High performance transflective liquid crystal display associated with fringe-field switching device

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Abstract: The outdoor readability of the most popular portable liquid crystal display (LCDs) viz. fringe field switching has been addressed both in single and dual cell gap transflective devices. The devices use dual orientation, such as, homogeneous alignment in transmissive (*T*) part and 64° twisted alignment in reflective (*R*) part. The dark states of the proposed devices are achieved by controlling phase retardation in *T* part and polarization rotation in *R* part and the white state is realized by rotating optic axis of liquid crystal and removing phase retardation in *T* and *R* parts, respectively. The devices show high light efficiency without requiring any optical compensation films, exhibiting strong potential for portable display applications.

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

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1. Introduction

Portable electronic devices such as mobile phones and tablet personal computers are widely used [1] in recent times. Liquid crystal displays (LCDs) play the major role for manufacturing displays of such devices as they exhibit very wide viewing angle and low power consumption with high resolution by utilizing in-plane switching (IPS) [2, 3] and fringe-field switching (FFS) [4, 5] driving schemes. Nevertheless, sunlight readability of conventional LCDs is still not satisfactorily and it needs to be improved to realize ubiquitous concepts of display. Various transflective LC driving schemes are proposed earlier for improving the readability in any natural light conditions, such as twisted nematic (TN) [6, 7], electrically controlled birefringence (ECB) [8, 9], vertical alignment (VA) [10, 11] etc. Interestingly, most of the earlier commercialized devices are driven by applying electric field perpendicular to the substrate. However, these devices required dual cell gap and several compensation films to match the optical path of the reflective (*R*) and transmissive (*T*) parts. Additionally, the devices do not exhibit wide-viewing-angle and are also not suitable for high resolution display. In order to solve these problems, single cell gap transflective LCDs adopting IPS [12–14] and FFS [15–17] modes have been proposed. These devices show very wide-viewing-angle owing to in-plane rotation of the LC directors. Between the couple of proposed wide viewing LC driving schemes, FFS mode possesses higher light efficiency and lower driving voltage in comparison with IPS mode. Hence, several transflective FFS-LCDs have been proposed. However, most of the proposed devices still require optical compensation films or in-cell retarders. Recently, we proposed transflective FFS-LCD devoid of any retarder [18]. However, it requires additional processing steps in device manufacturing and also require UV exposure process to polymerize reactive mesogen (RM) doped in LC.

In this paper, we have proposed single and dual cell gap transflective FFS-LCDs using low twisted nematic configuration in the *R* part instead of using any compensation film, in-cell retarder, or RM monomer. The optimal dark state is achieved by phase retardation in *T* part and polarization rotation in *R* part. High reflectance is also easily achieved by minimizing LC's retardation in *R* part. The proposed transflective LCDs exhibit strong merits such as very high light efficiency, single gamma curve, and simple optical configuration and hence best suitable for portable display applications.

2. Cell structure and switching principle of transflective LCD

Figure 1 schematically shows the cross-sectional and top view of the proposed dual and single cell gap transflective LCD using low twisted nematic LC in the *R* part. The *T* part is driven by fringe field and *R* part is driven by vertical field. In the dual cell gap device (Fig. 1 (a)), both pixel and common electrodes exists on the bottom substrate separated by passivation layer, and pixel electrodes are patterned in slit form maintaining fixed electrode width (w) and inter electrode distance (l) in the *T* part. In the *R* part, the pixel electrode exists on the bottom and the common electrode exists on the top substrate. Dual cell gap device can be realized using thick insulator layer coating only in the *R* part with two different optimized cell gaps, such as 4 µm and 1.9 µm in the *T* and *R* parts, respectively. Figure 1(b) shows cell structure of the single cell gap transflective LCD. Here, the electrode structure in the *T* and *R* parts is similar to that of dual cell gap device. The cell gap of T and R parts is same as 4 um because effective retardation λ/4 of LC layer in *R* part can be achieved with high pretilt angle. Here, the pretilt angle can be controlled by ion-beam exposure [19, 20] and nano-structured surfaces [21, 22]. Ideally, embossing reflector is embedded over plane shape pixel electrode in *R* parts. Figure 1(c) shows top view of electrode structure in both devices. The alignment direction of LC on top substrate is coincident with transmission axis of top polarizer in *T* part but is 64° twisted in *R* part. These devices require multi-alignment of LC on bottom substrate in order to construct different twist angle in *T* and *R* parts at initial state, which can be achieved using photo-alignment method [23, 24] or ion-beam irradiation on inorganic film [25]. Here, the pixel electrode direction with respect to vertical direction is defined as α as indicated in Fig. 1(c).

The LC medium appears to be uniaxial under crossed polarizer in *T* part of the device, whereas for *R* part, polarization rotating LC medium exists above reflector under parallel polarizer. The normalized transmittance (T / T_0) can be expressed by Eq. (1). The T / T_0 of proposed both structures in *T* part [17] is given by

$$T / T_o = \sin^2 2\theta(V) \sin^2 (\frac{\pi d \Delta n_{eff}}{\lambda}) \tag{1}$$

where θ represents an relative angle between axis of polarizer and LC director, d is cell thickness, Δn_{eff} is voltage-dependent effective birefringence of LC layer and λ is the wavelength of an incident light. In field off condition, the light wave after passing through the bottom polarizer and subsequent LC layers retaining same polarization state. As the relative angle between axis of polarizer and LC director remains 0°, the transmitted light is blocked by the analyzer, resulting in a dark state. With increasing field the cell starts transmitting as LC director starts to rotate. Finally, the transmission of the device reaches maximum as the effective retardation goes up to a value approximately equal to half of average wavelength of incident light and average rotating angle ~45°. On the other hand, the normalized reflectance (R/R_0) of both the proposed structures which has a twisted LC and a reflector under a polarizer can be calculated using Eq. (2). In normally white reflective cell which has a quarter wave film and twisted LC layer with a reflector under a polarizer, the normalized reflectance [26] is given by:

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$$R / R_o = \left[\frac{2\varphi(\Gamma / 2)}{\varphi^2 + (\Gamma / 2)^2} \right]^2 \sin^4 X \quad (2)$$

where ϕ is the twist angle, $\Gamma = 2\pi d\Delta n_{eff} / \lambda$, and $X = [\phi^2 + (\Gamma/2)^2]^{1/2}$. In order to have a maximum reflectance, $\phi = \Gamma / 2$ and sinX = 1. For the case that X = π/2, we get $\phi = \sqrt{2}\pi / 4$ (≒ 64°) and $d\Delta n_{eff} / \lambda = \sqrt{2} / 4$ (∴ $d\Delta n_{eff}$ ≒190 nm at 550 nm). Since the proposed device is normally dark without using quarter wave film, the obtained twist angle and retardation value of LC layer would result in a good dark state before applying voltages. In presence of an optimum vertical field, LC director tilts perpendicular to the substrate, resulting in $d\Delta n_{eff}$ ≒ 0. Hence, relative phase retardation vanishes and the polarization state of the electromagnetic wave propagating through the LC medium remains unchanged, resulting in a white state in both structures.

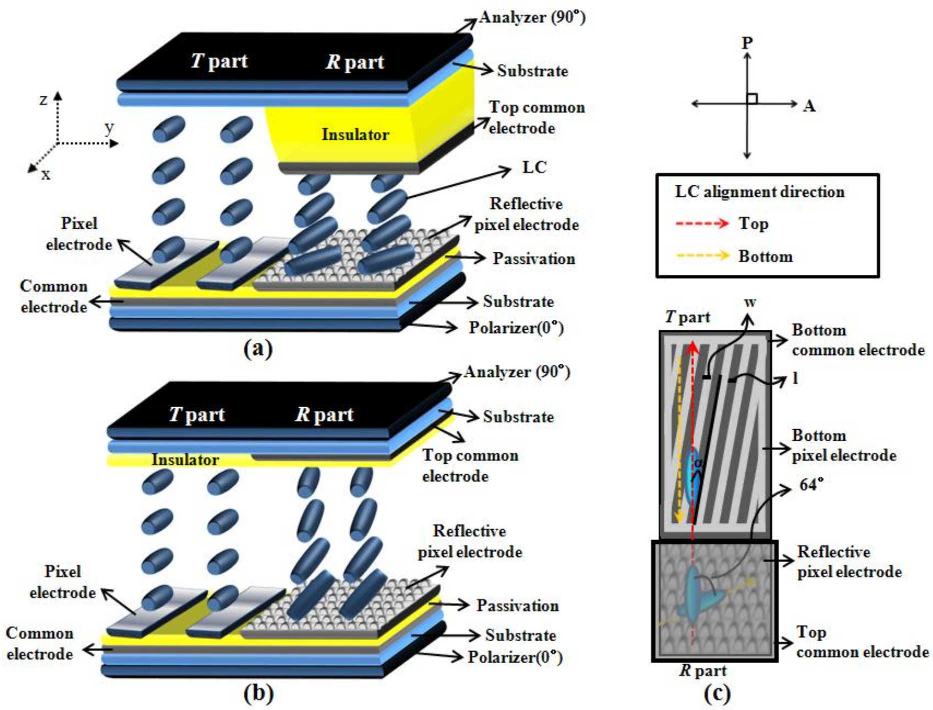

Fig. 1. Cell structure of the proposed dual (a) and single (b) cell gap transflective LCDs using the low twisted nematic liquid crystal only in *R* part and (c) top view of electrode structure in both Fig. 1(a) and Fig. 1(b).

3. Results and discussion

The simulations to obtain electro-optic characteristics of the proposed devices have been performed using "LCD master" (Shintech, Japan) software. For simulations, the pixel electrodes are assumed to be 3 µm wide maintaining periodic inter-didgitated electrode distance of 4.5 µm, in the T part. The LC with positive dielectric anisotropy (Δε = 7.4), and birefringence (Δn = 0.1) having elastic constants k_{11} = 11.7, k_{22} = 5.1, k_{33} = 16.1 (pN) has been used. The reflectance and transmittance of the device have been calculated using 2 x 2 extended Jones matrix method [27]. The transmittances for the single and parallel polarizers have been assumed to be 41%, and 35%, respectively. The dark state characteristics of the device has been analyzed by calculating light leakage curves according to twist angle and pretilt angle, respectively, as shown in Fig. 2. The minimum light leakage in the *R* part is found to be 0.05% for 64° twist angle with cell gap of 1.9 µm, whereas it reduces to 0.03%

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for 44° pretilt angle on both top and bottom substrates and 64° twist angle with cell gap of 4 μm.

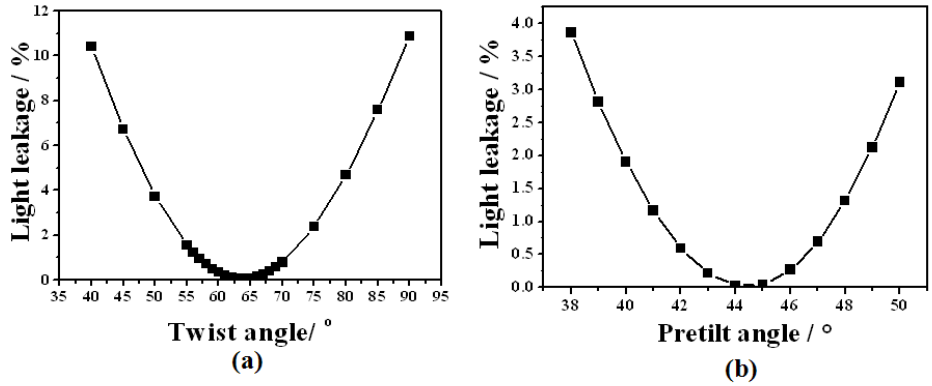

Fig. 2. The calculated light leakage: (a) dual cell gap structure and (b) single cell gap structure with a high pretilt angle.

Figure 3 shows calculated voltage-dependent reflectance (*V-R*) and transmittance (*V-T*) curves as a function of several important electro optic parameters [18, 28] in order to match gamma curves of the *R* and *T* parts in proposed pair of transflective devices.

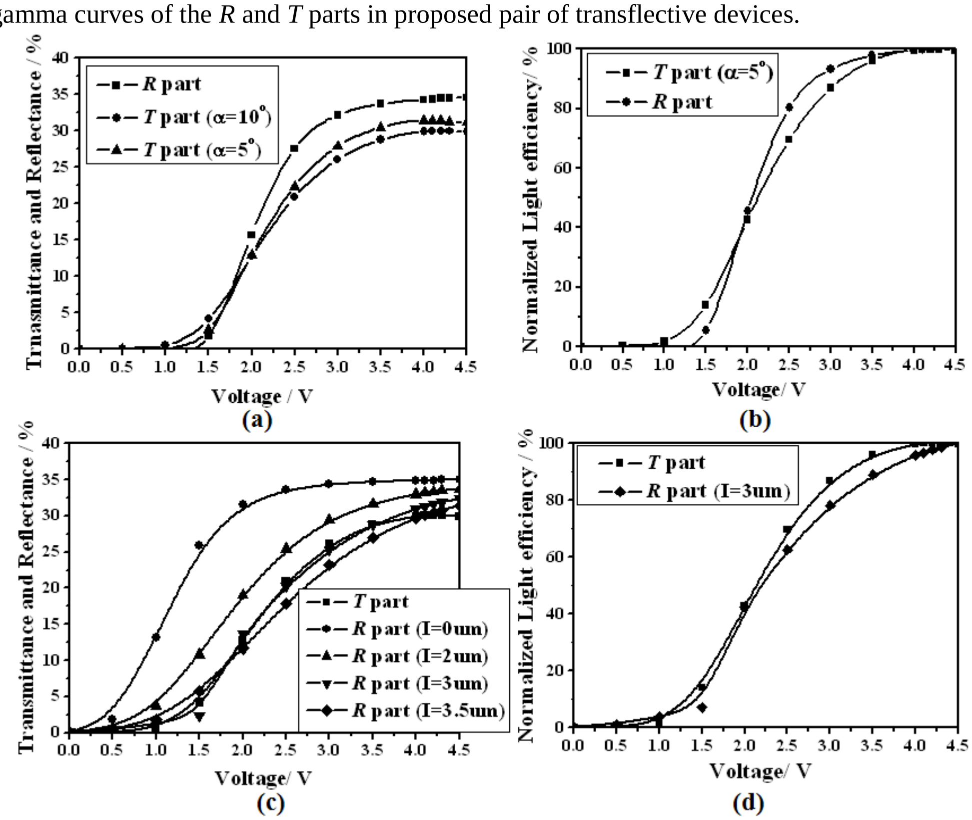

Fig. 3. (a) Calculated *V-R* and *V-T* curves as a function of α in the *T* part of Fig. 1(a), (b) Optimal normalized *V-R* and *V-T* curves of Fig. 3(a), (c) Calculated *V-R* and *V-T* curves as a function of *I* in the *R* part of Fig. 1(b) when the α is 10° in T part, and (d) Optimal normalized *V-R* and *V-T* curves of Fig. 3(c).

Figure 3 (a) depicts respective *V-R* and *V-T* curves for varying α in *T* part of dual cell gap device, in which α can be tuned by adjusting slit angle of pixel electrode [28]. Figure 3 (c)

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represents the variation of similar curves while varying insulator layer thickness (I) below top common electrode of the R-part in single cell gap device. The R part of dual cell gap device requires higher threshold voltage (V_{th}) than T part, however, the driving voltages of R and T parts are same as 4.1V as evident in Fig. 3 (a). In order to have higher V_{th} of the T part, we tuned α, as shown in Fig. 3 (b). The device when α is 5° shows better match between V-R and V-T curves than that of 10°. In case of single cell gap device the requirement of V_{th} is just reverse to that of dual cell gap device, that is, the R part has a lower V_{th} than T part, which is attributed to higher pretilt angle. Nevertheless the driving voltages in both R and T parts are the same each other with 4.2 V, as apparent from Fig. 3 (c). With increasing I, the V_{th} increases at the cost of decrease in reflectance in the R part. The simulated result shows respective V-R and V-T curves as a function of I and it shows best match when I is 3 µm, as shown in Fig. 3 (d). The results clearly invalidate the requirement of dual driving circuits for generating same gray level color chromaticity in the T and R parts. In addition to single gamma characteristics, reflectance of transflective LCDs in R part is most important for achieving excellent readability under sunlight. Reflectance of R part in dual and single cell gap device for the entire wavelength regime was very high enough exceeding 31%, that is, the light efficiency exceeds over 85% for both devices.

Figure 4 shows the wavelength dispersion of the dark and white states in T and R parts of proposed pair of devices. The wavelength dispersion of the dark states in T parts of both dual and single cell gap device are very small due to coincidence of initial LC director and transmittance axis of top polarizer. However, wavelength dispersion is slightly generated in dark states of the R parts as light wave retarded differently depending on wavelengths while propagating through the LC layers equivalent to a quarter wave plate. Excellent wavelength dependence has been observed in bright state of both parts in either type of devices as abovementioned.

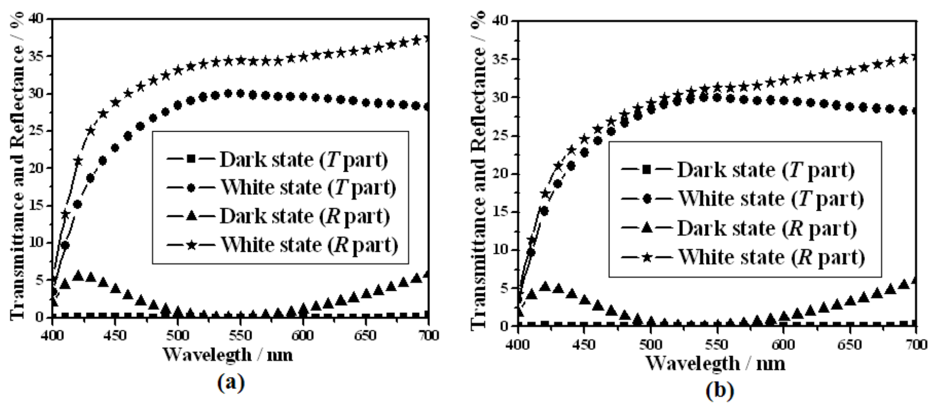

Fig. 4. Wavelength dispersion of dark and white states in T and R parts of (a) Fig. 1(a) and (b) Fig. 1(b), respectively.

Figure 5 shows iso-contrast curves in the T and R parts in each device for an incident light of 550 nm. In both devices, the T part shows very wide-viewing-angle such that the region in which the contrast ratio is greater than 10 exists at a polar angle of more than 60° in all directions, as shown in Fig. 5(a). In the R part of dual cell gap structure, the region in which the contrast ratio is greater than 5 exists at a polar angle of more than 60° almost in all directions, as shown in Fig. 5(b). In the R part of single cell gap structure, viewing-angle performance is slightly decreased due to a high tilt angle in the initial state such that it exist at a polar angle of more than 40° almost in all directions, as shown in Fig. 5(c). In general, the area of T part is much larger than that of R part. This indicates that viewing-angle performance is mainly determined by T part so that the proposed devices would still show high image quality in oblique viewing directions, while exhibiting high reflectivity that is most important requirement for sunlight readability.

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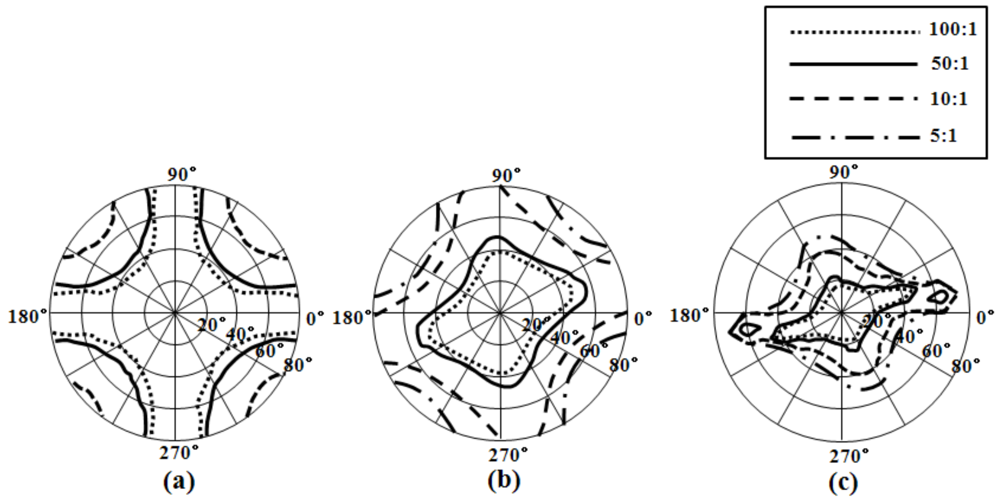

Fig. 5. Iso-contrast contour at an incident wavelength of 550 nm for (a) the T parts in both [Fig. 1(a)] and [Fig. 1(b)] and that for the R parts in the (b) [Fig. 1(a)] and (c) [Fig. 1(b)].

4. Summary

This paper proposes both dual and single cell gap fringe-field switching transflective LCDs, where liquid crystal directors are homogeneously aligned and low twisted in *T* and *R* parts, respectively. In the *R* parts of these devices, the dark state is optimized with 64° twist angle of LC in dual cell gap device and additionally same twist angle with a high pretilt angle in the single cell gap structure. The propose transflective LCDs have high reflectance and simple optical configuration because low twisted nematic LC driven by vertical electric field exhibits sufficient dark state and high reflectance without using any optical film. In order to match gamma curves in the *T* and *R* parts, α and *I* are optimized in the *T* part of dual cell gap structure and *R* part of single cell gap structure, respectively. Consequently, the proposed devices does not require compensation film, in-cell retarder or RM monomer, however, they show high reflectance, single gamma curves and wide-viewing-angle.

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