Viewing angle switching of vertical alignment liquid crystal displays by controlling birefringence of homogenously aligned liquid crystal layer

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Viewing angle switching from a wide viewing angle to a narrow viewing angle has been studied. Conventional multidomain vertical alignment (VA) mode offers the advantages of a high contrast ratio (CR) not only in the front view but also in the wide viewing directions only if compensation films such as a negative C plate and a positive A plate are used. The positive A plate can be replaced by a homogeneous aligned (HA) liquid crystal layer, and the retardation of the HA layer at the off axis can be controlled by applying an electric field while keeping the retardation value at zero in the normal direction. Consequently, the viewing angle range of a VA device can be controlled from a wide viewing mode (over 170° in terms of CR=10) to a narrow viewing angle mode (approximately 60° in terms of CR=2) in the horizontal direction while keeping a high image quality at the normal direction. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2435693]

A wide viewing angle is a major issue for liquid crystal displays (LCDs) in the flat-panel display market. Several technologies such as a wide view-twisted nematic (TN),[1] in-plane switching (IPS),[2] fringe-field switching,[3] multidomain vertical alignment (MVA),[4] and patterned VA (PVA) (Ref. 5) have been developed to increase the viewing angle of LCDs. However, according to the increasing use of portable displays such as notebook computers, mobile phones, personal digital assistants, and tablet personal computers, privacy protection on an individual hold is an important issue. For this purpose, LCDs with a narrow viewing angle are required. Unlike conventional LCDs showing either a wide or narrow viewing angle, new types of the LCDs that allow control of the viewing angle of TN (Refs. 6 and 7) and IPS (Ref. 8) modes have been reported.

The conventional VA mode has a high contrast ratio in front but VA-LCDs with no compensation film showed a very poor performance in the oblique viewing directions. In order to improve these viewing angle characteristics, the formation of a multidomain, as in the MVA or PVA mode, to improve the brightness uniformity in the gray levels and the addition of a compensation film to suppress light leakage in the dark state are essential. In the film compensation method, a negative C plate and positive A plate were added to VA-LCD to compensate for the dark state, so that a very wide viewing angle [the region in which the contrast ratio (CR) is over 10 is broadened from 30° to 80° of polar angle in all directions] could be obtained.[9,10]

This viewing angle switching display is mainly composed of a vertically aligned LC layer for displaying information, a homogeneous aligned (HA)-LC layer replacing the positive A plate for viewing angle switching, and a negative C plate for compensation under crossed polarizers, as shown in Fig. 1. The vertically aligned LCs with negative dielectric anisotropy is believed to tilt down to make an angle of 45° with respect to the crossed polarizers under a bias voltage since the transmittance is proportional to $\sin^2 2\psi(V)\sin^2(\pi d\Delta n_{\mathrm{eff}}(V)/\lambda)$, where ψ is an angle between one of the transmission axes of the crossed polarizers and the LC director, d is a cell gap, Δn_{eff} is a voltage-dependent effective birefringence of a LC medium, and λ is the wavelength of the incident light. The optic axis of the HA-LC layer with positive dielectric anisotropy is parallel to the

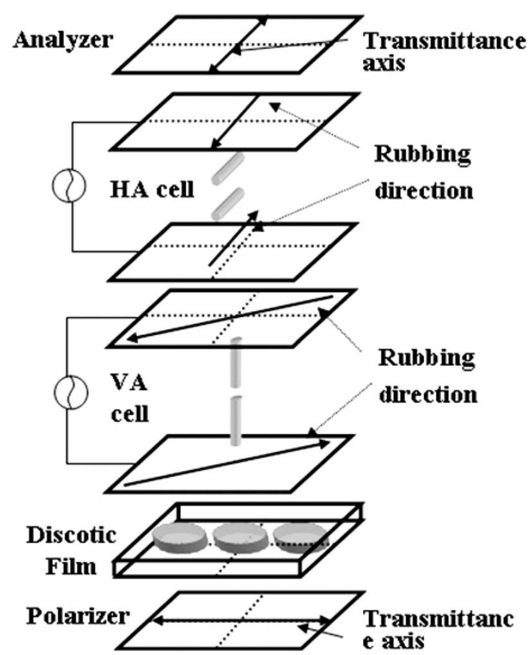

FIG. 1. Optical cell configurations of the viewing angle switchable VA display.

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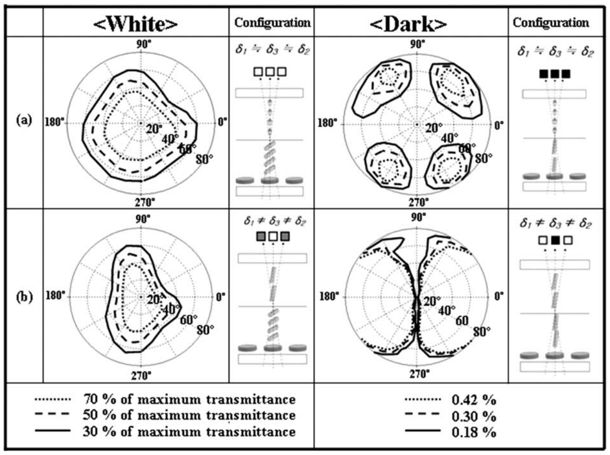

FIG. 2. Isoluminance contours in the white state and dark state at the visible wavelength and LC configuration: (a) wide viewing angle and (b) narrow viewing angle.

transmission axis of the analyzer. In this way, the linearly polarized light, after passing through a polarizer, does not change at the normal direction when propagating the negative C plate, VA-LC layer, and the HA-LC layer. Hence, the light is blocked by the analyzer. Therefore, the cell appears to be black in the absence of an electric field. Furthermore, light leakage in the oblique viewing direction is suppressed by the HA-LC layer and negative C plate. In the presence of an electric field, the vertically aligned LC director tilts down, giving rise to transmittance while the HA-LC layer remains in the initial state.

For viewing angle switching of the VA-LCD, the mid-director of the HA-LC layer is controlled by a vertical electric field as is used in the wide and narrow viewing angle, resulting in tilt angles of the mid-director of 2° and 70°, respectively.

In order to determine the optimal conditions of each optical layer to realize the excellent electro-optic characteristics in the proposed structure, a simulation was performed using the commercially available software "LCD MASTER" (Shintech, Japan), where the motion of the LC director is calculated based on the Eriksen-Leslie theory and an optical calculation was based on the 2×2 extended Jones matrix.[11] For the calculations, the retardation for the VA cell is 0.35 μm with a surface tilt angle of 88°. The HA-LC layer has a retardation value of 0.60 μm with a tilt angle of 2°. The retardation of negative C plate was 0.279 μm. The transmittances for the single and parallel polarizers were assumed to be 41% and 35%, respectively.

Figure 2 shows the isoluminance curves in the white and dark states in wide and narrow viewing angle mods, with a schematic LC configuration. Here, the LC was assumed to tilt down in 45° of the azimuthal angle. Considering the white state in wide viewing angle mode, the region at which the transmittance exceeds 30% with respect to the transmittance at the normal direction is more than 60° of the polar angle in the horizontal and vertical directions, and has a relatively symmetric shape compared with the asymmetric one in narrow viewing angle mode. On the other hand, in narrow viewing angle mode, it is less than 40° in the horizontal direction. This is due to the fact that when the mid-director of the HA-LC layer is zero, the phase difference, δ_3, at the normal direction is approximately the same as those in the

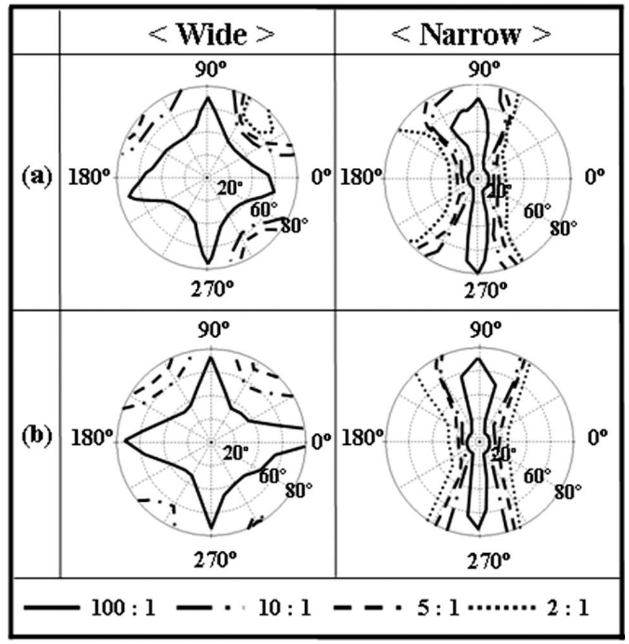

FIG. 3. Isocontrast ratio curves at the visible wavelength: (a) one-domain VA and (b) two-domain VA.

left (δ_1) and right (δ_2) directions without changing the polarization state of the incident light to the HA-LC layer, giving rise to such luminance. However, when the mid-director of the HA-LC layer is 70°, the δ_3 at the normal direction is not the same as those in the δ_1 and δ_2 directions. Moreover, the phase difference in the high tilted HA-LC layer cancels that of the low tilted VA-LC layer, giving rise to insufficient luminance than that at the normal direction. Considering the dark state, light leakage larger than 0.4% exists only in the polar angle of about 60° in the diagonal directions in wide viewing angle mode whereas it exists in most regions except in the vertical direction in narrow viewing angle mode. This means that when the HA-LC layer is switched off, it plays the role of a positive A plate so that light leakage is well controlled by compensation films of a positive A plate and negative C plate. However, when the HA-LC layer is switched on, it does not compensate for the VA layer. Instead, it becomes like a positive C plate, accelerating light leakage at the off-normal directions. The isocontrast contour was calculated in both wide and narrow viewing angle modes, as shown in Fig. 3. As clearly indicated in Fig. 3(a), the region at which the CR is larger than 10 is more than 80° of the polar angle in the horizontal and vertical directions for the wide viewing angle mode. However, it is less than 20° of the polar angle in the horizontal direction for narrow viewing angle mode. Moreover, the region at which the CR is 2 is only 30° of the polar angle in the horizontal direction. The multidomain VA is adopted in most commercialized VA products for monitors and televisions. Hence, isocontrast contours in two-domain VA were also calculated in wide and narrow viewing angle modes, as shown in Fig. 3(b), and the results showed the same trend.

When evaluating the image quality, the existence of gray scale inversion or not as well as a high CR is also important. Therefore, the degree of gray scale inversion was evaluated. Figure 4 shows the viewing angle dependence of the eight gray levels according to the polar angles in the horizontal direction at the two-domain VA cell. Gray scale inversion

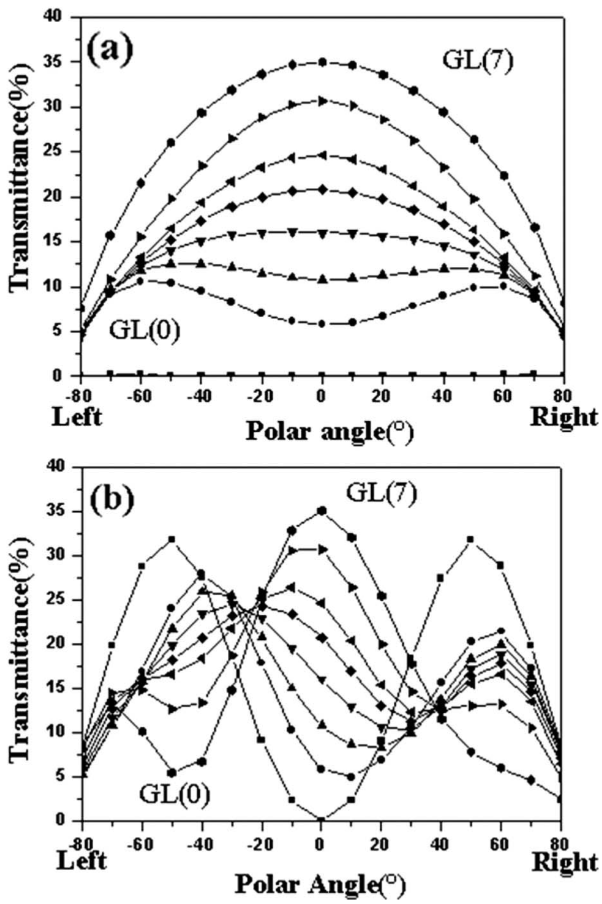

FIG. 4. Viewing angle dependence of the eight gray levels according to the polar angles in the horizontal direction at the two-domain VA structure: (a) wide viewing angle mode and (b) narrow viewing angle mode.

was not observed in wide viewing angle mode. However, it began to occur from 18° and 15° of the polar angles in the left and right directions in narrow viewing angle mode, respectively. This means that the high image quality in all directions in wide viewing angle mode dwindled to a limited viewing angle in the horizontal direction in narrow viewing angle mode, such that the image is protected within 20° of the polar angle in the horizontal direction.

In order to confirm the proposed device design, the HA-LC layer was fabricated and attached to a commercialized wide viewing 17.0 in. SXGA PVA LCD which has compensation films. Figure 5 shows the observed image quality in terms of the viewing directions. In wide viewing angle mode, the original image was well perceived in all angles due to film compensation and the multidomain structure of VA. On the other hand, in narrow viewing angle mode, the original image was not perceived in the horizontal direction when the viewing direction was larger than 30° of the polar angle in the horizontal direction due to gray scale inversion and a low CR. This demonstrates the outstanding effect of viewing angle switching of the proposed device.

In summary, this study examined viewing angle switching of a VA-LCD, where the viewing angle of the LCD can be controlled by controlling the birefringence of LC layer electrically. The optimized conditions were examined and the results were applied to a real panel. In a real LCD, the high image quality in wide viewing angle mode is limited to within a polar angle of 30° in the horizontal direction in narrow viewing angle mode, making viewing angle switching a reality. It is believed that this new viewing angle switching mode will have strong potential for future display applications.

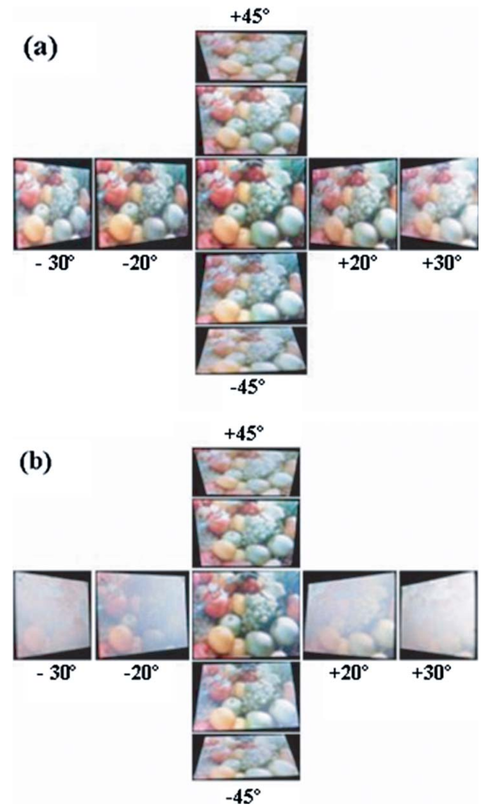

FIG. 5. Real images of the 17.0 in. PVA LCD: (a) wide viewing angle mode and (b) narrow viewing angle mode.

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