1-1-2005

High ambient-contrast-ratio display using tandem reflective liquid crystal display and organic light-emitting device

Jiun-Haw Lee

Xinyu Zhu
University of Central Florida

Yi-Hsin Lin
University of Central Florida

Wing Kit Choi

Tien-Chun Lin

See next page for additional authors

High ambient-contrast-ratio display using tandem reflective liquid crystal display and organic light-emitting device

Jiun-Haw Lee,[1] Xinyu Zhu,[2] Yi-Hsin Lin,[2] Wing Kit Choi,[1] Tien-Chun Lin,[1] Sheng-Chih Hsu,[1] Hoang-Yan Lin,[1] and Shin-Tson Wu[2]

[1]*Graduate Institute of Electro-Optical Engineering and Department of Electrical Engineering, National Taiwan University, Taipei 10617, Taiwan, Republic of China*
[2]*College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816*
swu@mail.ucf.edu

Abstract: A high ambient-contrast-ratio (A-CR) and large aperture-ratio display is conceptually demonstrated and experimentally validated by stacking a normally black reflective liquid crystal display (NB-RLCD) and an organic light-emitting device (OLED). Such a tandem device can be switched between the NB-RLCD mode and the OLED mode under bright and dark ambient light, respectively. The normally black characteristic of the RLCD also helps to boost the A-CR under OLED-mode operation. To obtain a better image quality in the RLCD mode, a bumpy and transmissive structure is used to eliminate the specular reflection and to increase the viewing angle performance that results in CR>2:1 over 55^{o} viewing cone. Besides, such a structure can also increase the external quantum efficiency of the OLED by 49.4%. In our experiments, regardless of the ambient intensity the A-CR is kept higher than 100:1.

OCIS codes: (230.3720) Liquid-crystal devices; (250.2080) Electro-optic olymers

References and links

1. C. W. Tang and S. A. Vanslyke, "Organic electroluminescent diodes," Appl. Phys. Lett. **51**, 913-915 (1987).
2. S. H. Li, H. Liem, C. W. Chen, E. H. Wu, Z. Xu, and Y. Yang, "Stacked metal cathode for high-contrast-ratio polymeric light-emitting devices," Appl. Phys. Lett. **86**, 143514-143516 (2005).
3. H. Aziz, Y. F. Liew, H. M. Grandin, and Z. D. Popovic, "Reduced reflectance cathode for organic light-emitting devices using metalorganic mixtures," Appl. Phys. Lett. **83**, 186-188 (2003).
4. S. T. Wu and D. K. Yang, *Reflective Liquid Crystal Displays*, (Wiley, New York, 2001).
5. X. Zhu, Z. Ge, T. X. Wu, and S. T. Wu, "Transflective liquid crystal displays", J. Display Technology. **1**, 15-29 (2005).
6. I. Fujieda, "Display device and driving method thereof," US patent application, 20030201960 (2003).
7. Z. Ge, T. X. Wu, X. Zhu, and S. T. Wu**,** "Reflective liquid-crystal displays with asymmetric incident and exit angles," J. Opt. Soc. Am. A **93**, 966-977 (2005), http://josaa.osa.org/abstract.cfm?id=83591.
8. H. J. Peng, Y. L. Ho, X. J. Yu, and H. S. Kwok, "Enhanced coupling of light from organic light emitting diodes using nanoporous films," J. Appl. Phys. **96**, 1649-1654 (2004).
9. G. Gu, G. Parthasarathy, P. E. Burrows, P. Tian, I. G. Hill, A. Kahn, and S. R. Forrest, "Transparent stacked organic light emitting devices. I. Design principles and transparent compound electrodes," J. Appl. Phys. **86,** 4067-4075 (1999).
10. H. Riel, S. Karg, T. Beierlein, W. Rieβ, and K. Neyts, "Tuning the emission characteristics of top-emitting organic light-emitting devices by means of a dielectric capping layer: An experimental and theoretical study," J. Appl. Phys. **94,** 5290-5296 (2003).
11. J. S. Lewis, and M. S. Weaver, "Thin-film permeation-barrier technology for flexible organic light-emitting devices," IEEE J. Select. Top. Quantum Electron. **10,** 45-57 (2004).
12. S. Möller and S. R. Forrest, **"**Improved light out-coupling in organic light emitting diodes employing ordered microlens arrays," J. Appl. Phys. **91,** 3324-3327 (2002).
13. M. K. Wei and I. L. Su, "Method to evaluate the enhancement of luminance efficiency in planar OLED light emitting devices for microlens array," Opt. Express **12**, 5777-5782 (2004), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-23-5777.

#8814 - $15.00 USD Received 16 September 2005; revised 2 November 2005; accepted 3 November 2005

14. S. Ishihara, "How far has the molecular alignment of liquid crystals been elucidated?" J. Display Technology. **1**, 30-40 (2005).

1. Introduction

Organic light-emitting device (OLED) exhibits several attractive features, such as self emission, high brightness, high contrast ratio, and potentially low cost [1]. However, when an OLED is operated under strong ambient light, most of the incident photons are reflected by the metal cathode and significantly decreases the ambient-contrast-ratio (A-CR) which makes the outdoor application difficult [2]. Typically, the reflected ambient light can be eliminated by adding a circular polarizer or a destructive interference layer called Black Layer^{TM} technique [3]. Such a device can be used effectively in both indoor and overcast outdoor environments with sufficiently high A-CR. However, it is still a challenge to use this emissive device under clear sky or direct sun.

By contrast, sunlight readability is one of the unique advantages of a reflective liquid crystal display (RLCD) [4]. Typically, by dividing a pixel into transmissive and reflective sub-pixels, a transflective LCD can be used for indoor and outdoor ambient [5], as Fig. 1 depicts. In the dark ambient, the backlight unit is switched on and the transflective LCD works in the transmissive mode (T-mode). While in the bright ambient, the reflective mode (R-mode) is activated and the backlight is turned off in order to save power. However, such a *planar* integration limits the aperture ratio of the T and R modes which, in turn, degrades the display resolution and brightness.

To utilize the advantages of both OLED and RLCD, in this paper, we demonstrate a tandem device structure which *vertically* integrates the RLCD and OLED together. A similar structure was conceived independently by Fujieda [6]. However, in Ref. (6) the device would exhibit a specular reflection for the RLCD which leads to a poor contrast ratio and narrow viewing angle [4]. In our design, we have implemented a bumpy transmitter as a front diffuser to improve the viewing angle and contrast ratio of the RLCD and, in the mean time, to enhance the external quantum efficiency of the OLED. Our simulation results agree well with experiment. In comparison with a conventional transflective LCD, our tandem device retains good image quality under extreme ambient conditions.

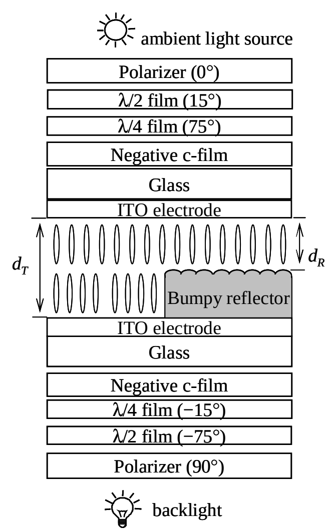


Fig. 1. Device structures of the conventional transflective LCD using vertically aligned LC.

#8814 - $15.00 USD Received 16 September 2005; revised 2 November 2005; accepted 3 November 2005

2. Simulation

Figure 2(a) shows the section view of the tandem device structure. By integrating an OLED and a RLCD in the vertical direction, a high A-CR display can be obtained regardless of the ambient light intensity since OLED and RLCD have excellent performances under dark and bright environments, respectively. Unlike the existing transflective LCD technology, such an integration of OLED and RLCD can make the aperture ratio as large as possible since the driving circuits are hidden underneath the opaque metal reflector, as shown in Fig. 2(a). Three thin-film transistors are used in each pixel, two for OLED and one for RLCD. As shown in Fig. 2(b), the RLCD is electrically isolated from OLED by the passivation layer of the OLED.

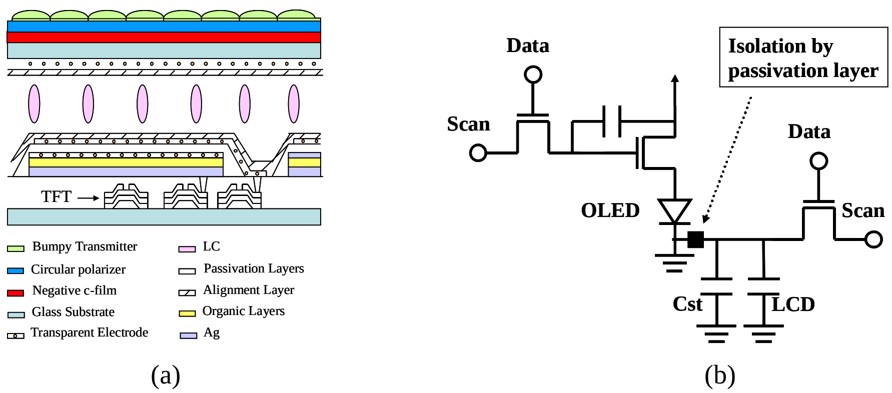


Fig. 2. (a) Cross section of the tandem device cell, and (b) the equivalent circuit of the display.

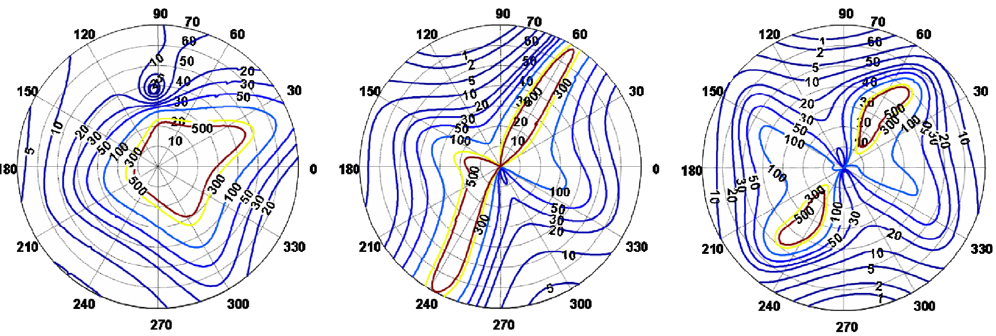
In our design, a normally-black RLCD is used to increase the A-CR under OLED operation. Here, the vertical aligned (VA) LC cell is adopted for its merits of higher contrast ratio (CR) and larger cell gap tolerance [7]. We should point out that the CR mentioned here is different from the A-CR mentioned above. Due to the dark-state light leakage in LCD, here the CR means the upper limit of the overall contrast ratio of a LCD without surface reflection. To reduce the dark-state light leakage at oblique viewing angles, a negative c-film is employed in the RLCD as shown in Fig. 2(a). Besides, a bumpy transmitter structure is laminated on the top surface to increase the viewing angle of the RLCD. This bumpy transmitter also helps to out-couple the waveguiding mode in the OLED for higher external quantum efficiency (EQE) [8].

On the bottom glass substrate, an opaque metal is used as the reflector for RLCD and also as the anode for OLED; the so-called top-emission OLED (TOLED) structure. Typically, a TOLED consists of a reflective anode, organic layers, and a transparent or semi-transparent cathode for light out-coupling [9,10]. The passivation layer upon the OLED cathode prevents the oxygen, moisture, and chemicals from attacking the OLED [11]. This passivation layer also isolates the driving circuit of RLCD from that of OLED, as Fig. 2(b) depicts. The ITO electrode for the LC cell is then deposited and followed by the LC alignment layer.

In our simulation, we use the extended Jones matrix to calculate the optical characteristics of the LCD device which is treated as a multilayer structure with anisotropic refractive indices in each layer. Due to the bumpy structure in transflective LCD and RLCD of the tandem device, the unfolding method is adopted to account for the asymmetric behavior of the incident and exit angles in these cases. The negative c-film, with an optimized thickness of 85 μm, has extraordinary and ordinary refractive indices of 1.5095 and 1.5110, respectively. The cell gaps for both the R-mode of the conventional VA transflective LCD and the RLCD of tandem device are 3 μm, while the cell gap for the T-mode is 6 μm. The LC material employed in our simulation is MLC-6608 with $\Delta n=0.083$. The pretilt angle of the LC directors is 2^{o} from the surface normal. Rubbing angle is oriented at 45^{o} with respect to the transmission axis of the polarizer.

#8814 - $15.00 USD Received 16 September 2005; revised 2 November 2005; accepted 3 November 2005

Based on our simulation, we found that the transmittance and reflectance at the normal incidence reach their maxima at $V=3.2V_{rms}$ for both T- and R-modes in the conventional VA transflective LCD as well as the RLCD in the tandem device. In calculating the viewing angle iso-contrast contour, we set the detection angle equals to the incident angle for T-mode. While for the R-mode, the incident angle is fixed at 30° and the detection angle varies from 0° to 70°. Figures 3(a)-3(c) show the calculated iso-contrast plots of the T- and R- mode of the conventional VA transflective LCD and the RLCD of the tandem device based on the structures of Fig. 1 and Fig. 2(a), respectively. From Fig. 3, the conventional VA transflective LCD with a bumpy reflector and RLCD with a bumpy transmitter both exhibit a contrast ratio greater than 2:1 over the ±50° viewing cone.



(a) (b) (c)

Fig. 3. Simulated iso-contrast contours of (a) T-mode of the conventional VA transflective LCD, (b) R-mode of the conventional VA transflective LCD, and (c) RLCD of the tandem device.

From Fig. 3(a), the viewing angle of the T-mode in the conventional VA transflective LCD is somewhat asymmetric. This is because the VA LC directors form a single domain deformation profile under applied voltage. On the other hand, the R-mode of the conventional VA transflective LCD and the RLCD of the tandem device exhibit a more symmetric viewing angle. This is because the incident light passes through the LC layer twice and the overall effect is equivalent to a two-domain LCD because of the mirror-image director profile [4]. Figure 3(c) shows the viewing angle of the RLCD of the tandem device. The only difference between the R-mode in transflective and the tandem device is the bumpy structure. That is to say, one is reflective and the other is transmissive. We can find that the CR is more symmetric in the tandem device than that in the transflective one. Since the bumpy transmitter redirects the propagation direction of both incident and exit beams, within the LC medium the reflected light is actually symmetric to the incident light with respect to the device normal. Therefore, it renders a more symmetric viewing characteristic, as Fig. 3(c) shows. On the other hand, the bumpy reflector in the conventional transflective LCD only redirects the exit light beam, which makes the reflected light asymmetric to the incident light within the LC medium. Consequently, its viewing angle is not as symmetric as that of the tandem device.

To calculate the emission characteristics of the OLED, we assume it is a Lambertian light source from the thin organic layers. When there is no bumpy transmitter, the light with incident angle larger than the critical angle is trapped inside the glass substrate. On the other hand, the corrugated surface of the bumpy transmitters with the semi-sphere shape acts as microlens arrays which can effectively increase the EQE of an OLED [12]. Using two-dimensional ray-tracing calculation, the far field radiation pattern of an OLED with and without the bumpy transmitter can be obtained. Since it is impossible to cover all the area with the hemisphere bumpy transmitters, the hemisphere radius and spacing have to be defined. Here, the hemisphere array is squarely arranged with a radius of 25 μm and spacing ranges of 49, 12.6, and 3 μm which corresponds to the area-ratio of 20%, 60%, and 90% covered by the

#8814 - $15.00 USD Received 16 September 2005; revised 2 November 2005; accepted 3 November 2005

bumpy transmitter, respectively. The receiver is set at 2 cm away from the source and the simulation program runs with 5 million rays for each case.

Figure 4 shows the simulation results. We find that the device with a bumpy transmitter has a higher intensity since this structure can effectively couple out the waveguiding mode from the glass substrate [13]. As the area covered by the hemisphere structures increases, the light output also increases. By integrating the overall intensity with different viewing angles, a 49.4% increase of EQE can be obtained with the bumpy structure area-ratio of 90%. However, under this calculation, the shape of the bumpy transmitter must be precisely hemispheric. Also, it does not account for the reflection from the surfaces and waveguiding losses.

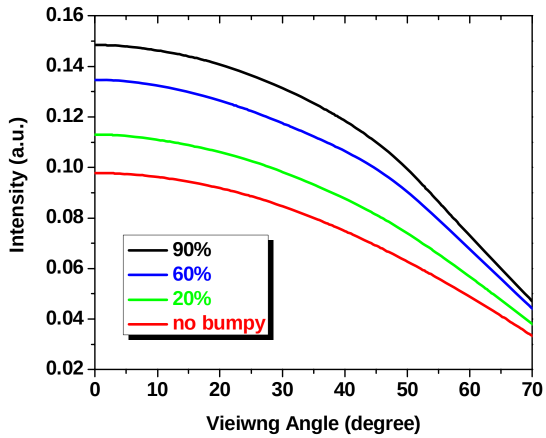


Fig. 4. Simulated viewing angle dependent OLED intensity at different bumpy-transmitter area-ratios.

3. Experimental results

Since the passivation layer upon TOLED, sputtering ITO for LC electrode, and the followed low-temperature alignment layer are still difficult to implement at this stage [14], an alternative device structure, as shown in Fig. 5, was used to prove the concept of this tandem device. In such a device, a conventional bottom-emission OLED and a VA-LC cell were stacked and driven independently. The metal cathode of the OLED was used as the reflector of the RLCD. The circular polarizer of the RLCD was used to reduce the ambient light reflection and hence to increase the A-CR in OLED mode. In such a device, a high A-CR over 100:1 can always be obtained with different illumination intensities. However, the two glass substrates between the LCD and OLED cause parallax and, consequently, reduce the viewing angle and contrast ratio of the NB-RLCD.

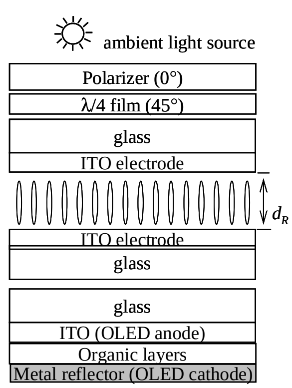


Fig. 5. The tandem device structure used for experimental measurements.

#8814 - $15.00 USD Received 16 September 2005; revised 2 November 2005; accepted 3 November 2005

In our experiments, the LC employed is Merck MLC-6608 and the cell gap is 3 μm. The active region of our OLED pixel is 1 cm × 1 cm. We use N^4,$N^{4'}$-Di-naphthalen-2-yl- N^4, $N^{4'}$-di-naphthalen-1-yl-biphenyl-4,4'-diamine (TNB) as the hole-transport layer material and bis(10-hydroxyben-zo[h]quinolinato) beryllium (Bebq2) as the emitting and the electron-transport layer material. The device structure is: ITO/TNB (80 nm)/ Bebq2 (40 nm)/LiF (0.7 nm)/ Al (100 nm). Such a device shows a green emission with peak wavelength at λ=508 nm and a FWHM of 100 nm.

To measure the A-CR, a He-Ne laser was used as the ambient light source to illuminate the tandem device at normal incidence. A quarter-wave plate and a polarizer were used as a circular polarizer placed in front of the tandem device. Output power was detected by a photodetector from the normal direction via a beam splitter. Under constant input optical power, maximum reflection is achieved at 4.7V_{rms} and 1 kHz. The reflectance of the RLCD at bright state (V=4.7V_{rms}) and dark state (V=0) is 25.5% and 0.22%, respectively, which leads to CR=115:1. The low CR value in our experiments may result from the multiple reflections from the RLCD and OLED glass substrates. The driving voltage for the OLED was kept at 4.5 V DC with the brightness of 3850 cd/m^2. After passing through the circular polarizer, the brightness is decreased to 48.3% of the original value. By varying the input power using a variable attenuator, the output power was recorded with RLCD-on, OLED-on, all-on, and all-off states, respectively. The A-CR is defined as:

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

Since we used a laser as the light source and a silicon photodetector in the experiment, it is more suitable to use radiometry than photometry unit during our A-CR measurements. Although its definition is different from the original one, the results are still meaningful. Figure 6 shows the measured A-CR at normal incidence angle for the RLCD-, OLED- and (RLCD+OLED)-modes of operation. The dots represent the experimental results while the lines stand for the fittings with Eq. (1) without any adjustable parameter. Under low ambient, the A-CR of the OLED is extremely high, but decreases sharply as the ambient intensity increases. On the other hand, the A-CR of the RLCD keeps at ~100:1, insensitive to the ambient light intensities. Such a high contrast ratio originates from the vertical alignment of the RLCD.

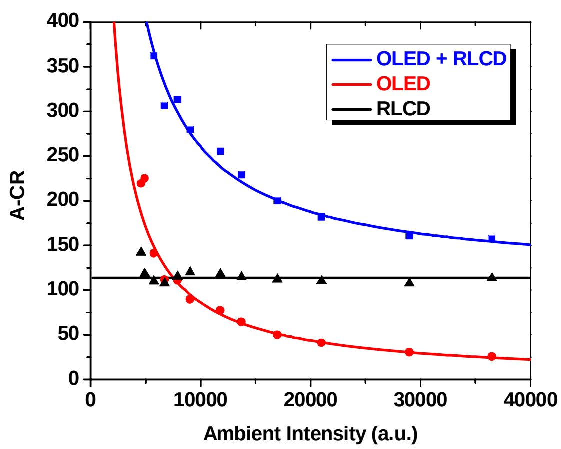


Fig. 6. Measured (symbols) and fitted (lines) ambient-contrast-ratio under different ambient intensities.

#8814 - $15.00 USD Received 16 September 2005; revised 2 November 2005; accepted 3 November 2005

Figure 7 shows the photos illustrating the operation principles of the tandem device. Figures 7(a)-7(c) show the examples under low ambient. When both RLCD and OLED are in the off-state the reflection from the surface is quite low and nearly invisible, as Fig. 7(a) shows. When the RLCD is on and the OLED is off, the reflection increases, as shown in Fig. 7(b). However, the red spot is quite dim since the ambient intensity is very low. On the other hand, when OLED is on and RLCD is off, a clear green light from OLED is observed (Fig. 7(c)). We cannot see any red color on the green OLED pixel. Since green and red colors exhibit the opposite hues, that means the OLED-mode can function properly under low ambient environment.

Figures 7(d)-7(f) demonstrate the device appearance under high ambient. As shown in Fig. 7(d), high ambient light results in a strong reflection on the sample surface if both RLCD and OLED are kept off. When the RLCD is on and OLED is off, the reflection is further increased and the red spot looks brighter, as shown in Fig. 7(e). When the OLED is turned on and the RLCD is off, we can see that the spot illuminated by the ambient light is red, not green, as shown in Fig. 7(f). That means the red reflection from the ambient overwhelms the OLED emission and the image A-CR is greatly degraded. Therefore, under bright ambient condition the information displayed by OLED is washed out severely.

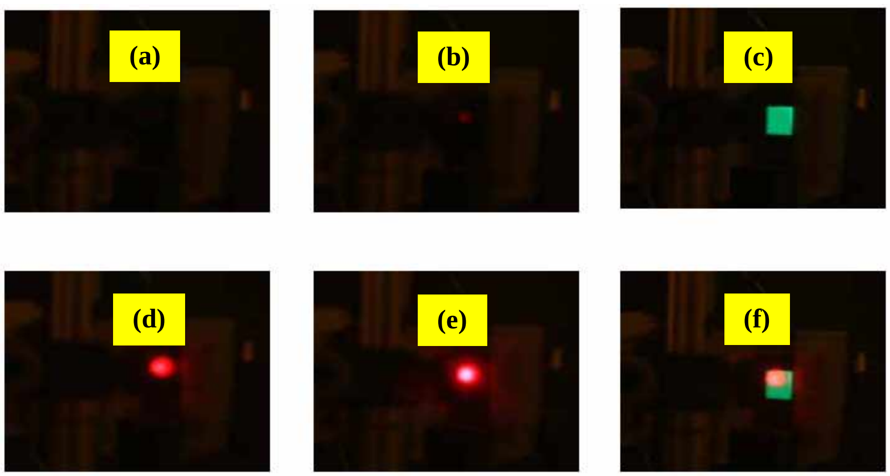


Fig. 7. Photographs showing the operation of the tandem device: (a) low ambient, RLCD-off, OLED-off; (b) low ambient, RLCD-on, OLED-off; (c) low ambient, RLCD-off, OLED-on; (d) high ambient, RLCD-off, OLED-off; (e) high ambient, RLCD-on, OLED-off; and (f) high ambient, RLCD-off, OLED-on.

4. Discussion

Even though the T-mode of the transflective LCD exhibits the same brightness as the OLED in the bright state, its A-CR is lower than that of the OLED due to the limited contrast ratio of the transflective LCD. Its A-CR value is finite under low illumination and decreases rapidly with the increased ambient intensity, the same tendency as the OLED. Since a transflective LCD consists of spatially separated T- and R-modes, its overall A-CR value is between the individual A-CR values of these two modes. On the other hand, in the tandem device in which RLCD and OLED are vertically stacked together, the overall A-CR value is that of the activated one, either RLCD or OLED. Furthermore, if both RLCD and OLED are activated simultaneously, the overall A-CR is the sum of the A-CR values of each individual device. Therefore, the tandem device where the RLCD and OLED are integrated vertically has a superior A-CR performance to the transflective LCD, in which the T- and R-modes are integrated in the transversal direction.

Another important question to ask is: although the A-CR of RLCD is high regardless of ambient light, is the brightness of RLCD high enough when OLED is not readable under high ambient? Here, we can make a simple estimation. First of all, a color filter must be inserted in the tandem device to achieve a full-color display. We assume it does not affect the brightness of the OLED and it filters 2/3 of the incident white light for the RLCD. Typically, an OLED panel with Black Layer technique can exhibit a brightness of 300 cd/m^2 and it is readable up to 10,000 lux ambient illumination [2]. With 2/3 absorption of the built-in color-filter in the tandem device, the OLED is still readable up to 30,000 lux ambient illumination. Beyond this ambient level, we can activate the RLCD and its corresponding on-state brightness is approximately 811.7 cd/m^2, which is even brighter than the OLED mode. Therefore, the RLCD is more readable than the OLED under strong ambient illumination and such a tandem device can operate under arbitrary ambient condition.

5. Conclusion

We have demonstrated a preliminary tandem display device consisting of a normally black VA-RLCD and an OLED. Such a device exhibits several advantages, such as high ambient contrast ratio, large aperture ratio, and wide viewing angle. In our design, a bumpy transmitter is employed to increase the viewing angle of the RLCD, and to enhance the external quantum efficiency of the OLED. The A-CR over 100:1 is achieved experimentally by our tandem device regardless of the ambient light intensity. Our experimental results confirm the feasibility of the new tandem device concept.

The NTU group is indebted to Chi-Mei Optoelectronics for the financial support. J. H. Lee is also grateful for the financial support from Pan Wen-Yuan Foundation and the technical assistance from Yuhua Huang and Yung-Hsun Wu of UCF. The UCF group is supported by Toppoly Optoelectronics (Taiwan).