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Optical Structure to Improve the γ-curve Distortion of a Four-domain (4-D) Twisted Nematic Liquid Crystal Cell

Byung-June Mun, Tae Young Jin and Gi-Dong Lee*

Department of Electronics Engineering, Dong-A University, Pusan 604-714, Korea

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The γ-curve represents the viewing angle characteristics of a liquid crystal (LC) cell in all gray levels, including the dark state. In this paper, we propose a optical configuration of a four-domain (4-D) twisted nematic (TN) LC cell for improving the γ-curve distortion in the oblique direction, without any deterioration in the optical property of a conventional 4-D TN cell. A positive A-plate and a negative A-plate are applied at the top and the bottom of the 4-D TN LC layer, respectively. The two A-films applied can be optimized at all viewing angles by calculating the polarization difference (Δp) as functions of the retardation and the optical axis of the films, so that the transmittance distortion in the middle gray scale can be compensated for in all viewing directions. As a result of a calculation of the gamma distortion index (GDI), the γ-curve can be improved by more than 70% in the off-axis at 0° and 180°, and by more than 50% in the off-axis at 90° and 270°.

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I. INTRODUCTION

Recently, the demand has been greatly increasing for high-level technologies in liquid crystal displays (LCDs), to satisfy the need for excellent image quality, including high resolution, wide viewing angle, and high contrast ratio. LC technologies proposed for better electro-optical performance include twisted nematic (TN) [1], patterned vertical alignment (PVA) [2, 3], multi-domain vertical alignment (MVA) [4], in-plane switching (IPS) [5,6], and fringe field switching (FFS) modes [7, 8]. Among advanced LC modes, the TN mode is most commonly used in LCDs due to its simple fabrication, low cost, fast response time, and high transmittance. However, it does not offer a symmetric viewing angle because the optical axis of the LC directors is oriented by the electric field to one direction in the voltage-on state [1,9]. Therefore, the TN mode can cause serious light leakage in the oblique direction, resulting in a low contrast ratio and narrow viewing angle.

The wide-view twisted nematic (WV-TN) cell [10,11] and the four-domain twisted nematic (4-D TN) cell [9, 12, 13] have been proposed to improve the viewing angle performance of the TN mode. The WV-TN optically compensates for the asymmetric transmittance of the TN cell in the applied voltage state by using WV films [10], such that it has the optical properties of the wide-viewing angle and high contrast ratio in the off-axis. In previous paper, we used optical films to compensate for the γ-curve distortion of this WV-TN LC cell due to the distortion in the viewing angles in all gray levels [14]. However, commercial applications of the WV-TN LC cell are seriously hampered by the high cost of the WV films. The 4-D TN LC cell can resolve this problem [9]. The 4-D TN LC cell with four different twist angles provides a wide-viewing property because the asymmetric optical characteristics can be overcome in the oblique direction by the four different optical axes in the midplane of the 4-D TN LC cell. This cell also depends heavily on the observed viewing direction in all gray scales; the image distortion that can be assessed by measuring the γ-curve occurs in the middle gray level in the oblique direction.

In this paper, the optical configuration for improving the γ-curve distortion in a 4-D TN LC cell without any optical deterioration of the contrast ratio in the oblique direction is proposed. A positive A-plate and a negative A-plate are applied at the top and the bottom of the 4-D TN LC layer, respectively The two A-films applied can be optimized at all viewing angles by calculating the average values of polarization difference (Δp) as functions of the retardation and the optical axis of the films [15, 16], so that the transmittance distortion in the middle gray scale can be compensated for in all viewing directions. The proposed optical configuration of the 4-D TN LC cell

*E-mail: gdlee@dau.ac.kr; Fax: +82-51-200-7712

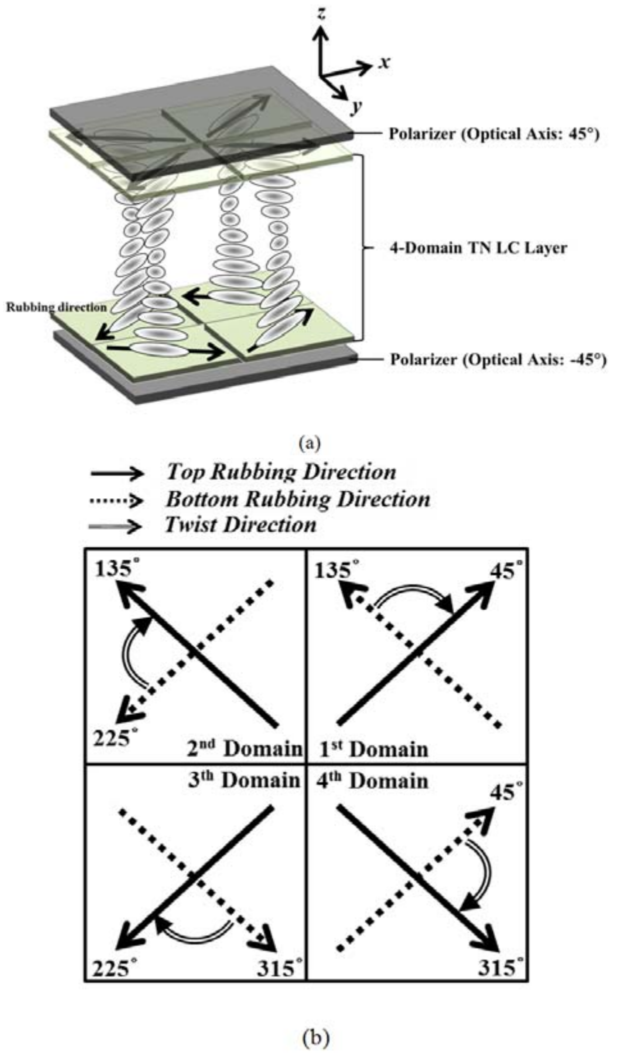

Fig. 1. (Color online) A conventional 4-D TN LC cell: (a) the optical configuration and (b) the twisted LC director configuration in each domain.

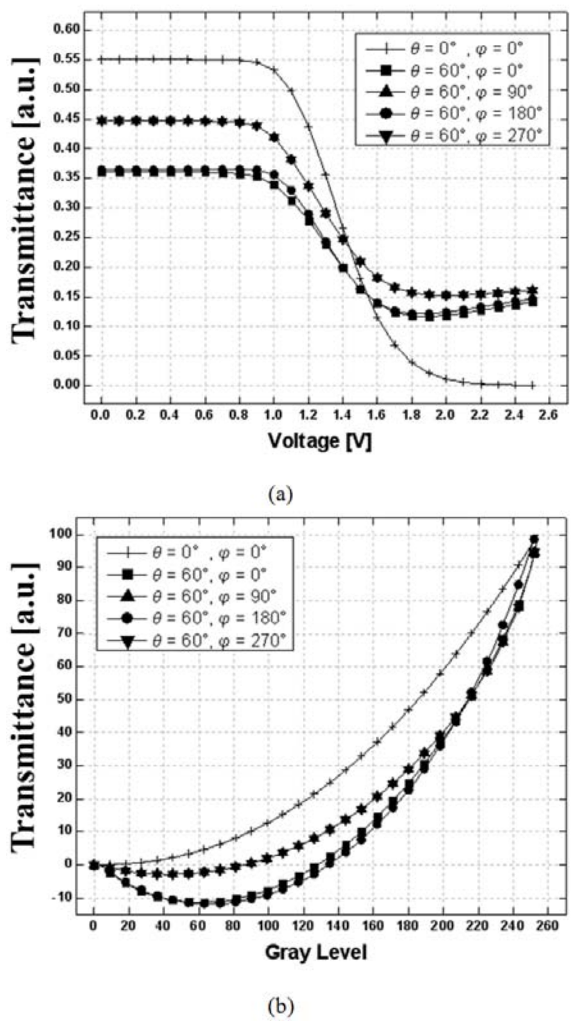

Fig. 2. The calculated (a) V-T curve and (b) γ-curve of the conventional 4-D TN LC cell on-axis ($\theta = 0°$, $\phi = 0°$) and off-axis ($\theta = 60°$, $\phi = 0°$, 90°, 180° and 270°).

with a pair of A-plates can improve the off-axis γ-curve so as to provide a high contrast ratio and a wide viewing angle.

II. ELECTRO-OPTICAL CHARACTERISTICS OF THE CONVENTIONAL 4-D TN LC CELL

Figures 1(a) and 1(b) show the conventional optical configuration of a 4-D TN LC cell and the twisted LC director configuration in each domain, respectively. From the conventional optical structure, we calculated a V-T curve and a γ-curve for the 4-D TN LC cell at normal (polar angle $\theta = 0°$, azimuth angle $\phi = 0°$) and oblique (polar angle $\theta = 60°$, azimuth angle $\phi = 0°$, 90°, 180° and 270°) viewing angles, as shown in Fig. 2. The calculation was performed by using the commercial LC software TechWiz LCD (Sanayi System Co., Korea).

In general, when viewers are watching the display screen in the normal direction, they can perceive high image quality and vivid colors because the γ-curve has a value of approximately 2.2, which is most fundamental value of the gamma index [17, 18]. However, the V-T curve distortion in the oblique direction is shown to be between 1.8 and 2.5 V. In Fig. 2(a), the light leakage of the dark state is caused by a gray inversion of the TN cell at each viewing angle. In particular, the high transmittance at the 2.5 volt state, compared with the middle gray level at 1.8 volt, can produce serious γ-curve distortion in the oblique direction, as shown in Fig. 2(b).

Figure 3 shows the polarization states of each domain for four oblique viewing angles on the Poincaré sphere. This calculation can be performed at the 22nd gray level (V = 2.2 V), which shows the maximum γ-curve distortion in the conventional 4D-TN cell, by using the Stokes

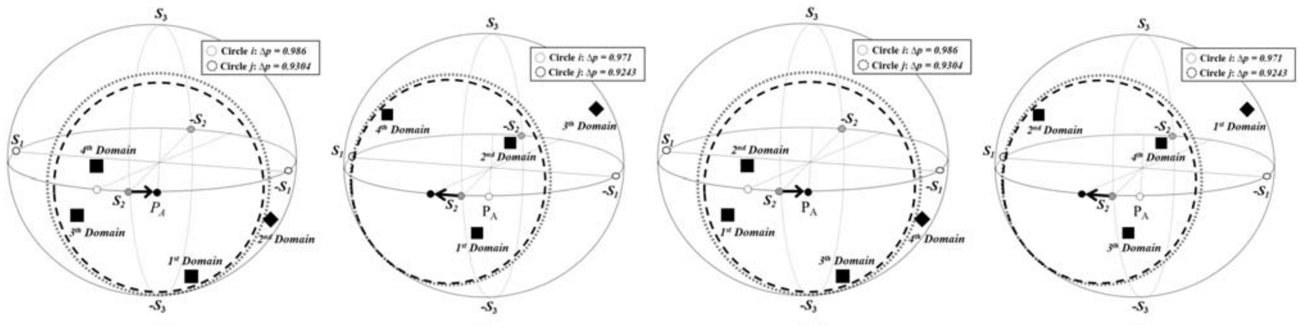

Fig. 3. The polarization positions of each domain in a conventional 4-D TN LC cell under an applied voltage of 2.2V in the oblique direction with azimuth angles of (a) 0°, (b) 90°, (c) 180° and (d) 270°.

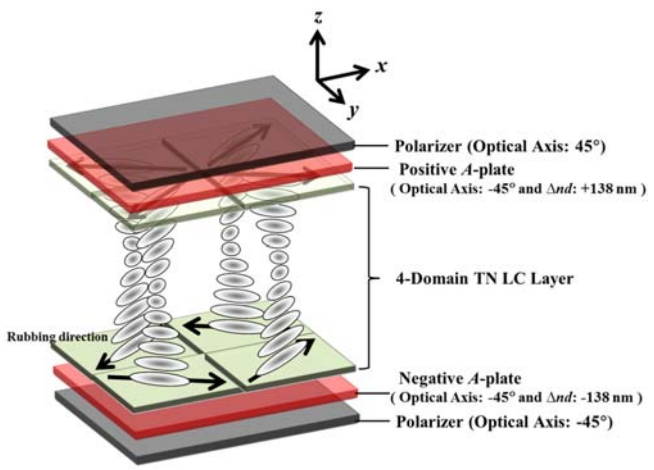

Fig. 4. (Color online) The proposed optical configuration of the 4-D TN LC cell.

parameter and the Muller matrix method. The black symbols in Fig. 3 represent the polarization states of the light in front of the output polarizer of each domain in the off-axis. Of the four symbols, only the diamond symbol is located on the opposite side from an absorption axis of the output polarizer (S_2), owing to the gray-inversion of the TN cell, so that light leakage occurs in the dark state in the off-axis. The circles in Fig. 3 represent the average intensity line that can be calculated by using the polarization difference (Δp) and the light intensity in the off-axis as follows [14,15,18]:

$$\Delta p = \{(S_{1(a)} - S_{1(p)}) + (S_{2(a)} - S_{2(p)}) + (S_{3(a)} - S_{3(p)})\}^{1/2} ,$$
$$I = I_0 cos^2(\Delta p/2) \quad (1)$$

where $S_{1(a)}$, $S_{2(a)}$, and $S_{3(a)}$ are the Stokes vector of the output polarizer absorption axis P_A, which deviates from the position S_2 by a deviation angle δ in the oblique viewing direction [19]. $S_{1(p)}$, $S_{2(p)}$, and $S_{3(p)}$ are the Stokes vector of the polarization position of the light in each domain in front of the output polarizer at 2.2 V. Therefore, the transmittance in the viewing direction can be shown from the Δp. In order to calculate the average intensity of the 4-D TN cell at the middle gray level 2.2 V, we first calculated the Δp for each of the four domains at all oblique viewing angles, by using Eq. (1); then, we calculated the average of each Δp. The average value of the calculated Δps is the same for two symmetric viewing angles. The calculated Δps are 0.9304 for two viewing angles with azimuth angles of 0° and 180°, as shown in Figs. 3(a) and 3(c), and 0.9243 for the azimuth angles of 90° and 270°, as shown in Figs. 3(b) and 3(d). A circle j, which implies an average intensity, represents the calculated Δp values at 2.2 V on the Poincaré sphere, as shown in Fig. 3.

Under 2.5 voltage in the dark state, by contrast, the calculated Δps are 0.986 for two viewing angles with azimuth angles of 0° and 180°, and 0.971 for azimuth angles of 90° and 270°. These calculated results have relatively high values of Δp when compared to the Δp at 2.2 V, so that the intensity increases in the dark state at 2.5 V. Therefore, if the γ-curve distortion at middle gray level in the 4-D TN LC cell is to be minimized, the circle i, which represents the average intensity line at 2.5 V, must be moved a position with a lower intensity than that of circle j.

III. OPTICAL CONFIGURATION FOR IMPROVING THE γ-CURVE DISTORTION AND OPTIMIZATION

In order to reduce the γ-curve distortion of the 4-D TN LC cell, we propose an the optical configuration that applies a positive A-plate and a negative A-plate to the top and the bottom substrates of the conventional 4-D TN cell, as shown in Fig. 4. This configuration should exhibit an excellent wide viewing property in all gray levels, so the parameters of the added films need to be optimized. Therefore, we can derive the optical condition for producing an excellent wide viewing property in the gray level as follows [14,18]:

$$\sum Retardation(Negative\ A + Positive\ A) = 0 \quad (2)$$

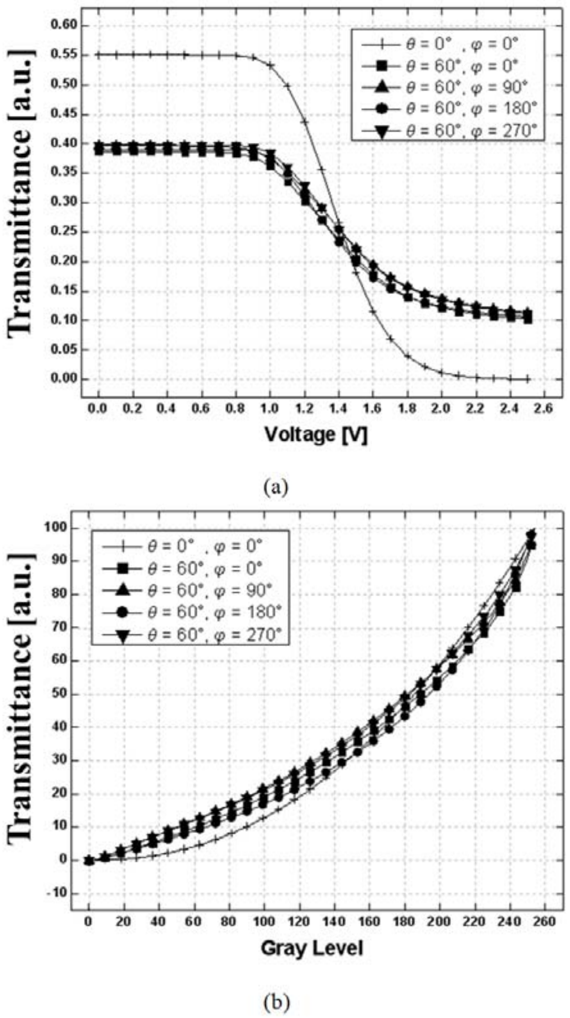

Fig. 5. The calculated (a) V-T curve and (b) γ-curve of the proposed 4-D TN LC cell for all viewing angles.

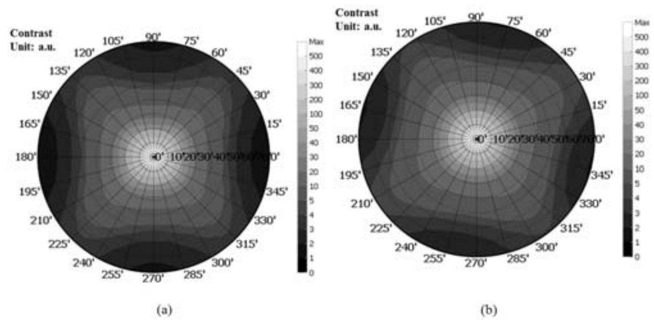

Fig. 6. Comparison between the iso-contrasts of (a) a conventional 4-D TN LC cell and (b) the proposed 4-D TN LC cell.

Equation (2) represents the optical relationship between the added pair of a positive A-plate and a negative A-plate for improving the wide viewing property in the gray scale. If this equation is satisfied, the optical performance in the dark state can be assumed not to be affected by the pair of A-plates, so that the pair of A-plates can be optimized without any deterioration of the optical performance in a conventional 4-D TN cell.

The optimal values of the retardation and the optical axis of a positive A-plate and a negative A-plate can be achieved. The optimization of the two films can be performed by calculating the polarization difference Δp as functions of the optical axis and the retardation. In order to investigate the optimized value of the optical films, we can set the optimization condition such that each average Δp is within 0.83 at 2.2 volt and within 0.8 at 2.5 volt for all oblique viewing angles simultaneously. The variation ranges of the optical axis and the retardation for optimization are from −180° to 0° and from 50 nm to 190 nm, respectively. The results of the calculations show that the optimized condition of a pair of A-plates is found to be an optical axis at −45° and a retardation (Δnd) of $\pm$138 nm.

The average Δp of the proposed 4-D TN LC was calculated for the optimal conditions in order to confirm a low intensity in the dark state at 2.5 volt compared to the middle gray level at 2.2 volt. The calculated values of Δp at 2.2 volt were 0.827 for two symmetric viewing angles with azimuth angles of 0° and 180° and 0.798 for azimuth angles of 90° and 270°. In the dark state at 2.5 volt, in particular, the calculated values of Δp were 0.797 for two viewing angles with azimuth angles of 0° and 180° and 0.773 for azimuth angles of 90° and 270°. The results of the calculations for Δp show that the total intensity of the 4-D TN cell at 2.5 V can be greatly decreased compared to the gray level of 2.2 V, and that light leakage in the dark state can be reduced.

Figure 5 shows the calculated V-T curve and the γ-curve of the proposed optical configuration of the 4-D TN LC cell. The V-T curve distortion between 1.8 V and 2.5 V is significantly improved in the oblique direction, as shown in Fig. 5(a). Therefore, the excellent γ-curve for the 4-D TN LC cell at all viewing angles is confirmed, as shown in Fig. 5(b).

Figures 6(a) and 6(b) compares the calculated iso-contrast contours of the conventional and the proposed 4-D TN LC cell. The proposed optical configuration exhibits excellent iso-contrast without any loss of optical performance, compared with the conventional structure, because the optical condition in Eq. (2) is satisfied.

In order to numerically verify the γ-curve distortion of the 4-D TN LC cell, we can calculated the GDI (gamma distortion index) parameter. The equation for the GDI parameter is as follows [14,18]:

$$GDI = Average\langle | L_{i(on-axis)} - L_{i(off-axis)} |\rangle_{i=0\sim255}\ , \tag{3}$$

where $L_{i(on-axis)}$ and $L_{i(off-axis)}$ represent the brightness between the ith gray level in the on- and the off-axis directions, respectively, and $< >$ denotes the average for all cases of arbitrary gray levels. As per the calculated results for the GDI, the γ-curve distortion of the proposed 4-D TN LC cell, compared to a conventional 4-D TN LC cell, is improved by more than 70% for oblique viewing angles of 0° and 180° and by over 50% for oblique viewing angles of 90° and 270°.

IV. CONCLUSION

In summary, an optical configuration of the 4-D TN LC cell is proposed for improving the γ-curve distortion in the oblique direction without any loss of the optical property of the conventional 4-D TN cell. The proposed configuration adds a positive A-plate and a negative A-plate to the top and the bottom of the 4-D TN LC layer. Optimization of pair of A-plates is performed by calculating the polarization difference Δp as a function of the optical axes and the retardation. When the films are used to minimize the γ-distortion, the proposed 4-D TN LC cell can show an excellent γ-curve in the middle gray level at all oblique viewing angles. An enhanced γ-curve of the proposed 4-D TN LC cell is verified using GDI. As a result, the calculated GDI can be improved by more than 70% in oblique viewing at angles of 0° and 180° and by more than 50% in oblique viewing at angles of 90° and 270° compared to a conventional 4-D TN LC cell. Therefore, we believe that the proposed 4-D TN LC cell can enhance the image quality of the TN LC cell by improving the γ-curve.

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