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Ambient contrast ratio of LCDs and OLED displays

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Abstract: We systematically analyze the ambient contrast ratio (ACR) of liquid crystal displays (LCDs) and organic light-emitting diode (OLED) displays for smartphones, TVs, and public displays. The influencing factors such as display brightness, ambient light illuminance, and surface reflection are investigated in detail. At low ambient light conditions, high static contrast ratio plays a key role for ACR. As the ambient light increases, high brightness gradually takes over. These quantitative results set important guidelines for future display optimization. Meanwhile, to improve an OLED's ACR at large oblique angles, we propose a new broadband and wide-view circular polarizer consisting of one linear polarizer and two biaxial films. Good performance is realized.

OCIS codes: (120.2040) Displays; (230.3720) Liquid-crystal devices; (160.3710) Liquid crystals.

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1. Introduction

Contrast ratio (CR) is a key display metric to achieve supreme image quality [1–4], especially, to enable high dynamic range (HDR) [2, 5]. For an emissive display, like organic light-emitting diode (OLED), its CR can approach 1,000,000:1 or even higher [6–8]. Whereas for a non-emissive liquid crystal display (LCD), its CR is limited due to the depolarization effects from thin film transistors, LC layer, and color filters. For example, the CR of a commercial multi-domain vertical alignment (MVA) LCD TV is about 5000:1 [9]. For other LCD modes, such as twisted nematic [10] and fringe field switching [11], it is about 2000:1. As a result, it is generally perceived that OLED shows much better performance than LCD in terms of contrast ratio. This is true at dark ambient. However, in reality, no matter indoor or outdoor, ambient light is inevitable. Thus, how these two display technologies perform under different ambient lighting conditions is a practically important concern.

To evaluate a display's performance in the presence of ambient light, a metric called ambient contrast ratio (ACR) should be considered for real working scenarios [12–15]. In fact, ACR has already been widely used to evaluate the sunlight readability of transflective LCDs [16]. Recently, this concept is also extended to OLED displays [17–19]. But a detailed comparison between LCD and OLED has not been reported. Also, most of previous studies

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focused on the ACR at normal viewing direction. For a wide-view display such as TV, ACR at oblique angles is equally important.

In this paper, we perform a systematic analysis about ACR for both LCD and OLED. Three applications are emphasized: mobile displays, TVs, and public displays. The influencing factors like display brightness, ambient light illuminance, and surface reflection are investigated in detail. Also, the ambient isocontrast contour is plotted for the first time. It reveals quantitative information about LCD/OLED performance at all viewing directions. Through our analyses, we find high static contrast ratio plays a key role in low ambient light conditions. As the ambient light increases, higher display brightness takes over. This finding sets important guidelines for future display optimization.

2. Modeling of ambient contrast ratio

As mentioned earlier, ambient contrast ratio (ACR) is an important parameter to quantitatively evaluate a display performance. It is generally defined as [12, 17]:

$$ACR = \frac{L_{on} + L_{ambient} \cdot R_L}{L_{off} + L_{ambient} \cdot R_L}, \quad (1)$$

where L_{on} (L_{off}) represents the on-state (off-state) luminance value of an LCD or OLED, and $L_{ambient}$ is ambient luminance. Mostly, illuminance (unit: lux) is used to quantify the ambient light. Here, to be compatible with display luminance (unit: nits), we convert the illuminance to luminance by dividing a factor of π in Eq. (1) [16]. Another parameter R_L in Eq. (1) is the luminous reflectance of the display panel. It is defined as [17]:

$$R_L = \frac{\int_{\lambda_1}^{\lambda_2} V(\lambda)S(\lambda)R(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} V(\lambda)S(\lambda)d\lambda}, \quad (2)$$

where $V(\lambda)$ is the photopic human eye sensitivity function, $R(\lambda)$ is the spectral reflectance of the display device, and $S(\lambda)$ is the spectrum of the ambient light (CIE standard D65 source is used in this work). Thus, the obtained ACR hereafter is not for a single wavelength; instead, it is for the whole visible region. Next, we will model the ACR of LCD and OLED separately, as they exhibit quite different device configurations. Please note that here we use the same definition of ACR [Eq. (1)] to establish our simulation model, but with two improvements: 1) we extend this concept to different viewing angles, and 2) we also consider the light leakage from the employed circular polarizer for OLED displays. Details will be discussed later.

2.1 ACR of an LCD

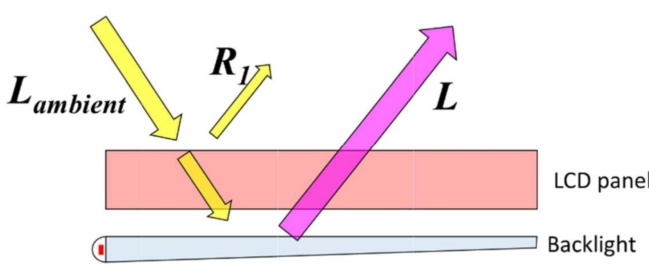

Fig. 1. Schematic diagram of an LCD.

Figure 1 shows the schematic diagram of an LCD, where the main reflections occur at the front surface of display device, denoted as R_1. The ambient light entering LCD panel is mostly absorbed by the crossed polarizers and other optical components. As a result, we assume no light is reflected back. Then its ACR can be described as:

$$\begin{aligned} ACR_{LCD}(\theta,\phi) &= \frac{L_{on}(\theta,\phi)+R_1}{L_{off}(\theta,\phi)+R_1}, \\ R_1 &= L_{ambient}\cdot R_{L\_surface}(\theta,\phi). \end{aligned} \tag{3}$$

Here, we try to simulate the ACR for the entire viewing zone. Therefore, θ and φ are chosen to represent the polar angle and azimuthal angle, respectively.

2.2 ACR of an OLED

Unlike LCD, OLED uses metal (e.g. Ag or Al) as the cathode electrode; hence, OLED itself is a highly reflective device [6, 20]. To block the reflected light from cathode, a broadband circular polarizer is commonly used, as shown in Fig. 2. However, this broadband circular polarizer (consisting of a linear polarizer, a half-wave plate, and a quarter-wave plate) works well only at normal angle. At large oblique angles, the light leakage (denoted as CP_{leak}) is relatively severe, as will be discussed later. Thus, in addition to the surface reflection, the light leakage from circular polarizer should be considered as well for OLED:

$$\begin{aligned} ACR_{OLED}(\theta,\phi) &= \frac{L_{on}(\theta,\phi)+R_1+R_2}{L_{off}(\theta,\phi)+R_1+R_2}, \\ R_1 &= L_{ambient}\cdot R_{L\_surface}(\theta,\phi), \\ R_2 &= L_{ambient}\cdot[1-R_{L\_surface}(\theta,\phi)]\cdot R_{L\_OLED}(\theta,\phi)\cdot CP_{leak}(\theta,\phi). \end{aligned} \tag{4}$$

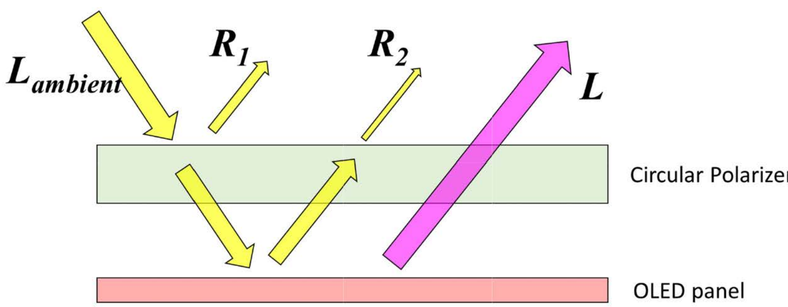

Fig. 2. Schematic diagram of an OLED.

3. Simulation results

With the introduction of ACR for both LCD and OLED, now we could perform the calculations. Firstly, we investigate how ACR changes as a function of ambient light. Then we focus on the ACR at different viewing angles, represented by *ambient isocontrast contour*. In our simulations, three different display applications: mobile displays, large-sized TVs, and public displays, are considered separately. Please be reminded that both LCD and OLED technologies are still advancing rapidly. Especially for OLED, its efficiency has been improved noticeably in the past three decades [19]. Therefore, to make a fair comparison, we mainly focus on the state-of-the-art LCD and OLED displays as examples.

3.1 Simulated ACR

a) Mobile displays

In this category, we choose smartphone as an example to do the comparison. For touch screen operations, normally anti-reflection (AR) coating is not used. As a result, the outer surface of

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display is a cover glass. Here, we assume it is BK-7. By calculation using Eq. (2), the corresponding luminous reflectance at normal angle $R_L(0°, 0°)$ is 4.2%. For an LCD smartphone, fringe field switching (FFS) mode with negative dielectric anisotropy LC mixture ($\Delta\varepsilon < 0$) is commonly used [10, 21]. Its CR is assumed to be 2000:1, with peak brightness ~600 nits. While for OLED, we assume its peak brightness is also 600 nits, and CR is assumed to be 1,000,000:1. Then we calculate the ACR at different ambient light conditions. Results are plotted in Fig. 3.

As expected, when the ambient light is weak, OLED shows a much higher ACR than LCD. But as the ambient light gets stronger, two ACR curves get much closer. At 300 lux (moderate indoor lighting), LCD shows comparable ACR to OLED (140.1 vs. 150.6). If we slightly increase the peak brightness of LCD (by increasing the backlight intensity) to 800 nits, two ACR curves crossover at 90 lux (typical lighting condition in office building hallway or toilet lighting). It means below 90 lux, OLED (with 600 nits of peak brightness) exhibits a higher ACR, but beyond 90 lux the situation is reversed for the LCD with 800 nits of peak brightness.

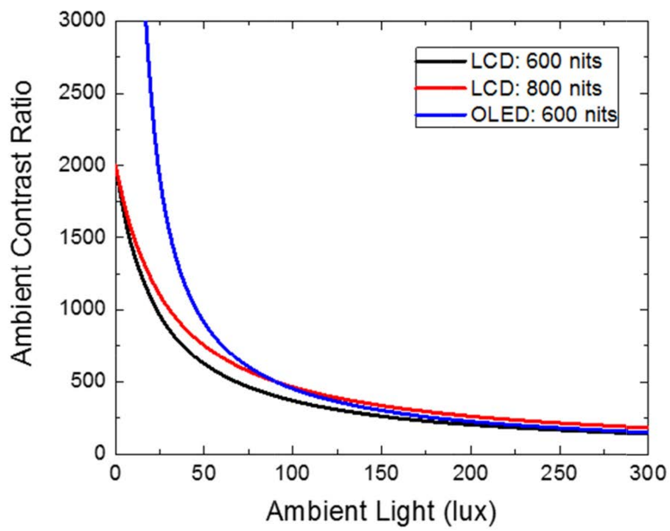

Fig. 3. Calculated ACR as a function of different ambient light conditions for LCD and OLED smartphones. Here, we assume LCD peak brightness is 600/800 nits and OLED peak brightness is 600 nits, and the surface reflectance is 4.2% for both LCD and OLED.

Table 1. Comparison between measured ACR and calculated ACR.

	Display type	Full brightness (nits)*	Static CR	Surface reflection	Measured ACR from DisplayMate**	Calculated ACR using Eq. (1)
iPhone X	OLED	634	Infinity	4.5%	141	141.9
Galaxy Note 8	OLED	423	Infinity	4.6%	92	93.0
Galaxy S8	OLED	420	Infinity	4.5%	93	95.0
iPhone 7	LCD	602	1762:1	4.4%	137	127.9
iPhone 6	LCD	558	1592:1	4.6%	121	113.7

* This brightness is measured for a screen that is entirely all white with 100% Average Picture Level. Auto-brightness is not considered here.

** This ACR is measured with a light source that uniformly illuminates the displays from all directions with 314 lux, which corresponds to 100 nits in calculation.

As discussed above, higher brightness is more critical for higher ACR. This is also verified by experimental results, as listed in Table 1. These testing results are obtained from DisplayMate Technologies Corp [22]. They use a light source to uniformly illuminate the displays from all directions, then measure the screen brightness and screen reflectance to get ACR (they call it contrast rating for high ambient light: CR HAL). More details could be found in [23]. From Table 1, iPhone X has the highest peak brightness, thus leading to the highest ACR. Also, it is found that our calculated ACR shows excellent agreement with the measured results. The validity of our model is therefore confirmed.

b) Large-sized TVs

For large-sized TVs, they are mostly operated by remote control, so that no touch functionality is needed. As a result, an AR coating is commonly adopted. Let us assume a single-layer AR coating with magnesium fluoride (MgF_2) is used, and its luminous reflectance at normal angle is $R_L(0°, 0°) = 1.5\%$ [17]. Also, TVs are powered by an electrical outlet. Thus, their peak brightness can be boosted compared to the battery-driven smartphones. Nowadays, the state-of-the-art LCD TV has ~1500 nits of peak brightness, while OLED has ~800 nits. In terms of static CR, MVA LCD is assumed to be 5000:1, while OLED is 1,000,000:1. With all these information, we can get ACR for both LCD and OLED TVs. Similarly, as shown in Fig. 4, OLED exhibits a higher ACR in the low illuminance region (dark room), but declines sharply as ambient light gets brighter. At 72 lux, OLED shows the same ACR as LCD. Beyond that, LCD is better. Again, this 72 lux is obtained based on the current LCD and OLED peak brightness (1500 nits vs. 800 nits). As both technologies continue to evolve, the crossover point will undoubtedly change with time.

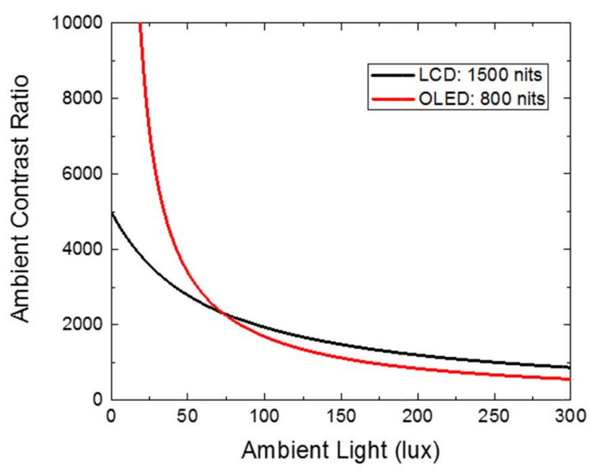

Fig. 4. Calculated ACR as a function of different ambient light conditions for LCD and OLED TVs. Here we assume LCD peak brightness is 1500 nits and OLED peak brightness is 800 nits, and the surface reflectance is 1.5% for both LCD and OLED.

c) Public displays

Recently, public display is emerging rapidly [24]. They have potential applications for advertisement, entertainment, and education, etc. For such displays, they have to endure very harsh environments, including very strong ambient light, or even direct sunlight. As a result, the display brightness has to be improved substantially; otherwise, the displayed images would be washed out. Currently, the LCD intended for public displays can get 2500 nits. Let us assume OLED public display can get 1200 nits. We can also boost the brightness for

OLED, but the tradeoffs are burn-in and compromised lifetime. As Fig. 5 shows, the crossover point of ACR takes place at 96.7 nits. For an overcast day, the ambient light illuminance is at least 1000 lux. It means for public displays, LCD is favored for most cases.

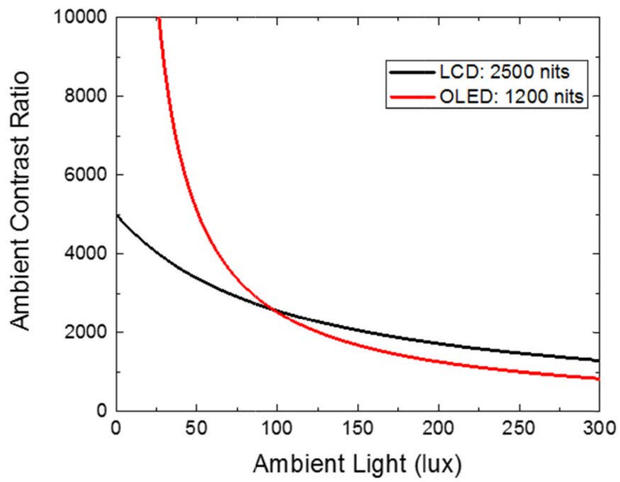

Fig. 5. Calculated ACR as a function of different ambient light conditions for LCD and OLED public displays. Here we assume LCD peak brightness is 2500 nits and OLED peak brightness is 1200 nits, and the surface reflectance is 1.5% for both LCD and OLED.

3.2 Simulated ambient isocontrast contour

So far, we concentrate on the ACR at normal angle. Next, we examine the ACR at different viewing angles. Before that, we have to elucidate the device parameters for both LCD and OLED. As discussed above, two LCD modes are used in our simulation: n-FFS for smart phones, and MVA for TVs and public displays. For both LCD modes, the parameters are the same as reported in [25]. Basically, the polarizer and analyzer are 24 µm thick with n_o = 1.5, k_o = 0.000306, n_e = 1.5, and k_e = 0.019027. Compensation films are implemented to suppress the color shift and gamma shift at large oblique angles. Also, their depolarization effect is considered to better present the real cases [25].

For OLED, as mentioned earlier, a broadband circular polarizer consisting of a linear polarizer, a half-wave plate, and a quarter-wave plate is used. Its optical configuration is plotted in Fig. 6(a). The parameter of linear polarizer is the same as that used in LCD. For the half-wave plate, it is 183.33 µm thick positive A-film with n_o = 1.5095 and n_e = 1.511 at 550 nm. The quarter-wave plate is using the same A-film, but with reduced thickness 91.67 µm. Then we calculate its light leakage at different wavelengths and different angles using a commercial simulation software TechWiz LCD (Sanayi-system, Korea). In our simulation, the OLED is replaced with a reflector. Figures 6(b) and 6(c) show the calculated results. At normal angle, the light leakage is less than 1% in the visible region (450 nm – 700 nm), the broadband feature is indeed validated. As the viewing angle increases, light leakage gradually increases and reaches up to almost 40%. This will undoubtedly affect the final perceived ACR at oblique viewing directions.

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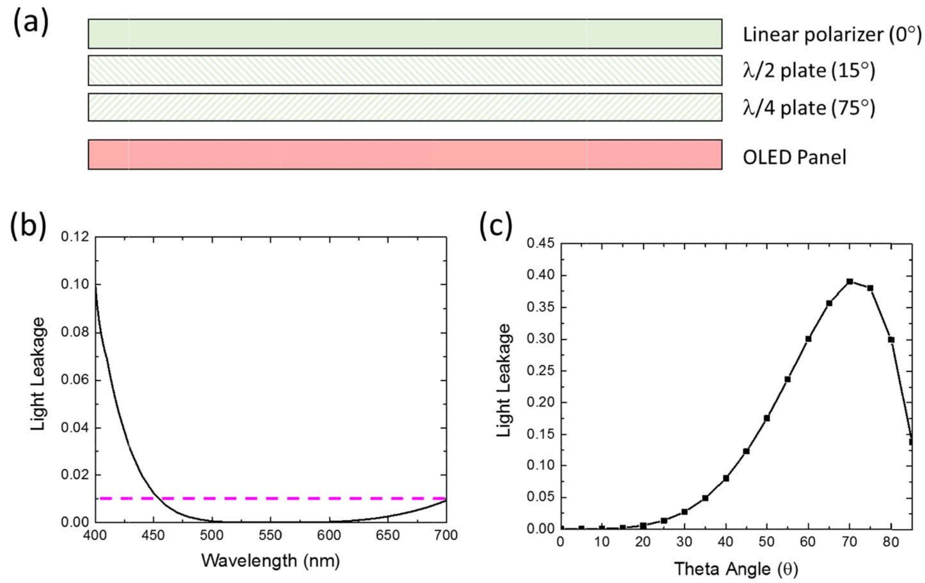

Fig. 6. (a) Schematic diagram of optical configuration of broadband circular polarizer; (b) Calculated light leakage at different wavelengths at normal angle (θ = 0°, φ = 0°); and (c) Calculated light leakage at different polar angles (φ = 0°).

In the above calculations for light leakage, OLED is assumed to be a perfect mirror. But to make it more accurate, we have to know the real reflectance of OLED panel, which is R_{L_OLED} in Eq. (4). Here, a typical multi-layer OLED device is considered, and the home-made MATALB codes are employed to calculate the angular-dependent luminous reflectance. More simulation details could be found in our previous paper [18]. Figure 7 shows the simulated results. It is seen that for the whole viewing zone, the obtained luminance reflectance doesn't change much (~80%). Please note, for different OLED structures, this reflectance may vary due to the strong interference/cavity effect.

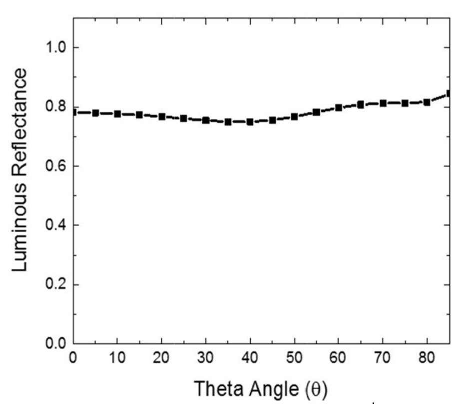

Fig. 7. Calculated angular-dependent luminous reflectance of a multi-layer OLED device.

a) Mobile displays

Again, we use n-FFS based LCD to compare with OLED smartphone. Both LCD and OLED are assumed to have the same peak brightness, which is 600 nits. BK-7 is used as the cover glass. Figure 8(a) shows the calculated luminous reflectance of BK-7 at different viewing

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directions. When the polar angle is less than 45°, R_L remains lower than 5%. But it increases sharply as viewing angle further increases. Another thing worth mentioning here is the decreased brightness. For OLED, it is self-emissive and its angular distribution is much broader than LCD. For instance, at 30° viewing angle, OLED brightness only decreases by ~20%, whereas LCD brightness decreases more than 50% [26].

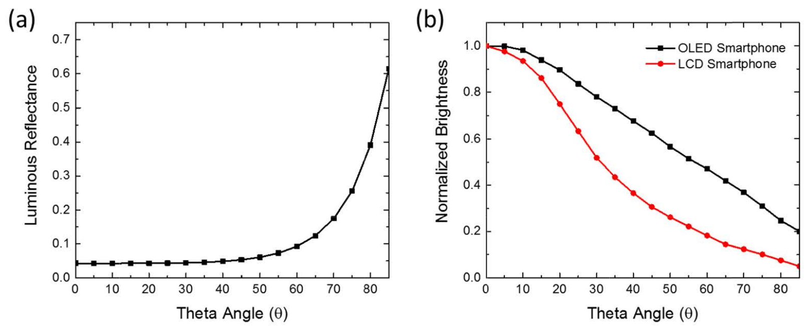

Fig. 8. (a) Calculated luminous reflectance of BK-7 cover glass at different angles, and (b) normalized brightness of LCD and OLED smartphones.

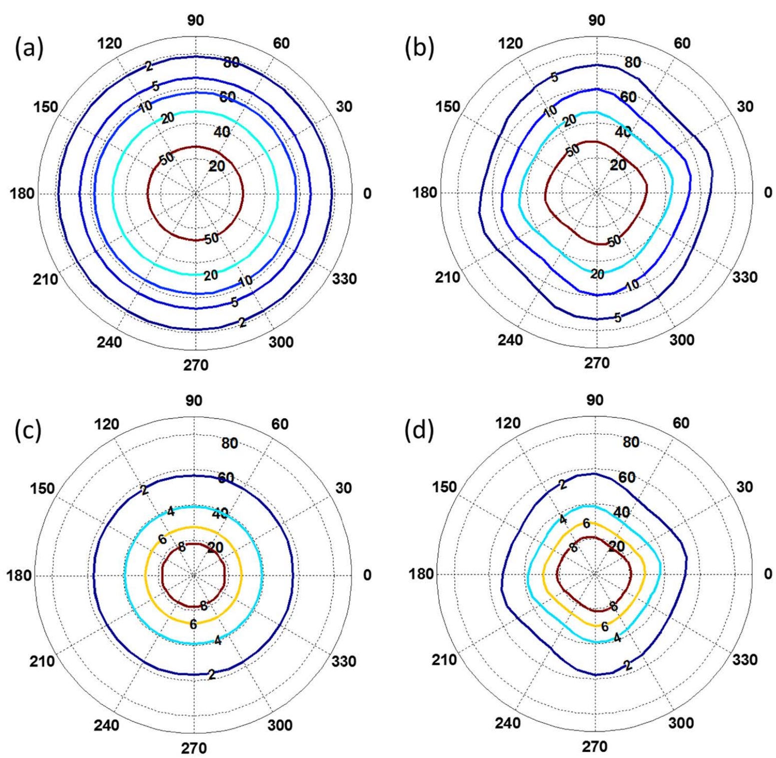

Fig. 9. Simulated ambient isocontrast contour for (a) LCD smartphone at 500 lux, where ACR_{max} = 86.1:1, ACR_{min} = 1.3:1, (b) OLED smartphone at 500 lux, where ACR_{max} = 89.2:1, ACR_{min} = 2.0:1, (c) LCD smartphone at 5000 lux, where ACR_{max} = 9.8:1, ACR_{min} = 1.1:1, and (b) OLED smartphone at 5000 lux, where ACR_{max} = 9.8:1, ACR_{min} = 1.1:1. Both LCD and OLED are assumed to have the same peak brightness: 600 nits.

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With all these information, we calculate the ambient isocontrast contour for both LCD and OLED. At 500 lux (office lighting), it is interesting to see LCD [Fig. 9(a)] and OLED [Fig. 9(b)] show quite similar contour patterns. In theory, OLED has a broader angular distribution, which is supposed to perform better at large angles. However, this advantage is evened out due to the light leakage of circular polarizer. Also, from these two figures, most of the viewing zone shows ACR ≥ 5:1, which is adequate for normal reading. As the ambient light increases to 5000 lux (outdoor with moderate overcast sky), LCD and OLED show much reduced but still quite similar ACR pattern. According to the analysis in [16, 27], ACR < 2 means display is unreadable. Therefore, from Figs. 9(c) and 9(d), the viewing zone for LCD and OLED is limited to ± 50° in an overcast day.

b) Large-sized TVs

To apply an AR coating for TVs, multiple approaches can be employed [28–31]. Currently, a single-layer magnesium fluoride (MgF_2) AR coating is a favored choice due to its simple configuration, low cost and fairly good performance [17]. Figure 10(a) shows the calculated luminous reflectance of AR-coated BK-7 at different angles. Within 45°, the R_L value is lower than 2%, which is about 2.5x lower than that of a bare BK-7 glass. Also, the decreased brightness for LCD and OLED is considered, as shown in Fig. 10(b). Unlike smartphones, wide view is more critical for TVs, aiming at multi-viewers applications. As a result, the brightness distribution is broader, e.g. OLED brightness decrease at 30° is less than 10%, while LCD is ~35%.

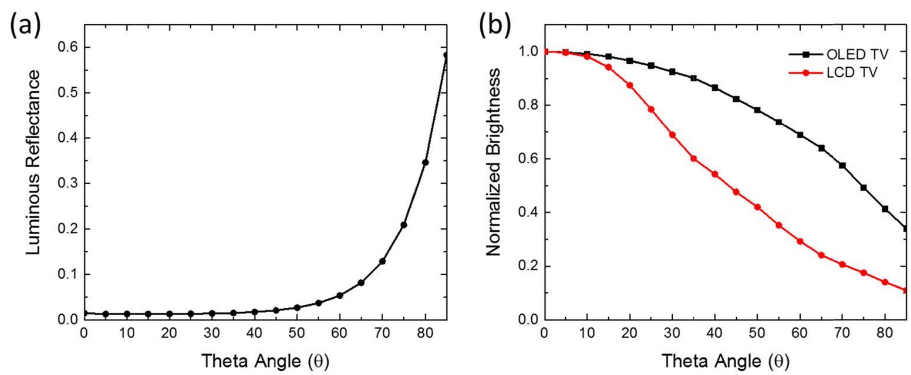

Fig. 10. (a) Calculated luminous reflectance of AR-coated BK-7 cover glass at different angles, and (b) normalized brightness of LCD and OLED TVs.

Figure 11 depicts the ambient isocontrast contour under ~50 lux of ambient light (a typical lighting condition in living rooms). From Fig. 11, firstly, both LCD and OLED can get reasonably good performance (ACR ≥ 50:1) at almost entire viewing zone (± 80°). Then in the central region, LCD shows superior ACR than OLED. For example, ACR ≥ 1000 has been extended to over ± 40° in LCD panel; whereas for OLED, it is limited to ± 30°. This is mainly because LCD exhibits a much higher peak brightness than OLED (1500 nits vs. 800 nits).

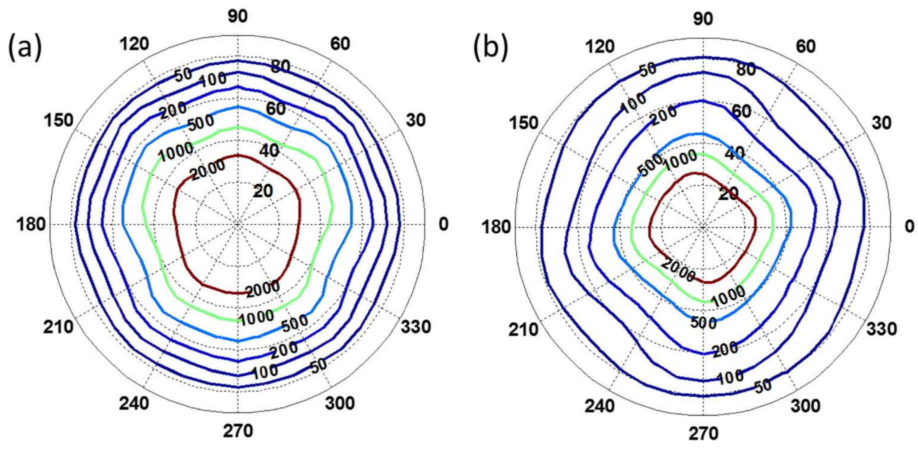

Fig. 11. Simulated ambient isocontrast contour for (a) LCD TV at 50 lux, where ACR_{max} = 2931.3:1, ACR_{min} = 16.2:1, and (b) OLED TV at 50 lux, where ACR_{max} = 3362.2:1, ACR_{min} = 27.8:1. The peak brightness for LCD is 1500 nits and for OLED is 800 nits.

c) Public displays

For public displays, we assume the AR coating and brightness distribution for LCD and OLED remain the same as those shown in Fig. 10; the only difference is their peak brightness is 2500 nits for LCD and 1200 nits for OLED. Here, ambient light is also much stronger than any other case discussed above: 10,000 lux to represent full day light (not direct sun). From Fig. 12, LCD exhibits great advantages over OLED. Firstly, its maximum ACR is over 2x higher than that of OLED: 61.2 vs. 29.5. Secondly, LCD's ACR is more than 5:1 within the 60° viewing cone, while OLED's is only ± 40°. This means, LCD exhibits a better sunlight readability. Lastly, LCD's viewing zone with ACR ≥ 2:1 is as large as ± 75°. These results clearly indicate that display brightness plays the key role for improving sunlight readability.

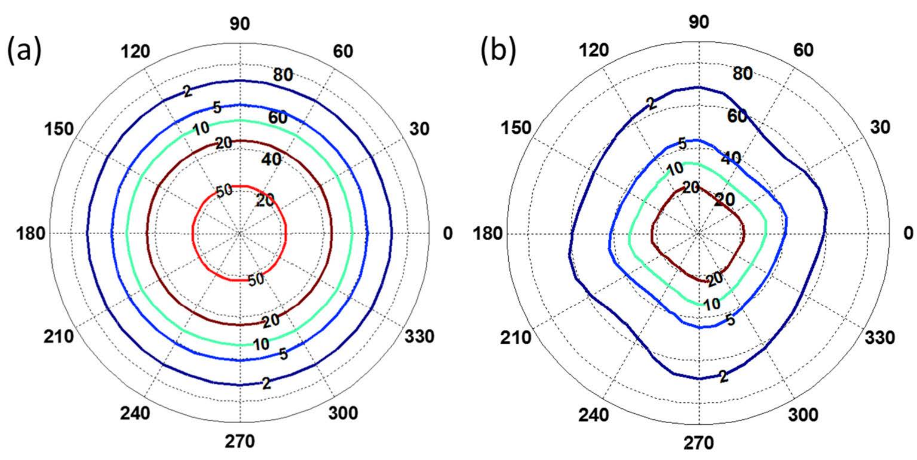

Fig. 12. Simulated ambient isocontrast contour for (a) LCD public display at 10,000 lux, where ACR_{max} = 61.2:1, ACR_{min} = 1.2:1, and (b) OLED public display at 10,000 lux, where ACR_{max} = 29.5:1, ACR_{min} = 1.2:1. The peak brightness for LCD is 2500 nits and for OLED is 1200 nits.

4. Discussion

From the above discussions, we can tell ACR is jointly determined by several factors, like display brightness, ambient light illuminance, surface reflection, and light leakage, etc. To improve ACR, LCD and OLED camps should have different strategies.

4.1 Enhancing an LCD's ACR

For an LCD, high brightness is its major strength, leading to an excellent ACR, especially at strong ambient light conditions. But under low ambient light, LCD has room for improvement. The key is to suppress the light leakage at voltage-off state. Recently, an LCD panel with in-cell polarizer was proposed to decouple the depolarization effect of LC layer and color filter array [25]. The CR of a MVA LCD TV could be boosted to 20,000:1. Also, a dual-panel LCD system is proposed to further enhance the CR to more than 1,000,000:1 [4].

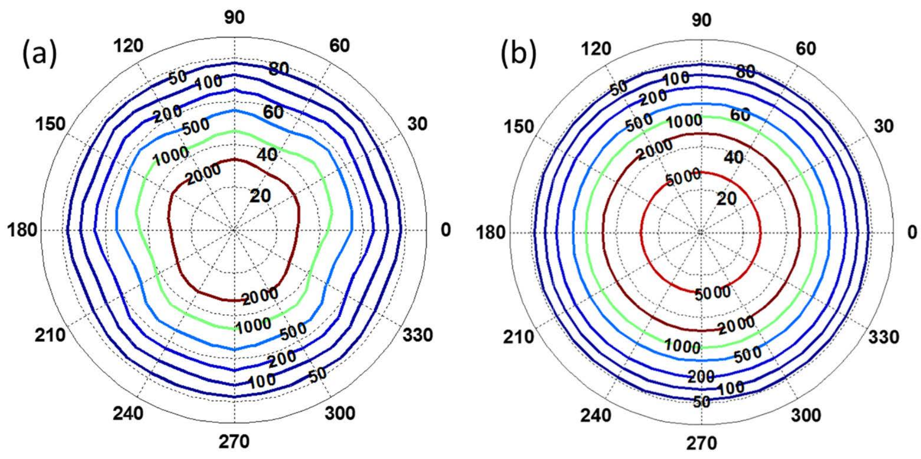

Fig. 13. Simulated ambient isocontrast contour for (a) conventional LCD TV at 50 lux, where ACR_{max} = 2931.3:1, ACR_{min} = 16.2:1, and (b) new LCD TV with mini-LED backlight at 50 lux, where ACR_{max} = 7312.5:1, ACR_{min} = 18.8:1.

Another option is to use local dimming [32–34]. In theory, its CR can approach infinity to one, as long as all LEDs are turned off. Especially, when mini-LED technology (LED chip size is 100-200 μm) is getting mature, dimming number and accuracy will be improved significantly. Here, we compare the viewing angle performance between conventional LCD and mini-LED-enhanced LCD. Their ambient isocontrast contours are plotted in Fig. 13. With the help of mini-LED, LCD TV can get over 2x higher ACR at normal direction (7312.5 vs. 2931.3). Besides, its high ACR region is widened. For example, ACR ≥ 2000:1 is expanded to almost ± 50°. For conventional LCD, it is only ± 30°.

4.2 Enhancing an OLED's ACR

For an OLED, it shows inherent true black state, leading to an excellent ACR at dark ambient. But this advantage gradually disappears as the ambient light increases, due to the inadequate brightness. To improve that, it needs substantial improvement on OLED materials and device configurations [19, 35]. Another limiting factor is the employed circular polarizer. Through our analysis, this polarizer is broadband but not wide view. Light leakage as high as 40% exists at large oblique angles. To suppress light leakage, the N_z value (= n_x-n_z/n_x-n_y, where n_x, n_y, and n_z are the refractive indices in the *x*, *y*, and *z* directions) of wave-plates should be optimized [36]. Also, negative wavelength dispersion films or other achromatic wave-plates could be implemented [37–39]. Here, we propose a new configuration by replacing the two uniaxial films with new biaxial films, as shown in Fig. 14(a). The physical parameters for

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these two films are: Biaxial film #1: d = 78.57 µm, n_x = 1.5124, n_y = 1.5089, n_z = 1.50978 @ 550 nm, and biaxial film #2: d = 39.29 µm, n_x = 1.5124, n_y = 1.5089, n_z = 1.51055 @ 550 nm [40]. Clearly, compared to the conventional circular polarizer [Fig. 14(b)], the new circular polarizer shows much suppressed light leakage [Fig. 14(c)]. Within ± 40°, it is less than 2%. The highest light leakage is about 10%. In comparison, it is more than 40% for conventional case.

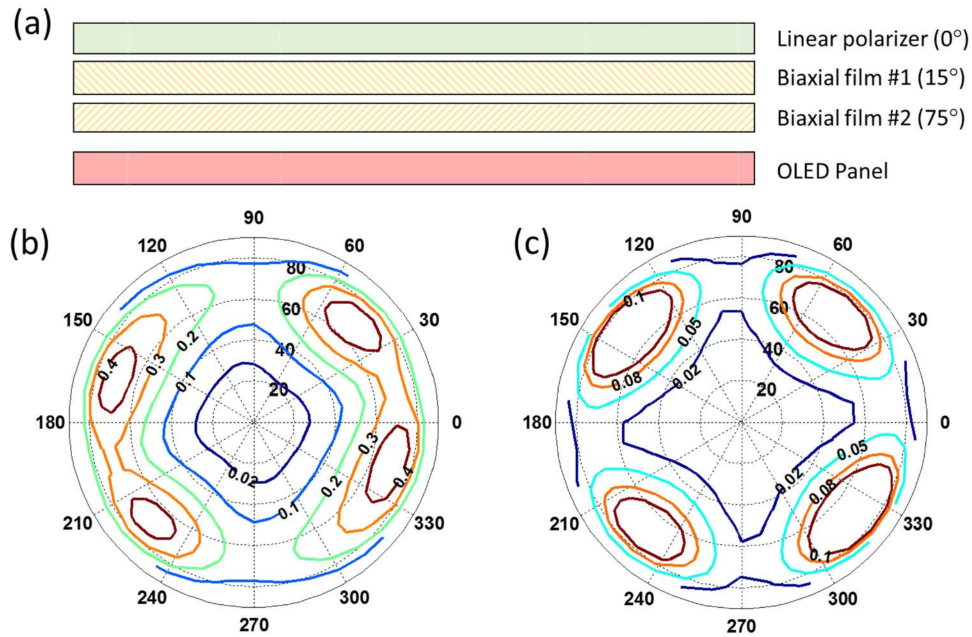

Fig. 14. (a) Schematic diagram of optical configuration of newly proposed broadband and wide-view circular polarizer with two biaxial films; Calculated light leakage for (b) conventional broadband circular polarizer, and (c) new broadband circular polarizer.

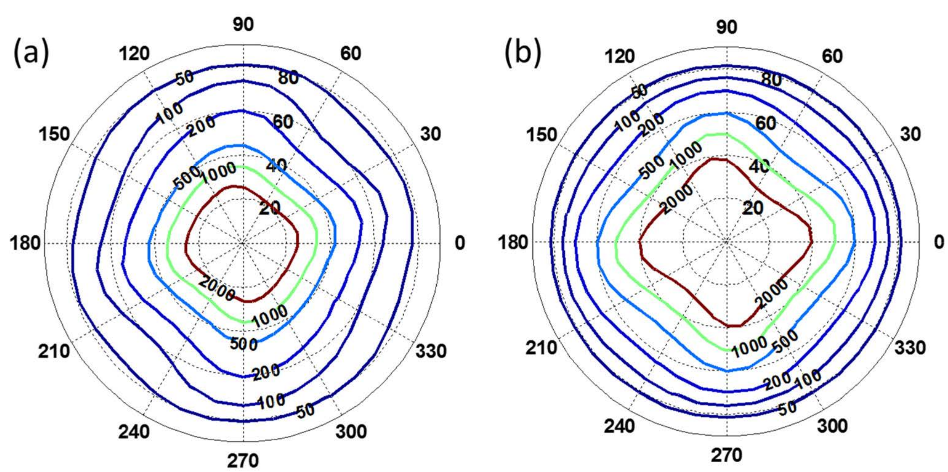

Fig. 15. Simulated ambient isocontrast contour for (a) OLED TV at 50 lux with conventional broadband circular polarizer, where ACR_{max} = 3362.2:1, ACR_{min} = 27.8:1, and (b) OLED TV at 50 lux with new broadband circular polarizer, where ACR_{max} = 3363.3:1, ACR_{min} = 29.4:1.

With the new broadband and wide-view circular polarizer, we plot the ACR for an OLED TV. Results are shown in Fig. 15. The viewing angle is widened significantly, especially in

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the central region, where ACR ≥ 500 is approaching ± 60° [Fig. 15(b)]. By contrast, if a conventional circular polarizer is used, the viewing cone with ACR ≥ 500 is limited to ± 40° [Fig. 15(a)].

5. Conclusion

We have analyzed the ambient contrast ratio of LCD and OLED systematically. It is found that high static CR is important in low ambient light conditions. But under strong ambient light, higher brightness is more critical. This gives important guidelines for future display development. The LCD camp should improve its dark state; while OLED camp should improve its peak brightness. Also, the ambient isocontrast contour is plotted under different scenarios. It provides thorough information about LCD and OLED viewing performance. To improve an OLED's ACR at large oblique angles, we propose a new broadband and wide-view circular polarizer by using two biaxial films. Good performance is demonstrated.

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