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Viewing angle switching of liquid crystal display using fringe-field switching to control off-axis phase retardation

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Abstract
A viewing angle switchable liquid crystal display associated with fringe-field switching mode is proposed. In the device, one pixel is composed of a main pixel and a sub-pixel, in which both pixels are formed to generate a fringe electric field. However, the field directions are different from each other so that in the main pixel, the fringe field rotates the liquid crystal for displaying the main image, whereas it controls only the tilt angle of the liquid crystal without rotating in the sub-pixel region. In this way, phase retardation to cause leakage of light at the off-normal axis can be generated in the sub-pixel, and by utilizing the light, the main displayed image in the normal direction can be blocked in the oblique viewing direction.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

At present, large-sized liquid crystal displays (LCDs) show very high image quality owing to the invention of several wide viewing angle liquid crystal (LC) modes such as wide view-twisted nematic (WV-TN) [1, 2], in-plane switching (IPS) [3], fringe-field switching (FFS) [4–6] and multi-domain vertical alignment [7–9]. And even relatively small-sized LCDs such as notebook computers, mobile phones and tablet PCs have started adopting this wide viewing angle technology so that the displayed image can be seen well even in oblique viewing directions. However, such displays are undesirable in a situation where a user needs privacy protection on an individual hold, that is, the displays with narrow viewing angles are favoured in this case. Therefore, LCDs with the function of controlling viewing angle are in demand.

Recently, several viewing angle switchable LCDs with two major different approaches have been reported. The first group [10–14] adds an additional LC panel for viewing the angle control. However, this approach increases the thickness, cost and total power consumption, which is not suitable for portable displays. The second group [15–18] divides one pixel into a main region and a sub-region and then the sub-pixel controls the viewing angle. Two of the representative LC modes in the latter cases are the IPS and FFS modes. In both modes, the LCs are homogeneously aligned at an initial state, and then rotate in-plane by an in-plane or fringe electric field in the main pixel, giving rise to transmittance, whereas they tilt upwards by a vertical electric field in the sub-pixel as in the electrically controlled birefringence (ECB) mode. By controlling the degree of tilt of the LC in the sub-pixel, phase retardation in the oblique viewing direction can be tuned and thus a leakage of light is generated. Utilizing this leakage of light, the viewing angle can be controlled at the off-normal axis. However, in order to tilt the LC upwards, extra common electrodes should exist on the top substrate. This increases not only the number of processes, but also the cost.

In this paper, we propose a viewing angle controllable LCD using one panel of FFS mode. Unlike the conventional device [17] which is driven by a vertical field in the sub-pixel,

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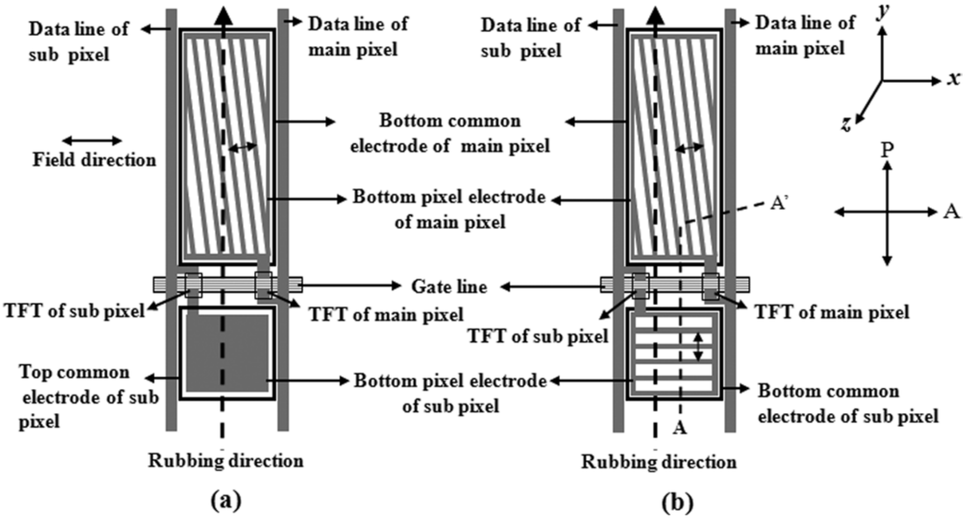

Figure 1. Top view of the electrode structure of the viewing angle controllable FFS-LCD: (*a*) conventional device, (*b*) proposed device.

the proposed device utilizes fringe electric field in both main pixel and sub-pixel for light modulation at the normal and off-normal axes.

2. Switching principle and viewing angle control

In the LCD where uniaxial LC medium exists under a crossed polarizer, the normalized transmission can be easily described by

$$T = \sin^2 2\psi(V)\sin^2(\delta/2), \qquad (1)$$

where ψ is an angle between the polarizer and the LC director, and δ is the phase difference between the ordinary and extraordinary rays passing through the LC, defined by $\delta = 2\pi d\Delta n_{\mathrm{eff}}(V, \Theta, \Phi, \lambda)/\lambda$ where d is the cell gap, Δn_{eff} is the voltage-dependent effective birefringence of the LC layer, Θ is a polar angle, Φ is an azimuthal angle and λ is the wavelength of the incident light, respectively. According to the equation, to obtain a fully white state, it should be satisfied that δ is π and the rotating angle of the LC ψ is 45° while ψ should be zero to achieve a dark state in the normal direction and δ should be close to zero to achieve a good dark state at the off-normal axis. On the other hand, δ should have some value at the off-normal axis to generate leakage of light in the oblique viewing direction.

Figure 1 shows the top view of the conventional and proposed pixel structures. Both devices have two transistors so that the voltage applied to the pixel electrodes in the main pixel and sub-pixel can be controlled separately through two thin film transistors. The aspect ratio between the long and short axes of a pixel is 3 : 1 and the area ratio of the main pixel and the sub-pixel is 2 : 1 in both devices. As shown in figure 1(*a*), the conventional device [17] is composed of a main pixel and a sub-pixel in which the former has a normal FFS electrode structure, that is, the common and pixel electrodes exist on the bottom substrate with a passivation layer between them and the latter has a plane shaped pixel electrode and a plane shaped common electrode is additionally patterned on the top substrate. The rubbing direction and the polarizer orientation are the same for both main pixel and sub-pixel. This gives a good dark state for both normal and oblique incidence at an initial state. For the main pixel, the pixel electrode makes an angle of 10° with respect to the rubbing direction. Therefore, the reorientation of the director by an applied voltage is in-plane. Consequently, the white state and the intermediate grey levels are uniform across a wide range of viewing angles.

In the case of the conventional sub-pixel, a voltage is applied across the patterned upper and lower rectangular electrodes. This induces reorientation vertically (in the y–z plane). For normal incidence, the transmittance is unaffected by this reorientation and the sub-pixel remains dark. However, significant transmission will result in the case of oblique incidence.

However, this conventional device in which LC orientation is controlled as in the ECB mode in the sub-pixel has the disadvantage that an additional process to pattern the common electrode on the top substrate is required and also an accurate assembly between the top and bottom substrates is required, which increases the manufacturing cost. Here we propose a modified sub-pixel design, in which fringing field electrodes patterned perpendicularly to the rubbing direction are used to induce this vertical reorientation, as shown in figure 1(*b*). In this arrangement the fringing fields do not cause any in-plane rotation of the director in the sub-pixel. In the device, both common and pixel electrodes exist on the bottom substrate with a passivation layer between them as in the normal FFS device. The pixel electrodes are patterned in a slit form but the patterned electrode direction is different from each other. In the main pixel, the electrode direction has an angle of about 10° with respect to the vertical direction, so that when initial alignment of LC is made to the y direction, the fringe field has an angle of 80° with respect to the LC director. In the sub-pixel, the electrode direction makes an angle of 0° with respect to the horizontal direction so that the horizontal field direction (E_y) of the fringe field is parallel to the LC director. At an initial state, both main pixel and sub-pixel show a dark state because of $\psi = 0°$.

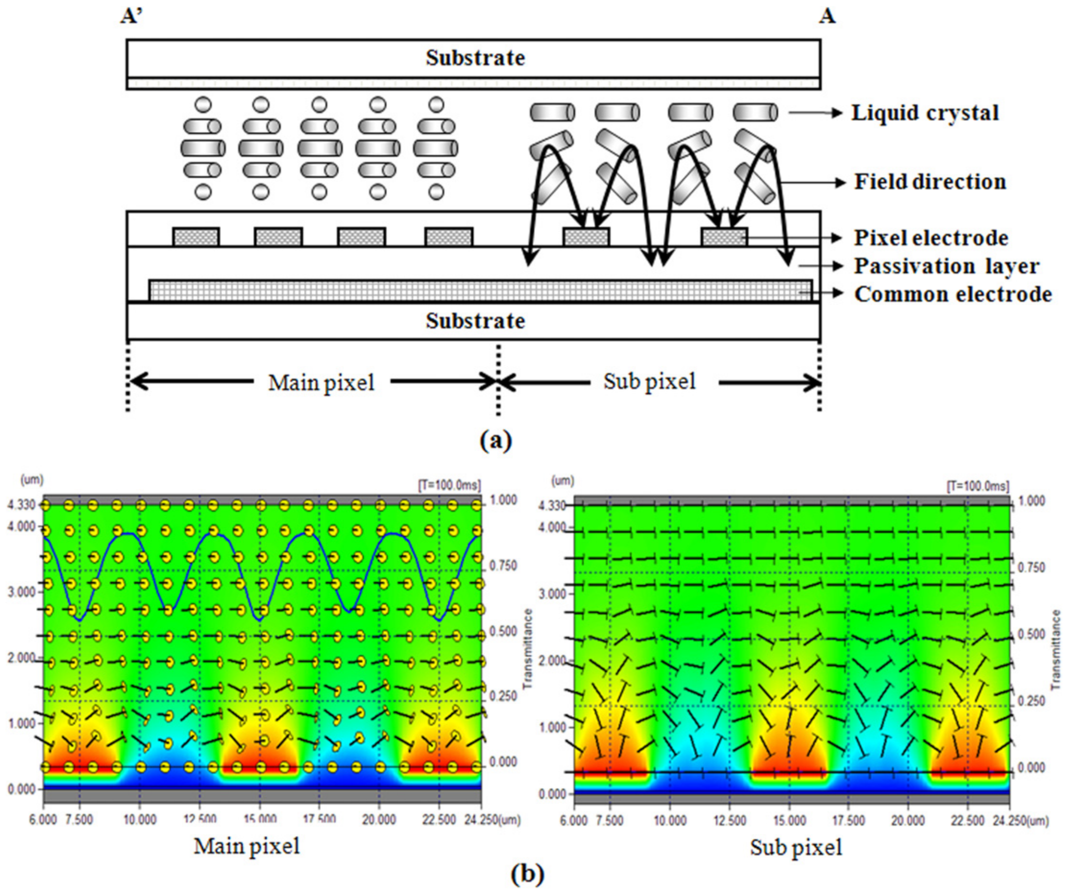

Figure 2. Cross-sectional view of viewing angle switching FFS cell with the LC director field along A–A′ of figure 1(*b*) when an operating voltage is applied in the main pixel and the sub-pixel: (*a*) schematic LC profile and (*b*) simulation data.

Figure 2 shows the schematic and simulated LC director field with applied voltages in the main pixel and the sub-pixel. With bias voltage, the LC in the main pixel rotates by a dielectric torque ($\psi = 0°$), giving rise to transmittance (see main pixel of figure 2(*a*)). In contrast, the LC in the sub-pixel does not rotate at all ($\psi = 0°$) because E_y is parallel to the LC director with a positive dielectric anisotropy and thus the dark state is well maintained in the normal direction. Although the rotating angle of the LC director is zero, the tilt angle of the LC will be generated such that the tilt angle is formed along the fringe field line because the fringe field has a vertical component, as shown in the sub-pixel of figure 2(*a*). Simulated results also clearly prove that the LC mainly reorients in in-plane, while it reorients in the vertical direction without any rotation, as shown in figure 2(*b*). Depending on the applied voltage to the sub-pixel, the degree of tilt angle of the LC, that is, effective phase retardation in the oblique viewing angle of horizontal direction can be controlled. This retardation will change the polarization state of an incident beam passing through the bottom polarizer in the viewing direction and let it pass through the top polarizer, generating leakage of light in that direction. Using this light leakage, the characters or images can be displayed at the off-normal axis in addition to the displayed image in the main pixel. Consequently, this generates an extra image over the main image in oblique viewing directions, that is, the original image is overlapped by the image made by the sub-pixel when the voltage to the sub-pixel is controlled for controlling the viewing angle without distorting the image quality in the normal direction. Due to different pixel patterns only in the bottom substrate, the proposed device has the advantage of low cost and simple processing.

3. Results and discussion

In order to confirm the proposed concept and level of light leakage, 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 [19]. For the calculations, the retardation for the FFS cell is 0.40 μm with $d = 4\,\mu$m and a surface tilt angle of 2°. The dielectric anisotropy of the LC is 8.2 with elastic constants $k_{11} = 9.7$ pN, $k_{22} = 5.2$ pN and $k_{33} = 13.3$ pN. The thickness of the pixel and common electrodes is 0.04 μm and the width of the pixel electrode and the distance between them are 3 μm and 4.5 μm, respectively. The thickness of the passivation layer between the pixel and common electrode is 0.29 μm. The transmittances for the single polarizer, pairs of parallel and crossed polarizers were assumed to be 41%, 35% and 0.0092%, respectively.

Under the cell conditions, optical principle for the proposed configurations with regard to light path associated

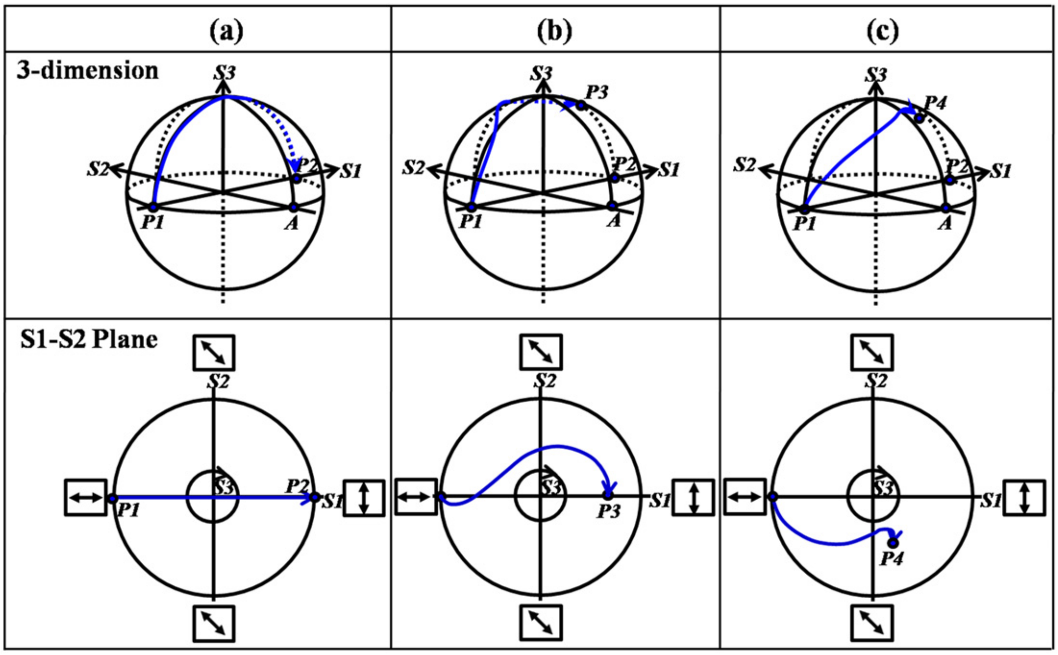

Figure 3. Poincaré sphere representation of the polarization path of the (*a*) retarder of λ/2 retardation in the normal direction and (*b*) ECB and the (*c*) FFS modes at a polar angle of 60° in the dark state of the sub-pixel.

with leakage of light is simply described on the Poincaré sphere as follows. Figure 3 shows the polarization path of the light passing through the cell on the three-dimensional Poincaré sphere and S1–S2 plane. The figure shows the evolution of the polarization state of the light as it propagates through the LC layer. P1 and P2 indicate the polarization positions of the polarizer and the analyzer, respectively. The starting position of the light passing through the polarizer can be set at position P1, which implies the horizontal linear polarization, on the Poincaré sphere. In order to achieve the bright state in the transmissive mode, we generally use a LC cell with λ/2 retardation because the polarization position of the light passing through the LC layer will rotate to the opponent position P2, which means the vertical linear polarization position, and same to the position of the analyzer, if the optical axis of the LC cell is set to 45° that has a position *A* on the Poincaré sphere as shown in three dimensions in figure 3(*a*). This is an ideal condition which maximizes the transmittance. In the sub-pixel with ECB mode of figure 1(*a*), the analyzer axis and the rubbing direction of the LC layer coincide with each other. In the normal direction, therefore, the polarization of the light passing through the ECB cell stays at position P1 even if the voltage is applied. However, the polarization of the light at a polar angle of 60° in the horizontal direction will move to position P3 when the applied voltage is 3 V because the light experiences the retardation of the cell during its travel into the cell as shown in figure 3(*b*). The light leakage of ECB mode at a polar angle of 60° is lower than that of the retarder with λ/2 retardation, but it is enough to generate leakage of light for controlling the viewing angle. In the sub-pixel with FFS mode of figure 1(*b*), when a bias voltage of 10 V is applied, the LC also tilts up in the vertical direction in response to the fringe electric field. Figure 3(*c*) shows the polarization of the light passing through the LC layers of the FFS LC cell at a

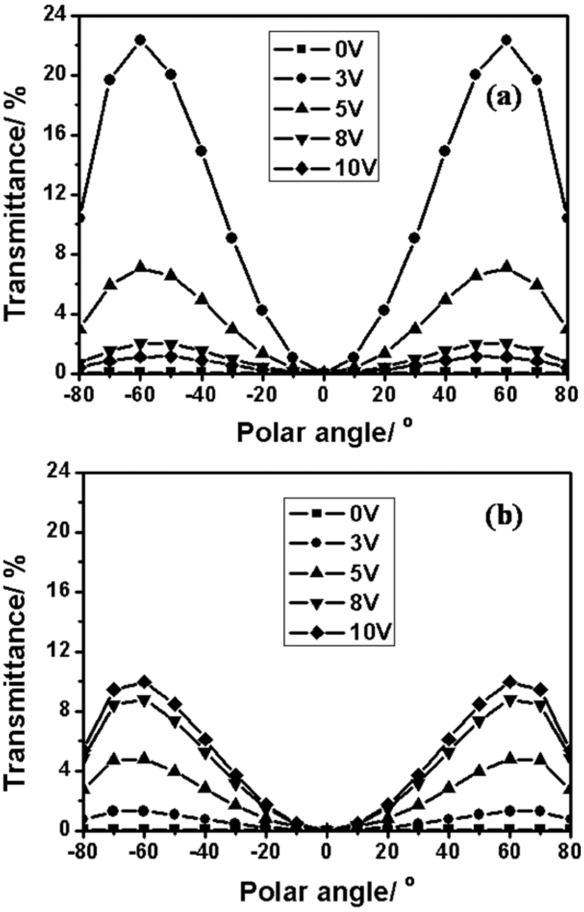

Figure 4. Calculated light leakage along the horizontal direction according to applied voltages when the sub-pixel is operated by (*a*) ECB and (*b*) FFS modes.

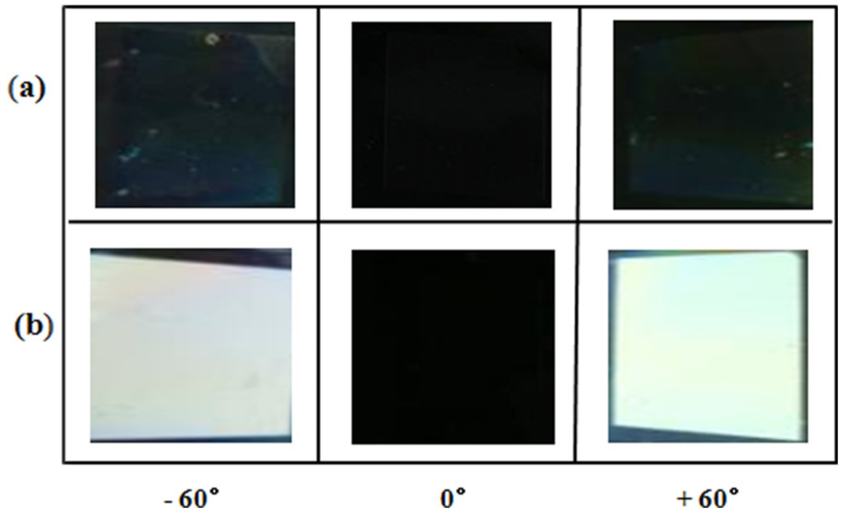

Figure 5. Photographs of the FFS cells in the dark state in the normal direction and at a polar angle of ±60°: (*a*) wide viewing angle mode, (*b*) narrow viewing angle mode.

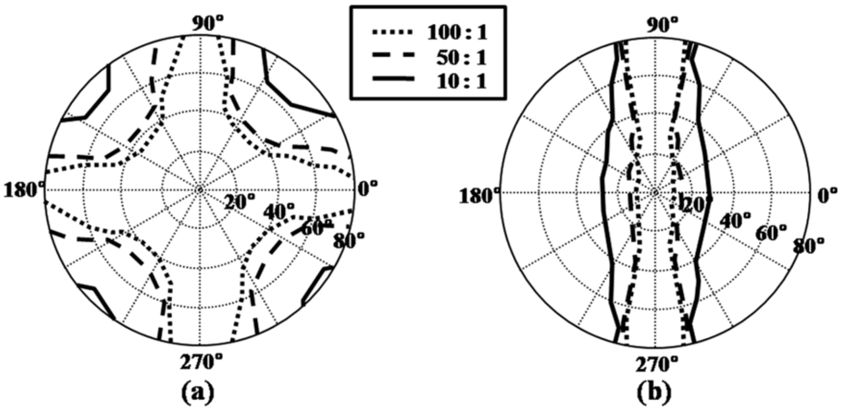

Figure 6. Iso-contrast contours of the proposed device: (*a*) wide viewing angle mode, (*b*) narrow viewing angle mode.

polar angle of 60° in a horizontal direction. We can observe that the final polarization state (P4) at the polar angle is close to position P3 in the ECB LC cell; however, we can conclude that the leakage of light is enough to control the viewing angle something like in the ECB cell.

Such a change in the polarization state of light after passing through the LC layer in the sub-pixel for both cases is calculated as the transmittance of light leakage, according to polar angles along the horizontal direction as shown in figure 4. In the ECB mode, the calculated leakage of light is almost zero at 0 V in the normal direction, and even in the oblique viewing direction it remains to be very low, showing an excellent dark state. However, the effective phase retardation in the oblique viewing direction increases with increasing voltage because the LC tilts upwards according to the increase in the applied voltage and becomes maximal at 3 V, generating 22.36% leakage of light at a polar angle of 60° at 3 V while showing a perfect dark state in the normal direction, as shown in figure 4(*a*). In the FFS mode, the calculated light leakage is zero at 0 V in the normal direction and even in the oblique viewing direction, as shown in figure 4(*b*). However, it increases with increasing voltage and increasing polar angle due to an increase in $d\Delta n_{\mathrm{eff}}$ while maintaining a good dark state in the normal direction. The transmittance of light leakage reaches 9.98% at a polar angle of 60° at 10 V. Here, the applied voltage can be controlled by changing the pixel electrode width and the distance between them and also the dielectric anisotropy of the LC. In addition, it occurs symmetrically with respect to the normal direction because the tilt angle of the LC is generated to left and right directions symmetrically along the fringe electric field. The leakage light of the proposed device is low compared with the ECB mode; however, it is large enough for controlling the viewing angle.

To confirm the calculated results, unit cells under similar conditions as in the simulation are fabricated. As shown in the experimental data of figure 5, when 0 V is applied to the sub-pixel, an excellent dark state is maintained not only in the normal direction but also at a polar angle of ±60° (see figure 5(*a*)). On the other hand, when a 10 V is applied, strong leakage of light is generated at the same polar angle (see figure 5(*b*)). Selecting the applied voltage in the sub-pixel between 0 and 10 V, the dark state of the device can be controlled as mentioned above. In this way, if 0 V is chosen, the dark state is well maintained in all the viewing directions so that a wide viewing angle is realized; however, if 10 V is selected, relatively strong leakage of light is generated in the oblique viewing direction and thus a narrow viewing angle is realized.

Finally, the viewing angle is calculated for both modes in terms of contrast ratio. As indicated in figure 6(*a*), for the wide viewing angle mode, a region in which the contrast ratio is 10 exists at a polar angle over about 120° in all the viewing directions and, in addition, it exists over 160° in the horizontal direction. However, it exists only at a polar angle of 60° in the horizontal direction of the narrow viewing angle mode. In this way, viewing angle in terms of contrast ratio 10 can be controlled from 160° to 60° in the horizontal direction. In a practical situation, the characters can be made in oblique viewing directions utilizing this leakage of light so that the main displayed image is overlapped by these characters generated in the sub-pixel, protecting the main image.

4. Summary

In summary, this study proposed a highly efficient way of viewing angle switching of a FFS LCD. In the device, one pixel is composed of a main pixel and a sub-pixel and the viewing angle of the LCD can be controlled only by controlling the tilt angle of the LC layer, that is, phase retardation in oblique viewing directions, electrically. Unlike the conventional approach, the device utilizes a fringe field for viewing angle control and thus it does not require an additional common electrode on the top substrate, which can save cost and process steps. It is believed that this new viewing angle switching mode will have strong potential for future display applications.

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References

[1] Mori H 2005 *J. Display Technol.* **1** 179

[2] Park C H, Lee S H, Jeong J, Kim K J and Choi H C 1996 *Appl. Phys. Lett.* **89** 101119

[3] Oh-e M and Kondo K 1995 *Appl. Phys. Lett.* **67** 3895

[4] Lee S H, Lee S L and Kim H Y 1998 *Appl. Phys. Lett.* **73** 2881

[5] Lee S H, Kim H Y, Lee S M, Hong S H, Kim J M, Koh J W, Lee J Y and Park H S 2002 *J. Soc. Inform. Display* **10** 117

[6] Yu I H, Song I S, Lee J Y and Lee S H 2006 *J. Phys. D: Appl. Phys.* **39** 2367

[7] Takeda A, Kataoka S, Sasaki T, Tsuda H, Ohmuro K, Koike Y, Sasabayashi T and Okamoto K 1998 *Soc. Inform. Display Tech. Digest* **29** 1077

[8] Kim S G, Kim S M, Kim Y S, Lee H K, Lee S H, Lee G-D, Lyu J-J and Kim K H 2007 *Appl. Phys. Lett.* **90** 261910

[9] Lee S H, Kim S M and Wu S-T 2009 *J. Soc. Inform. Display* **17** 551

[10] Hisatake Y, Kawata Y and Murayama A 2005 *Soc. Inform. Display Tech. Digest* **36** 1218

[11] Adachi M and Shimura M 2006 *Soc. Inform. Display Tech. Digest* **37** 705

[12] Jeong E, Lim Y J, Rhee J M, Lee S H, Lee G-D, Park K H and Choi H C 2007 *Appl. Phys. Lett.* **90** 051116

[13] Adachi M 2008 *Japan. J. Appl. Phys.* **47** 7920

[14] Jeong E, Chin M H, Lim Y J, Srivastava A K, Lee S H, Park K H and Choi H C 2008 *J. Appl. Phys.* **104** 033108

[15] Jin H S, Chang H S, Park J K, Yu S K, Lee D S and Chung I J 2006 *Soc. Inform. Display Tech. Digest* **37** 729

[16] Baek J-I, Kwon Y-H, Kim J C and Yoon T-H 2006 *Proc. 13th Int. Display Workshops (Otsu, Japan)* p 201

[17] Lim Y J, Jeong E, Kim Y S, Jeong Y H, Jang W-G and Lee S H 2008 *Mol. Cryst. Liq. Cryst.* **495** 186

[18] Lim Y J, Jeong E, Chin M H, Ji S, Lee G-D and Lee S H 2008 *J. Phys. D: Appl. Phys.* **41** 085110

[19] Lien A 1990 *Appl. Phys. Lett.* **57** 2767