Viewing angle controllable liquid crystal display with high transmittance

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Abstract: All conventional viewing angle switchable liquid crystal displays with pixel division have drawback in light efficiency because the sub-pixel that controls viewing angle does not transmit the incident light at normal direction. In this paper, we propose new viewing angle controllable homogeneously aligned liquid crystal display in which the pixel is composed of red, green, blue, and white pixels. The colored pixels are driven by fringe-field switching and the white pixel is driven by complex field. In wide-viewing angle mode, the liquid crystal (LC) directors in all pixels rotate in plane, contributing to high transmittance. In narrow-viewing angle mode, the LC directors in color pixels rotate in plane for light transmission while the LC directors in white pixel can rotate or tilt upward by simultaneous fringe and vertical electric field. The high tilted LC directors generate light leakage in oblique directions which can be utilized for viewing angle control and also transmission at normal direction for image expression. The proposed device overcomes the long standing problem of transmittance sacrifice in the conventional devices.

OCIS codes: (160.3710) Liquid crystals; (230.3720) Liquid-crystal devices.

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1. Introduction

Wide viewing angle (WVA) characteristic is one of the most important issues of liquid crystal display (LCD) to attain high image quality in all viewing directions. One of the easiest approaches to achieve it is to use homogeneous alignment of LC in the initial state with in-plane reorientation of LC's optic axis. The main driving modes of homogeneously aligned LC devices are in-plane switching (IPS) [1–3] and fringe-field switching (FFS) [4–7] which are well known to exhibit WVA. However, according to the increasing demand of portable displays, privacy protection on an individual hold is also another matter of concern. Accordingly, various viewing angle controllable (VAC) LCDs from WVA to narrow viewing angle (NVA) have been developed [8–15]. To achieve extra NVA characteristic on wide viewing LCDs, initially, an additional control panel was added above the main panel [8–12]. However, this method has some problems such as increase in thickness, manufacturing cost and power consumption, which are improper for portable display applications. In order to solve such issues, pixel division method was proposed in which one pixel is divided into two sub pixels such that one pixel is for displaying the main image and the other one for controlling viewing angle [13–15]. This approach solves the problem of thickness enhancement, but loses light efficiency due to low aperture characteristic because the transmittance does not occur at all in the viewing angle controlled region. High transmittance is one of key parameters to be equipped with for portable displays so that new solution for viewing angle control needs to be proposed.

In this paper, in order to solve abovementioned problem of pixel division method, we propose VAC-LCD with high aperture ratio characteristic associated with FFS mode. The proposed device is composed of red (R), green (G), blue (B), and white (W) pixels in which R, G, and B pixels are for displaying images and W pixel for both viewing angle control and image expression. To obtain high transmittance, the pixel electrodes, especially W pixel is optimized to contribute the transmittance of the panel at normal direction and also to control viewing angle in horizontal direction utilizing the leakage of light.

2. Cell structure and switching principle of VAC-LCD

Figure 1 shows the proposed pixel structure of VAC-LCD using the FFS mode, which is composed of R, G, B, and W pixels. Here, three main pixels for image expression have R, G, and B color filter and sub pixel for both image expression and viewing angle control has only a transparent resin without color filters on top substrate. Owing to use of transparent resin in W pixel, little enhanced light transmission immensely improves the total transmittance of the panel and on the other hand, slight light leakage in oblique viewing directions would be strong enough to be noticed easily. Considering pixel structures, both pixel and common electrodes exist on the bottom substrate of the device with passivation layer between them. The pixel electrodes are patterned in a slit form such that the slit is directed at 10° angle with respect to y axis. The LC molecules are homogenously aligned with its optic axis along y direction so that the fringe field maintains an angle of 80° to the LC director. In the W pixel, an additional electrode has been provided on the top substrate for controlling viewing angle. Here, all pixels are controlled by one data and one gate line like the conventional transmissive FFS-LCD.

The normalized transmittance (T/T_o) of the FFS device filled with uniaxial LC medium under crossed polarizers, is given by $T/T_o = \sin^2 2\psi(V)\sin^2(\pi d\Delta n_{eff}(V,\theta,\varphi)/\lambda)$, where ψ is an voltage-dependent angle between the input polarizer and LC director, d is a cell gap, Δn_{eff} is

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the voltage- and viewing-angle-dependent effective birefringence of the LC medium, and λ is the wavelength of incident light. To achieve maximum transmittance at normal direction, ψ should be 45° and $d\Delta n_{\mathrm{eff}}$ should be $\lambda/2$, respectively.

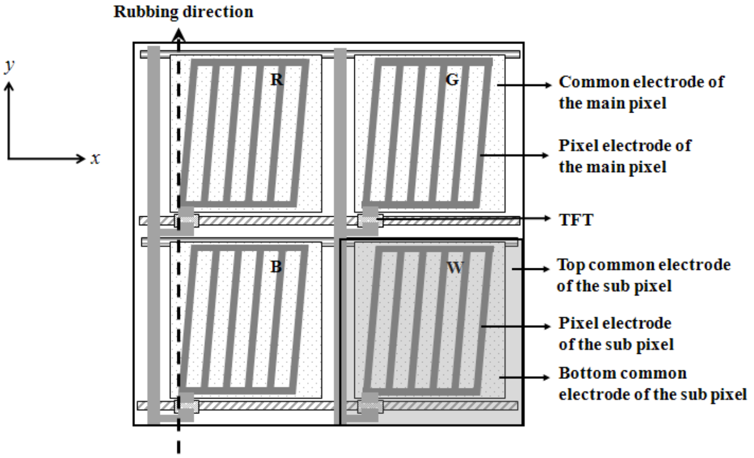

Fig. 1. Schematic pixel structure of the VAC-LCD using FFS mode.

The WVA mode exhibits dark state without application of signal voltage in pixels because LC director is homogeneously aligned with a condition $\psi = 0°$ at normal direction. Even in oblique viewing direction, $d\Delta n_{\mathrm{eff}}$ is not sufficiently large and hence ensuring a good dark state. When signal voltage is applied only in pixel electrodes on bottom substrate, a grey or white state of the WVA mode at normal direction is obtained because the generated fringe electric field rotates the LC director almost in plane not only in R, G, B pixels but also in W pixel. In the NVA mode, the dark state in R, G, and B pixels is obtained when signal voltage is not applied; however, the one in W pixel is obtained when a voltage is applied only to the electrode on top substrate to make LC tilt upward along vertical field. As a result, $d\Delta n_{\mathrm{eff}}$ becomes large enough even at off normal axis, giving rise to strong leakage of light in the dark state. Using this light leakage, any type of information such as the image or character can be made in oblique viewing direction. As a result, the original image is overlapped with the made image displayed by main pixels. In this case, W pixel can also contribute to total panel transmittance, as shown in Fig. 2. In the main pixel, the LC directors are rotated by a dielectric torque when the voltage is applied in main pixel such as R, G, and B pixels, giving rise to transmittance (see Fig. 2(a)). On the other hand, by applying proper voltages in all electrodes on bottom and top substrates of the sub pixel, the LC directors are tilted up and also rotated at the same time, as shown in the Fig. 2(b). This driving condition with proposed structure causes not only transmittance in normal direction but also controls viewing angle in oblique viewing directions, simultaneously.

3. Calculated and experimental results and discussion

To analyze electro-optic characteristics of the proposed VAC-LCD, 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]. The calculations are made with the initial conditions such that retardation for the proposed cell is 0.40 µm with $d = 4$ µm and the surface tilt angle is 2°. The dielectric anisotropy of the LC is 7.4 with elastic constants $k_{11} = 11.7$, $k_{22} = 5.1$, and $k_{33} = 16.2$. The width of pixel electrode and the distance between them are 3 µm and 4.5 µm, respectively. The thickness of passivation layer between pixel and common electrode is 0.29 µm. The transmittances for the single and parallel polarizers were assumed to be 41% and 35%, respectively.

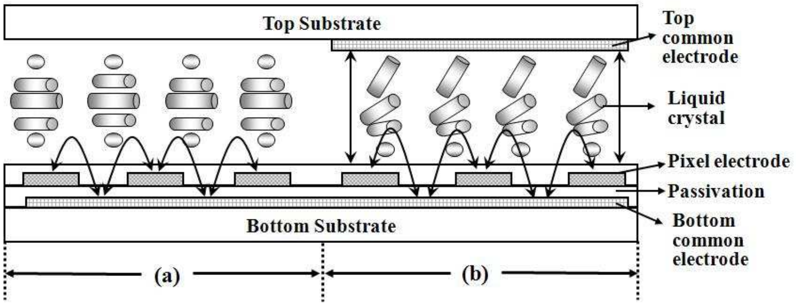

Fig. 2. Cross-sectional view of viewing angle controllable FFS cell with LC profile when an operating voltage is applied to main pixel (a) and also top common electrode of the subpixel (b).

Figure 3 shows calculated and measured light leakage along horizontal direction according to applied voltage in the W pixel. As indicated in Fig. 3(a), the calculated light leakage is very low at 0 V, showing a perfect dark state even at a large polar angle. However, the effective phase retardation in oblique viewing direction increases with increasing voltage because the LC tilts upward as the applied voltage on top common electrode increases and the light leakage becomes maximal at 2.5V, generating 26.4% at polar angle of 60° while showing a perfect dark state in normal direction. In addition, the light leakage is found to be symmetric with respect to the normal direction as the LC tilts symmetrically to left and right directions, along the track of rubbing. The experimental data also confirms the increase in the amount of light leakage with increasing voltage, reaching a peak at 3.0 V, generating a light leakage of 3.3% at a polar angle of 60°, while showing a perfect dark state in the normal direction, as shown in Fig. 3(b). Here, the measured transmittance for two parallel polarizers using LCMS-200 (Sesim Photonics Technology) was found to be 5.3%.

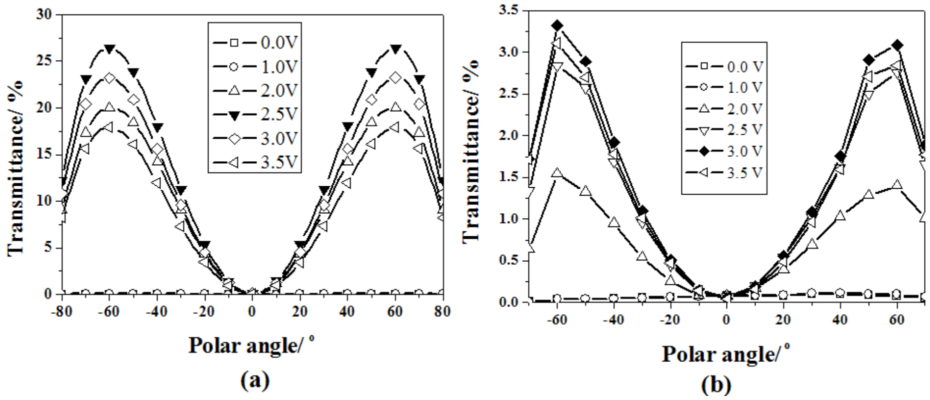

Fig. 3. Caculated (a) and measured (b) leakage of light along horizontal direction according to applied voltage in the W pixel.

To confirm the simulation results, unit cells for W pixel were fabricated which were similar to those used in the simulation and are shown in Fig. 4. When 0V is applied in the W pixel, an excellent dark state is achieved, not only in the normal direction, but also at polar angles of ± 30° and ± 60° (see Fig. 4(a)). On the other hand, when a potential difference between top and bottom common electrode is 3.0V, the strong leakage of light occurs at the same polar angles (see Fig. 4(b)). By varying the applied voltage in the W pixel between 0V and 3V, the dark state of the device can be controlled, as mentioned above. In this way, a satisfactory dark state is maintained by applying 0V to the W pixel in all viewing directions, so that wide viewing-angle characteristics can be realized. However, by applying 3V, the relatively strong leakage of light is generated in the oblique viewing direction and, thus, a narrow viewing-angle is realized. In real active matrix LCDs, the light leakage can be utilized as a certain image or some characters so that the main displayed image in oblique viewing direction can be overlapped with the generated image or characters, letting viewers see duplicated images. Nevertheless, if the main displayed image is composed of only very bright grey levels, the effect of viewing angle control is reduced, which is one of demerits with pixel division method.

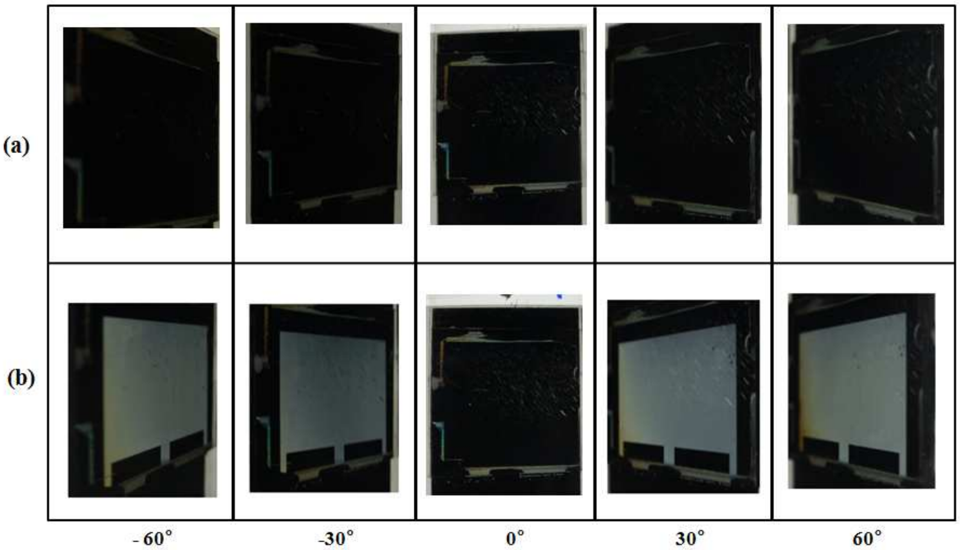

Fig. 4. Photographs of the FFS cells in the dark state at normal direction and at polar angles of 30° and 60° of the (a) WVA and (b) NVA modes.

Figure 5 shows voltage-dependent transmittance (V-T) curves considering whole pixels in WVA and NVA modes. Here, the operating voltage (V_{op}) in both the WVA and NVA modes are the same, being about 4.2V; however, the transmittance in the WVA mode is less than that in the NVA mode at V_{op}. To understand the difference in transmittance, it is necessary to analyze the transmittance along the electrode position.

Figure 6 shows the dependence of the maximal transmittance on the electrode position in the WVA and NVA modes. In the NVA mode, transmittance at positions A and C is slightly lower compared to position B due to vertical electric field by the application of 2.5V on the top common electrode. In the WVA mode, position A does not transmit light due to strong vertical field by the application of 4.2V between pixel electrode on bottom substrate and common electrode on the top substrates of the W pixel. Therefore, the average transmittance in the WVA mode is found to be low because the transmittance difference between position A, and position B, C is very large compared to that in the NVA mode. Nevertheless, the proposed device in the WVA mode has a strong merit that the W pixel also contributes to panel transmittance unlike the conventional devices with pixel division method that shows no transmittance in the viewing angle control sub pixels. In the NVA mode, the transmittance at normal direction can contribute to the total panel transmittance if viewing angle control is performed just using contrast ratio in oblique viewing directions, however, if one wants to control viewing angle by displaying some images or characters using the light leakage, the transmittance cannot be contributed to the total panel transmittance.

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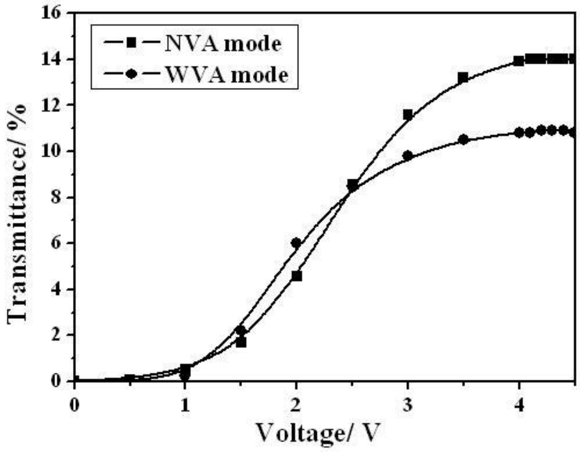

Fig. 5. Voltage-dependent transmittance (V-T) curves in WVA and NVA modes.

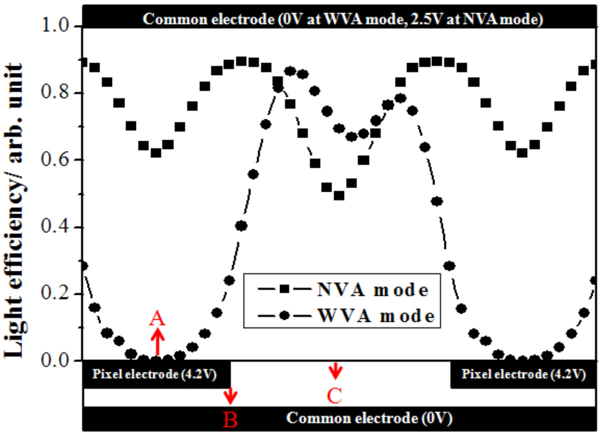

Fig. 6. Comparison of the transmittance distribution of the white state along the electrode in the WVA and NVA modes.

Finally, Fig. 7 shows the calculation of the iso-luminace curves in the white and dark states and the iso-contrast curves at 550nm considering whole pixels in the WVA and NVA modes. The calculated iso-luminace curves considering 70%, 50% and 30% of maximum transmittance of WVA mode in bright and dark states are contoured. In both modes, iso-luminance curves are similar to each other, however, strong leakage of light which exceeds 70% of maximum transmittance is observed over 30° of polar angle at both left and right directions. Consequently, a high contrast ratio larger than 100 is achieved in all horizontal direction in the WVA mode, however, in the NVA mode, the region in which contrast ratio is 5 exists only at a polar angle of 45° in left and right directions. In this way, the viewing angle providing contrast ratio of 5 can be adjusted from an angle of 180° to 90° in the horizontal direction.

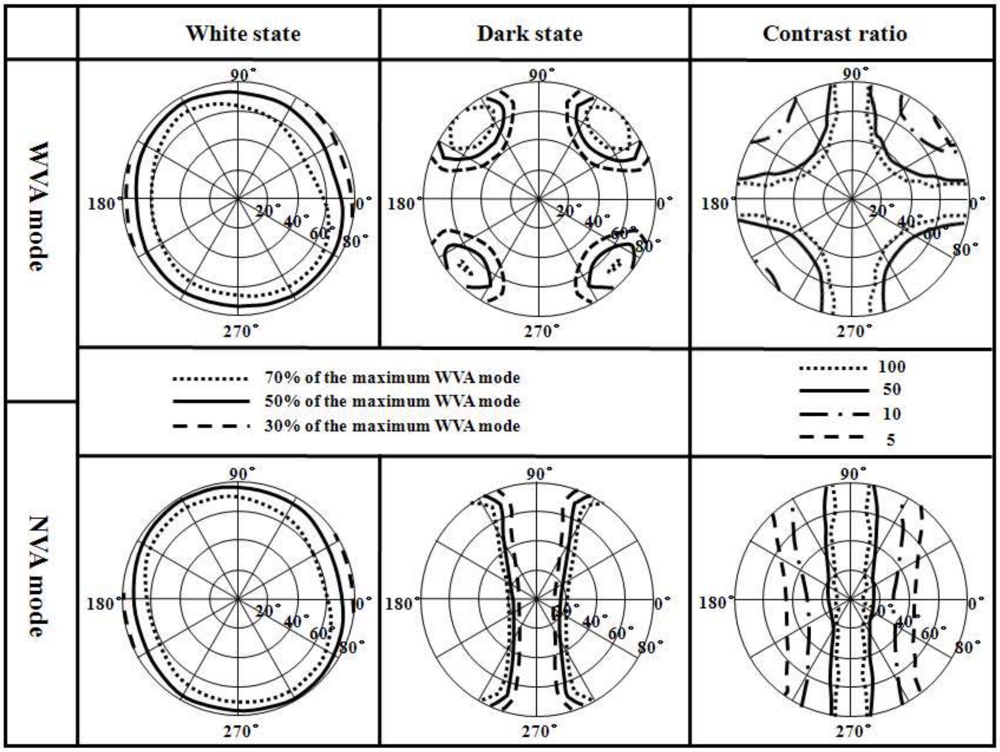

Fig. 7. Iso-luminance curves in the white and dark states and iso-contrast contours of the device in the WVA and NVA modes.

4. Summary

We propose a VAC-LCD driven by FFS mode with high aperture ratio characteristics. This device is composed of R, G, B, and W pixels, in which the R, G, and B pixels display the image and the W pixel is used for both viewing angle control and displaying the image. Unlike conventional VAC-LCDs using the pixel division method, this device can generate transmittance in the whole region, because the LC directors of the VAC region are rotated and tilted up simultaneously by the fringe and complex electric field. Consequently, this device is advantageous in terms of its viewing angle control in the off-normal direction and high transmittance in the normal direction.

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