Switching of off-axis viewing quality in twisted nematic liquid crystal display by controlling phase retardation of additional liquid crystal layers

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This study examined the viewing angle control of twisted nematic liquid crystal displays (TN-LCDs). Conventional TN mode has intrinsic characteristics, such as a narrow viewing angle along the vertical direction and a relatively wide viewing angle along the horizontal and diagonal directions. Our study shows that the viewing angle of the TN-LCD can be made wider and smaller than that of a normal TN cell by adding one or two homogeneously aligned liquid crystal layers between the TN cell and polarizers, and controlling their retardation with an applied voltage.
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I. INTRODUCTION

Recently, the range of liquid crystal display (LCD) applications has expanded from small size screens in mobile phones and tablet (personal computers) PCs to large screens in monitors and liquid crystal (LC) televisions. For small size displays, the twisted nematic (TN) mode was dominant on account of its very high light efficiency, low driving voltage, and wide process margin.[1–3] However, TN mode has a large problem in that the image quality is strongly dependent on the viewing direction. One of the major problems for a narrow viewing angle in the TN mode is caused by the strong light leakage in the dark state in oblique viewing directions, and has been solved by applying a compensation film known as a wide view (WV) film.[4–7] In contrast, over the past ten years, there have been significant improvements in image quality using other types of LC modes, such as in-plane switching (IPS),[8] multidomain vertical alignment (VA),[9] fringe-field switching,[10] and patterned VA.[11] Nevertheless, TN mode is still very popular in many display applications, such as mobiles, outdoor small displays, notebooks, and monitors.

There are situations that require person's privacy while displayed an image on portable displays, such as notebook computers, mobile phones, and tablet PC. In this case, a wide viewing angle is unsuitable and a narrow viewing angle LCD is preferred. In previous work,[12] a narrow viewing angle LCD was realized by attaching a micropatterned film to the LCD. However, in this case, the viewing angle was fixed as a narrow viewing angle at all times. Therefore, it is better to control the viewing angle of the LCDs according to the user's preference and private intentions.

There have been many approaches to controlling the viewing angle of LCDs from narrow to wide only by pushing a functional switch. In this way, the display shows high image quality in situations for multiviewers, and a very narrow viewing angle when personal privacy is needed. One of the major devices that can protect a person's privacy when using portable displays was developed by using VA mode.[13] This device utilizes an additional LC layer outside the main LC cell so that the brightness of the white and dark states at the off axis is controlled. In another method for viewing angle control by adopting IPS mode[14,15] an additional pixel was added inside the LC cell, which controls the viewing angle. In this device, light leakage at off axis was controlled using the birefringence effect.

This paper proposes a cell structure for TN mode, in which the viewing angle can be controlled by switching additional LC layers. The additional LC layers are composed of homogeneously aligned (HA)-LC layers that are driven by a vertical field. Before switching the additional LC layers, which can be one or two, the TN-LCD shows wider viewing angle than that of a conventional TN. However, when switching the one or two HA-LC layers, the viewing angle is narrower than that of a conventional TN.

II. PRINCIPLE OF VIEWING ANGLE SWITCHING

One of the major drawbacks of normally white (NW) TN-LCD in terms of the viewing angle characteristics is light leakage in the dark state at the off axis due to residual birefringence. In order to solve this problem, two WV films composed of hybrid aligned discotic LC were used at both sides of the TN cell to remove the residual birefringence.[5] Hence, a high contrast ratio (CR) was achieved in all directions.

Besides this approach, uniaxial compensation films consisting of rodlike LC layers can also suppress the light leakage to some degree,[16,17] which improves the image quality of the TN cell. Figure 1(a) shows the basic concept for compensating for residual birefringence of the TN cell using two rodlike films. As indicated, the interface of the LC director of the TN cell and a uniaxial film results in negative C-plate properties optically and a vertically aligned mid-director

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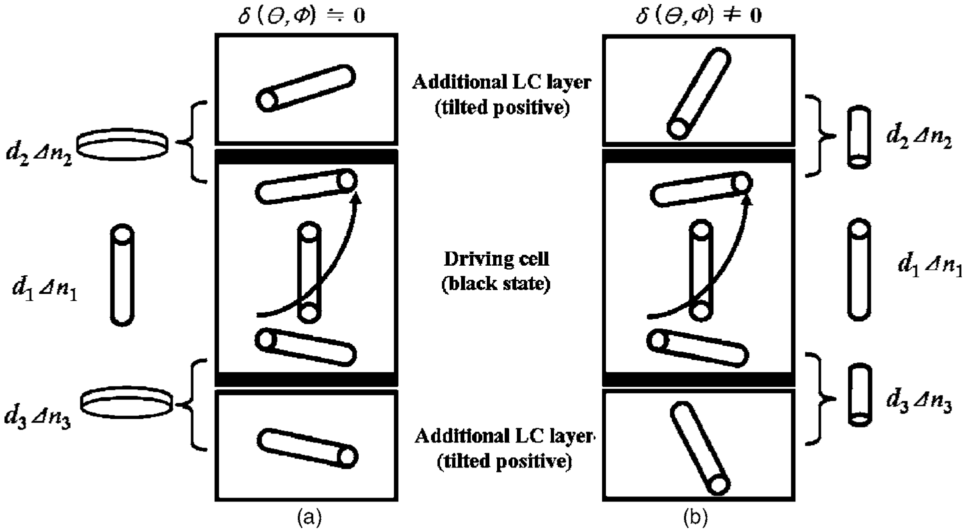

FIG. 1. Concepts of viewing angle switching for a TN-LCD with a tilted positive compensation film: (a) wide viewing angle mode and (b) narrow viewing angle mode.

with optically positive C-plate properties. Therefore, the total phase difference $\delta_{\text{total}}(\theta,\varphi)$ in the cell can be described as follows:

$$\delta_{\text{total}}(\theta,\varphi) = 2\pi(d_1\Delta n_1 - d_2\Delta n_2 - d_3\Delta n_3)/\lambda,$$

where d and Δn indicate the thickness and birefringence of each optical layer, and labels 1, 2, and 3 indicate the LC layer, and top and bottom compensation films, respectively. Consequently, with optimal retardation adjustment of each layer, the residual birefringence decreases in all directions, giving rise to reduced light leakage in the dark state compared to that of the normal TN cell. The CR of LCDs is defined by the transmittance of a white state divided by the transmittance of a dark state. Therefore, the CR of the display depends mainly on the degree of light leakage in the dark state, i.e., a high CR is achieved in all viewing directions when there is less light leakage in the dark state in all directions.

In the proposed device, two uniaxial films can be replaced by two HA-LC layers, i.e., HA-LC layers whose orientation is controlled by a vertical electric field. At the off state, two HA-LC layers, whose optic axes are aligned perpendicular to each adjacent LC layer in a TN cell, play the role of uniaxial films, which reduces the level of light leakage in the dark state of a TN cell resulting in a better viewing angle than with conventional TN cells, as described in Fig. 1(a). If a voltage is applied to two HA-LC layers, the LC director tilts up so that the two HA-LC layers behave like an O plate, resulting in mismatch in retardation between the TN LC cell and two HA-LC layers, as described in Fig. 1(b). Consequently, the level of light leakage of the TN cell in the dark state becomes larger than that of a normal TN cell. This means that the CR in the oblique viewing direction becomes lower than a normal TN cell, which can produce a narrow viewing angle.

III. CALCULATED RESULTS AND DISCUSSION

A simulation using commercially available software, "LCD MASTER" (Shintech, Japan), was used to calculate the motion of a LC director based on the Eriksen–Leslie theory. A 2×2 extended Jones matrix was used to calculate the optical transmittance.[18] The transmittance for single and parallel polarizers was assumed to be 41% and 35%, respectively. Here, the LC with physical properties (dielectric anisotropy $\Delta\varepsilon=+8.2$, $K1=9.7$ pN, $K2=5.2$ pN, $K3=13.3$ pN, $\Delta n=0.1$) and a cell gap of 4.8 μm was used. The retardation value of each HA-LC layer was 0.16 μm with a pretilt angle of 2°. Control of the viewing angle was examined in two cases: TN+two HA-LC layers and TN+one HA-LC layer.

Figure 2 shows the optical configuration of the proposed viewing angle switchable NW-TN-LCD. The optic axes of the two HA-LC layers are perpendicular to the nearby rubbing direction of the TN cell. This suggests that, although a voltage was applied to the HA-LC layers to tilt up the LC director, there was no retardation generated at the normal

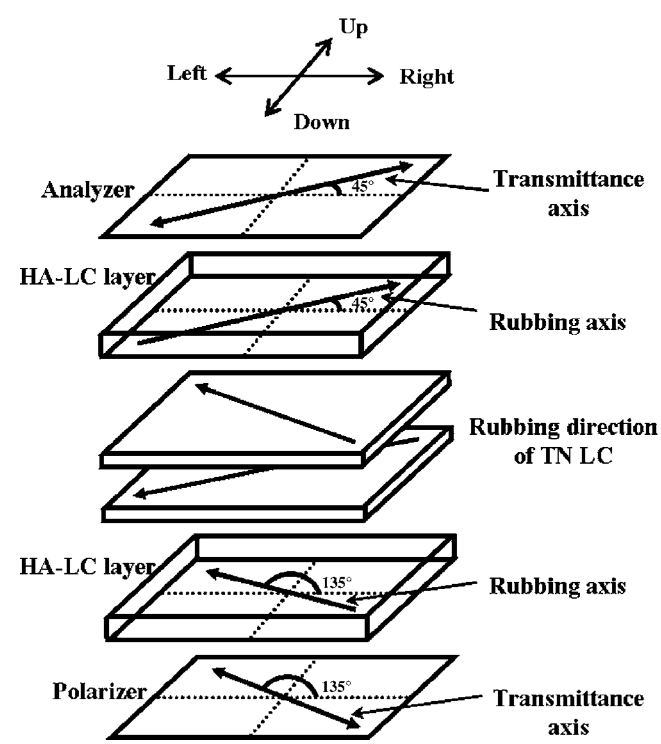

FIG. 2. Cell configuration used for the simulation when using two HA-LC layers.

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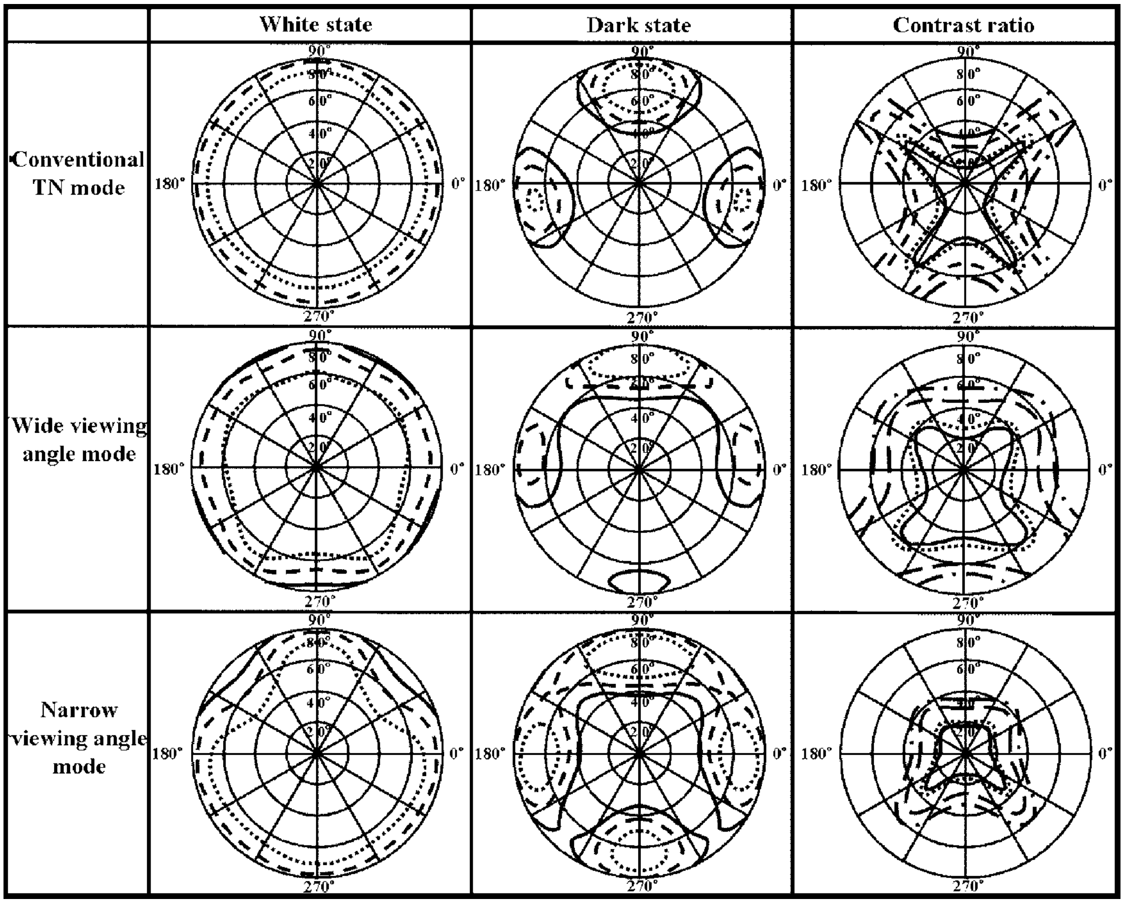

FIG. 3. Simulated isoluminance contour in the white and dark states (70%, 50%, and 30% of each maximum for transmittance in white and dark state: dotted, dashed, and solid) and simulated isocontrast ratio (CR100: solid, CR50: dotted, CR10: dashed, CR5: dashed and dotted) at an incident wavelength of 550 nm.

direction due to self-compensation between the two HA-LC layers. As a result, the image quality at the normal direction was not disturbed.

The TN cell showed a dark state at 4.4 V. The level of the dark state in the TN cell at the off normal axis was calculated as a function of the applied voltage to two HA-LC layers. According to these calculations, when the tilt angle of the mid-director in the two HA-LC layers is 14°, a better dark state was achieved in the oblique viewing direction compared to that of a pure TN cell. On the other hand, when it is 60°, the light leakage of the dark state at the off normal axis is larger than that of a pure TN cell. Consequently, a decrease and increase in light leakage at the off normal axis will increase and decrease the CR in the oblique viewing directions, which can control the viewing angle. The former and latter case is known as the wide viewing and narrow viewing angle modes, respectively.

The viewing angle quality was evaluated by calculating the isoluminance contour in the white and dark states, and iso-CR contour, as shown in Fig. 3. As indicated, the isoluminance contour of the white state shows similar results in both the conventional and wide viewing angle TN cells. However, the isoluminance contour was distorted slightly in a narrow viewing angle TN cell. As already mentioned, the two HA-LC layers were inserted in order to control the light leakage in the dark state. As expected, the isoluminance contour in the dark state was greatly changed. The level of light leakage for the dark state in wide viewing angle mode was less than that of a conventional TN cell, and there was more light leakage in the dark state in narrow viewing angle mode than in a conventional TN cell at all viewing angle directions. Considering the iso-CR contour, in the case of a wide viewing angle TN cells, the region at which $CR > 5$ is more than 120° of the polar angle in the horizontal and vertical directions. However, the region at which $CR > 5$ is less than 80° of the polar angle in the horizontal and vertical directions for the narrow viewing angle mode.

Figure 4 shows the viewing angle dependences of the eight levels of transmittance in the horizontal direction for wide viewing angle, narrow viewing angle, and conventional TN modes. The voltages applied for a gray-level $0[G(0)]$ and gray-level $7[G(7)]$ were 4.4 and 0 V, respectively. Six intermediate gray levels between $G(7)$ and $G(0)$ are determined in order to provide an appropriate gray scale for human eyes. In order to obtain the linear gamma characteristics $(\gamma=1.0)$ in LCD, the transmittance at each gray level was divided by the equal transmittance difference. In conventional TN-LCD, transmittance inversion occurs when the polar angle is more than +30° and −30° in the horizontal direction but for a wide viewing angle mode, transmittance inversion does not occur at all gray levels. Moreover, the transmittance inversion region of the narrow viewing angle mode is equal to conventional TN-LCD at approximately +30° and −30° in the horizontal direction. However, light leakage occurred on the

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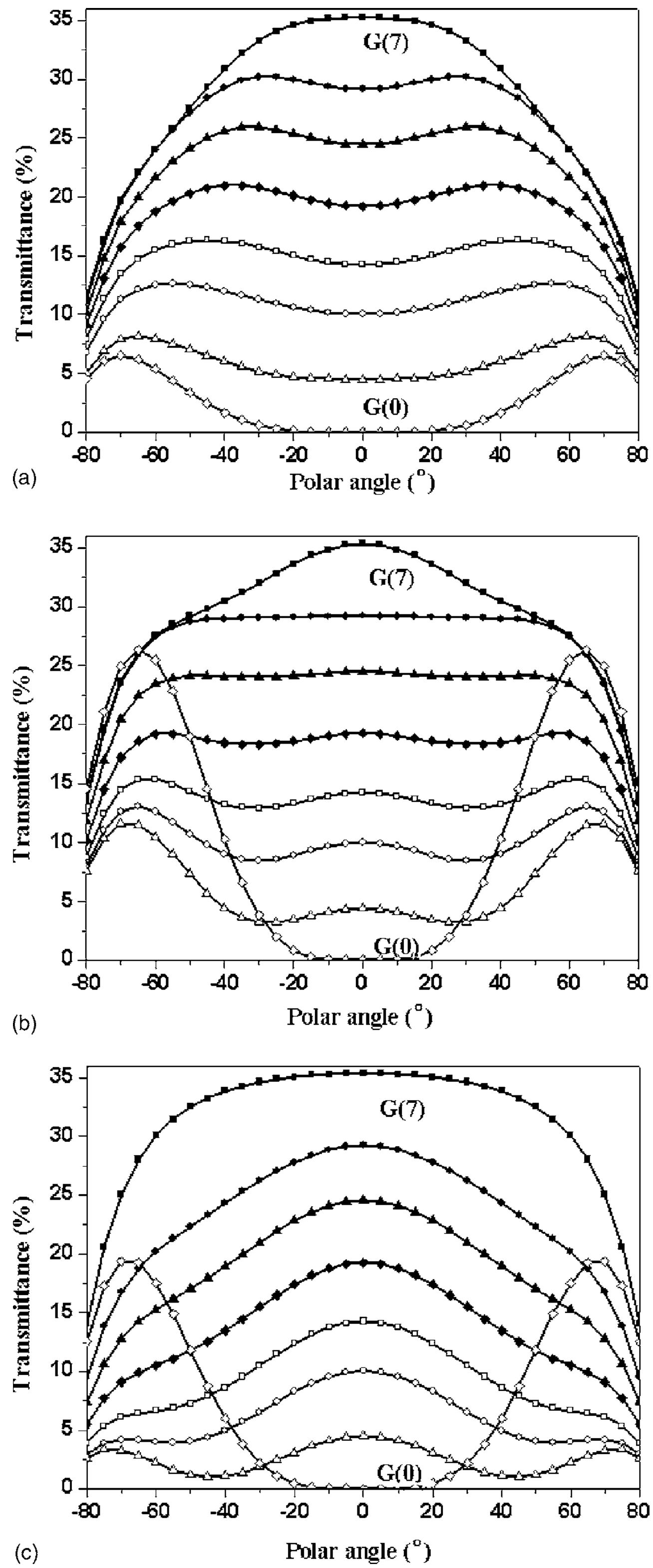

FIG. 4. Simulated viewing angle dependences of the eight levels of gray scale for the different polar angles at the horizontal direction: (a) wide viewing angle mode, (b) narrow viewing angle mode, and (c) conventional TN mode.

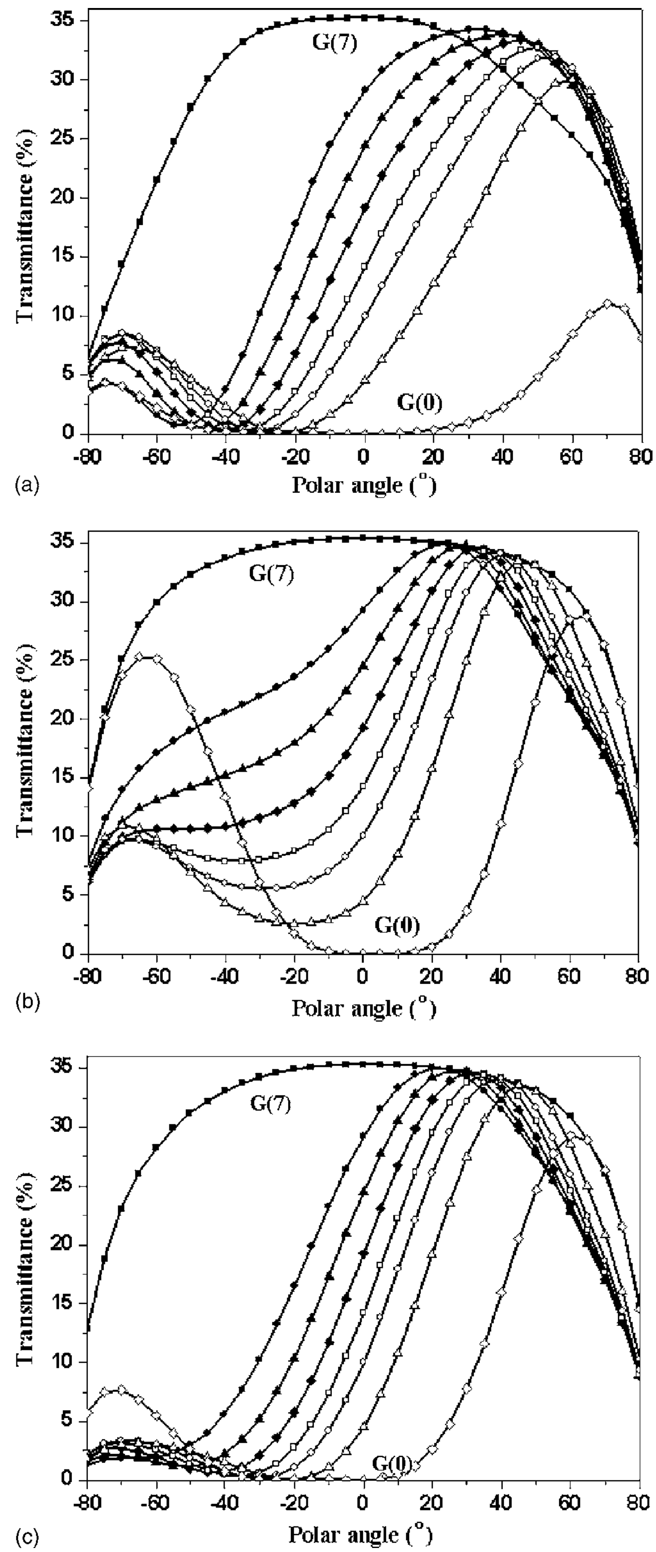

FIG. 5. Simulated viewing angle dependences of the eight levels of gray scale for the different polar angles at the vertical direction: (a) wide viewing angle mode, (b) narrow viewing angle mode, and (c) conventional TN mode.

large side for the $G(0)$ in the horizontal direction, indicating that a displayed image is more distorted in narrow viewing angle mode than that in a conventional TN-LCD.

Figure 5 shows the viewing angle dependences of the eight levels of transmittance in the vertical direction for wide viewing angle, narrow viewing angle, and conventional TN modes. In a conventional TN-LCD, gray scale inversion occurs when polar angle is more than +34° and −30° in the vertical direction. In the wide viewing angle mode, the region of gray scale inversion is more than 20° upward but the level of light leakage at the $G(0)$ is greatly reduced so that

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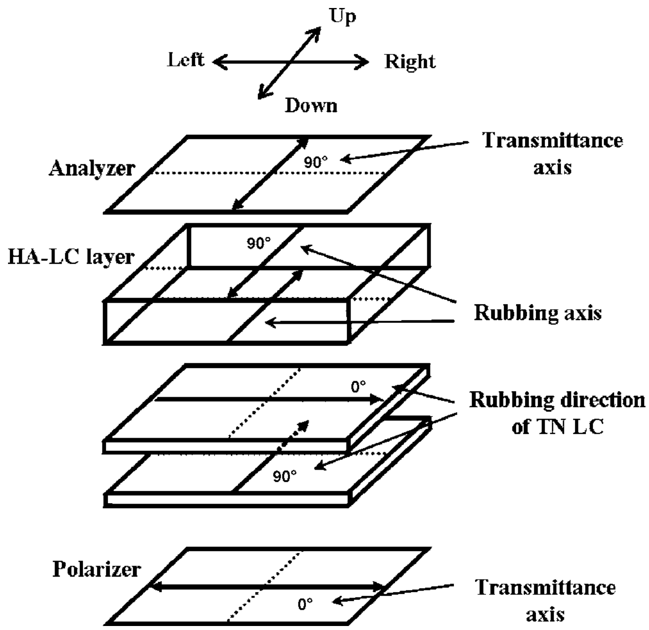

FIG. 6. Cell configuration used for the simulation in the case of one compensation layer.

the real image quality is much better in this case than normal cases. For narrow viewing angle mode, the region of gray scale inversion-free is reduced to +30° and −20° with strong light leakage at the dark state. Nevertheless, the image quality in the vertical direction is less influenced by the switching of two additional HA-LC layers compared to those in the horizontal direction.

The NW-TN-LCD with two HA-LC layers, which can control viewing angle switching, has an advantage of changing the readability for a display according to the user's intention or surroundings. However, the device has a drawback when it comes for use in mobile displays because it consumes more power due to the use of two HA-LC layers. In order to overcome this, we currently examine a viewing angle switching display consisting of a NW-TN-LCD and one HA-LC layer.

Figure 6 shows the optic structure of NW-TN-LCD using one HA-LC layer. The HA-LC layer is located between the NW-TN-LCD and two polarizers. The retardations of the HA-LC layer and TN cell were 0.60 and 0.48 μm, respectively. In the absence of a voltage on the HA-LC layer, the tilt angle of the mid-director of HA-LC layer is 2° for wide viewing angle mode. When the voltage is on, the tilt angle of the mid-director of HA-LC layer is 60° for narrow viewing angle mode. In this case, the top and bottom rubbing directions of the TN cell are 0° and 90° and the polarizer axes are perpendicular to the rubbing direction, making an O-mode structure.

Figure 7 shows the isoluminance contour in the white

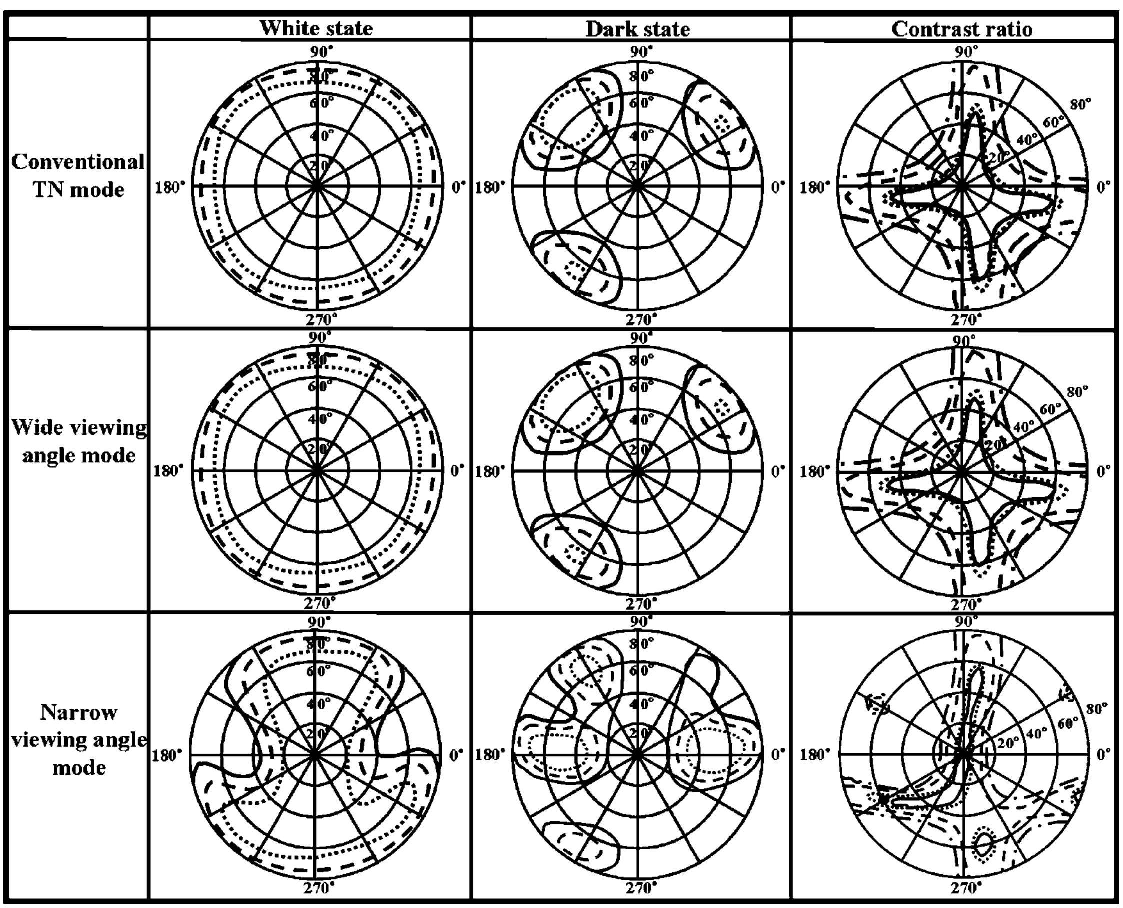

FIG. 7. Simulated isoluminance curves in white and dark states (dotted, dashed, and solid lines represents 70%, 50%, and 30% of each maximum transmittance in white and dark states) and simulated isocontrast ratio (CR=100: solid, CR=50: dotted, CR=10: dashed, CR=5: dashed and dotted) at an incident wavelength of 550 nm.

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and dark states, and iso-CR contour curves for a wide viewing angle, narrow viewing angle, and conventional TN mode at 550 nm. The isoluminance contour and iso-CR contour of the wide viewing angle mode is similar to those of conventional TN mode. However, the luminance of the white state for the narrow viewing angle mode decreases more rapidly than in the case of conventional TN mode at the horizontal direction. Moreover, due to more light leakage from right and left directions than in conventional TN mode in the dark state for the narrow viewing angle mode, the regions at which CR > 5 are 15° of the polar angle in the horizontal direction and 80° of the polar angle in the vertical direction in all viewing angles.

Figure 8 shows the simulated viewing angle dependences of the eight gray levels as a function of the polar angles at the horizontal direction for wide viewing angle, narrow viewing angle, and conventional TN modes. The viewing angle dependences for wide viewing angle mode are similar to conventional TN mode. However, gray-scale inversion occurs when the viewing angle is at the 5° polar angle in narrow viewing angle mode. This suggests that the readability of the displayed image at the horizontal direction is significantly lower in the narrow viewing angle mode due to low CR and existence of gray scale inversion while a readability characteristic on normal direction is unchanged.

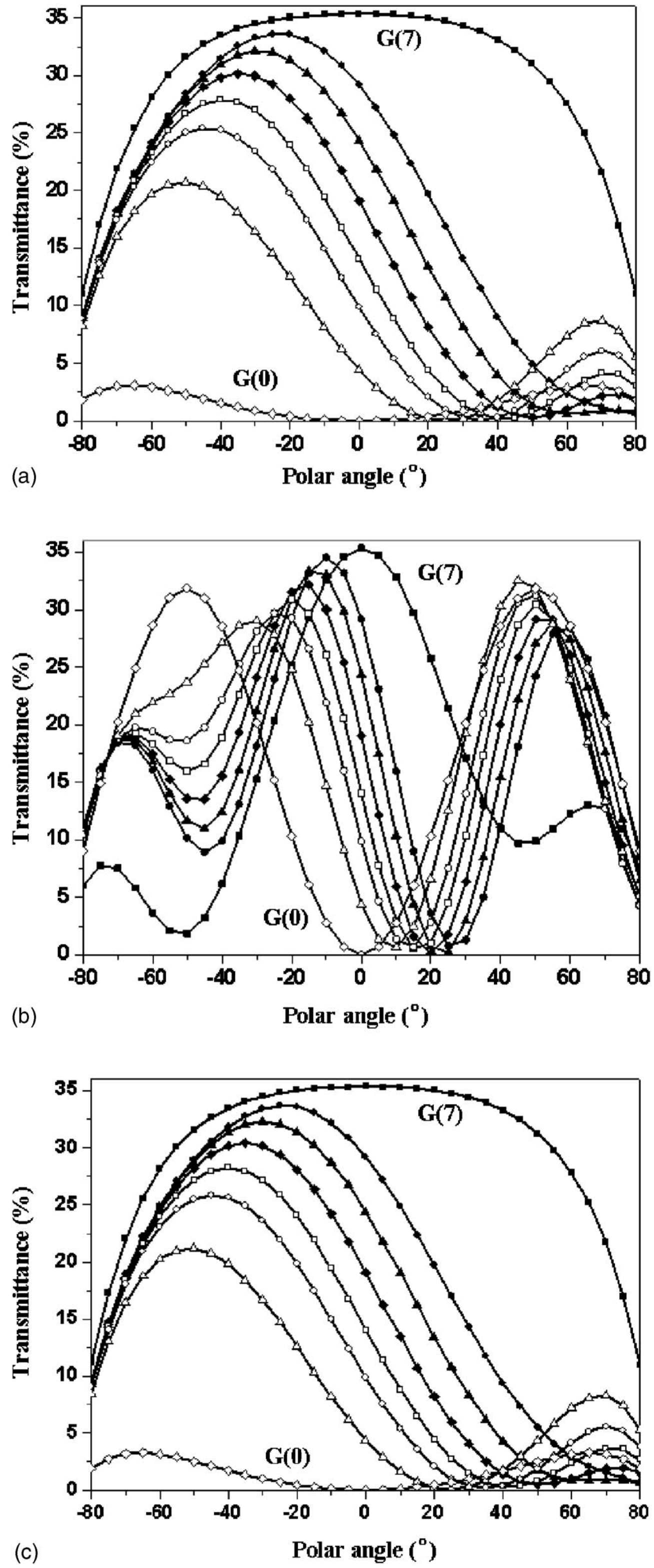

FIG. 8. Simulated viewing angle dependences of the eight gray levels as a function of the polar angle at the horizontal direction: (a) wide viewing angle mode, (b) narrow viewing angle mode, and (c) conventional TN mode.

IV. EXPERIMENTAL RESULT

In order to confirm the performance of the proposed device design, a device with one homogeneously aligned LC layer was fabricated and attached to a commercialized 5.0 in. TN-LCD based on the simulation data with the existence and nonexistence of voltage for a single HA-LC layer, as shown in Fig. 9. Figure 9(a) shows that a wide viewing angle was obtained on the horizontal direction, as predicted by the simulation data, and that the dark state was unaffected. However, in narrow viewing angle mode, the displayed image at the normal direction was distorted at polar angles of ±30°. In addition, the dark state was not well kept, giving rise to considerable light leakage, decreasing readability characteristics, as shown in Fig. 9(b). Consequently, a narrow viewing angle can be obtained in the horizontal direction, as predicted by the simulation data. In particular, light leakage on the off-axis viewing angle and the existence of gray scale inversion distorts the displayed images in the oblique viewing of the horizontal direction.

V. SUMMARY

This paper proposed a NW-TN-LCD that allows viewing angle control using one or two HA-LC layers. In the case of two HA-LC layers outside the TN cell, the device showed wider viewing angle characteristics than the conventional NW-TN-LCD because of the compensation effect for a dark state of driving cell. However, upon the application of voltage to the HA-LC layers in which the tilt angle of the mid-director is 60°, the device showed very narrow viewing angle characteristics due to gray scale inversion at all viewing directions. Furthermore, we developed a modified NW-TN-LCD with only one HA-LC layer, which distorts the displayed image at oblique viewing of the horizontal direction. This device has the advantage of viewing angle control and simple manufacturing compared to the method using two HA-LC layers. Hence, either wide viewing angle mode or narrow viewing angle mode of NW-TN-LCD in the proposed device can be selected according to their requirements.

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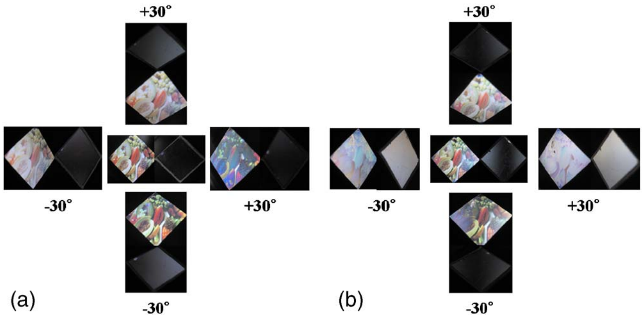

FIG. 9. (Color online) Observation of images and dark state depending on the viewing angle in viewing angle switching TN-LCD: (a) wide viewing angle mode and (b) narrow viewing angle mode.

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