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Enhancement of surface anchoring energy in low power consumption transflective liquid crystal displays with three display modes

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ABSTRACT

Power consumption saving in transflective liquid crystal displays (TR-LCDs) with three display modes was proposed in our previous study [1]. Two of the display modes in the TR-LCD are designed to reduce power waste in common TR-LCD under dim/strong ambient lights environment. The required surface anchoring energy (SAE) of the previous design (2.0436×10^{-5} J/m^2) is too weak for practical fabrication processes. The SAE of the new TR-LCD proposed in the current work is increased to 1.2238×10^{-4} J/m^2. However, the tradeoff is the relatively high operation voltage, which is effectively reduced by compensation films (CMPFs). The design of CMPFs and the impact of cell gap and SAE errors on the dark state of TR-LCDs are investigated in detail. Comparisons between our previous work and the current study are also made. Further discussions on power saving concept of the TR-LCD are given in detail. Moreover, the fabrication example to approach such TR-LCDs using dual-pretilt-angle method based on photo manners is proposed. The reported results can give useful references about CMPFs design for TR-LCDs and/or other types of LCDs.

1. Introduction

Transflective liquid crystal displays (TR-LCDs), which have been studied worldwide for decades, can clearly display high contrast ratio (CR) images even under an environment with strong ambient lights [1–7]. A pixel of TR-LCDs is commonly divided into transmissive (T-) and reflective (R-) regions. The liquid crystals (LCs) in the former and latter regions modulate the intensity of the transmissive and reflective lights from the backlight unit and the ambient light, respectively. For real industrial applications, single-cell-gap (SCG) TR-LCDs are preferred over double-cell-gap TR-LCDs because of their relatively simple fabrications [2]. When the ambient light is strong enough, the backlight unit of a common TR-LCD can be switched off to save battery life. Fig. 1(a) shows that the LCs in T-regions still work even when the backlight is turned off. Such a shortcoming causes power wastage. By contrast, Fig. 1(b) shows that common TR-LCDs work normally indoors when the backlight unit is turned on. However, at the same time, LCs in R-regions are still working when ambient lights are dim. Battery power is consumed to rotate the LCs in R-regions, but the intensity of the reflective light is close to zero. To save battery life, in Ref. [1], we have proposed the TR-LCD with three display modes, namely, T-, R-, and TR-modes, to reduce the power consumption in R-region when ambient lights are dim. Fig. 1 gives more clear descriptions about the motivation to design the powering saving TR-LCD [1].

The suitable mode can be selected on the basis of the conditions of ambient light and/or battery life. The main concept is to reduce power consumption as the proposed TR-LCD works outdoors with strong ambient lights and indoors with dim ambient lights. The operating voltages of the T- and R-modes are lower than that of the TR-mode. In addition, the T-, R-, and TR-modes of the proposed TR-LCD have a good and stable common dark state. In exploring the concept, we state that the surface anchoring energy (SAE) levels of both top and bottom substrates are weak ($\sim 10^{-5}$ J/m^2) [1], which can be precisely controlled by soft embossing processes [7–9]. However, such a design with low SAE is not suitable for practical applications and causes slow decay response time for LCs [1,7,10]. Moreover, Bryan-Brown et al. proposed to use the moderate surface anchoring (10^{-4} J/m^2) of LCs to approach low operating voltage and fast electro-optic response by adding an oligomeric additive into the LC host to reduce surface anchoring [10].

The current study extensively discusses our previous work [1]. Here, we increase the SAEs of the two substrates to 1.2238×10^{-4} J/m^2, which is six times greater than that in our previous work (2.0436×10^{-5} J/m^2) [1,7]. One advantage is the reduction of the decay response time, but the tradeoff is the increase in operating voltage [11]. To reduce the operating voltage, we employ two uniaxial phase compensation films (CMPFs) for the reported design [6]. A moderate SAE is used in this work to avoid significant increases in operation voltage. Additionally,

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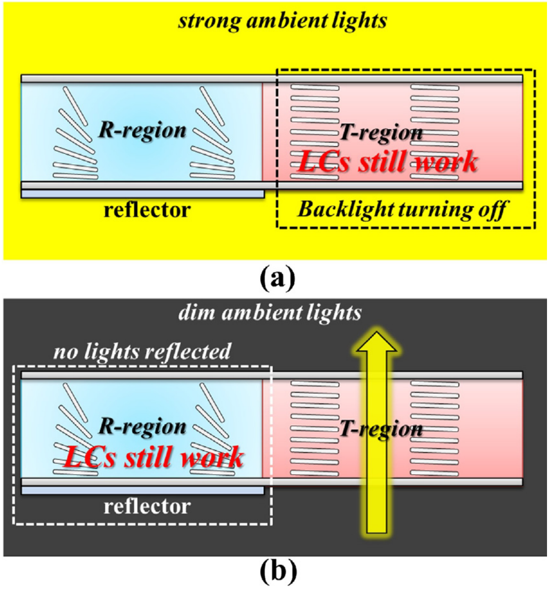

Fig. 1. (a) LCs in T-regions still work even when the backlight is turned off. (b) LCs in R-regions still work when ambient lights are dim, indicating that no lights reflected from R-regions can be observed. This causes power/battery life waste in T- and R-regions.

the designed cell gap is reduced from 5.15 μm (Ref. [1]) to 4.3 μm to reduce the operating voltage caused by the increase of SAE. The impacts of SAE and cell gap errors on the common dark state and the comparison of the performance of LC devices in the previous and current studies are also investigated. Moreover, the fabrication example based on photo manners to approach such TR-LCDs using dual-pretilt-angle method is proposed. These results can give useful references about the designs of CMPFs for TR-LCDs and/or other types of LCDs.

2. Simulation method and design concept

Fig. 2 presents the schematic configuration of the proposed 4.3 μm 4 bit single-cell-gap TR-LCD. For the theoretical calculation, the SAEs of the top and bottom substrates are set to 1.2238×10^{-4} J/m^2 [7]. The pretilt angle of the LCs close to the top and bottom substrates (gray color) of the T-regions is 2°, and those for the R-regions are 2° and 60°, respectively. The feasibility to approach patterned large LC pretilt angle in R-regions will be discussed later [1]. The reason to approach large pretilt angle in R-regions is to reduce the operation voltage of LCs in R-regions. This is reasonable because there is no threshold voltage in R-regions due to the large enough pretilt angle on top substrate [1,7]. Moreover, the LC configuration shown in Fig. 2 is an example to elucidate the proposed concept. Other LC configurations in T- and R-regions, such as normally black mode display [1–3,5,6], can be adopted to increase the performance of the proposed TR-LCD. Consistent with that adopted in Ref. [1], n_e and n_o of the LCs, MLC-6297-000 (Merck), are 1.6187 and 1.4898 (at 546 nm), respectively. $\varepsilon_{\perp}(\varepsilon_{//})$ of the adopted LCs is 3.6 (10.5); it is also known as $\Delta\epsilon$ of +6.9. Moreover, K_{11}, K_{22}, and K_{33} of the LCs are set to 13.4, 6, and 19 pN, respectively. All LC directors are set to rotate in the $\boldsymbol{xz}$ plane. Two of the same CMPFs (orange color) are designed herein to eliminate the residual phase retardation produced by the LCs close to the substrates [6,7,12]. One CMPF is placed on the bottom of the top wideband quarter waveplate [2,6]; the other CMPF is placed on top of the bottom wideband quarter waveplate. The birefringence (in the $\boldsymbol{xy}$ plane) of the employed CMPFs is positive ($\Delta n_{CMPF} > 0$) [6]. A reflector is placed beneath the bottom substrate of the R-region.

Considering the operation mechanism, we set the angles of the transmissive axis of the top and bottom linear polarizers between the +$\boldsymbol{x}$-axis to −45° and +45°, respectively. The top (bottom) wideband quarter waveplate can transform linear polarized lights into right/left (left/right) circularly polarized lights. Therefore, the linear polarization state remains unchanged after passing through the top and bottom wideband quarter waveplates in the T-region if all the LCs rotate to be perpendicular to the substrates through the application of a suitable voltage. The LCs in the T-region are sandwiched between cross-polarizers. With the use of the wideband quarter waveplates, the LCs in the R-region can also be viewed as sandwiched between cross-polarizers [6]. Hence, Fig. 2 shows that when the directors of LCs are rotated to be perpendicular to both the substrates by applying a suitable external voltage, the good dark states of the R- and T-regions can be approached [6]. Notably, the thickness, real/imaginary part of n_o, and real/imaginary part of n_e of the linear polarizers are 100 μm, 1.5/0, and 1.5/0.0043768, respectively.

The transmittance (T) of a common homogeneous alignment cell sandwiched between cross-polarizers can be calculated using Eq. (1) [6].

$$T \propto \sin^2\left(\frac{\Gamma}{2}\right), \tag{1}$$

where Γ is the phase retardation and $\Gamma = 2\pi d\Delta n/\lambda$. Here, d, Δn, and λ are the cell gap, birefringence of LC, and incident light wavelength, respectively. On the basis of Eq. (1), Γ can be obtained with Eq. (2) as T is known.

$$\Gamma \propto 2\sin^{-1}\left(\sqrt{T}\right), \tag{2}$$

For the proposed TR-LCD (Fig. 2), the transmittance (T_T) and phase retardation (Γ_T) of the T-region of the proposed TR-LCD can be exactly described according to Eq. (1),

$$T_T \propto \sin^2\left(\frac{\Gamma_T}{2}\right), \tag{3}$$

As a result of the use of the wideband quarter waveplate, the reflectance of the R-region (R_R) of the TR-LCD can be calculated as follows:

$$R_R \propto \cos^2\left(\frac{2\left(\Gamma_R + \Gamma_{\lambda/4}\right)}{2}\right) = \sin^2\left(\Gamma_R\right), \tag{4}$$

Γ_R represents the phase retardation provided by the LCs in the R-region as light passes through the LC layer in the R-region once. Γ_R and $\Gamma_{\lambda/4}$ should be multiplied by two, as shown in Eq. (4), because light passes through the LC in the R-region and the wideband quarter waveplate twice. The entire simulation method is elucidated briefly in the following. First, the phase retardation Γ_T of the T-region and Γ_R of the R-region versus the various applied voltages must be obtained. The strategy is to simulate separately the transmittances (T) of the light passing through the LCs in the R- and T-regions once under various applied voltages (0–20 V) using 1D-DIMOS based on the configuration shown in Fig. 2 without the CMPFs and the wideband quarter waveplates. The cell gaps of the R- and T-regions are equal to 4.3 μm. Second, the transmittances (T) can be transformed to Γ_T and Γ_R using Eq. (2). T_T and R_R can be calculated by substituting Γ_T and Γ_R into Eqs. (3) and (4). We check the suitable values of T_T and R_R versus various applied voltages for the proposed TR-LCD. The simulation and calculation methods used in our previous works are consistent with those described above. Hence, two wideband quarter waveplates should be designed in Fig. 1 of Refs. [1] and [7] and in Fig. 10(a)–10(c) of Ref. [1]. The conclusions/descriptions in Refs. [1] and [7] remain unchanged.

3. Results and discussions

Fig. 3(a) presents T_T versus the applied voltage (T–V) curve and R_R versus the applied voltage (R–V) curve of the proposed TR-LCDs without CMPFs. The selected wavelength for the simulation shown in Fig. 3(a)