Switchable transmissive and reflective liquid-crystal display using a multi-domain vertical alignment

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Abstract — A wide-view transflective liquid-crystal display (LCD) capable of switching between transmissive and reflective modes in response to different ambient-light conditions is proposed. This transflective LCD adopts a single-cell-gap multi-domain vertical-alignment (MVA) cell that exhibits high contrast ratio, wide-viewing angle, and good light transmittance (*T*) and reflectance (*R*). Under proper cell optimization, a good match between the VT and VR curves can also be obtained for single-gamma-curve driving.

Keywords — *Transflective liquid-crystal displays, single cell gap, wide viewing angle, switchable.*

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1 Introduction

The rapid development of portable electronics such as mobile phones generates a growing demand for displays with low power consumption, good outdoor readability, and compact size. According to the capability to meet these requirements, sunlight-readable transflective LCDs are promising candidates for mobile displays requiring frequent indoor and outdoor usage.[1] Most transflective LCDs generate transmissive (*T*) and reflective (*R*) functions by adopting a sub-*T* region and a sub-*R* region simultaneously in each pixel in a double cell gap[1–3] to compensate for the optical path difference between the *T* and *R* regions. Besides dual cell gaps, different electric-field intensities can also be designed between the *T* and *R* regions for single-cell-gap operation.[4–6] Recently, the subpixel (R, G, or B) size of mobile displays has been reduced to ~50 μm in order to maintain good panel resolution, thus generating a large fabrication challenge for transflective LCDs with divided *T* and *R* regions. Therefore, a good solution for transflective LCDs that can provide high light efficiency and wide viewing angle while having a simple manufacturing process is of great research interest and practical importance.

In this paper, we propose a new wide-view transflective LCD that can be switched between a major *T* and a major *R* state according to different ambient conditions by adopting a transflector below the LC layer and two thin-film transistors (TFTs) in each pixel. This device employs a multi-domain vertical alignment (MVA) LC cell under a single-cell-gap configuration for wide viewing angle and easy fabrication. Under proper cell optimization, the voltage-dependent transmittance (VT) curve in the major *T* state the and voltage-dependent reflectance (VR) curve in the major R state match reasonably well, making a single gray-level-control gamma curve adequate for the display.

2 Cell design and mechanism

Figure 1(a) shows the device configuration of our new switchable transflective LCD and Fig. 1(b) depicts its equivalent circuit. TFT1 is a signal controller that works to turn on/off each pixel by passing/blocking the voltages from the data line; and TFT2 functions as a general panel switch that controls the display to work under two different states: the *T*-dominance mode or the *R*-dominance mode. In real fabrication, both TFT1 and TFT2 can be formed simultaneously under the same manufacturing process without additional masks compared to the case having only one TFT. A conductive transflector (Tr) with a bumpy surface is further deposited above these TFTs to obtain transflective functions. And a passivation layer with a thickness d_P and capacitance C_P is formed between the bottom pixel electrode (Pix) and the conductive transflector. The LC cell has two parts for synthesizing a single gamma curve: region I where the pixel electrode Pix I is directly connected to the drain side of TFT1 and region II where pixel electrode Pix II is connected to the drain side of TFT2. A slit is made between the pixel electrodes in regions I and II to generate multi-domain LC profiles to enhance the viewing angle. In addition, to reduce the influence of sunlight specular surface reflection, instead of using an AR coating on the display surface,[7,8] a method is used to generate a diffusive property in the LCD such as by forming beads in the color-filter layer.[9] For a transflective LCD using separate *T* and *R* subpixels, the diffusive properties can be controlled separately. In our design, the diffusive property can be achieved by forming bumpy patterns on the transflector surface as shown in Fig. 1(a). Such a diffusive transflector can be made by using just a few lithographic steps: first, an exposure method is applied to obtain the bumpy surface profile on a passivation layer surface, followed by deposition of a thin layer metal material (alumi-

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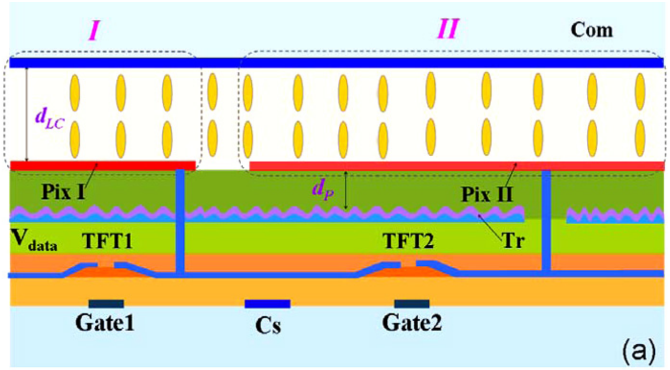

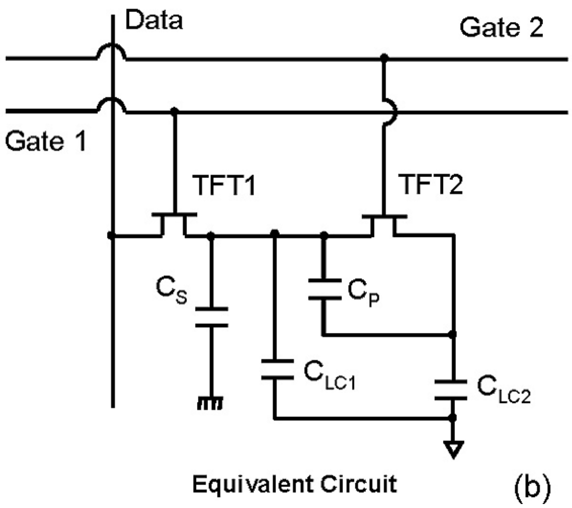

FIGURE 1 — (a) Configuration of the switchable transflective LCD and (b) its equivalent circuit.

num), and, finally, dense tiny holes are etched on the metal layer of the transmissive area.[10] The diffusive property can be controlled by the first exposure in forming bumpy surface, and the *T*/*R* ratio of such a transflector can be controlled by the total area and density of the open holes.

According to Fig. 1(b), for low-ambient environments, we designed this display to work dominantly under the *T* mode by applying a universal switch-on voltage through gate line 2 to turn on TFT2 (*switch-on state*) in every pixel and short circuit the passivation capacitor C_P. Accordingly, the data voltage is fully applied to both C_{LC1} and C_{LC2}, thus yielding a strong electric field to drive the LC to a large tilt angle. On the other hand, when the ambient light becomes very strong, such as outdoor sunlight at noon, TFT2 in all the pixels can be turned off (*switch-off state*) to make the C_{LC2} (in LC region II) in series with C_P, resulting in a reduced electric field and LC tilt angle; and the display works dominantly in the *R* mode. As a result, it is possible to make the overall VR curve (averaged from regions I and II) in the *switch-off state* for outdoor applications to match well with the VT curve in the *switch-on state* for indoor use by adjusting proper parameters of the LC cell, passivation layer, and driving electrodes.

3 Results and discussion

To validate our device concept, we studied the electro-optic properties of our device in a 4-μm LC cell using MLC-6608 with a birefringence $\Delta n = 0.083$ (at $\lambda = 550$ nm) and dielectric anisotropy $\Delta\varepsilon = -4.2$. The employed passivation layer is SiO_2 with a dielectric constant of 3.9. To assure single-gamma-curve operation, the area ratio between *R* regions I and II and the thickness of the passivation layer are very critical.[5,6] To obtain the optimal values, we first use a 1D LC simulator based on the finite element method[11] to calculate the VT curve in the *switch-on state* and VR curves in the *switch-off state* for a single-domain VA cell. For a single-domain VA cell (the slit is not taken into consideration), a surface pretilt angle is needed in order to achieve a uniform LC distribution during the voltage-on state, thus we assign it at 89.5°. The simulation results are shown in Fig. 2. With similar voltages, the VT curve (T, $V_{th} \sim 2.2\ V_{rms}$) in the *switch-on state* lies between the VR curves of region I ($R1$, $V_{th} \sim 2.2\ V_{rms}$) and region II ($R2$, $V_{th} \sim 2.6\ V_{rms}$) in the *switch-off state*. We find that when the optimized SiO_2 layer thickness d_P is ~1 μm and the ratio between *R* regions I and II is at ~1:3, the averaged VR curve ($R1 \times 0.25 + R2 \times 0.75$) in the *switch-off state* (for strong ambient) coincides with the VT curve (T) in the *switch-on state* (for low ambient). At V = 4.0 V_{rms}, both the normalized *T* and *R* reach 85% (32% in reference to the maximum transmittance from two parallel linear polarizers at 37.5%).

Wide viewing angle is also very important for mobile-display applications. In our design, we propose to use the slits between the *R* regions I and II to form multi-domains and obtain rubbing-free process. Here we employed the 3D Techwiz software (from Sanayi Company) to simulate the structure shown in Fig. 1(a) with an initial area ratio at 1:3

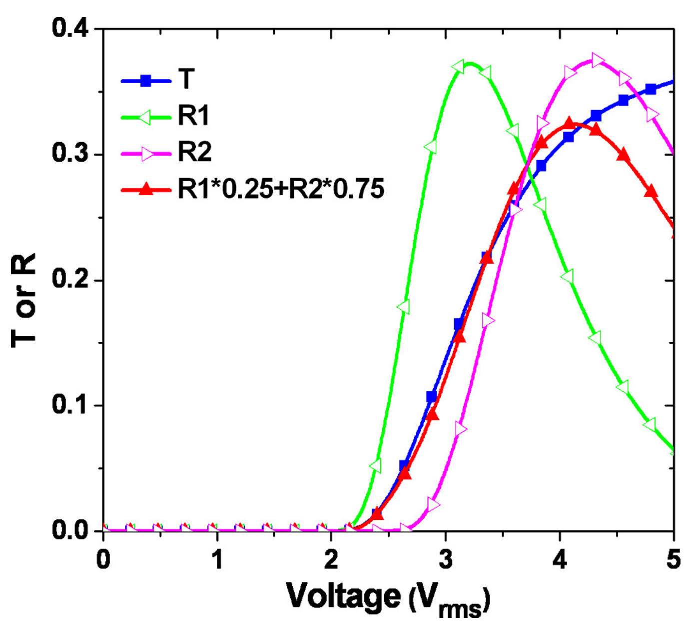

FIGURE 2 — VT and VR curves from 1D simulation in both major *T* and major *R* states.

and LC cell parameters obtained from above 1D calculation. The optimized slit width is found to be about 4 μm, and the ratio between R1 and R2 is about 1:2.54. In Fig. 3(a), the VT and VR curves in the *switch-on state* (T dominant) are plotted in blue and those in the *switch-off state* (R dominant) are plotted in red. The VT curve in the *switch-on state* (blue lines with solid rectangles) and the VR curve in the *switch-off state* (red lines with solid triangles) coincide very well with each other between 0 V_{rms} and the operating voltage at 4.0 V_{rms}, and T reaches about 0.33 (~88%) and R reaches about 0.31 (~83%) at V = 4.0 V_{rms}, respectively. These values only designate, but clearly point out, the maximum possible light efficiency from the TFT LC cell under two crossed linear polarizers, regardless of the specific T/R ratio of the transflector targeted for certain applications. According to different requirements, the T/R ratio of the transflector can vary from 2/8 to 8/2. And the final light efficiency for the T mode (or R mode) should have the transflector T ratio (or R ratio) as an additional multiplication factor to the transmittance (or reflectance) from all other components including the LC cell, polarizers, color-filter, *etc.* The 3D simulation results here are quite close to the predicted ones from the 1D simulation as shown in Fig. 2. In addition, the normalized VT and VR curves (normalized to the value at V = 4.0 V_{rms} of each curve) as shown in Fig. 3(b) exhibit a fairly good overlap with each other. In other words, this device only needs to adopt a single gray-level control gamma curve to operate these two dominant modes for different ambient conditions.

The mismatch of the VT and VR curves [in the same color in Fig. 3(a)] in each single *switch-on state* or *switch-off state* will not affect the color saturation in our display, even only when one gamma curve is utilized. For the low-to-medium ambient conditions (light intensity <500 lux),[12] the TFT2 is *switched on,* we assume that the T mode dominates at ~200 nits [blue curves in Fig. 3(a)]. Here, the maximum R_{LC} from

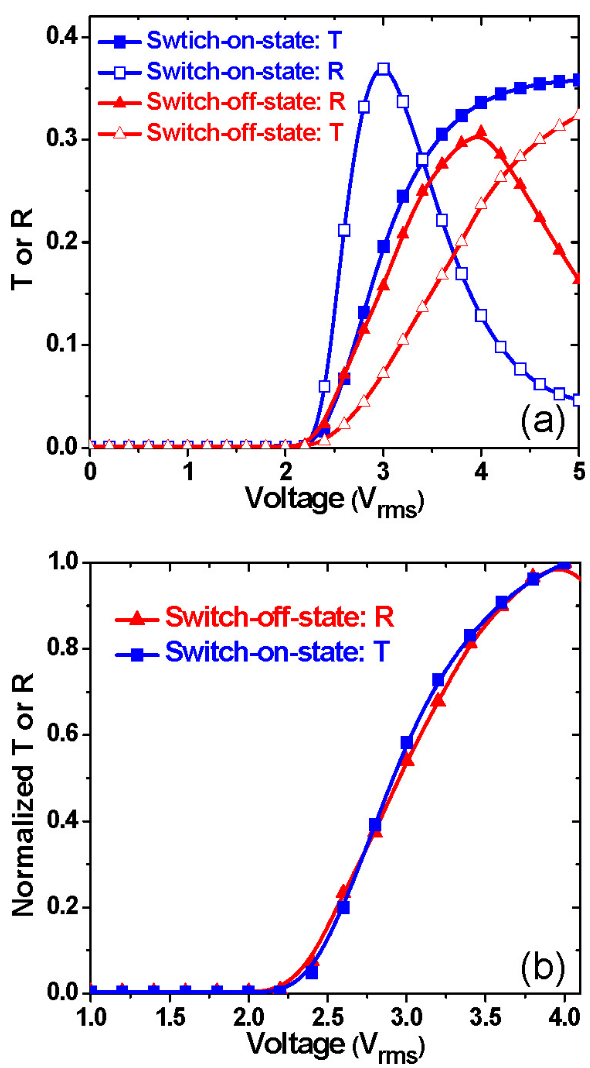

FIGURE 3 — (a) VT and VR curves from 3D simulations and (b) normalized VT of the *switch-on state* and VR curves of the *switch-off state*.

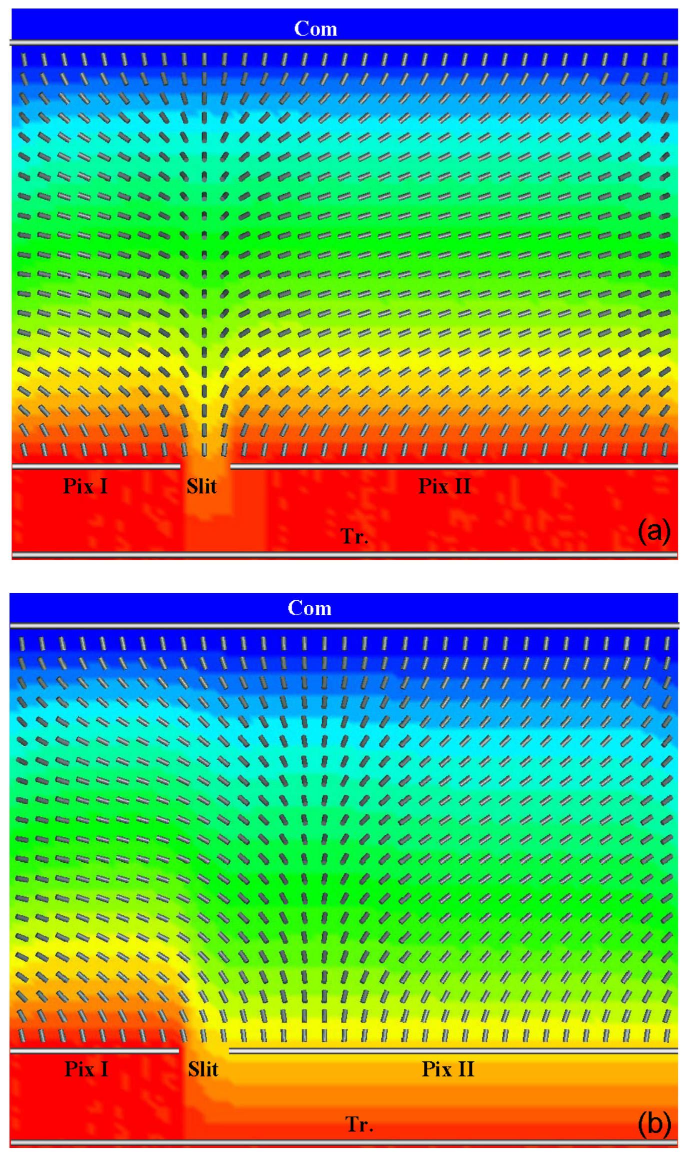

FIGURE 4 — LC director profile for (a) T mode in the *switch-on state* and (b) R mode in the *switch-off state*.

the LC cell is only <15 nits ($\alpha \times 500 \times 0.3 \times 10\%$, where 5% is the reflectance of the display device, 0.3 is the designated reflection ratio of the transflector (T ~ 0.7 of the transflector), and α is the coefficient to correlate the illumination in lux (lm/m^2) and luminance in nit (lm/m^2/steradian). For a typical display surface, α is less than 1, *i.e.*, for the display surface receiving 1 lux of illumination from an external source, it feedbacks like a surface having a brightness of less than 1 nit in luminance). As a result, color purity is well maintained by the dominant *T* mode. Similarly, when the display is used under strong sunlight (>20,000 lux),[12] the display can be operated at the *switch-off state* [red curves in Fig. 3(a)]. Now, the *R* mode dominates and *T* in the VT curve (red lines with empty triangles) at V = 4.0 V_{rms} is about 60%. Besides, below 4.0 V_{rms}, the red VT curve is always below the VR curve and *T* from the backlight can also be used to help boost the display brightness in addition to the ambient-light source, or the backlight can just be turned off for power-savings purposes. Moreover, because of the bumpy surface of the reflector, the surface mirror reflection (as a noise) will not coincide with the R_{LC} (as a signal), thus its contrast would be adequate for sunlight readability. Moreover, in reference to Fig. 1(a) in which the Pix I electrode is always connected to the transflector, we can use the storage-capacitor surface made of opaque metals to function as this Pix I electrode to fully use the TFT aperture. Overall, this design is versatile in both conditions while only a single gamma curve is required to meet major applications in either the *T*-dominant or *R*-dominant mode. In comparison, a pure transmissive display under strong sunlight could be washed out completely.

The LC-director distributions for the *switch-on state* and *switch-off state* are shown in Figs. 4(a) and 4(b), respectively. The color denotes the potential intensity, which decreases from a red color (warm color) to a blue one (cold color) as voltage decreases. In Fig. 4(a), when the switch TFT2 is on, pixel electrodes Pix I and Pix II share the same voltage at 4.0 V_{rms} as the conductive transflector (Tr). The driving voltages are fully applied onto the LC cell except those above the slit, thus the LC directors experience a large tilt in both regions I and II. In addition, fringe fields from the slit make the LC directors at different slit edges tilt towards opposite directions and a transition boundary forms near the slit center. On the other hand, when TFT2 is switched off, electrode Pix II is floating and the driving voltage from TFT1 is fully applied to only the transflector and the Pix I electrode. And the driving voltage is shared by the passivation layer and the LC layer in region II, thus the LC directors there have a weaker tilt compared to those in region I. Besides, in Fig. 4(b), the voltage difference between electrodes Pix I and Pix II also make the LC directors transition boundary between two different tilt directions move from the slit center to a little to the right of the slit into region II. These types of LC director distributions make the VT curve in the *switch-on state* and the VR curve

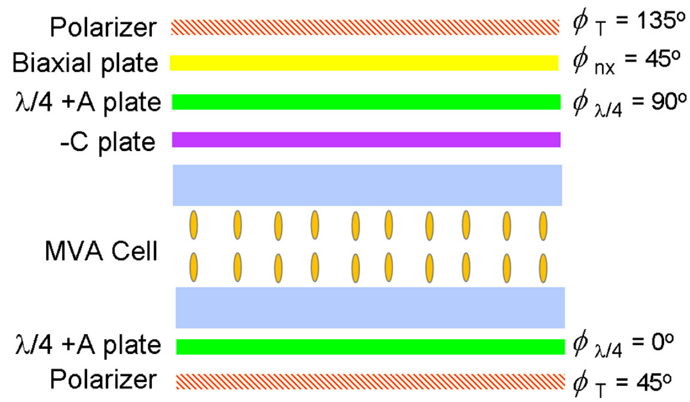

FIGURE 5 — Optical configuration of the transflective LCD using a wide-view circular polarizer.

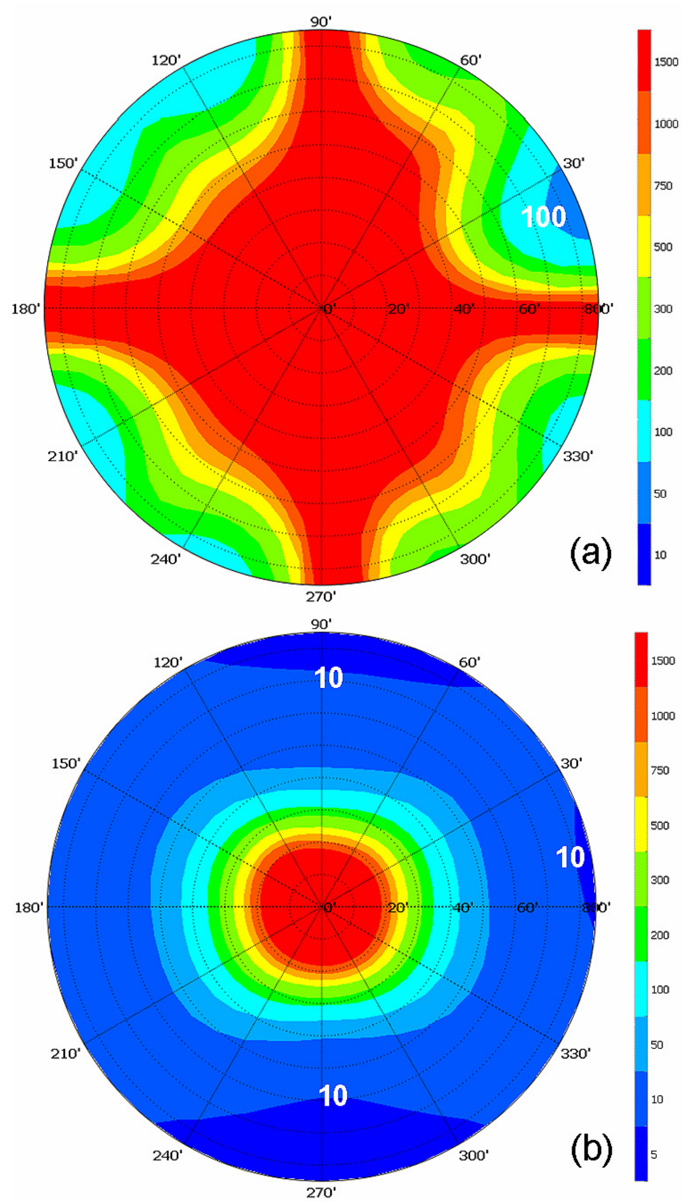

FIGURE 6 — Iso-contrast plots for (a) *T* mode in the *switch-on state* and (b) *R* mode in the *switch-off state*.

in the *switch-off state* overlap with each other, and multi-domain structures in both states help to expand the viewing angle.

Figure 5 shows the optical configuration of the transflective LCD, where a wide-view circular polarizer with one biaxial plate[13] is adopted. The uniaxial negative C plate has its extraordinary and ordinary refractive indices n_e and n_o at 1.4925 and 1.5024, respectively. Its thickness d is set to at about 24.37 μm to make the overall phase retardation $d\Delta n/\lambda$ together with the LC cell (like a positive C plate) at about 0.165. The biaxial plate has a N_z factor $[N_z = (n_x - n_z)/(n_x - n_y)]$ at about 0.35 and the in-plane phase retardation $d(n_x - n_y)/\lambda$ is set at about 0.34.[13] The two quarter-wave plates are made from uniaxial positive A plates. Figures 6(a) and 6(b) show the viewing angle of the T and R modes in the proposed device under a wide-view circular polarizer configuration, respectively. As expected, the T mode shows an inherent wide viewing angle with CR > 100:1 over the 85° viewing cone at most directions (CR < 100:1 only appears at a corner on the contour plot) in Fig. 6(a). From Fig. 6(b), the R mode also exhibits a wide viewing angle with CR > 10:1 over 70° at most directions. The wide-view property is quite desirable for mobile displays.

4 Conclusion

We proposed a new high-contrast transflective MVA LCD that can be switched between two states where the T or R mode dominates, respectively, according to the ambient-light intensity. This single-cell-gap transflective LCD can be fabricated with a rubbing-free process. It operates below 4.0 V_{rms} with a high light efficiency (~83% for the R mode in the *switch-off state* and ~88% in the *switch-on state* for the T mode) under one single gamma curve. With proper compensation, this display also exhibits a wide viewing angle (T: CR > 100:1 over 85° and R: CR > 10:1 over 70° at most directions). We believe this design has a great application potential for future wide-view and low-power sunlight-readable mobile displays.

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