents the calculated $\Delta u'\nu'$ of the conventional and the proposed VA LCD as a function of viewing angle in the horizontal ($\phi = 0°$) and the diagonal ($\phi =$

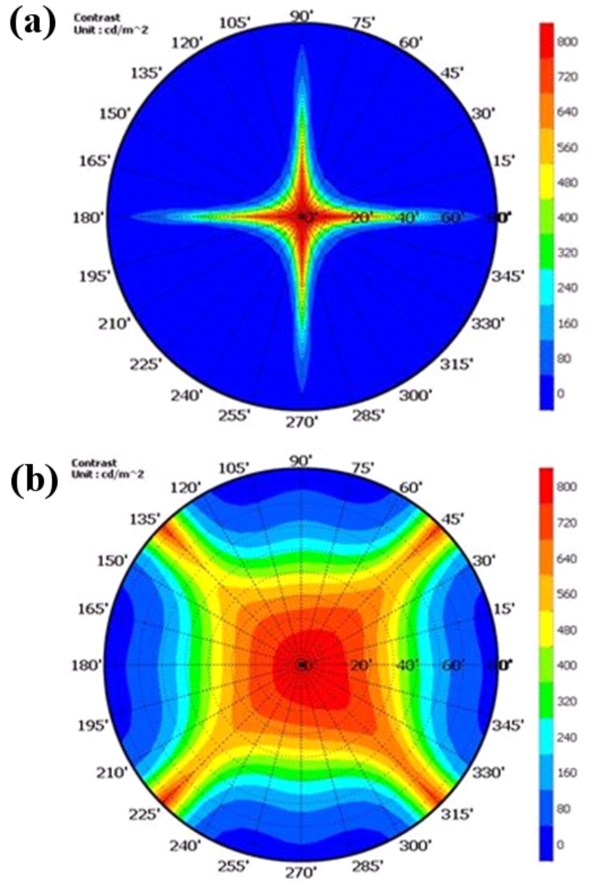

Fig. 5. Calculated iso-contrast contour (a) for the conventional VA LC cell and (b) for the proposed VA LC cell.

45°) directions. In the calculation results, the characteristics of the $\Delta u'\nu'$ value for vertical viewing are very similar to those of the $\Delta u'\nu'$ value for the horizontal direction. For the conventional optical configuration, the $\Delta u'\nu'$ value for a blue wavelength at $\theta = 70°$ is much higher (≈0.05) than the $\Delta u'\nu'$ value for the green and the red wavelengths (≈0.01), especially in the diagonal direction. On the other hand, we can see that the proposed optical configuration can improve the color difference in all directions, even in the diagonal direction, compared to the conventional configuration.

Figure 4 shows a comparison of the luminance for the proposed LC cell to the luminance for the conventional LC cell in the dark state, and Fig. 5 compares the iso-contrast contour of the conventional configuration to that of the proposed configuration in the visible wavelength range. In this letter, we applied a non-uniform LC director by using a patterned electrode to obtain the exact bright luminance of the LC cell. From the calculated results of Figs. 4 and 5, we confirm that in the calculations, the proposed VA LC cell effectively eliminates light leakage in the dark state so that the off-axis contrast ratio of the proposed LC cell can increase far beyond that of the conventional LC cell.

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

[1] M. Oh-e and K. Kondo, Appl. Phys. Lett. **67**, 3895 (1995).
[2] S. H. Lee, S. L. Lee and H. Y. Kim, App. Phys. Lett. **73**, 2881 (1998).
[3] K. H. Kim, K. H. Lee, S. B. Park, J. K. Song, S. N. Kim and J. H. Souk, in *Proceeding of Asia Display'98* (Society for Information Display, 1998), p. 383.
[4] K. Ohmuro, S. Kataoka, T. Sasaki, Y. Koike, SID Int. Symp. Digest Tech. papers **28**, 845 (1997).
[5] Q. Hong, T. X. Wu, X. Zhu, R. Lu and S-T. Wu, Appl. Phys. Lett. **86**, 121107 (2005).
[6] C.-H. Lin, App. Phys. Lett. **90**, 151112 (2007).
[7] J. Chen, K.-H. Kim, J.-J. Jyu, J. H. Souk, J. R. Kelly and P. J. Bos, SID Int. Symp. Digest Tech. papers **29**, 315 (1998).
[8] S.-H. Ji, S. H. Lee and G.-D. Lee, Appl. Opt. **48**, 48 (2009)
[9] P. Yeh and C. Gu, *Optics of Liquid Crystal Displays* (Wiley, New York, 1999).
[10] A. Lien, Appl. Phys. Lett. **57**, 2767 (1990).
[11] X. Zhu, Z. Ge and S.-T. Wu, J. Disp. Tech. **2**, 2 (2006).
[12] D.-K. Yang and S.-T. Wu, *Fundamentals of Liquid Crystal Devices* (Wiley, New York, 2006).
[13] Y. Fujimura, T. Kamijo and H. Yoshimi, Proceeding SPIE 5003, 96 (2003).
[14] J.-H. Lee, H. C. Choi, S. H. Lee, J. C. Kim and G. D. Lee, Appl. Opt. **45**, 7279 (2006).
[15] D. Goldstein, *Polarized Light* (CRC Press, New York, 2003).
[16] J. E. Bigelow and R. A. Kashnow, Appl. Opt. **16**, 2090 (1977).
[17] K. Vermeirsch, A. D. Meyere, J. Fornier and H. D. Vleeschouwer, Appl. Opt. **38**, 2775 (1999).