Viewing-angle controllable liquid crystal display using a fringe- and vertical-field driven hybrid aligned nematic liquid crystal

Eun Jeong,[1] Young Jin Lim,[1] Mi Hyung Chin,[1] Jin Ho Kim,[1] Seung Hee Lee,[1,a)] Seung Hoon Ji,[2] Gi-Dong Lee,[2,b)] Kyoung Ho Park,[3] Hyun Chul Choi,[3] and Byung Chul Ahn[3]
[1]*Polymer BIN Fusion Research Center, Department of Polymer Nano Science and Technology, Chonbuk National University, Chonju, Chonbuk 561-756, Republic of Korea*
[2]*Department of Electronics Engineering, Dong-A University, Pusan 607-735, Republic of Korea*
[3]*LG Display, Kumi, Kyungbook 730-726, Republic of Korea*

(Received 15 May 2008; accepted 10 June 2008; published online 1 July 2008)

Viewing-angle controllable liquid crystal display (LCD) without using an additional panel or pixel division is proposed. In the device, hybrid aligned nematic liquid crystal using a liquid crystal with negative dielectric anisotropy is used. The device shows narrow viewing angle when it is driven only by fringe-electric field, however, it exhibits wide viewing angle if driven by vertical- as well as fringe-electric field. With the approach, the viewing angle of the LCD can be controlled from 120° to 20° in horizontal direction.
[DOI: 10.1063/1.2953456]

Recently, various viewing-angle controllable displays from wide viewing angle (WVA) to narrow viewing angle (NVA) have been developed. The approach can be classified into four different approaches. The first group uses additional liquid crystal (LC) panel outside the main panel,[1–3] such that the main panel is used for displaying the main image and the other for viewing-angle control. This approach increases panel thickness and cost. The second group uses pixel division in which one pixel is divided into two subpixels such that one pixel is for displaying the main image and the other for controlling viewing angle.[4,5] This approach decreases aperture ratio of the man pixel, which results in decreased luminance of the display. The third case is associated with dual light sources for backlight system,[6] which also increases cost and thickness in display. The fourth case associated with use of the portable viewing-angle controllable film that has minute line called microlouver line is suggested,[7] however, one has to carry the film all the time to control viewing angle.

According to previous works[8–11] hybrid aligned nematic LC display (HAN-LCD) driven by a fringe-electric field has the advantages such as a low operating voltage, fast response time, no rubbing on one substrate, and NVA when an optical compensation film is not used. This NVA results from strong light leakage in a dark state in oblique viewing directions due to hybrid alignment of LC. On the other hand, a homogeneously aligned LC driven by a fringe-electric field shows very WVA characteristics even without using the compensation film due to small light leakage in a dark state and in-plane rotation of the LC director in a white state.[12–14]

In this study, we propose viewing-angle controllable LCD using the hybrid aligned LC layer, in which the LC rotates almost in plane with low tilt angle by vertical as well as fringe field for WVA and it rotates with high tilt angle by fringe-electric field for NVA.

The normalized transmittance in which uniaxial medium exists under crossed polarizer is given by

$$T/T_o = \sin^2 2\psi(V)\sin^2(\pi d\Delta n_{\rm eff}(V,\theta,\phi)/\lambda), \quad (1)$$

where ψ is a voltage-dependent angle between the input polarizer and adjacent LC director, d is a cell gap, $\Delta n_{\rm eff}$ is the voltage- and viewing-angle-dependent effective birefringence of the LC medium, and λ is the wavelength of incident light.

In LCDs, the level of leakage of light in the dark state defines a degree of viewing angle, that is, if it is very low in all viewing directions it has a high chance of giving rise to WVA with high contrast ratio in all directions. However, if it is high it results in NVA with high possibility of gray scale inversion. In this device, without bias voltage, ψ is zero at normal direction so that it gives a perfect dark state for both WVA and NVA modes. Nonetheless, the situation becomes different at off normal axis, that is, the crossed polarizer condition does not apply anymore due to change in effective angle between absorption axes of those polarizers in accordance with observation direction[15] and also the effective birefringence is strongly dependent on the LC orientation. With homogenous orientation of the LC in the dark state, the effective LC retardation in oblique viewing directions is much smaller than that with hybrid alignment. Therefore, the LC orientation with homogenous alignment is a key requirement for the WVA mode while one with hybrid alignment is a key requirement for the NVA mode. In addition, if the LC rotates almost in plane with low tilt angle, then change ratio in the effective LC retardation is very little with changing viewing direction, giving rise to good brightness uniformity like in the pure in-plane switching mode. This condition is required for realizing the WVA mode. If the LC rotates in plane with high tilt angle in one direction, then the effective cell retardation strongly depends on viewing directions, resulting in nonuniformity in brightness. This condition is required for the NVA mode. This paper examines how the above-mentioned phenomenon can be realized with a single LCD panel.

Figure 1 shows schematic configuration of a proposed viewing-angle controllable display, in which LC molecules with negative dielectric anisotropy are initially hybrid

[a)]Electronic mail: lsh1@chonbuk.ac.kr.
[b)]Electronic mail: gdlee@dau.ac.kr.

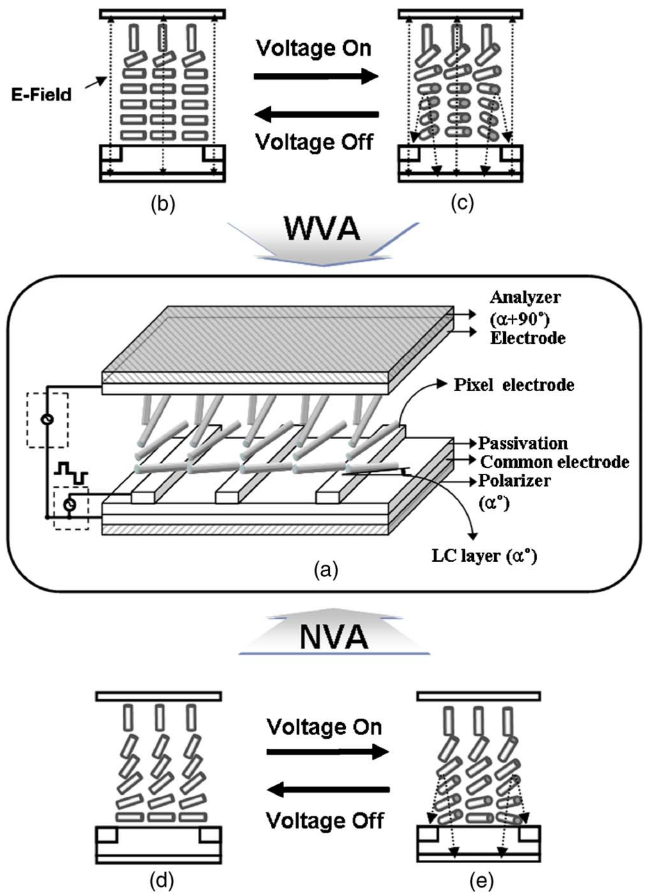

FIG. 1. (Color online) Schematic configuration of a proposed viewing-angle controllable display with LC orientation and driving scheme: (a) fringe- and vertical-field driven cell structures, (b) dark and (c) white states in the WVA mode, and (d) dark and (e) white states in the NVA mode.

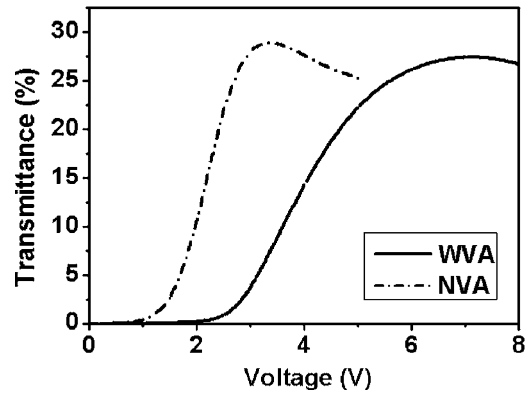

FIG. 2. Voltage-dependent transmittance curves in the proposed viewing-angle switching display when the incident light is 550 nm.

aligned with homogeneous alignment on the bottom substrate and vertical alignment on the substrates, respectively. The bottom substrate has two transparent electrode layers; the first layer with plane shape plays role of common electrode and the second layer above passivation layer with multiple numbers of slit shape plays role of pixel electrode. On the other hand, the top substrate has also an electrode of which the potential can be controlled [see Fig. 1(a)]. In this way, when a potential difference between pixel and common electrodes exists, a fringe-electric field line is formed while the vertical-field line is formed if the potential difference between top electrode and pixel and common electrodes in bottom substrates. Utilizing the field distribution we could realize WVA and NVA using HAN LC. For instance, when a vertical electric field between top and bottom substrates is applied the tilt angle of the LC which is continuously distributed from few degrees to 90° due to hybrid alignment will be reduced greatly because the LCs with negative dielectric anisotropy try to orient perpendicular to the vertical-field direction [see Fig. 1(b)]. Now, the LC orientation is similar to the homogenous alignment and then the LC director rotate almost in plane by fringe-electric field generated from bottom electrode, giving rise to the transmittance [see Fig. 1(c)]. As a result, the leakage of light in the dark state might not be so large and brightness uniformity is good in the on state, which will give rise to good viewing angle in all directions. On the other hand, if the LC is controlled only by fringe-electric field, the LC rotates in plane with high tilt angle in both off and on state [see Figs. 1(d) and 1(e)], which will give rise to strong dependency of the displayed image according to the viewing directions.

In order to confirm the feasibility of the proposed device, 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.[16] For the calculations, the electrode width and the distance between them are 3 and 4.5 μm, respectively. The passivation thickness is 0.29 μm with dielectric constant of 6.5. The retardation of the HAN cell is 0.595 μm with a birefringence of LC 0.085 at 550 nm. The dielectric anisotropy of the LC is −4.0 with three elastic constants $K1=13.5$, $K2=6.5$, and $K3=15.1$. The alpha (α) angle between LC director and horizontal component of a fringe-electric field is 7°. The cell gap is 7 μm with surface tilt angles of 2° and 90° for homogenous and vertical alignment, respectively. The transmittances for the single and parallel polarizers are 41% and 35%, respectively.

Figure 2 shows that voltage-dependent transmittance curves in the proposed viewing-angle switching display for both WVA and NVA modes. In the WVA mode, the cell showed a transmittance of 27.7% at an operating voltage of 7 V when the voltage difference is 9 V between top and bottom substrates. On the other hand, in the NVA mode, the transmittance is 29.1% at an operating voltage of 3.5 V. In both modes, the operating voltage is reasonably low with light efficiency of about 80%.

The readability of the displayed image can be judged by contrast ratio, gray scale inversion, and luminance and luminance uniformity of the display. At first, the degree of gray scale inversion for each viewing-angle mode in horizontal direction is evaluated considering eight gray levels, as shown in Fig. 3. In order to get the linear gamma characteristics ($\gamma=1.0$) in LCD, transmittance for each grey level is divided by equal transmittance difference. In the WVA mode, gray scale inversion did not occur within ±60° of the polar angles and even the level of inversion is minor, indicating that high image quality can be achieved even in wide-viewing directions. However, in the NVA mode, it starts to occur from ±10° of the polar angles with strong leakage of light in a dark state (G0), indicating that high image quality in normal direction can be distorted easily in oblique viewing direction.

Next, the isoluminance curve in white and dark states is calculated and then from these results the isocontrast ratio in

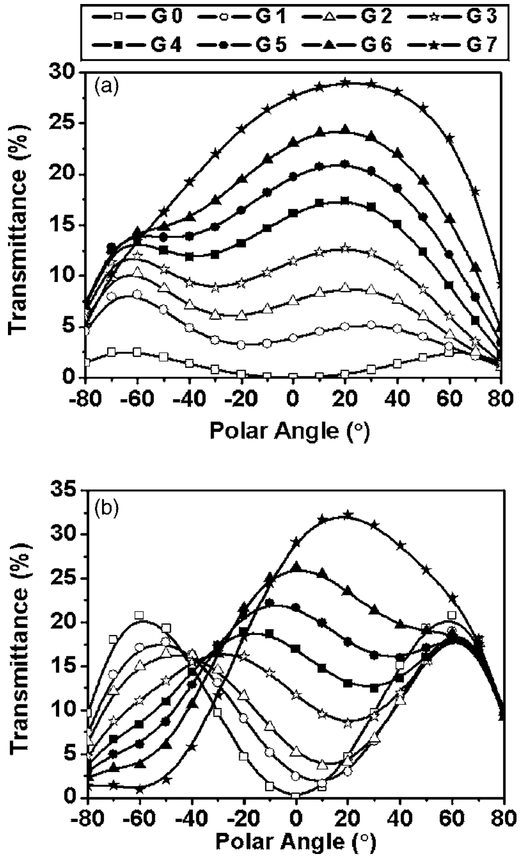

FIG. 3. Simulated viewing-angle dependences of eight gray levels as a function of polar angle along the horizontal direction: (a) WVA mode and (b) NVA mode.

the WVA and NVA modes is calculated, as shown in Fig. 4. As a result, the region in which the CR equals to 5 in horizontal direction exists over 150 in the WVA mode while it exists within about 45° in the NVA mode. The low CR in the NVA mode comes from mainly strong light leakage in the oblique viewing direction due to the hybrid alignment of the LC and also nonuniformity in luminance of the white state. Consequently, in the WAV mode, the CR is high enough without gray scale inversion even in wide oblique viewing direction, however in the NVA mode, the CR decreases very rapidly with occurrence of gray scale inversion as the viewing direction increases over 10 in left and right directions.

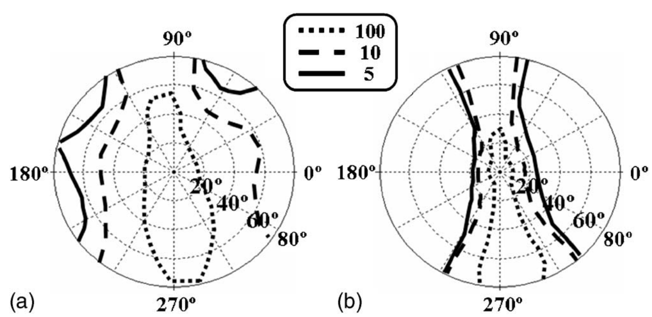

FIG. 4. Isocontrast curves at an incident wavelength of 380–780 nm: (a) WVA mode and (b) NVA mode.

In summary, viewing-angle controllable LCD in which the whole panel can be used for wide-viewing and narrow-viewing modes without using addition panel or subpixel or compensation film is proposed. The device utilizes a HAN alignment driven by fringe- and vertical-electric fields. It is confirmed that viewing angle, in the horizontal direction, can be controllable from 120° to about 20° in terms of the CR equal to 5 and free of gray sale inversion. We strongly believe this device has a high potential to be applicable to portable displays such as personal digital assistants, notebook, and cellular phone to protect the privacy.

This research was supported by the Ministry of Education and Human Resources Development (MOE), the Ministry of Commerce, Industry and Energy (MOCIE), and the Ministry of Labor (MOLAB) through the fostering project of the Laboratory of Excellency.

[1]M. Adachi and M. Shimura, SID Int. Symp. Digest Tech. Papers **37**, 705 (2006).
[2]E. Jeong, Y. J. Lim, J. M. Rhee, S. H. Lee, G.-D. Lee, K. H. Park, and H. C. Choi, Appl. Phys. Lett. **90**, 051116 (2007).
[3]E. Jeong, M. H. Chin, Y. J. Lim, A. K. Srivastava, S. H. Lee, K. H. Park, and H. C. Choi, "Switching of off-axis viewing quality in twisted nematic liquid crystal display by controlling phase retardation of additional liquid crystal layers," J. Appl. Phys. (unpublished).
[4]H. S. Jin, H. S. Chang, J. K. Park, S. K. Yu, D. S. Lee, and I. J. Chung, SID Int. Symp. Digest Tech. Papers **37**, 729 (2006).
[5]Y. J. Lim, E. Jeong, M. H. Chin, S. H. Ji, G.-D. Lee, and S. H. Lee, J. Phys. D: Appl. Phys. **41**, 085110 (2008).
[6]K.-W. Chien, Y.-J. Hsu, and H.-M. Chen, SID Int. Symp. Digest Tech. Papers **37**, 1425 (2006).
[7]O. Andrew, B. Olester, D. Wayne, D. Douglas, L. Tanya, M. Donald, M. Lynette, S. Thomas, W. David, and H. Charles, Japanese Patent No. 2,008,026,922 (2008).
[8]S. Matsumoto, M. Kawamoto, and K. Kizunoya, J. Appl. Phys. **47**, 3842 (1976).
[9]S. H. Hong, Y. H. Jeong, H. Y. Kim, and S. H. Lee, Jpn. J. Appl. Phys., Part 2 **40**, L272 (2001).
[10]S. H. Hong, H. Y. Kim, J. H. Kim, S. H. Nam, M. H. Lee, and S. H. Lee, Jpn. J. Appl. Phys., Part 1 **41**, 4571 (2002).
[11]W. C. Kim, Y. H. Jeong, and S. H. Lee, Jpn. J. Appl. Phys., Part 1 **43**, 637 (2004).
[12]S. H. Lee, S. L. Lee, and H. Y. Kim, Appl. Phys. Lett. **73**, 2881 (1998).
[13]S. H. Hong, I. C. Park, H. Y. Kim, and S. H. Lee, Jpn. J. Appl. Phys., Part 2 **39**, L527 (2000).
[14]S. H. Lee, H. Y. Kim, S. M. Lee, S. H. Hong, J. M. Kim, J. W. Koh, J. Y. Lee, and H. S. Park, J. Soc. Inf. Disp. **10**, 117 (2002).
[15]T. Ishinabe, T. Miyashita, and T. Uchida, Jpn. J. Appl. Phys., Part 1 **41**, 4553 (2002).
[16]A. Lien, Appl. Phys. Lett. **57**, 2767 (1990).