Luminance Enhancement Cover Glass for MicroLED Displays

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Abstract

Brightness enhancement of an encapsulated micro-LED display panel was demonstrated by integrating a brightness enhancement cover glass. This cover glass has a light scattering layer formed on the back side of the encapsulation cover plate to manage the display emission angular distribution.

Author Keywords

Micro LEDs; displays; brightness; cover plate; cover glass.

1. Introduction

Micro-LED displays are emerging as a competitive emissive display technology with advantages of higher brightness, improved efficiency, good thermal stability, and long lifetime. This is due to the semiconductor-based materials, higher-resolution, and semiconductor processes [1-7]. In addition, the small micro-LED emitter area makes it possible, in principle, to achieve high ambient contrast by suppressing ambient reflections outside of the emission area. Micro-LED displays normally need to be encapsulated to address some mechanical reliability issues, such as physical contact causing micro-LEDs to detach. The typical encapsulation method is to laminate a transparent cover plate (such as glass plate) to a micro-LED display using optical clear adhesive (OCA). This also enhances the display rigidity. However, this encapsulation causes some optical issues, such as a significant degradation of the display brightness and edge light leakage of the tiles. Light leakage at the tile edges is a concern since it results in tiled micro-LED display seam visibility [5-7]. Two major reasons for these issues are: 1) encapsulation changes the light emission properties of the micro-LEDs due to the alteration of the surrounding optical condition of the light emission surfaces; 2) light confinement and guiding by the waveguide formed by the cover plate and OCA layer. Current methods to control micro-LED emission involve fabricating optical elements on the micro-LED surface and placing the micro-LEDs within reflector cavities. Although these methods affect the micro-LED emission pattern, they do not suppress optical waveguiding in the cover glass that is a root cause of the brightness reduction. These approaches also require additional processing and complexity to either the micro-LED or display backplane which already suffer from low yield. There is a need for an easily implementable solution that addresses the optical waveguiding in the display cover glass to increase brightness and reduce edge emission.

In this paper, a method to address the above issues is presented. In this method, a light scattering layer is introduced to the back side of the encapsulation cover plate. This enhances the normal encapsulated micro-LED display brightness through the management of the angular distribution of micro-LED emission.

2. Concept and principle

Figure 1(a) shows the schematic (cross-section view) of a conventional encapsulated micro-LED display. In this display, a cover plate (such as glass plate) is laminated to the micro-LED display by an OCA layer. Both the cover plate and the OCA layer have high transmission in visible spectra and negligible light scattering. Figure 1(b) illustrates the proposed method to encapsulate micro-LED displays for enhancing the display normal brightness. Compared to the conventional encapsulation, a cover glass with a light scattering layer is used to laminate the micro-LED display by a thin OCA layer. The principle behind of the normal brightness enhancement of a micro-LED display by cover glass with a light scattering layer is as follows. Compared to conventional size LEDs, with typically Lambertian light emission, the significant size micro-LED reduction results in an angular distribution that is broader than Lambertian. Consequently, the peak intensity of output light in angular space is not normal to the top emission surface. In addition, the immersion of micro-LEDs in OCA (which has a refractive index of ~1.5, higher than that of the air) further enhances the above phenomena. The introduction of a light scattering layer near the emission surfaces of micro-LEDs can redistribute more of the micro-LED emission towards the normal in angular space. This result is in the normal brightness enhancement of the micro-LED display.

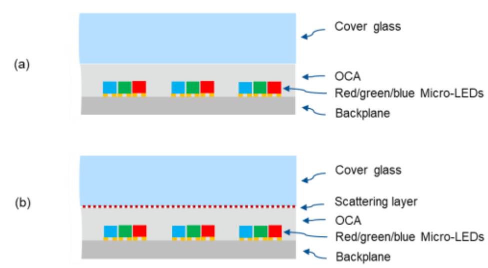

Figure 1. (a) Schematic (cross-section view) of a conventionally encapsulated micro-LED Display, in which a cover glass is laminated to the micro-LED display by an OCA layer. (b) Schematic (cross-section view) of a micro-LED display encapsulated by the proposed brightness enhancement cover glass.

3. Modeling

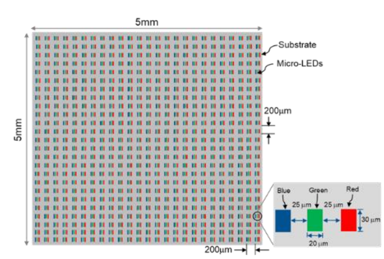

Figure 2. Schematic (top view) of micro-LED display used in the modeling.

Figure 2 shows the schematic of a micro-LED display which is used for the modeling. The display consists of 25x25 pixels with a pitch of 200μm, and each pixel includes one red micro-LED,

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one green micro-LED, and one blue micro-LED, and the spacing between the two adjacent LEDs is 25μm, and the size of R/G/B micro-LEDs is 30μmx20μm.

Table 1. Modeling cases and relevant parameters.

Case #	Lamination	Cover glass			OCA	
		Thickness (mm)	Refractive index at 550nm	Scattering factor of scattering layer σ (deg)	Thickness (μm)	Refractive index at 550nm
Case 1	No	-	-	-	-	-
Case 2	yes, cover glass w/o scattering layer	0.5	1.51	-	20	1.49
Case 3	yes, cover glass with scattering layer	0.5	1.51	Variable	20	1.49

Three cases were modeled to validate the concept. Table 1 shows the three modeling cases and relevant modeling parameters. Case 1 is the micro-LED display without laminating cover glass. Case 2 is the micro-LED display laminated with conventional cover glass (cover glass without scattering layer). Case 3 is the micro-LED laminated with cover glass featuring different scattering layers. The scattering property of a scattering layer can be characterized by using a collimated laser beam. The collimated laser beam illustrates the scattering layer from the surface normal angle, and the intensity angular distribution of the transmission light can be described by Gaussian scattering function:

$$I(\theta) = I_0 \, exp\left[-\frac{1}{2}\left(\frac{\theta}{\sigma}\right)^2\right] \quad (1)$$

where, θ is the angle (in degree) from the surface normal, $I(\theta)$ is the intensity in the θ direction, I_0 is the intensity of in the surface normal direction, and the scattering factor σ is the standard deviation of the Gaussian distribution, in degree.

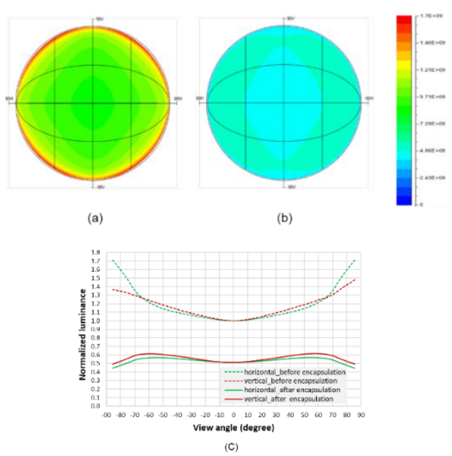

Figure 3. Display luminance distributions of (a) case 1 and (b) case 2 in angular space. (c) Cross-sections of luminance distribution in angular space of the micro-LED display before (upper two curves, case 1) and after conventional encapsulation (lower two curves, case 2).

Figures 3(a) and 3(b) show the luminance distributions in angular space of the micro-LED display before (case 1) and after laminating with cover glass without a scattering layer (case 2), respectively. Figure 3(c) shows the cross-sections of luminance distributions in angular space of the micro-LED display before (upper two curves) and after the encapsulation (lower two curves). The luminance of the display in all spatial angles drops by more than 48% after the encapsulation, and the luminance at the display normal decreases about 50%. Figure 4 shows the changes of the luminance distribution of the display for (a) case 1, (b) case 2, (c-f) cases 3 for the scattering layer with different scattering factors (σ=4, 10, 20, and 30 degrees). As shown in Figures 4(c-f), with an increasing the scattering factor, more light is directed away from the higher angles to lower angles (near the display normal: 0-degree angle). This results in the display at lower angles having increased brightness. When the scattering factor σ=30degrees (Figure 4(f) of cases 3), the normal brightness of the display is approximately 50% higher than that of the display laminated with the cover glass without the scattering layer (case 2).

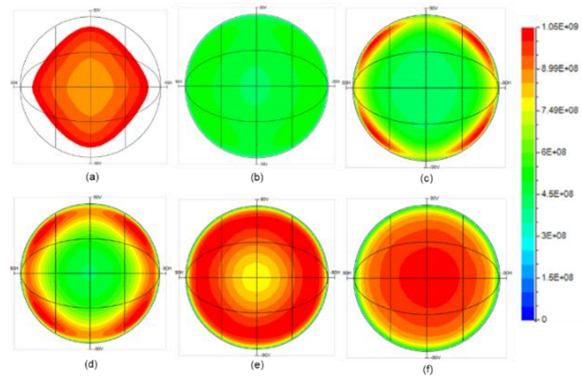

Figure 4. Display luminance distributions of case 1, and 2, case 3 (with different scattering factor σ) in angular space. (a) case 1: display without encapsulation. (b) case 2: display laminated by cover glass without scattering. (c-f) case 3: display laminated by cover glass with the scattering layer with different scattering factor (σ=4, 10, 20, or 30 degrees).

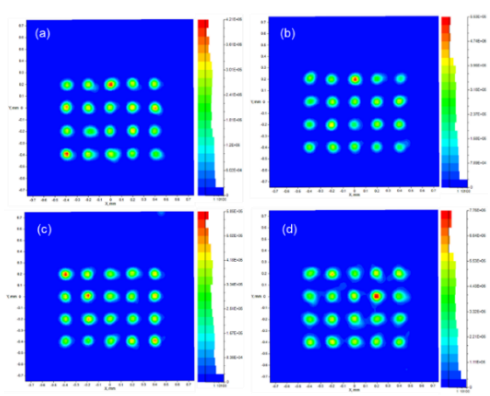

Figure 5. Images of the display with 4x5 switched-on pixels for (a) case 2 (no scattering layer) and the case 3 in which the scattering layer is with (b) σ=10degrees; (c) σ=20degrees; or (d) σ=30degrees.

The introduction of a light scattering layer in the cover plate can improve the brightness of an encapsulated micro-LED display. However, it might also cause crosstalk between pixels which results in the degradation of display contrast. Thus, we also conducted crosstalk simulations. Considering the calculation time and computer capability, in all simulations, only the micro-LEDs of 4x5 pixel array located at the display center are switched on. Figure 5(a) show the images of the display with 4x5 switched-on pixels for the case 2 (no scattering layer) and the case 3 in which the scattering layer is with (b) σ=10degrees; (c) σ=20degrees; or

(d) σ=30degrees. No noticeable crosstalk between pixels is observed with the scattering factor up to σ=30degrees. This result indicates case 2 can improve the display brightness without introducing significant crosstalk between pixels when the scattering factor of the scattering layer is less than 30 degrees.

4. Experimental results and discussions

In our experiments, blue micro-LED array modules with an emission area of 14mm x 14mm were used for the concept validation. The devices integrated 20μm x 20μm size blue micro-LEDs with a pitch of 180μm.

Table 1 show the three experimental cases which used in the experimental study. The first case (reference case) is a micro-LED module laminated to 0.5mm thick Corning glass with a 25μm thick OCA layer. The second case is a micro-LED module laminated to 0.5mm thick Corning glass with scattering layer SL1 using a 25μm thick OCA layer. The third case is a micro-LED module laminated to 0.5mm thick Corning glass with scattering layer SL2 using a 25μm thick OCA layer. The significant difference in these conditions is the scattering layer presence and type.

Table 1. Experimental cases to be studied.

Experiment #	Cover glass	OCA thickness (μm)
1	0.5mm thick Corning glass *without* scattering layer	25
2	0.5mm thick Corning glass *with* scattering layer SL1	25
3	0.5mm thick Corning glass *with* scattering layer SL2	25

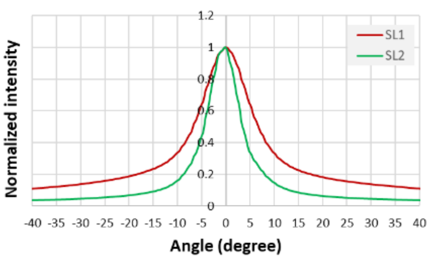

Figure 6. Measured scattering functions of scattering layers SL1 and SL2.

Figure 6 shows the measured scattering functions of the scattering layers SL1 and SL2. The scattering layer (SL1 or SL2) was fabricated on the back surface of the 0.5mm thick Corning cover glass. The thickness of the scattering layer is ~2μm.

Figures 7(a) and 7(b) show the luminance distributions the micro-LED module of Case 1 in angular space before and after laminating the cover glass, respectively. Figure 7(c) shows the cross-sections of luminance distributions of the micro-LED module before (upper two curves) and after the encapsulation (lower two curves). The luminance of the display at all spatial angles drops after the lamination, and the luminance at the display normal angle decreases about 49%, which is in good agreement with the modeling prediction. Figures 8(a) and 8(b) show the luminance distributions of the micro-LED module of Case 2 in angular space before and after laminating the cover glass with scattering layer SL1, respectively. Figure 8(c) shows the cross-sections of luminance distributions of the micro-LED module before (upper two curves) and after the encapsulation (lower two curves). Unlike Case 1, the scattering layer integration causes the luminance of the display at the normal to be almost unchanged after the lamination. Figures 9(a) and 9(b) show the luminance distributions of the micro-LED module of the case 3 in angular space before and after laminating the cover glass with scattering layer SL2, respectively. Figure 9(c) shows the cross-sections of luminance distributions of the micro-LED module before (upper two curves) and after the encapsulation (lower two curves). Compared with Case 1 the improved scattering layer properties, cause the luminance of the display at the normal angle after the lamination to be even higher than that before the lamination. Figure 10 compares the changes of the average normal brightnesses of the three micro-LED modules after lamination of cover glasses. For Case 1 the average normal brightness of the module drops about 49% due to the cover glass lamination, while the introduction of the scattering layer results in the average normal brightness of the module decreasing by only 0.3% after the lamination in Case 2, and even increasing 12.7% after the lamination in Case 3.

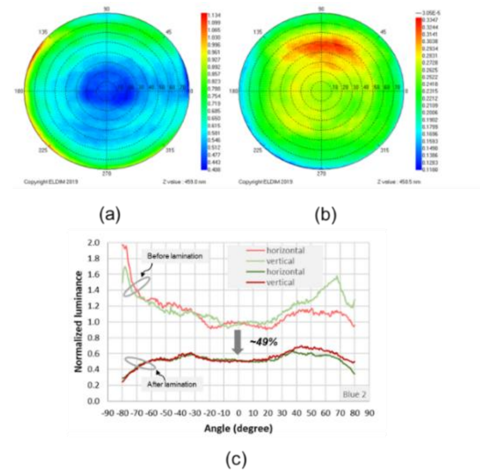

Figure 7. Display luminance distributions of the micro-LED module of the Case 1 before and after laminating the cover glass. (a) and (b) Display luminance distributions in angular before and after laminating the cover glass. (c) Cross-sections of luminance distributions before (upper two curves) and after (lower two curves, case) laminating the cover glass.

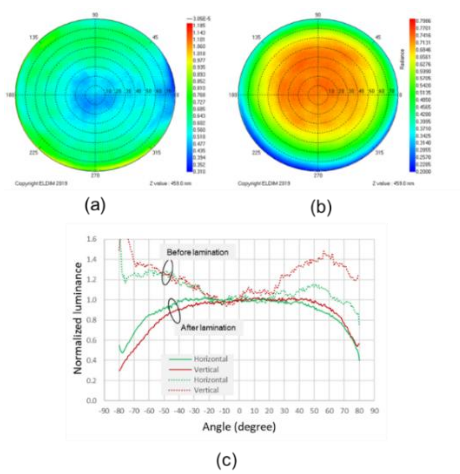

Figure 8. Display luminance distributions of the micro-LED module of the Case 2 before and after laminating the cover glass with scattering layer SL1. (a) and (b) Display luminance distributions in angular before and after laminating the cover glass. (c) Cross-sections of

luminance distributions before (upper two curves) and after (lower two curves, case) laminating the cover glass.

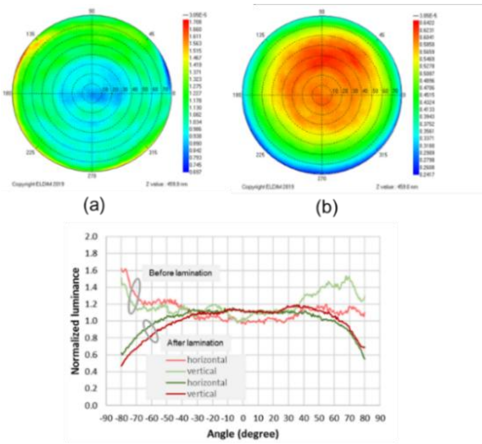

Figure 9. Display luminance distributions of the micro-LED module of the Case 3 before and after laminating the cover glass with scattering layer SL2. (a) and (b) Display luminance distributions in angular before and after laminating the cover glass. (c) Cross-sections of luminance distributions before (upper two curves) and after (lower two curves, case) laminating the cover glass.

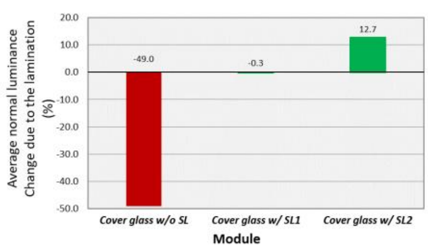

Figure 10. Changes of the average normal brightnesses of the three micro-LED modules due to the lamination of cover glasses.

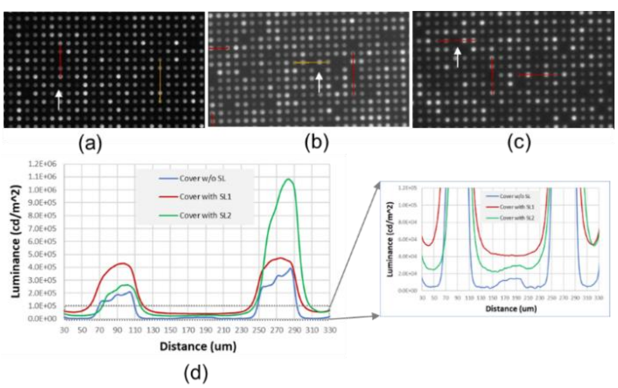

Figure 11. Raw images of the three switched-on micro-LED modules. (a) micro-LED module laminated by cover glass without scattering layer. (b) micro-LED module laminated by cover glass with scattering layer SL1. (c) micro-LED module laminated by cover glass with scattering layer SL2. (d) Cross-sections of luminance distributions of the three micro-LED modules at the locations with one dark pixel. The left insert figure is the plot of zooming the Y-axis.

The light crosstalk between the pixels in a display is an important performance metric which affects the display contrast ratio (CR). Figure 11 shows the raw images of the three switched-on micro-LED modules and the cross-sections of luminance distributions of the three micro-LED modules at the locations one of specific dark pixels. Compared with the micro-LED module laminated with cover glass without scattering layer (Case 1), the increased light crosstalk is observed in the micro-LED modules of Cases 2 and 3. However, in comparison to the micro-LED module with SL1 (Case 2), the crosstalk level of the micro-LED module with SL2 (Case 3) is reduced by ~50%. As shown in Figure 6, the crosstalk improvement should come from the reduction of light scattering of the scattering layer at large angles. Through optimization, scattering layer properties can further improve the brightness and crosstalk of a micro-LED display.

5. Conclusion

Corning has developed a method to enhance the brightness of an encapsulated micro-LED display. Higher brightness than non-laminated micro-LED arrays was experimentally demonstrated by using a cover glass with a properly engineered scattering layer. Although increased light crosstalk was observed in the modules laminated by the covers with scattering layer, experimental results confirmed that the crosstalk could be suppressed by optimizing the property of scattering layer. which can cause the issue of tiling seam visibility in a tiled display. This method is easy to be implemented because of non-alignment requirement between the optical features and the LED emitters.

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