Transflective device with a transparent organic light-emitting diode and a reflective liquid-crystal device

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Abstract — A high-transmittance transflective device based on a hybrid structure consisting of a transparent organic light-emitting diode (OLED) stacked on top of a reflective liquid-crystal device (RLCD) was conceptually demonstrated. By placing the transparent OLED on top of a vertically aligned LCD operated under normally black mode, a transmittance as high as 75.7% was obtained due to the asymmetric emission characteristics of a transparent OLED. To further improve the performance in the transmissive mode, a polarizer-free LCD was used, which yielded an ultra-high transmittance (82.2% overall).

Keywords — *RLCD, OLED.*

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1 Introduction

The organic light-emitting diode (OLED) holds great promise as a display technology due to advantages such as self-emission, high brightness, and potentially low costs.[1] Because the OLED is an emissive device, its performance (such as light intensity, color, and contrast ratio) is excellent under low ambient. However, the displayed image is washed out under high ambient due to reflection from the reflective electrode. Several approaches, *e.g.*, using a circular polarizer or inserting a "black layer," have been developed to improve the ambient contrast ratio (A-CR) and to enable OLED displays for indoor and cloudy outdoor applications. Nevertheless, sunlight readability is still a major issue for such emissive displays.[2–4] By splitting a pixel into transmissive (T) and reflective (R) parts, the use of sunlight readable transflective liquid-crystal displays (LCDs) has been made possible in mobile displays.[5,6] Such a planar integration limits the aperture ratio for both the T- and R-modes which, in turn, degrades the device resolution and brightness. On the other hand, vertical integration of the OLED and reflective LCD (RLCD) holds promise for a transflective device with the advantages of high A-CR and large aperture ratio for both T- and R-modes.[7–10] In this paper, we demonstrate a hybrid device by using a vertical alignment (VA) or phase-changed guest-host (PCGH) RLCD stacking with an OLED to achieve high A-CR. Notably, the integrated device with the R-mode of the PCGH RLCD exhibits a higher transmittance and allows for simpler fabrication processes compared to the VA case due to its polarizer-free characteristics.

2 Experimental details

2.1 Operational mechanism

The conceptual structure of this hybrid device is elucidated in Fig. 1. A normally black (NB) RLCD on the top of the tandem device was employed as shown in Fig. 1(a). The NB characteristic of the RLCD helps to boost the A-CR under OLED-mode operation (meaning that the OLED is the dominant device). By using the definition of a transflective LCD, in this tandem device, the OLED and RLCD functions as T- and R-mode, respectively. This tandem device exhibits a high A-CR regardless of the ambient light by using an OLED and RLCD under dark and bright ambient, respectively. Also, an emi-flective LCD combining the former structure with a nano-particle transflector in a unit cell has been reported to further enhance the A-CR.[9,10] To drive such a device, typically three transistors are needed in a sub-pixel, one for the RLCD and two for the OLED. Hence, the T- and R-modes can operate separately or simultaneously. Under T-mode operation, the NB-RLCD functions like a circular polarizer that eliminates the reflection and increases the contrast ratio. It should be noted that the light intensity emitted from the OLED is absorbed (50% theoretically) by the polarizer in the RLCD part when placing the RLCD on top of the OLED as shown in Fig. 1(a).

In a transflective display, the T-mode is used more frequently than the R-mode due to its higher contrast ratio, better color saturation, and wider viewing angle. To improve the transmittance under T-mode operation, we integrated a transparent OLED on top of the RLCD as shown in Fig. 1(b). When the OLED and RLCD are both switched on, a portion of the OLED emission propagating toward the

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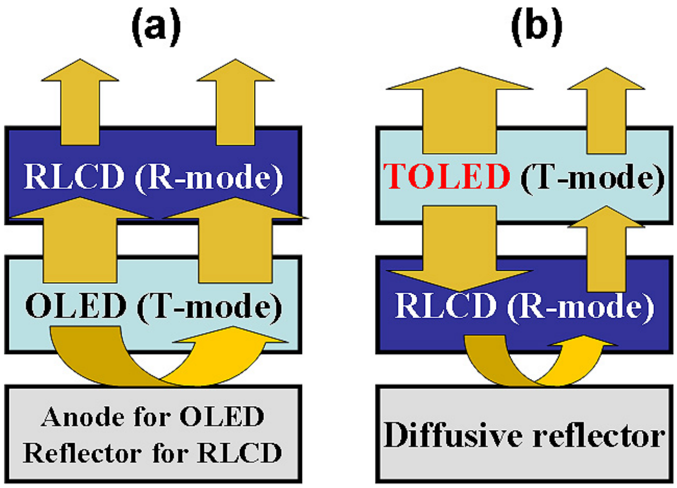

FIGURE 1 — Device structures of the tandem OLED and RLCD with (a) R over T and (b) T over R configurations.

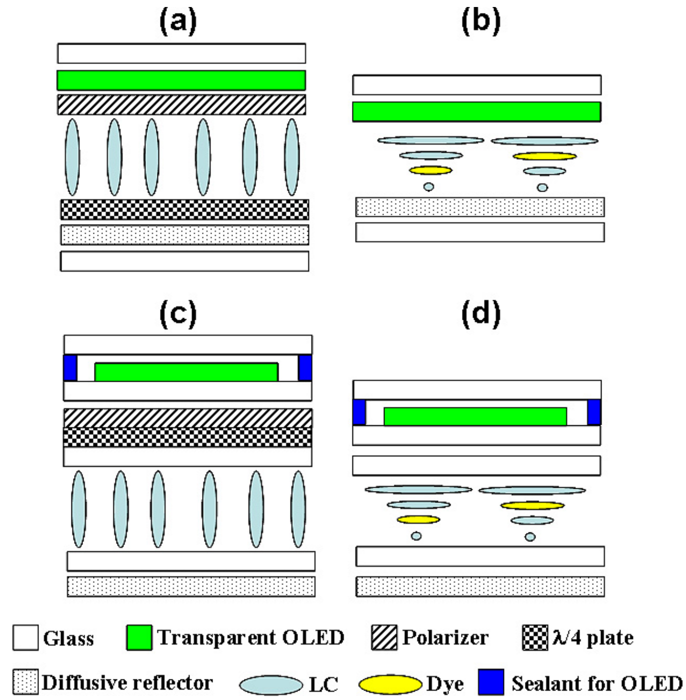

FIGURE 2 — Cross sections of (a) and (b) proposed and (c) and (d) experimental device structures with VA and PCGH as RLCD, respectively.

bottom was reflected back from the RLCD, resulting in a 50% enhancement in transmittance theoretically, provided that the OLED is a Lambertian emitter. In our experiment, through the use of a VALC for R-mode operation, the transmittance increased from 35.7% to 75.7%, corresponding to a 112% enhancement, the result of the asymmetric emission from both sides of the transparent OLED due to thin-film interference.[11,12] Furthermore, one can regard the device configuration in Fig. 1(b) as a switchable black (or color for a full-color display) background of the transparent OLED. In addition to the VA RLCD, a PCGH RLCD was also utilized in this hybrid device to remove a large portion of the absorption from the polarizer, yielding a 82.2% transmittance. Because the GH is a polarizer-free RLCD, the fabrication process of this device is much simpler than that for the VA RLCD.

2.2 Device structure and characterization

The cross sections of the proposed device structure are shown in Figs. 2(a) and 2(b). By placing a transparent OLED on top of a RLCD, a higher transmittance for the T-mode operation can be achieved. In this configuration, the thin-film transistors (TFTs) used for driving the OLED need to be fabricated on the top glass, instead of underneath the reflector of the RLCD, causing the aperture ratio to decrease.[8] There are two possible solutions to overcome this drawback. The first approach makes use of the dual-plate OLED display structure by depositing the TFTs and OLED on a separate glass substrate and then connecting them electrically *via* a contact spacer, was demonstrated on a 15-in. XGA OLED panel.[13] The second method involves implementing the transparent TFTs on the top glass, which is insensitive to visible light and exhibits high mobility for driving the OLED.[14] As shown in Fig. 2(a), a NB VA-LC was used for RLCD operation, due to the advantages of higher A-CR and larger cell-gap tolerance. The in-cell retarder and polarizer were necessary because the RLCD was placed underneath the transparent OLED.[15] To reduce the fabrication complexity, we also consider a PCGH-LC for the R-mode operation in Fig. 2(b). Despite some tradeoffs among the optical performance (such as contrast ratio, reflectivity, driving voltage, and switching speed, *etc.*) for R-mode operation, the T-mode transmittance in this configuration can be further improved because there is no polarizer.

There are three experimental bottlenecks in fabricating a RLCD on an OLED: (1) the manufacture of a highly transparent OLED device, (2) the passivation layer on the OLED against oxygen and moisture attack, and (3) the alignment layer on the passivation layer for the RLCD.[16,17] For the first case, we have recently developed ITO sputtering techniques for fabricating the transparent OLED.[11] The emission intensity ratio from the top/bottom (cathode/anode) was 1.6, which increased the transmittance of the T-mode operation. The driving current density for the OLED was kept at 100 mA/cm^2 DC with a brightness of 2850 and 1780 cd/m^2, from the top and bottom side, respectively. Besides, a transmittance value at 632.8 nm of the overall TOLED (including substrate glass, device, and encapsulation glass) is 69%.

However, the passivation for the OLED and the alignment layer on top of the OLED, as mentioned above, remains an issue in our fabrication, although it could be resolved as outlined in Ref. 10. Hence, an alternative device structure was used to demonstrate the concept in this stage, as shown in Figs. 2(c) and 2(d), corresponding to VA and PCGH as the RLCD part, respectively. In these two configurations, the transparent OLED was encapsulated with a cover glass, which was mechanically stacked with an RLCD. A Merck MLC-6608 with a 4-μm cell gap was used as the

TABLE 1 — Device performances of R- and T-mode operation.

	R_{Max}	R_{Min}	A-CR of RLCD	T_{Max} R over T	T_{Max} T over R
	(%)	(%)		(%)	(%)
VA	25.5	0.22	115	35.7	75.7
PCGH	17.82	1.34	13.3	47.8	82.2

VA-RLCD as shown in Fig. 2(c). To fabricate the PCGH-RLCD as shown in Fig. 2(d), a 5-μm twisted-nematic cell was filled with Merck MLC-6815 as the host and 3-wt.% dichroic dye S428 as the guest. Under a He–Ne laser beam with constant input optical power, maximum reflection was achieved at 4.7 and 30 V_{rms} at 1 kHz for the VA- and PCGH-LC, respectively. The reflectance of the VA- (GH-) RLCD at high and low voltages were 25.5% (17.8%) and 0.22% (1.34%), giving rise to a CR = 115:1 (13.3:1), respectively, as shown in Table 1. In all our reflectance measurements, the laser beam was tilted at less than 2° to the normal of the device. Such a small tilt angle had little effect on the CR value. However, the reflected beams from different surfaces were spatially separated provided that the optical path was long enough. A pinhole was employed to filter out the unwanted light rays, which yielded high reflectance without an anti-reflection coating. However, such a technique can be used only for a highly coherent and collimated beam, such as a laser, and is not suitable for a broadband white-light source. The ambient contrast ratio (A-CR) is defined as

$$\mathrm{A-CR} = \frac{\text{Device luminance (On)} + \text{Reflected ambient light}}{\text{Device luminance (Off)} + \text{Reflected ambient light}}. \quad (1)$$

The measurement of the A-CR was accomplished by controlling the optical intensity of a He–Ne laser illuminated normally upon the stacked device. Without the photoluminescence effect, our green-emission OLED, with peaks at 540 nm for the top and bottom sides, respectively, was transparent to the red emission from the He–Ne laser, with a peak wavelength at 632.8 nm. The reflected signal and light emission from the OLED were determined by a photodetector from the normal direction *via* a beam splitter. To measure the A-CR, a broadband white-light source with a photometric unit is more suitable. Although the definition of the light source and measuring unit were different from the original cases, the results were still meaningful.[8]

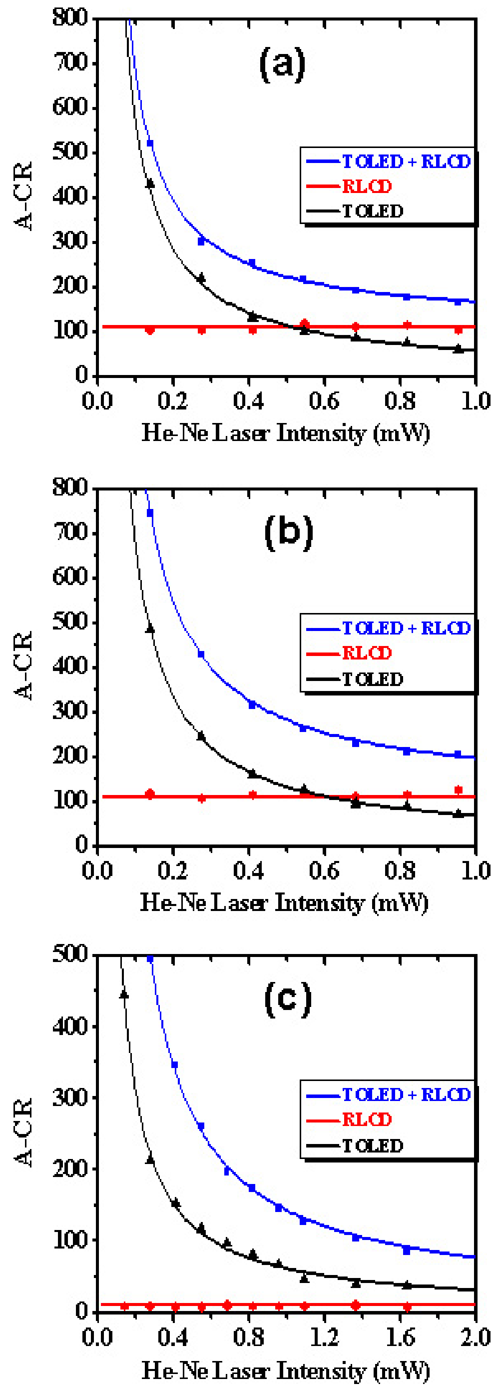

FIGURE 3 — (a) and (b) A-CR under different He–Ne laser intensities, corresponding to the device structures of Figs. 1(a) and 1(b), respectively, with VA-RLCD. (c) A-CR under different He–Ne laser intensities with PCGH-RLCD. Symbols and lines are measured data and fitted results.

3 Results and discussions

Figures 3(a) and 3(b) show the measured A-CR at normal incidence for the RLCD, OLED, and (RLCD + OLED) modes of operation, corresponding to the device structures shown in Figs. 1(a) and 1(b), respectively. Here, a NB VA-LC was used for the RLCD operation. The dots represent the experimental results while the lines represent the fittings with Eq. (1) without any adjustable parameter. Under low ambient, the A-CR of the OLED was extremely high, but decreased sharply as the ambient intensity increased. On the other hand, the A-CR of the RLCD held stable at ~105:1 and was insensitive to the ambient light intensities for both device configurations. When the RLCD and transparent OLED were both turned on, the overall A-CR was even higher than that for the individual devices. Compared with Fig. 3(a), the A-CR in Fig. 3(b) was higher for the T- and (R + T)-modes because the transparent OLED was placed on the polarizer of the RLCD, which decreased the optical loss and increased the transmission of the T-mode. As shown in Table 1, one can also see that there was a tremendous improvement (112%) in the maximum transmittance when placing the OLED on top of RLCD. In this configuration, the transmittance was as high as 75.7%, surpassing even the theoretical limits of a transflective LCD, *i.e.*, 50%. To simplify the fabrication process and further improve the transmittance, a PCGH RLCD was employed. Figure 3(c) shows the A-CR measurement at different ambient intensities for the configuration shown in Fig. 2(d). One can see that the A-CR for the R-mode was only 13.3, comparable to the A-CR of a sheet of newspaper. The maximum transmittance, as shown in Table 1, could go as high as 82.2%. However, the overall A-CR when turning on the OLED and RLCD was lower than that for the VA LC as shown in Figs. 3(a) and 3(b). This resulted from the low A-CR of the PCGH RLCD.

A benchmark for the A-CR values of this work, compared with the existing transflective LCD, can be a CR > 100:1 over 85° and CR > 10:1 over 70° for the T- and R-modes, respectively.[18] In our tandem device, for T-mode operation, because there is no light leakage during OLED off-state, the CR ratio is infinite at all viewing angles. Besides, the vertically stacking structure increases the aperture ratio of the T-mode (as well as R-mode) region compared with a transflective LCD. Hence, under the same display luminance and ambient condition, A-CR under T-mode operation in our tandem device is always higher than that of a conventional transflective LCD. In our previous paper,[8] for R-mode operation, our simulation results showed that a CR > 2:1 over a 55° viewing cone (in this case, A-CR is equal to CR) can be achieved by using VA-LC. For the PCGH case which is an absorption-type LC, the CR is typically limited to ~5:1 due to the insufficient dichroic ratio of the guest dye.[6]

Figure 4 consists of photos taken under different ambient intensities (Thorlabs OSL1 Fiber illuminator), which illustrate the operation principles of the tandem device. A sheet of white paper was used as a diffused reflector. The OLED with green emission was always lit for all the cases. Figures 4(a) and 4(b) show the cases under low ambient (below 1 nit). There was no discernible difference when the RLCD was turned off (a) or on (b). On the other hand, the transparent OLED was clearly visible which meant the T-mode of this transflective device was functioning properly under low ambient. One can also see some parallax images of the OLED at the right and bottom sides in Fig. 4(b), which originated from the multiple reflections of the glass substrate due to the increased reflection of the RLCD. Figures 4(c) and 4(d) demonstrate the device appearance under high ambient (over 10,000 nits). One would not be able to observe the OLED emission (although it was always on) because it was completely washed out by the high ambient. On the other hand, one could switch the RLCD off and on, as shown in Figs. 4(c) and 4(d), respectively, under high ambient. For the human eyes, the RLCD and OLED were the

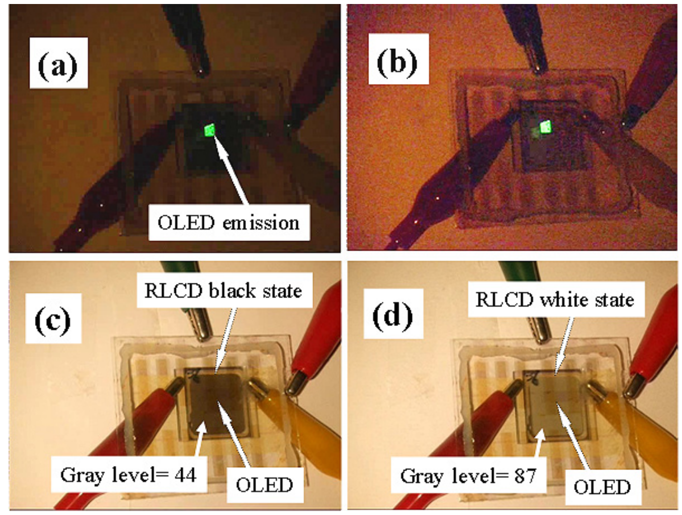

FIGURE 4 — Photographs showing the operation of the tandem device: (a) low ambient, RLCD-off; (b) low ambient, RLCD-on; (c) high ambient, RLCD-off; (e) high ambient, RLCD-on. OLED is always lit on in all cases.

dominant device at high and low ambient, respectively. A high contrast for this tandem device was obtained with both the RLCD and OLED on [as shown in Figs. 4(b) at low ambient, and 4(d), at high ambient] and off simultaneously.

As shown in Figs. 3 (a)–3(c), although A-CR measurements were meaningful, however, (1) the light source was a well-collimated monochrome laser beam in our experiments and (2) unwanted light was filtered out by a spatial filter. These may lead to the wrong impression in real devices, as shown in Figs. 2(c) and 2(d): that the contrast ratios in such mechanical stacking devices are also high (105 and 13.3 for VA and PCGH devices, respectively) in real ambient illumination. By analyzing the gray levels in Figs. 4(c) and 4(d), which are 44 and 87, respectively, A-CR = 1.97 at the "display region" can be achieved. Such a low A-CR resulted from (1) broadband light-source illumination, (2) oblique incident light, (3) scattering from the white paper, and (4) complex interface reflections. By using a laser as the light source, together with a pinhole to filter out the reflection at different interfaces (air/glass and air/metal), a CR (or A-CR in R-mode) = 13.3 was achieved for our PCGH LC at the device normal. This may be the highest value that can be obtained based on the same materials and device configuration. It is also possible to further improve the CR by using a new device structure and fabrication. For example, a CR = ~200:1 was achieved by using a dye-doped gel.[19] In our experiments, as shown in Fig. 1(d), there were four air/glass interfaces. At a rough estimation:

$$R_{\text{air/glass}} = \left(\frac{n_{\text{glass}} - 1}{n_{\text{glass}} + 1} \right)^2 , \qquad (2)$$

where $R_{\text{air/glass}}$ is the reflectance of air/glass interface and n_{glass} is the refractive index, about 1.5, respectively. It yields a $R_{\text{air/glass}}$ = 4%. On the other hand, as shown in Fig. 1(b), using the fully integrated structure, there is only one air/glass interface, which would greatly improve the A-CR value. An anti-reflection coating on the outer surface of the glass substrate can further remove the air/glass reflection. Besides, one should note that the transmittance of the whole TOLED is only 69%. Actually, as shown in Fig. 1(d), there were three air/glass interfaces in this TOLED, which resulted in a 77.99% transmission of the device itself. Here, the transmission of the cathode was 80.84%.[11] That means about 20% of light was absorbed or reflected, which also decreases the A-CR. By modifying the cathode structure (*e.g.*, without an Ag thin layer) and the using wide-bandgap organic material, reflection from the TOLED can be reduced, which further improves the A-CR.

5 Conclusion

We have demonstrated a conceptual tandem display device consisting of a transparent OLED on top of an NB RLCD, which increases the transmittance for T-mode operation. Compared to the device structure of an RLCD on an OLED, an increase in the transmittance from 35.7% to 75.7% was experimentally observed with the VA-LC as the R-mode, which could be attributed to the asymmetrical emission of the transparent OLED. To simplify the process flow and further increase the transmittance, PCGH-LC was employed, yielding a 82.2% transmission.

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