Study on Viewing Angle of Novel Ultra-Large OLED Display

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Abstract

This paper presents an investigation into the specific requirements pertaining to viewing angle, viewing angle of optical correction, and viewing distance in the context of a display device's viewable angle within a top-emission OLED, as display sizes scale up from mobile phone dimensions to over 100 inches. The larger display size is, the slower L-decay rate with varying viewing angles must be. The paper proposes an approach to optimize display difference of viewing angles by incorporating an auxiliary cathode within OLED, which thinning the cathode thickness while ensuring that impedance requirements. Additionally, an enhanced light diffusion layer is introduced in the MDL structure to broaden the display's viewing angle, achieving less than 50% L-decay at viewing angle of 66° and color shift below 2 JNCD. The optimization of the viewing angle contributes to improving image quality and advancing technology in ultra-large size OLEDs.

Author Keywords

Ultra-large size OLED Display, Viewing Angle, Optical Performance, Microcavity.

1. Introduction

In the field of ultra-large size displays, compared with LCD and OLED which are limited by generation line size, LED direct displays with no size limitation, high luminance, long life, wide viewing angle and other outstanding features, currently become the main technology of ultra-large size displays.[1] However, LED direct displays face inevitable challenges due to their small dot pitch, which results in increasing costs associated with the mass-transfer process and the large number of display chips required. In contrast, OLED technology inherently are perfect for high pixel per inch (PPI) display, and issues related to the bezel and lifespan have gradually been solved. Consequently, OLED can seamlessly align with the requirements of ultra-large size displays, positioning it as the potential mainstream technology [2].

OLED has proven to be a highly successful display technology in the markets for mobile phones, wearable devices, flat-panel displays, automotive displays, notebooks and other applications.[3] This is attributed to its impressive features, including a wide color gamut, rapid response time, broad viewing angle, low power consumption, and versatile form. However, in the field of ultra-large size display, some technology issues still need to be solved. OLED achieves luminescence by generating photons through radioactive excitation of excitons formed by electrons and holes, and the mainstream OLED devices use a top-emission structure[4]. Its circuit layer is positioned within the back plane, with the anode layer use fully reflective materials and the cathode serving as a semi-reflective layer. This structure forms a microcavity effect, enhancing the efficiency of light output. Fig.1 illustrates the structure and the luminance-viewing angle curve of the typical top OLED.

The microcavity effect in top OLED enhances the front light-extraction while simultaneously diminishing the side ones, which leads to an extra rapid L-decay at wide viewing angles. As illustrated in Fig.1, the typical top OLED retains less than 40% luminance at a 45° viewing angle. There are variations in color coordinates at different viewing angles, which are commonly assessed by JNCD metric.

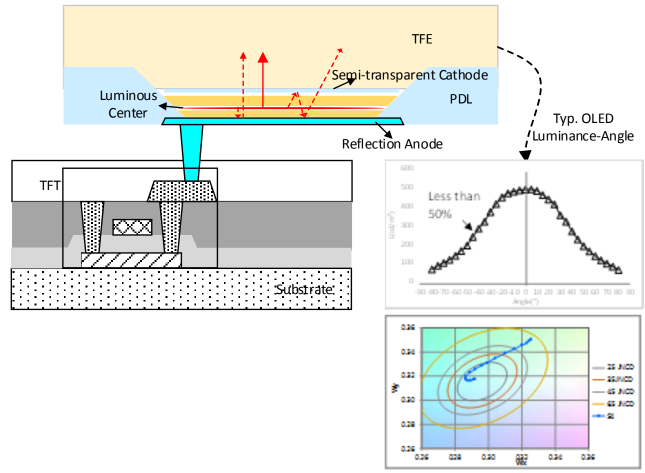

Figure 1. Schematic structure and luminance curve of the top-emission device

2. Impact of Viewing Angle on OLED Display Uniformity

2.1 Display Uniformity

The application scenes for large and small size displays differ significantly, leading to different demands for viewing angles. As depicted in Fig.2, which illustrates the typical differences of sizes and viewing angles between a 6.1-inch OLED mobile phone and a large-size P0.9 4K (4096x2160) OLED display. Taking the edge of the display as the viewpoint, the light emitted from different areas of screen enters the viewer's sight from different angles, as indicated by the data presented in Table 1.

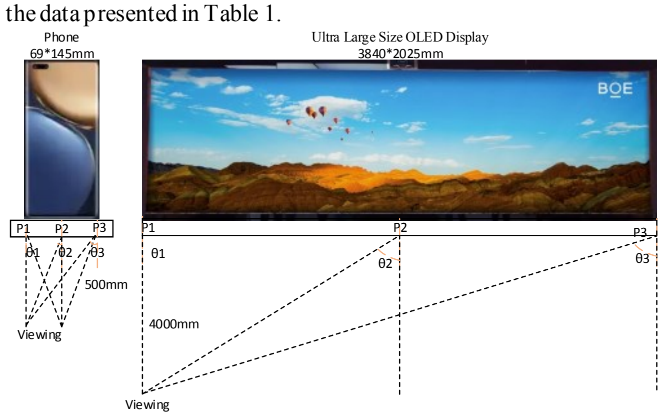

Figure 2. Typical differences of size and viewing angle between phone and ultra-large size OLED

The viewing distance for mobile phone is relatively short with an optimal range of 40 to 50 centimeters. At this distance, the difference in viewing angle is less than 10°, and the luminance difference is under 2%, which is imperceptible to the human eye. However, when dealing with ultra-large size displays viewed from a distance of 4 meters or more, the difference in viewing angles can reach up to 45°, and the luminance difference may exceed to 50%. The luminance in the area that far away from viewer is quite low compared with close area, significantly affecting the uniformity of the display from the

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viewer's perspective.

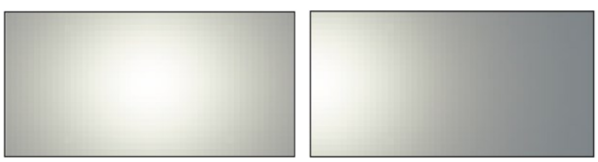
Table 1. Difference in viewing angles for OLEDs of different sizes

	P1		P2		P3	
	Ang °	Lum. (nit)	Ang °	Lum. (nit)	Ang °	Lum. (nit)
Phone	0	100%	3.9	99%	7.8	98%
Large size OLED	0	100%	25.6	84%	43.8	49%

Factors affecting display uniformity vary by sizes:
(1) For small size OLED, the difference in viewing angles is so small, that the display uniformity perceivable by the human eye is only related to the display uniformity of the screen itself at the vertical viewing angle.
(2) For ultra-large size OLED, the viewing angle of the whole screen varies greatly. The display uniformity is related to the luminance-view angle curve of the device and the viewing angle, as well as the display uniformity of the screen itself. The display of any viewing position of the screen can be expressed as equation (1), the luminance and color coordinates of any position is a function of the viewing angle of the OLED device.

$$(L,x,y)_{\theta 1}, (L,x,y)_{\theta 2} \dots\dots (L,x,y)_{\theta n}$$ **Formula (1)**

In accordance with the typical luminance-viewing angle curve of OLED, Fig.3 illustrates the simulation of full screen luminance distribution for a 4K display, (a) and (b) depict the viewing positions P1 and P2, respectively. Notably, the overall luminance uniformity is less than 50%, falling short of the standards necessary for ultra-large size displays. Consequently, the existing viewing angle of the top-emission device need to be optimize within the context of ultra-large OLED displays.



(a) P2 viewing position (a) P1 viewing position

Figure 3. The simulation of luminance distribution of full screen at different viewing positions

2.2 Optical Correction with Viewing Angle

Ultra-large size OLED displays need optical correction to optimize the display differences between display modules after assembly, which is called secondary optical correction [5]. The second optical correction requires the calibration equipment to be placed in the best viewing position for the human eye to obtain the luminance and chromaticity data of the whole screen, then calculate and adjust the settings to improve the display uniformity of the whole screen.

When the display size is extended beyond 100 inches, the luminance and color coordinates of various display areas, obtained during the secondary optical calibration as depicted in Fig.4, exhibit variations depending on the test viewing angle. For instance, if the calibration device is positioned at the center point, the left and right viewing angles may exceed 45°.The luminance and color coordinates are dependent on the viewing angle, denoted as (L, x, y)_θ. The device is unable to account for the un-uniform display resulting from the viewing angle, so that applying a correction which uses the same correction parameter (Y=a*X+b) will introduce an error due to variations in the test viewing angle.

After correction, when the viewing angle is consistent with the correcting angle, the luminance and color coordinate differences can be eliminated after optical correction. However, when the angle is different, secondary error will be introduced due to the luminance and color bias of differing viewing angles, the actual viewed luminance and color satisfy formula(2), which is a quadratic function of the viewing angle.

$$[a_1 \times (L,x,y)_{\theta 1} + b_1]_{\varphi 1}, \dots [a_n \times (L,x,y)_{\theta n} + b_n]_{\varphi n}$$ **Formula(2)**

When viewed from the left or right side, the luminance can be greater than the standards, the color coordinates could deviate from the standard white balance, with low luminance at the center and a possible rise in luminance at the far end. Those would lead to an imbalance in display uniformity after optical correction. That's why the current top OLED structure need to be optimize to ensure the accuracy of optical correction.

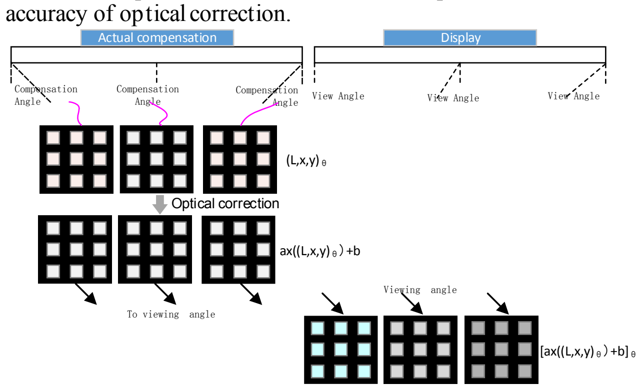


Figure 4. Optical correction on full screen

2.3 The Demands of Viewing Angle for Ultra-Large Size OLED

Compared to mobile phone displays which have a high PPI design, the ultra-large size display has a larger pixel pitch, typically like 0.9375 mm. Based on the Contrast Sensitivity Function (CSF) benchmark, which satisfies the spatial frequency requirements of the Human Visual System (HVS), the cycle per degree (CPD) must attain a minimum of 30 to eliminate any perception of spacing between adjacent pixels. The minimum viewing distance D1 of ultra-large size OLED satisfies the formula3[6]:

$$D_1 = \frac{Pixel\ Pitch}{tan(\frac{\theta 1}{2})}$$ **Formula (3)**

As shown in Fig.5, based on the CPD 30 benchmark, the minimum viewing distance of the display under the pixel pitch of 0.9375 mm needs to be greater than 3160 mm to ensure that pixel dot cannot be seen. Under the minimum viewing distance D1, the difference in viewing angles in the viewing position P1 is larger compared to the P2. At the P1 position with 8K size display, the leftmost side of the screen is in the 0° viewing angle, gradually transitioning to the right to the maximum viewing angle of 66°, which meets the formula D1=L/tan(θ/2). The viewing angle at the P2 position undergoes a gradual transition from 48° on the left to 0° at the center, and then to 48° on the right. However, the maximum viewing angle difference of P1 position with 4K size display is only 48°, which shows that the viewing angle difference gets larger when display size increases.

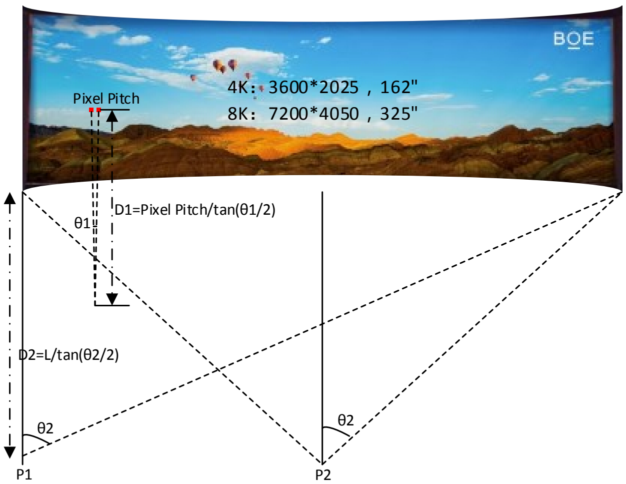


Figure 5. Calculations of viewing angle

3. Study on Optical Properties of Ultra-Large Size OLED

3.1 Microcavity Effect

As illustrated in Fig.1, the conventional top OLED utilizes a semi-transparent cathode to achieve the microcavity effect and enhance the frontal light extraction efficiency. However, this microcavity effect exacerbates the L-decay at oblique viewing angles, which is detrimental to the display quality of ultra-large size OLEDs. Consequently, the microcavity structure must be optimized.

In the theory of the microcavity effect, primary factors influenced the microcavity include the reflectivity of the reflective anode, the reflectivity of the semi-transparent cathode, the optical cavity length, and the distance between the light-emission center and the anode.[7] Among these, the optical cavity length and the distance between the light-emission center and the anode are particularly challenging to optimize because they are correlated with the wavelength of the light-emission materials. The reflectance and transmittance of cathode are determined by the cathode properties and its thickness. As illustrated in Table 2, various thicknesses of cathode have been evaluated. The results indicate a trend: as the cathode thickness decreases, the transmittance increases, the 45° L-decay decreases, but the cathode impedance increases.

Table 2. Cathode properties at different thicknesses

Cathode Thickness/A	120	140	160	180
Transmittance @850nm	78%	71%	65%	58%
Impedance Ω/sq	25	22	19	17
Luminance@45°	40%	36%	33%	31%

Reducing the thickness of the cathode can enhance the luminance-viewing angle performance, however, this result in an increase in cathode impedance, which consequently rises power consumption and display quality suffers detrimental impacts. In contrast to conventional mobile phones, which typically have a pixel pitch of 60 µm, ultra-large size OLED gain a pixel pitch of 937.5 µm. This offers ample space for the incorporation of auxiliary cathode connection points between pixels. As illustrated in Fig.6, after adding auxiliary cathode connection points, when calculating cathode impedance, only the cathode transmission between pixel pitches need to be considered and not full screen transmission. The impedance increase resulting from a reduction in cathode thickness can be disregarded, leading to an improvement in the luminance-viewing angle curve of the OLED.

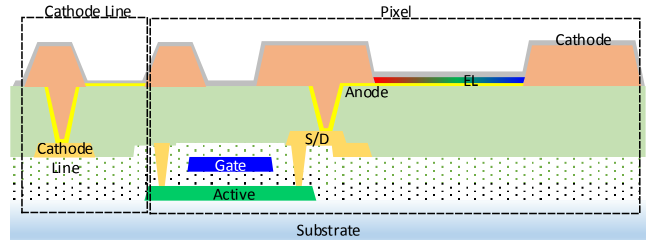


Figure 6. Schematic diagram of auxiliary cathode

3.2 Matching of RGB Viewing Angle Curves

Top OLED commonly exhibit independent RGB pixel designs, each has its unique microcavity structures, which lead to different luminance-viewing angle curves. As illustrated in Fig.7, the actual viewing angle-curve of R is flatter compared to G and B, increasing the color coordinate viewing angle deviation. To avoid the color shift of ultra-large size OLED brought at different viewing angles, the most potential strategy would be to ensure that the RGB curves are as closely matched as possible.

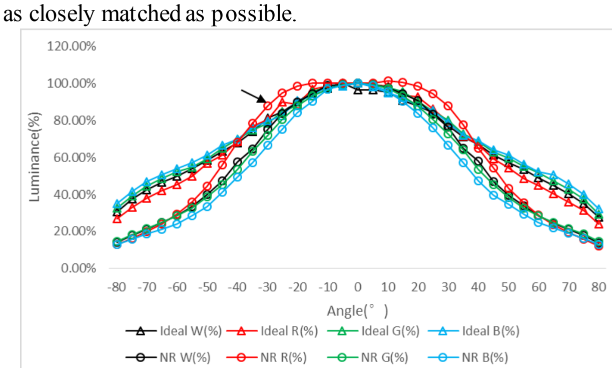
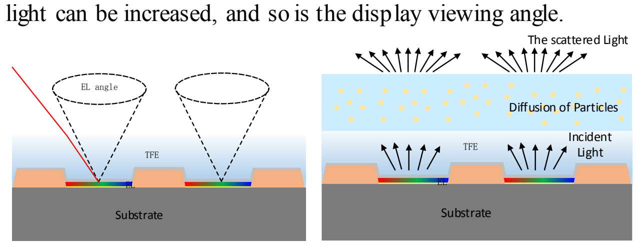


Figure 7. Luminance-viewing angle curves of RGB

3.3 Optical Diffusion

The MDL structure of OLED also represents a significant factor influencing the display viewing angle. As illustrated in Fig.8, an optical diffusion layer comprising a high transmittance substrate and randomly dispersed scattering particles is incorporated on the encapsulation. The substrate and scattering particles exhibit disparate refractive indices, which will cause refraction, reflection and scattering when light goes through. In this case, the rate of side light can be increased, and so is the display viewing angle.

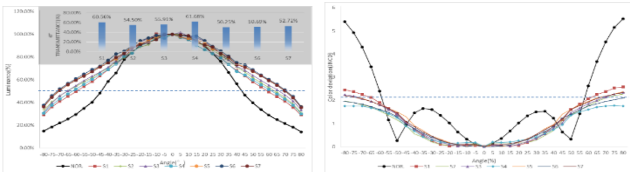


(a) Conventional OLED (b) Optical diffusion OLED

Figure 8. Schematic diagram of optical diffusion

The size, refractive index, concentration and thickness of the diffusion particles exert an influence on the light diffusion, which in turn affects the viewing angle of the display. As illustrated in Fig.9, different diffusion materials exhibit distinct characteristics regarding their impact on the brightness and color shift viewing angle curve.

Although there is a notable improvement, the extent of it is contrary to the vertical transmittance. Therefore, it is essential to meet balance between transmittance and viewing angle brightness.



(a) Luminance curve (b) Color shift curve

Figure 9. Viewing angle curves for different diffusion materials

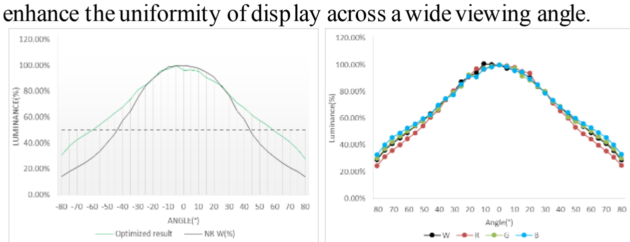
4. Results and Discussion

As demonstrated in Table 3, the viewing angle was markedly enhanced following the optimisation of the cathode thickness, R color microcavity structure and diffusion layer material. After optimized, the 50% luminance can be viewed at 62°, and the color shift at 60° is reduced from 3.7 JNCD to 1.8 JNCD. However, there is a 32% loss of 0° transmittance.

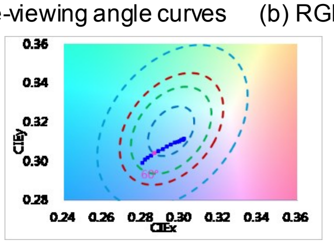
Table 3. Optical characteristic

Parameter	Luminance (nit)	Viewing angle (50%)	Color shift (60° JNCD)	0°transmitta-nce (%)
** Mobile Phone	500	43°	3.7	100%
Optimized	500	62°	1.8	68%

The actual viewing angle brightness, color trajectory and RGB viewing angle curves are shown in Fig.10. Following optimization, the luminance viewing angle curve is more smoothly and the RGB luminance-viewing angle curves are largely coincident. The color trajectory is now a short, straight line in the same direction, which enhance the uniformity of display across a wide viewing angle.



(a) Luminance-viewing angle curves (b) RGB curves

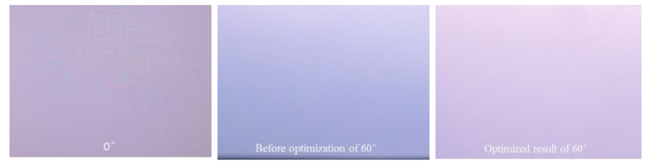


(c) Color trajectory

Figure 10. Viewing angle curves after optimisation

The actual optimized display results are presented in Fig.11, (a) and (b) illustrate the results for the 0° and 60° viewing angles of scenery image and 255 grayscale after Gamma. The left, middle and right of the screen are 0°, before optimization of 60°, optimized result of 60°. It can be clearly seen that there is a color deviation in the 60° viewing angle before optimization. After optimization, the color of 60° viewing angle closely matches which of 0°, presenting a notable improvement.

(a) 0° and 60° viewing angles of scenery image



(b) 0° and 60° viewing angles of 255 grayscale

Figure 11. Display differences of different viewing angles before and after optimization

5. Conclusion

This paper addresses the necessity for viewing angle in ultra-large size OLED displays, particularly in comparison to the dimensions of mobile phones. The discrepancy in viewing angles due to the size of the display can lead to significant display uniformity issues. Additionally, the implementation of a full screen optical correction can further exacerbate the differences in viewing angles. The optimization of OLED viewing angle primarily includes microcavity effect, the matching of the RGB viewing angle curves, and the external optical diffusion. The luminance and color deviation can be enhanced after optimization, thereby meeting the requirements for a 66° viewing angle in ultra-large size displays. This paper outlines the novel requirements for the viewing angle of ultra-large size OLED displays, and proposes enhancements from multiple dimensions, thereby achieving a superior display.

References

1. C.-H. Oh, H.-J. Shin, et al. Technological progress and commercialization of OLED TV. SID Digest, 2013.
2. Weifeng Zhou, Xiangfei He, Yunpeng Zhang, et al. A Novel Ultra Large Size OLED Display Base on Small-size OLEDs. SID Digest, 2013.
3. H. J. Shin, S. H. Choi, D. M. Kim et al. A Novel 88-inch 8K OLED Display for Premium Large Size TVs. SID Digest, 2021, 52(1):611-614.
4. Hong-Jae Shin, Soo-Hong Choi, Yong-Ho Kim, et al. A Novel Ultra Large Size OLED Display for Premium TVs. SID Digest, 2023.
5. Ting Han, Shi Shiming, Le Zhu, et al. Algorithm Compensation Solution for Tiled OLED Displays. SID Digest, 2024.
6. P. Barten. Evaluation of subjective image quality with the square-root integral method, Journal of the Optical Society of America A, 1990, 7(10):2024-2031.
7. H Lee，Y Hwang，T Won. Numerical Investigation on Micro-Cavity Effect of Top-Emitting Organic Light Emitting Diode. Journal of Nanoscience & Nanotechnology, 2015.