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A device for operating viewing angle-switchable liquid crystal displays has been developed based on an optically isotropic liquid crystal (OILC). The device comprises two panels, main and switching. Depending upon the voltage applied, the optical state of the OILC layer in the switching panel can be changed to the anisotropic uniaxial state, taking on the role of a positive C film. In this manner luminance at oblique polar angles can be suppressed, resulting in a dark image at an off-normal axis, at the same time retaining good image quality in the normal direction. Depending on the switching of the OILC layer, wide or narrow angles of viewing can be obtained.

Keywords: viewing angle-switching; liquid crystal display; optically isotropic liquid crystal; wide viewing angle; narrow viewing angle

1. Introduction

Liquid crystal displays (LCDs) have been widely adopted as a means of displaying information. As their size has increased, wide-viewing LCDs offering high image quality at all viewing directions have been developed, using a variety of driven modes including fringe-field switching (FFS) [1–4], in-plane switching (IPS) [5], patterned vertical alignment (PVA) [6, 7] and multi-domain vertical alignment (MVA) [8, 9]. However, there remains a demand from the public for protection of the privacy of the information displayed. In order to meet this demand, functional LCDs are required that are able to switch between wide and narrow angles of viewing. A broad range of concepts have previously been suggested [10–16].

LCDs using optically isotropic liquid crystals (OILCs), such as polymer-stabilised blue phase [17] or polymer-stabilised nanostructured LCs [18], have been extensively studied. These are simple to produce and offer sub-millisecond response times. The challenge to replace conventional LCDs with optically anisotropic nematic LCs is being addressed, but high operating voltages and low light efficiency are still issues that have to be overcome [19–22].

A number of switching techniques are available which block the displayed information at oblique viewing angles, such as displacing images with patterns utilising light leakage [10–14], or darkening the images by the use of a dual light source system or an additional nematic LC panel [15, 16]. The most effective way of controlling viewing angle is luminance control at off-normal angles, in which the displayed image in the normal direction becomes darkened when viewed obliquely. Image darkening can be achieved by adding an extra LC panel to the main LCD panel incorporating three polarisers. All conventional approaches employ a nematic LC in the extra panel, which tends to affect image quality at wide viewing angles due to optical birefringence. This allows control of viewing direction, but only in the horizontal direction. In the present paper we describe a viewing angle-switchable device with luminance control, effective not only in the horizontal but also in the vertical direction, by producing a change in the optical condition of the OILC layer from isotropic to anisotropic in the presence of an electric field. In this paper the OILC has been assumed to be in the polymer-stabilised blue phase.

2. Cell structure and the switching principle

The device comprises two panels, containing nematic and OILC layers and incorporating three polarisers. Figure 1(a) shows a conceptual diagram of the device. The nematic LC panel is sandwiched between crossed polarisers, and the inserted OILC panel has an additional polariser with transmission axis parallel to that enclosing the nematic LC panel. In the extra panel, transparent electrodes are provided

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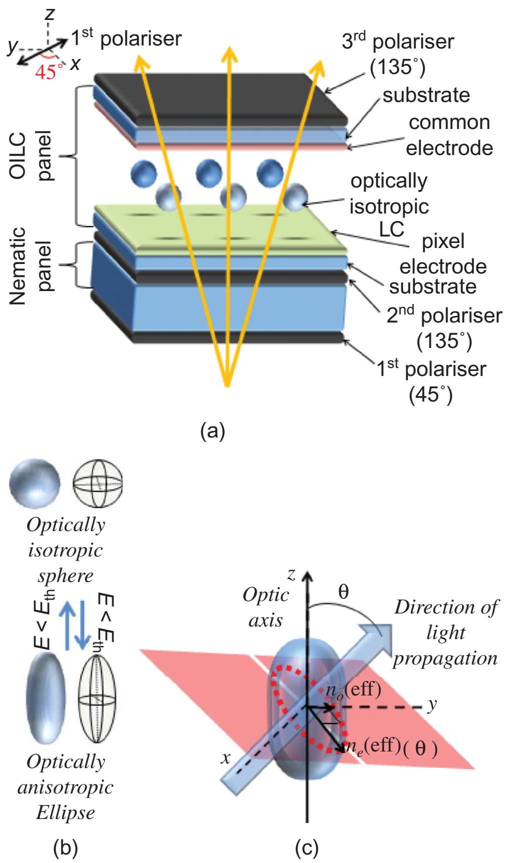

Figure 1. (a) Cell structure of viewing angle-switching LCD using OILC panel when an operating voltage is not applied in the OILC panel, (b) optical illustration of OILC depending on an electrical field (E_{th} is the threshold field), and (c) direction of light propagation passing through the optical indicatrix in the off-normal direction ($n_{e(\mathrm{eff})}$ (θ) is the extraordinary refractive index induced by the applied electrical field in the off-normal direction) (colour version online).

on the upper and lower substrates, so that when a voltage is applied a vertical electric field results.

With regard to the principle of switching the viewing angle, the normalised luminance of an OILC panel between two parallel polarisers can be simply described by

$$T/T_0 = \cos^2(\delta(V,\theta,\phi,\lambda)/2), \tag{1}$$

where δ is the viewing angle-dependent phase difference between ordinary and extraordinary rays passing through the LC medium, V is voltage, θ is polar angle, Φ is the azimuthal angle and λ is the wavelength of the incidence light. Without a bias voltage, δ for the OILC layer is zero, and it therefore does not affect the electro-optical performance of the wide-view nematic LC panel for all viewing directions, and gives a wide viewing angle. When a bias voltage is applied birefringence is induced, with extraordinary optical axis perpendicular to the nematic LC panel, and the quality of the display is not affected. However, if δ matches π at a certain viewing direction the luminance becomes close to zero, and the image cannot then be observed from that direction.

At wide angles of view, the OILC panel remains unbiased and only the nematic LC panel is affected by the electrical field. Any type of nematic LC panel, such as FFS, IPS, PVA or MVA, which provides a wide viewing mode can be used in the device. In the present paper, the FFS mode has been applied to the nematic LC panel to display the main images. In this case, a wide viewing angle exactly similar to that of the pure FFS mode is possible, since the optical state of the OILC panel is isotropic, as represented in Figure 1(b) by spheres. To achieve a narrow viewing angle a vertical electric field is applied to the OILC layer. In the presence of the electrical field, birefringence results due to the Kerr effect, indicated in Figure 1(b) by ellipses. The induced optical axis is uniaxial and is aligned normal to the substrates; consequently the layer plays the role of a *positive C film* ($n_x = n_y < n_z$). The induced birefringence (Δn_i) in the OILC depends on the strength of the applied electrical field and can be calculated using the Equation [23]:

$$\Delta n_i = \lambda K E^2, \tag{2}$$

where K and E are the Kerr constants of the OILC and electric field intensity, respectively. In the device, as seen in Figure 1(b), there is no phase retardation in the normal direction, whereas in an off-normal direction the retardation varies with the incident angle. In this case δ may be determined by the following Equation [24]:

$$\delta(V,\theta,\phi,\lambda) = \frac{2\pi}{\lambda}(n_{e(\mathrm{eff})}(V,\theta,\phi) - n_{o(\mathrm{eff})}(V,\theta,\phi)) \cdot d_{\mathrm{eff}}(\theta,\phi), \tag{3}$$

where $n_{o(\mathrm{eff})}$ and $n_{e(\mathrm{eff})}$ are the ordinary and extraordinary refractive indexes induced by applied electric field, respectively, so that $n_{e(\mathrm{eff})} - n_{o(\mathrm{eff})}$ is Δn_{eff}, which can be extended for oblique viewing angle using a trigonometric function for all viewing directions from Δn_i. In addition, the optical axis of the OILC layer parallel to the z-axis is constant, regardless of Φ, in the off-normal direction. Equation (3) may then be modified as follows:

$$\delta(V,\theta,\phi,\lambda) = \frac{2\pi}{\lambda}(n_{e(\text{eff})}(V,\theta) - n_{o(\text{eff})}(V,\theta)) \cdot d_{(\text{eff})}(\theta), \quad (4)$$

where $n_{o(\text{eff})}(V, \theta)$ and $n_{e(\text{eff})}(V, \theta)$ in Equation (4) are defined as follows [25]:

$$n_{o(\text{eff})}(V,\theta) = n_{o(\text{eff})}(V), \quad (5)$$

$$n_{e(\text{eff})}(V,\theta) = \left[\frac{\cos^2\theta}{n_{o(\text{eff})}{}^2(V)} + \frac{\sin^2\theta}{n_{e(\text{eff})}{}^2(V)}\right]^{-1/2}. \quad (6)$$

Equation (4) can then be modified using Equations (5) and (6) as follows:

$$\delta(V,\theta,\phi,\lambda) = \frac{2\pi}{\lambda}\left(\frac{n_{e(\text{eff})}(V)n_{o(\text{eff})}(V)}{\sqrt{n_{e(\text{eff})}{}^2(V)\cos^2\theta + n_{o(\text{eff})}{}^2(V)\sin^2\theta}} - n_{o(\text{eff})}(V)\right) d_{(\text{eff})}(\theta). \quad (7)$$

In addition, $d_{(\text{eff})}(\theta)$ for the OILC layer in the off-normal direction in Equation (7) may be expressed as:

$$d_{(\text{eff})}(\theta) = \frac{d}{\cos\theta}. \quad (8)$$

Finally, $n_{o(\text{eff})}(V)$ and $n_{e(\text{eff})}(V)$ can be calculated as follows. Firstly, $\Delta n_i(V)$ depends on the applied electric field as follows:

$$\Delta n_i(V) = n_{e(\text{eff})}(V) - n_{o(\text{eff})}(V). \quad (9)$$

Moreover, we may assume that there is no change in the refractive index of the host LC due to the applied voltage, and the average refractive index of the OILC layer as a function of applied voltage $n_{\text{avg}}(V)$ should be the same as n_{iso}, and is given by

$$n_{\text{avg}}(V) = \frac{1}{3}(n_{e(\text{eff})}(V) + 2 \cdot n_{o(\text{eff})}(V)) = n_{iso} \quad (10)$$

From Equations (9) and (10), $n_{o(\text{eff})}(V)$ and $n_{e(\text{eff})}(V)$ are given as follows:

$$n_{o(\text{eff})}(V) = n_{iso} - \frac{1}{3}\Delta n_i(V), \quad (11)$$

$$n_{e(\text{eff})}(V) = n_{iso} + \frac{2}{3}\Delta n_i(V). \quad (12)$$

In Figure 1(c), θ is the angle between the optical axis and the direction of light propagation, and the optical indicatrix is cut in the plane perpendicular to the direction of polarised light propagated at the centre of the index ellipsoid. From Equations (7) and (8), Δn_{eff} is therefore the practical value of the birefringence in the off-normal direction of the OILC medium. As a result, the refractive index difference (Δn_{eff} (V,θ)) according to the direction of light propagation is $n_{e(\text{eff})}(V,\theta) - n_{o(\text{eff})}(V,\theta)$. In this case, the suppression of luminance can be achieved at an oblique viewing angle with an effective phase retardation value of $\lambda/2$.

Figure 2 shows the Poincaré sphere representation, which is an ideal geometrical method for analysing the propagation of polarised light through birefringent and optically active media [26]. The incident light, **O** (0, 0, 0), from a back light unit becomes polarised on penetrating the first polariser on ***p*** (0, –1, 0), and the point, ***a*** (0, 1, 0), indicates the second and third polarisers in the normal direction. At oblique viewing, the transmissive axes of the first, second and third polarisers are not on the axis of **S2**; the points **P1**, **P2** and **P3,** which deviate from ***p*** and ***a***, respectively refer to these axes of the polarisers. When the incident light encounters the device at an oblique angle, linearly polarised light on **P1** moves to **B** through the nematic LC layer and penetrates the second polariser, **P2**. Next, it moves from **P2** to **A** again when it encounters the OILC layer. A dark state is then achieved, since point **A** deviates from **P3** by phase retardation ($\lambda/2$), in which the third polariser (**P3**) lies parallel to the second.

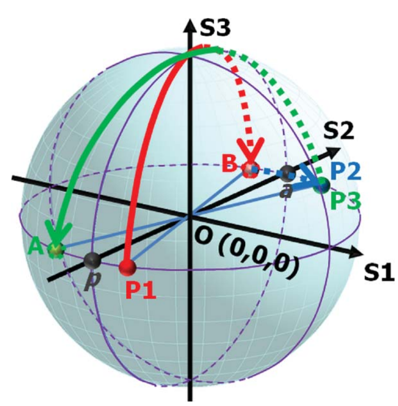

Figure 2. Poincaré sphere representation of the polarisation path of the proposed viewing angle-switching LCD, using an OILC panel for an oblique viewing direction in white state of the narrow viewing angle mode (colour version online).

In the OILC layer, optical anisotropy of the host LC ($\Delta n_h = 0.26$), the cell gap of OILC layer ($d_p = 5$ µm), and the Kerr constant ($K = 44.8$ nm V^{-2}) were determined. At lower operating voltages, higher K and a thinner OILC layer are the key factors. At higher values of K, a more advanced OILC design needs to be developed to realise the full potential of the device. In effect, the simulation model is based on the induced birefringence arising from the Kerr effect on an OILC.

Numerical calculation of the electro-optical characteristics of the device was carried out in steps. Firstly, we calculated the electrical field distribution in the OILC medium of the device using the Laplace equation, and from the electric field we were then able to calculate the induced birefringence. Finally, the transmittance of the device was calculated by means of a 2 × 2 extended Jones matrix [27], embedded in a three-dimensional simulation tool, Techwiz (Sanayi, Korea). In the study, the transmittance of the three parallel polarisers was calculated as 32.42%, which is the maximum transmittance that the device can cater for.

3. Results and discussion

With regard to switching performance, the iso-luminance and contrast ratio (CR) contours in wide and narrow viewing angle modes were calculated, as shown in Figure 3. In the bright condition of the wide

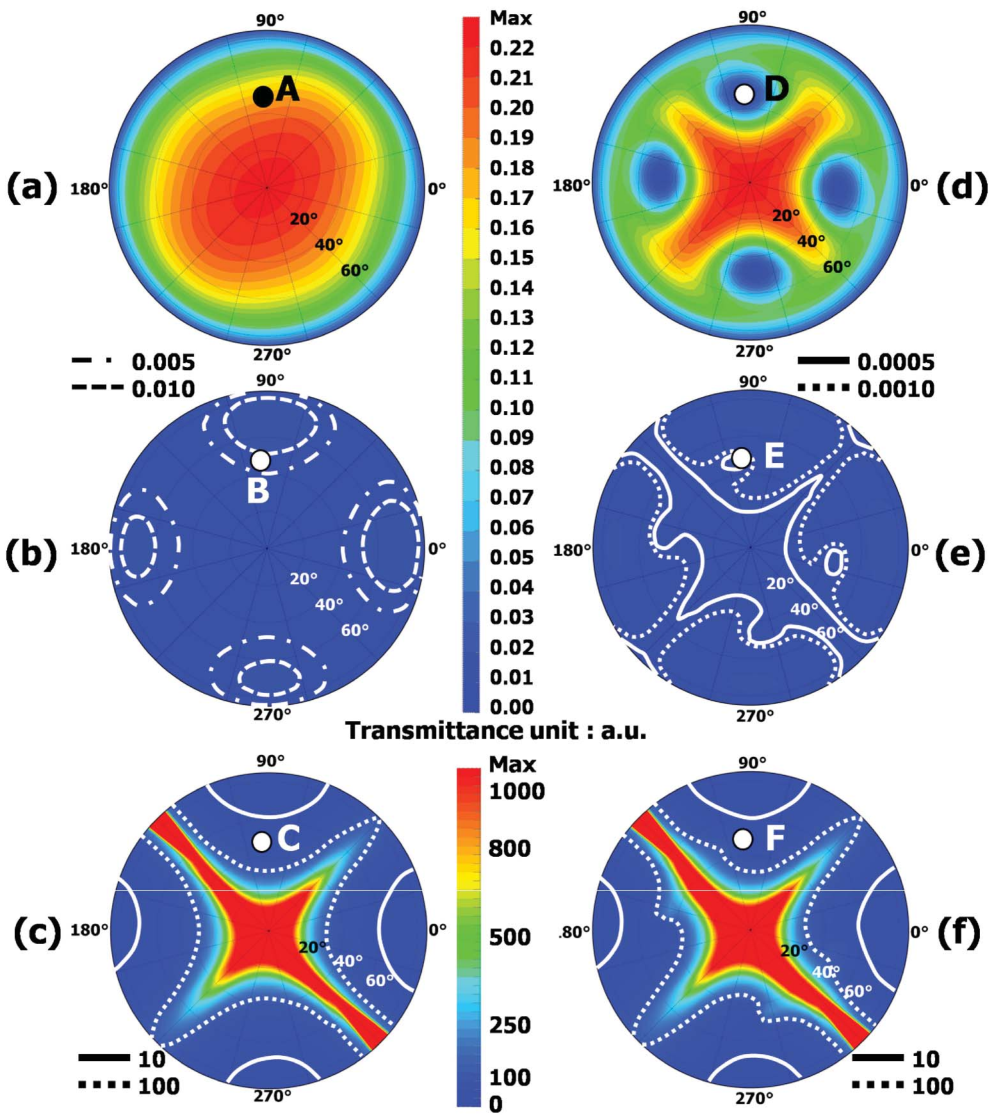

Figure 3. The viewing angle characteristics of the device: iso-luminance contours of (a) white, and (b) dark states of the wide viewing angle mode, (c) white, and (d) dark states of the narrow viewing angle mode and iso-contrast contours of the (e) wide, and (f) narrow viewing angle modes.

view in Figure 3(a), 22.35% of light efficiency was achieved in the normal direction and more than 17% was achieved over a 120° polar angle range, including the normal axis. On the other hand, in the bright state of the narrow viewing angle mode with 20 V_{rms} (4 V μm^{-1}) of voltage applied to the OILC panel in Figure 3(d), the viewing angle was restricted to a polar range of 35° in both horizontal and vertical directions, with less than 3% of light efficiency, and below 0.7% in the darkest region, specifically at point **D**. In the dark state of the narrow viewing angle mode in Figure 3(e), the luminance was similar to that of the wide viewing angle mode of the dark state in the normal direction, at 0.013%, but in oblique viewing the dark state was slightly better than in the wide view of the dark state, since the OILC layer played the role of a *positive C film* under the applied voltage. Iso–CR contours in both cases were not very different, as shown in Figures 3(c) and 3(f).

At first sight these results seem somewhat unexpected. However, if we recall the definition of CR – the ratio of the luminance in the bright state to that in the dark state – they become reasonable. In the narrow viewing angle mode, the luminance of the bright state at an oblique viewing direction (point **D** in Figure 3(d)) is much smaller than that in the wide view (point **A** in Figure 3(a)); on the other hand, the luminance of the dark state in an oblique viewing direction in the wide view (point **B** in Figure 3(b)) is much larger than in the narrow view (point **E** in Figure 3(e)). This means that a similar CR in oblique viewing directions is achieved in both the narrow and the wide view. To be more specific, the CR for a wide view is 0.1834 (point **A**) / 0.0063 (point **B**) = 29.1 (point **C**), whereas in the narrow view it is 0.0041 (point **D**) / 0.0002 (point **E**) = 20.5 (point **F**). Evidently, for viewing angle switching, controlling luminance is the key factor and the CR is less important.

For reassurance as to the performance of the proposed device, the quality of the displayed images as a function of polar angle was calculated and is demonstrated in Figure 4. The images were calculated based on gamma, 2.2, and grey level, 256. In the wide viewing angle mode, the original image of the FFS mode was perceived in all viewing angle directions, as shown in Figure 4(a). On the other hand, in the narrow viewing angle mode the original images began to darken rapidly in both horizontal and vertical directions at a polar angle of 40° and were almost perfectly black at 50°. At the same time an excellent quality image was seen in the normal direction, as is seen in Figure 4(b).

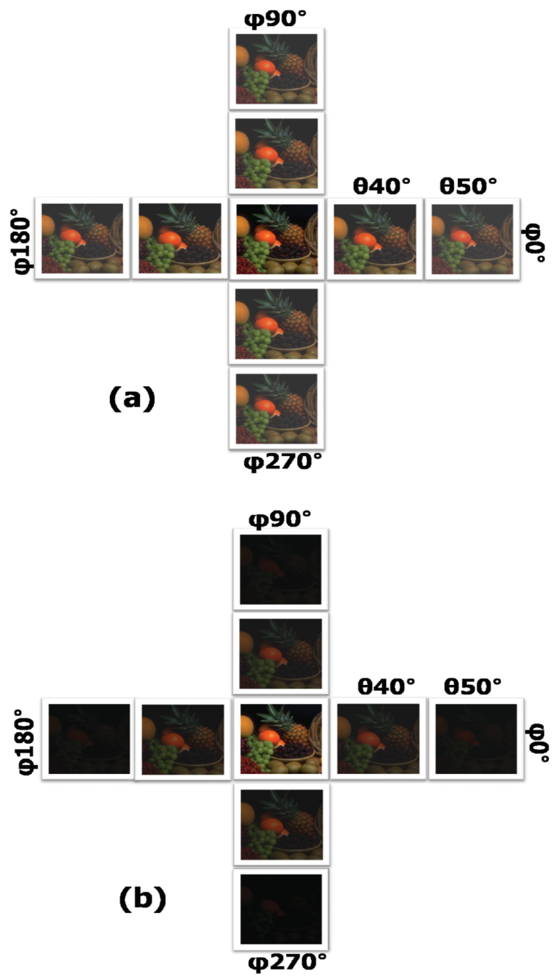

Figure 4. Calculated image of the proposed device in the normal direction and polar angles of 40° and 50°: (a) wide, and (b) narrow viewing angle mode (colour version online).

4. Summary

We have developed a novel viewing angle-switchable device containing an optically isotropic LC layer with three polarisers, utilising phase transition of the optical state from isotropy to anisotropy, based on the Kerr effect. The device is able to control the viewing angle by the decreasing luminance, not only in the horizontal but also in the vertical polar viewing direction. This allows the protection of information regarded as private, and overcomes the disadvantage of conventional devices that control only one direction.

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