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Viewing angle switching of patterned vertical alignment liquid crystal display

Young Jin Lim[1], Eun Jeong[1], Mi Hyung Chin[1], Seunghoon Ji[2], Gi-Dong Lee[2] and Seung Hee Lee[1]

[1] Polymer BIN Fusion Research Center, Department of Polymer Nano Science and Technology, Chonbuk National University, Chonju, Chonbuk 561-756, Korea
[2] Department of Electronics Engineering, Dong-A University, Pusan 607-735, Korea

E-mail: gdlee@dau.ac.kr (GDL) and lsh1@chonbuk.ac.kr (SHL)

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Abstract
Viewing angle control of a patterned vertical alignment (PVA) liquid crystal display using only one panel is investigated. In conventional PVA modes, a vertically aligned liquid crystal (LC) director tilts down in four directions making 45° with respect to crossed polarizers to exhibit a wide viewing angle. In the viewing angle control device, one pixel was divided into two sub-pixels such that the LC director in the main pixel is controlled to be tilted down in multiple directions making an angle with the polarizer, playing the role of main display with the wide viewing angle, while the LC director in the sub-pixel is controlled to be tilted down to the polarizer axis, playing the role of sub-pixel to the viewing angle control for the narrow viewing angle. Using sub-pixel control, light leakage or any type of information such as characters and image can be generated in oblique viewing directions without distorting the image quality in the normal direction, which will prevent others from peeping at the displayed image by overlapping the displayed image with the made image.

1. Introduction

Recently, with increasing use of portable displays, display contents are visible to other people around a user. Accordingly, in portable displays such as notebook computers, mobile phones, personal digital assistants and tablet personal computers, privacy protection becomes an important issue. For this purpose, liquid crystal displays (LCDs) with a narrow viewing angle are required. On the other hand, there is a situation where LCDs are viewed by a large number of people. In this case, the LCDs should exhibit a wide viewing angle. Therefore, unlike conventional LCDs exhibiting either only a wide or a narrow viewing angle, a new type of LCD in which viewing angle control is possible is required [1–6]. Among several wide viewing angle liquid crystal (LC) modes, the patterned vertical alignment (PVA) mode has a high contrast ratio (CR) in front [7–9]. However, in order to have a high CR in all directions, optical compensation films with a negative C-plate and a positive A-plate are required [10–12]. Here, the positive A-plate can be replaced by an electrically controllable birefringence cell, and by controlling the birefringence of this cell, the viewing angle can be switched [13, 14]. However, this approach increases the total cell thickness, which is undesirable in slim displays.

In this paper, we propose a new structure of viewing angle control LCD with one panel of the PVA mode, in which one pixel is divided into two sub-pixels and its pixel electrode in each pixel is patterned to generate the electric field in different directions and correspondingly the LC directors tilt down in different directions between sub-pixels. In this way, the device can be switched from a wide viewing to a narrow viewing angle display. The detailed cell structure, switching principle and its electro-optic characteristics are reported herein.

2. Cell structure and switching principle for viewing angle switching

In the PVA device in which a uniaxial LC medium exists under a crossed polarizer, the normalized light transmission is given by

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

$$\delta = 2\pi d\Delta n_{\mathrm{eff}}(\theta, \Phi, \lambda, V)/\lambda, \quad (2)$$

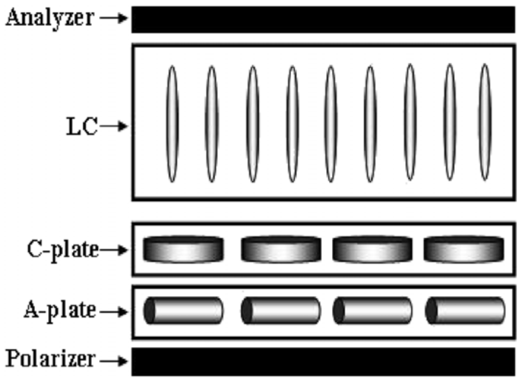

Figure 1. Schematic configuration of the film compensated VA device.

where ψ is the voltage-dependent angle between the transmission axes of the crossed polarizers and the LC director, δ is the phase difference generated by the LC layer defined by equation (2), where d is the cell gap, Δn_{eff} is the effective birefringence of the LC layer dependent on polar (θ) and azimuthal (Φ) angles in spherical coordinates as well as voltage (V) and λ is the wavelength of the incident light. Therefore, a white state in the normal direction can be achieved when $\psi = 45°$ and $\delta = \pi$; however, δ depends largely on a voltage-induced phase retardation of the LC cell and incident angle.

Figure 1 shows the optical configuration of the film compensated PVA device. In the normal direction, the device without compensation films shows a perfect dark state due to $\delta = 0$; however, at off-normal axis δ is not zero any more due to phase retardation of the LC layer so that films such as the A-plate and the C-plate are required to cancel the retardation of the LC layer [11]. As a result, an excellent dark state is achieved in all viewing directions if the following condition is satisfied:

$$(d\Delta n)_{\text{eff-LC}} + (d\Delta n)_{\text{A-plate}} + (d\Delta n)_{\text{C-plate}} = 0. \qquad (3)$$

Figure 2 shows the orientation of the LC director with the applied voltage and the electrode structure of a controllable viewing angle PVA-LCD. The controllable viewing angle LCD is divided into the main pixel for image expression and the extra pixel for viewing angle control. Here, two pixels are controlled by one data line and two gate lines. In the main pixel, the LC director tilts downwards in four directions making an angle of 45^o with respect to the crossed polarizers due to patterned electrodes in diagonal directions, giving rise to transmission. In the extra pixel, the LC director tilts down in vertical directions due to horizontally patterned electrodes such that the angle of Ψ is not generated even at applied voltages. Therefore, in the extra pixel, although the LC director tilts down, the transmittance is not generated; however, the degree of the tilt angle can be controlled by an applied voltage. For the wide viewing angle mode, the extra pixel is unbiased so that the LC layer maintains the vertical state. So the device shows excellent luminance uniformity in all grey levels due to four domain LC layers and an excellent dark state with two compensation films, and as a result, the device shows a wide viewing angle. For the narrow viewing angle mode, we could

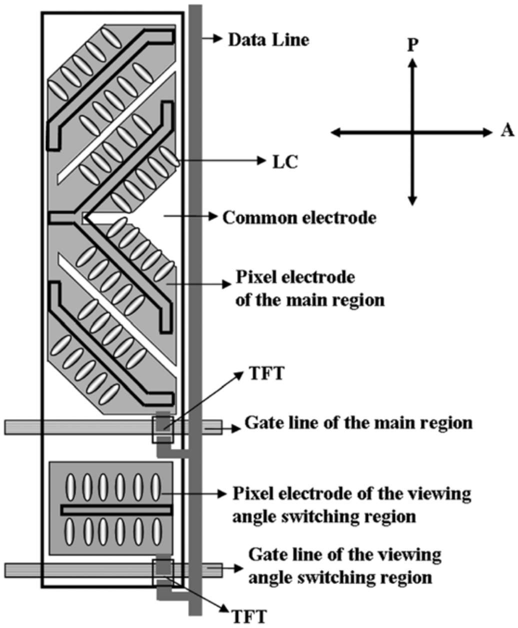

Figure 2. Electrode structure of the controllable viewing angle PVA-LCD with LC director direction in the on state.

change the effective phase retardation of LC cell in equation (3) in oblique viewing directions by applying voltage at the extra pixel, and as a result, total phase retardation is not zero anymore in the oblique direction of the dark as expressed by equation (4):

$$(d\Delta n)_{\text{eff-LC}} + (d\Delta n)_{\text{A-plate}} + (d\Delta n)_{\text{C-plate}} \neq 0. \qquad (4)$$

This condition will cause light leakage in oblique viewing directions due to mismatch of cell retardation between the LC layer and the compensation film, although the dark state is perfectly kept in the normal direction and the degree of light leakage can be controlled by the applied voltage. The light leakage will deteriorate the image quality in oblique viewing directions. In addition, using this light leakage, any type of information such as characters and image in oblique viewing directions can be generated and, as a result, the original image is overlapped with the made image when the voltage is controlled to the extra pixel for viewing angle control. In this way, the main image in the normal direction is not disturbed at all but it is protected from peeping by others in viewing directions.

3. Results and discussion

Figure 3 shows the arrangement of a colour filter for the pixel structure shown in figure 2. The main pixel is composed of red, green and blue colour filter and the extra pixel has only a transparent resin. With this structure, light absorption is minimized in the extra pixel, and the light leakage in the oblique viewing direction can be maximized when a voltage is applied to the extra pixel. In the narrow viewing angle mode, any type of information such as characters and image can be generated in the oblique direction utilizing the generated light leakage. The generated extra image is displayed over the main image in oblique viewing directions, that is, the original

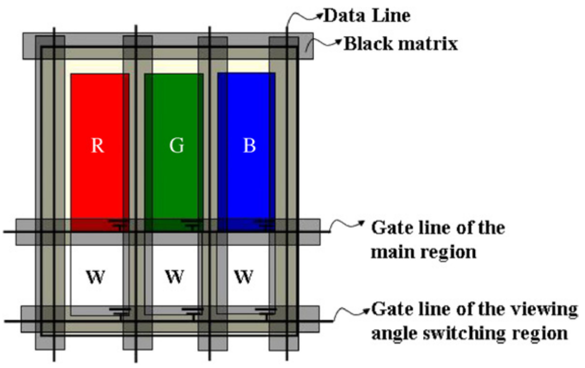

Figure 3. Arrangement of colour filter corresponding to figure 2. (This figure is in colour only in the electronic version)

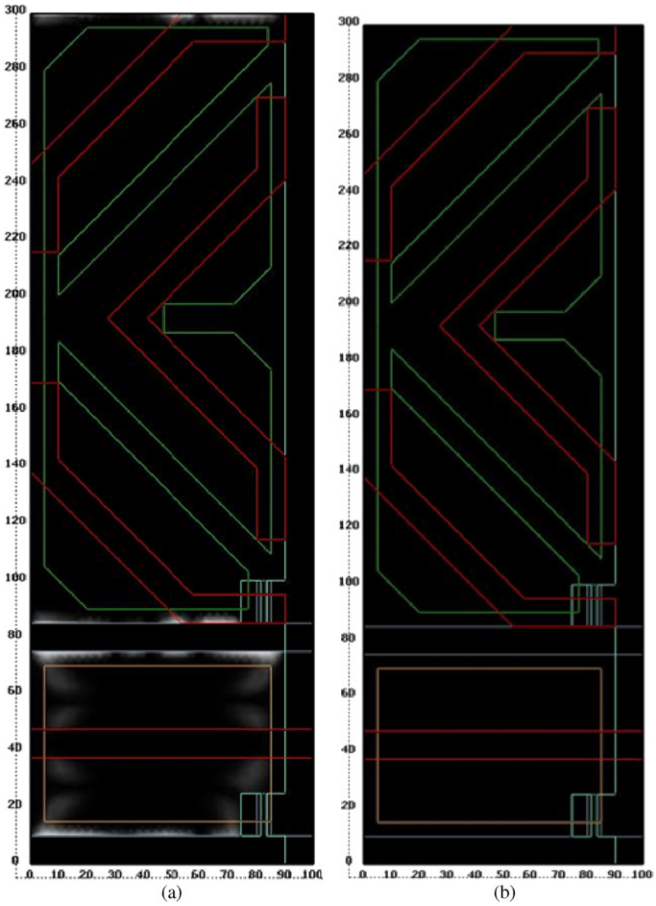

Figure 4. Light leakage of the controllable viewing angle PVA-LCD in the dark state: (*a*) narrow and (*b*) wide viewing angle modes.

image is overlapped with the made image when the voltage is controlled to the extra pixel for the viewing angle control.

To calculate electro-optic characteristics of a switchable viewing angle PVA-LCD a simulation was performed using a simulator based on the three-dimensional finite element method (FEM) module from TechWiz LCD (Sanayi System, Korea). For calculation of optical transmittance, a 2×2 extended Jones matrix [15] was used. In this study, we used a LC with physical properties such as: dielectric constant $\Delta\varepsilon = -4$, three elastic constants $K_1 = 13.5$ pN, $K_2 = 6.0$ pN, $K_3 = 15.1$ pN, birefringence $\Delta n = 0.09$ at 550 nm and the cell gap was 3.8 μm.

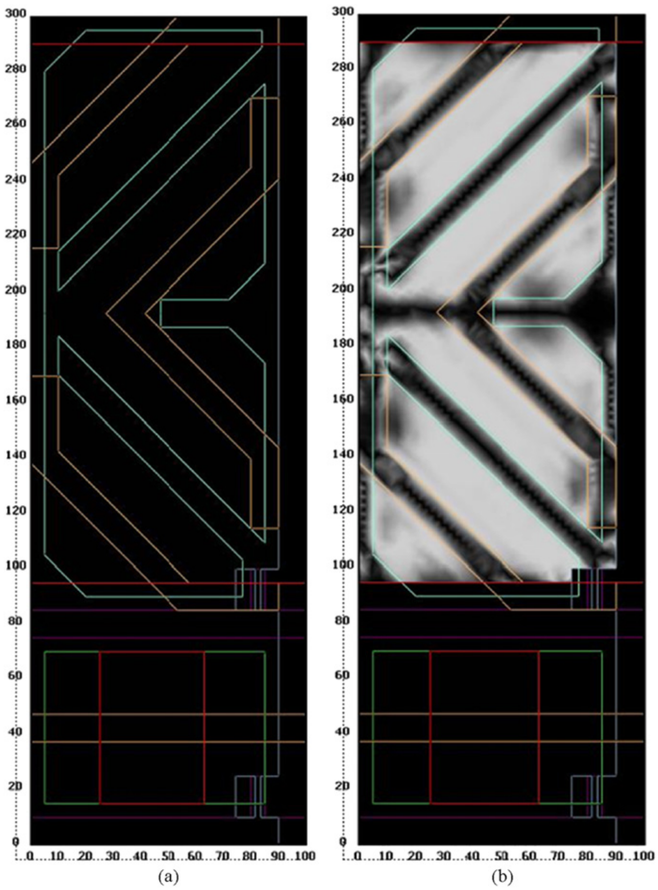

Figure 5. (*a*) Dark and (*b*) white states of the controllable viewing angle PVA-LCD using BM for both narrow and wide viewing angle modes.

Figure 4 shows light leakage of the controllable viewing angle PVA-LCD in the dark state in the narrow viewing angle mode and the wide viewing angle mode. Figure 4(*a*) shows the dark state of the pixel at the applied voltage of 3 V to the sub-pixel for a narrow viewing angle mode. Here, the voltages at the upper gate line and the pixel electrode in the main pixel remain as -10 V and 0 V, respectively. Light leakage is generated in the edge of the viewing angle control pixel and gate lines, as shown in figure 4(*a*). The reason is that the tilting direction of the LC director is mismatched with the axes of the crossed polarizers because the field directions between the common and the pixel electrode of the viewing angle control pixel are not perfectly vertical at the edge of the pixel and besides the field directions are affected by the near gate line. However, light leakage is not generated when the voltage is not applied to the viewing angle control pixel, as shown in figure 4(*b*). In the dark state, when light leakage is generated, the CR of the displayed image in the normal direction decreases considerably. Consequently, an optimal design of the black matrix (BM) to remove light leakage is absolutely required to achieve a high CR in the normal direction.

Figure 5 shows the dark state and the white state of the controllable viewing angle PVA-LCD using the BM in both narrow viewing angle mode and wide viewing angle mode.

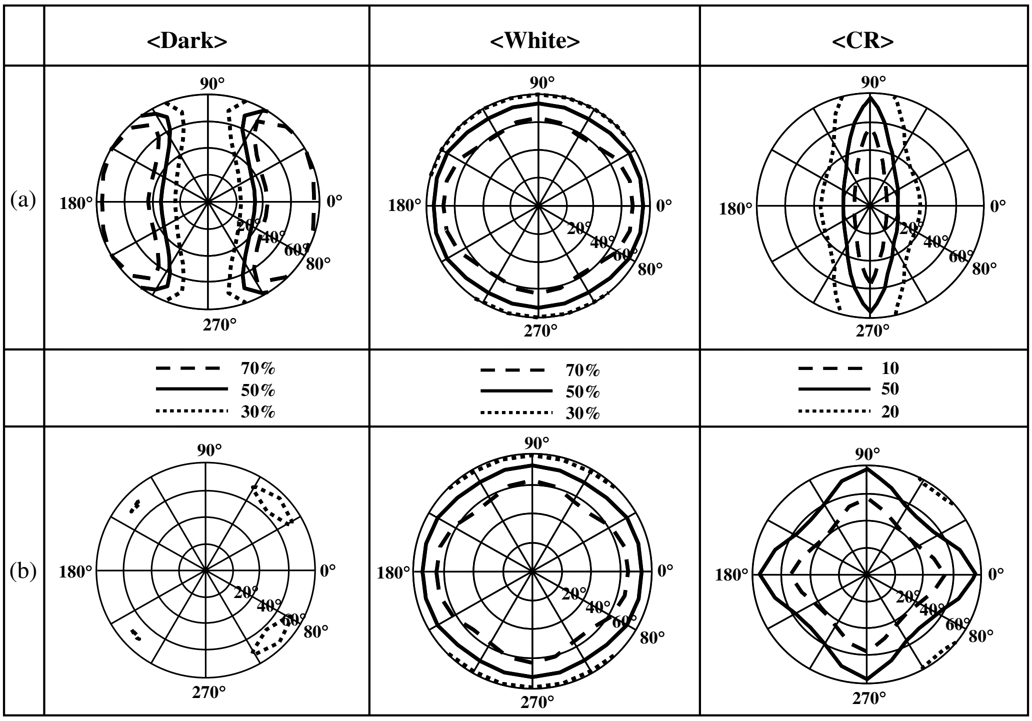

Figure 6. Iso-transmittance curves in the white and dark states and iso-contrast curves: (*a*) narrow viewing angle mode and (*b*) wide viewing angle mode.

Both the narrow viewing angle mode and the wide viewing angle mode show the same transmittance distribution because using the BM covers over the light leakage in figure 4(*a*). Both the narrow viewing angle mode and the wide viewing angle obtain a perfect dark state, as shown in figure 5(*a*). The white state in the main pixel is achieved by applying 6 V to the main-pixel electrode and the transmittance occurs only in the main pixel, as shown in figure 5(*b*). Recall that in the extra pixel, the LC director tilts down in vertical directions due to horizontally patterned electrodes such that there is no angle of Ψ. Therefore, in the extra pixel, although the LC director tilts down, the transmittance is not generated.

Finally, the iso-luminance curves in white and dark states and the iso-CR in wide and narrow viewing angle modes in the cell structure are calculated, as shown in figure 6. The values of the iso-luminance curves in figure 6(*b*) correspond to the standard iso-luminance of figure 6(*a*). In the white state, the region at which the transmittance exceeds over 30% with respect to the transmittance in the normal direction exists over about 80° of the polar angle in all azimuthal directions and has a symmetric shape for both wide and narrow viewing angle modes, that is, the white state is not affected by the extra pixel. However, considering a dark state, light leakage is well controlled in a wide viewing angle mode, but light leakage occurs strongly except in normal and vertical directions in a narrow viewing angle mode, which comes from mismatch of phase retardation between the LC layer and compensation films in the extra pixel as described in equation (4). Consequently, a high CR is achieved in all viewing directions in the wide viewing angle mode such that a CR of over 20 exists up to about 80° of the polar angle in all azimuthal directions, whereas the region in which the CR is only 20 exists at 40° of the polar angle in left and right directions in the narrow viewing angle mode. However, the CR in the narrow viewing angle mode is still high in the vertical direction. Accordingly, we need to control the viewing angle with made letters or images when the voltage is controlled to the extra pixel for the narrow viewing angle mode, in order to protect the main image in the normal direction. The narrow CR even in the vertical direction could also be achieved if the extra pixel has a four domain structure such that the LC director tilts down in both horizontal and vertical directions. However, the issue is that Ψ should be zero in any structure, in order not to deteriorate a displayed image in the normal direction.

4. Summary

We propose a new structure of the viewing angle control PVA-LCD with one panel. The device has an extra pixel to the main pixel in which the LC director tilts downwards to the polarizer axis. In this way, the image quality in the normal direction is not distorted at all but it is blocked in oblique viewing directions by either strong light leakage or characters and images made utilizing light leakage. The device has two advantages for the function of viewing angle control and a simple structure in comparison with another viewing switching LCD. Consequently, this device has the advantage of selecting either the wide viewing angle mode or the narrow viewing angle mode according to the person's environment of private business and purpose. So this device will be an influential LC mode for privacy protective LCD in the competitive personal display market.

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