18.4: A New Seamless Foldable OLED Display Composed of Multi Display Panels

HongShik Shim, InSeo Kee, SunKook Kim, YoungTea Chun, HyukJun Kwon, YongWan Jin, and SangYoon Lee
Samsung Electronics, Yongin, Gyeonggi, Korea

DongWon Han, JinHo Kwack, DongHun Kang, HaeKwan Seo, MyoungSeop Song, MyungHo Lee and SungChul Kim
Samsung Mobile Display, Yongin, Gyeonggi, Korea

Abstract
A new seamless foldable OLED display composed of multi display panels is proposed. To verify seamless viewing and robust folding-unfolding reliability, a 138 ppi resolution, 5.4" diagonal size AM-OLED seamless foldable display prototype is fabricated.

1. Introduction
Because foldable display can reduce the form factor of display device, it has a lot of potential benefits. For example, recent mobile devices boast mainly 2~3" size displays, which are not enough to fully satisfy the customer's needs such as full web browsing, e-mailing, document reading, and HD-level video playback capabilities. Foldable display can satisfy those demands by making 5~7" size screen in the same form-factor [1]. Usually, foldable displays are recognized as a part of flexible displays, and the roadmap of foldable display is not different to that of flexible display. Despite recent much progress in flexible displays, high-performance active matrix displays on flexible substrate still possess some problems which might be hurdle to be commercialized. Recently, a new approach to create a foldable display using individual two LCD panels was developed [2]. This method has the advantage that already mature, high-quality display panels such as TFT-LCD are available, but the physical seam line on the screen causes a bad impression to viewers. Our research was originally started to aim for OLED tiling display [3, 4], but we extended our technology to make foldable display which is composed of more than two individual AMOLED display panels. As a result a new foldable AMOLED display which can show the seamless imaging and robust mechanical folding ability is developed. In this paper, we describe seamless viewing method, prototype fabrication process, and the evaluation results of our seamless foldable AMOLED display.

2. Seamless Imaging

2.1. Optical simulation design
Before fabricating the foldable display prototype, several optical simulations were made using computer simulator for predicting the optical characteristics of the display and reducing the number of errors. All model design and optical simulation of this foldable display were performed using commercial software, RayWiz (Insideoptics Co. Ltd., Korea). For the same reason as our previous work, we choose the overlap structure as the basic concept of our foldable display. [3, 4]. In order to fit the actual situation, top emission type OLED panel structure is adopted as a simulation model. Differing from our previous work as shown in the figure 1, the preliminary simulation results show that there are two dark visible seam lines on the screen which are denoted as line A and line B. And the locations of each lines match to the pixel to pixel junction (line A) and the boundary of panel 1 and transparent plate (line B) respectively.

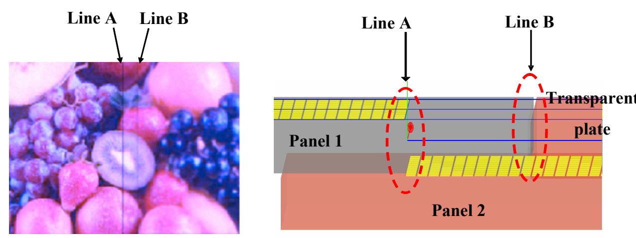


Figure 1. Two dark visible seam lines occur in display. (a) is the simulation image and (b) is the schematic diagram

Based on these preliminary results, we intend to quantify these dark visible seams in detail by split simulation. Same as previous works, 4 main items are considered as split parameters.

(1) Perfection of attachment between OLED panels and transparent plate

If there is any air gap between the two dielectric materials, some of the light can be reflected off that surface. This reflection causes luminance decrease in the boundary area.

(2) Refractive index of transparent plate

Refractive index of transparent plate also affects edge reflection of lights.

(3) Vertical gap between two emission layers

Vertical gap between two emission layers in each OLED panel is related to the glass substrate thickness.

(4) Observation direction changes.

We also monitor the luminance deviation relative to the observation angle. Notation of direction is described in the fig 2.

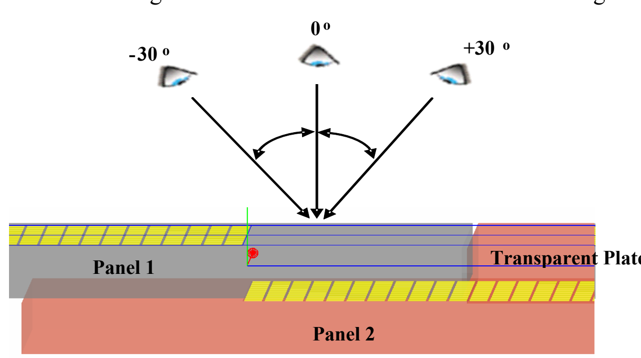


Figure 2. Observation directions

2.2. Simulation Results

Figure 3 shows the luminance distribution results at 0.5 mm the glass thickness. The decrease of luminance can be seen as yellow and green vertical lines in the overlapping region of the two panels. The severe decrease of luminance is related to contact/non-contact status and observation direction. In some cases, two seam lines are occurred which is same to previous preliminary simulation results.

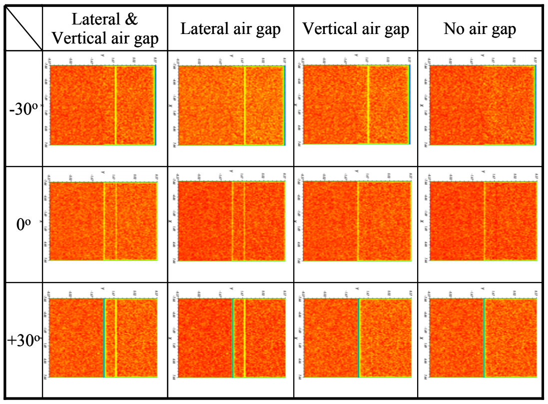
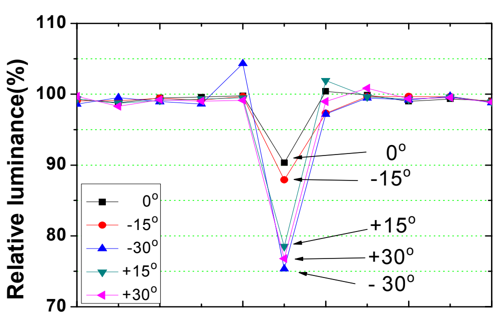
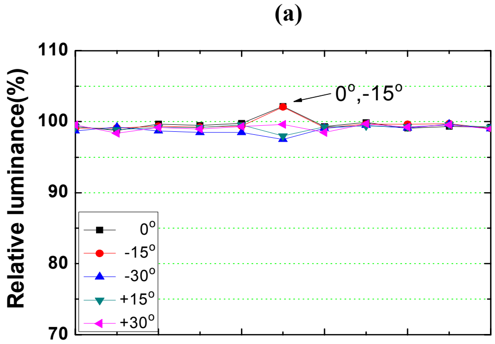


Figure 3. Luminance simulation results

From those results, lateral air gap and the line B are expected to be involved. If there is no lateral air gap and the observation direction is restricted as normal and positive direction, line B does not occurred. More detail luminance simulation results are shown in fig 4. Figure 4 (a) and (b) present a degree of luminance decay of line B whether there is a lateral air gap or not respectively.



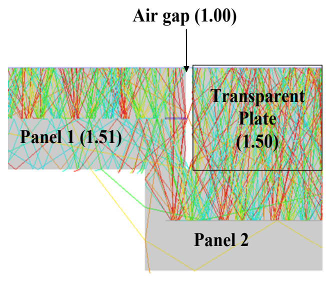
(a)

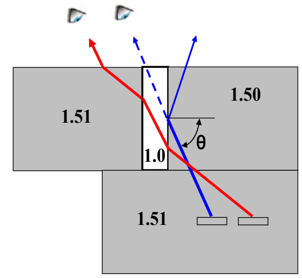


(b)

Figure 4. Relative luminance of line B. (a) is in the case of lateral air gap is exist and (b) is in the case of lateral air gap is not exist.

In the case of lateral air gap (Fig 4. (a)), a considerable luminance decrease of line B is observed. In the case of 0° and +15° observation angle, the degree of luminance decrease is about 10%. And in the case of other viewing angle observation, luminance of line B is about 20% darker than other areas. On the other hand, if there is no lateral air gap, luminance decrease does not appear in most cases (Fig 4. (b)).





(a) (b)

Figure 5. (a) is the schematic side view of adjacent two panels and (b) shows some ray traces

Those results are due to the total reflection which occurs on the boundary edge between the dielectric plate and the air gap. Fig. 5.(a) shows the schematic side view of the adjacent two panels, and Fig 5.(b) shows some ray traces which crosses the boundary between materials with different refractive index. When there is no lateral air gap, even the effect is relatively smaller than that of air gap, refractive index variation of transparent plate affects the luminance change of line B. These luminance changes are presented in Fig 6.

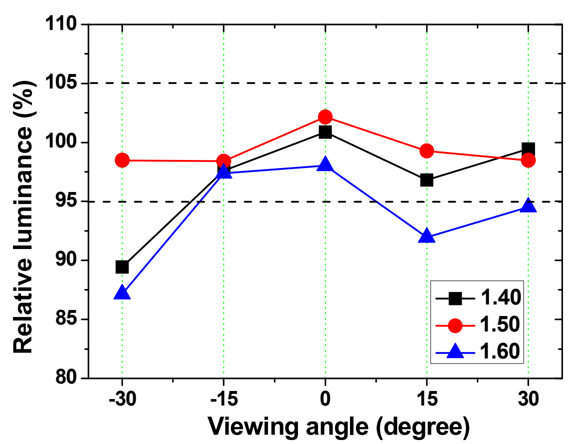
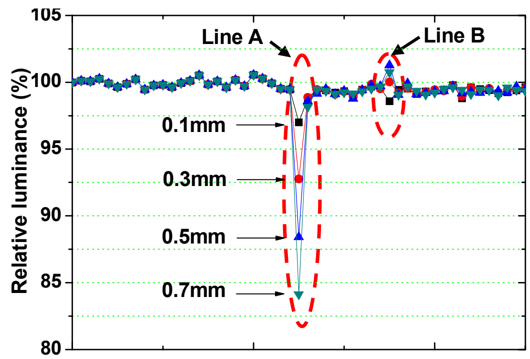


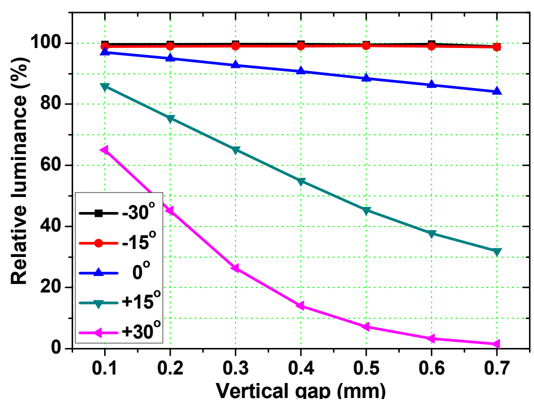
Figure 6. The minimum luminance decreases of line B when the refractive index of transparent plate and viewing angle are changed.

In the case where the refractive index is 1.50, all luminance changes are within ± 3%. But in the case of 1.40 and 1.60 refractive indexes, in large viewing angles, over 5% luminance decrease is observed. To prevent this luminance decrease, the refractive index of transparent plate must be similar as that of panel (glass).

Fig 7 (a) shows the luminance simulation when the vertical gap between two light emissive layers is incremented from 0.1mm to 0.7mm by 0.2mm. We can confirm that the luminance of line A is diminished as the vertical gap increases. On the other hand, the luminance of line B is almost not affected by the gap change.



(a)



(b)

Figure 7. (a) is the luminance decrease of line A and line B when the vertical gap between two light emitting surfaces is changed and the observation angle is 0° (b) is the minimum luminance decrease of line A when the vertical gap and observation angle are changed.

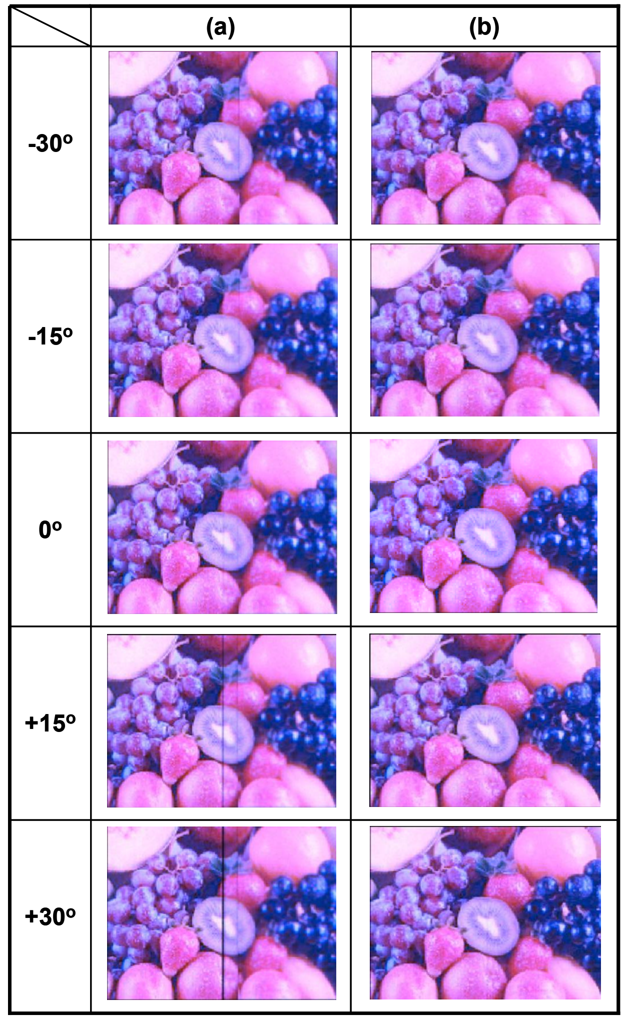


Figure 8. Several image simulation results. (a) is the results when the vertical gap between two emissive layer is 0.7mm, lateral air gap is exist and the additional overlapped pixel line is not applied. (b) is the results when the vertical gap is 0.2mm, lateral air gap is not exist and the additional overlapped pixel line is applied.

Fig. 7 (b) shows the relationship between viewing angle and luminance decrease degree of line A. When the viewing angle is tilted to OLED panel 1 (negative viewing angle), luminance change is almost negligible. But in the case of positive viewing angle observation, the luminance of line A is proportional to the vertical gap and the degree of luminance decrease grows heavier as the positively tilting angle is enhanced. The reason why the local luminance decrease happens and the way how can reduce that is mentioned in our previous work.[4].

Several image simulations are performed to predict the image on a real display device. Fig. 8 (a) is the image simulation results for 0.7mm vertical gap, lateral air gap and no pixel overlap, while Fig. 8 (b) is the results for 0.2mm vertical gap, no lateral air gap and slightly overlapped pixel structure. We can confirm that the dark line (luminance decrease) on the images in Fig. 8 (a) are almost eliminated in Fig. 8 (b).

From these and several other computer simulation results, we conclude that three methods to reduce the dark seam line in display images are reducing the horizontal gap between the light emissive layers of both OLED panels, eliminating the air gap between the transparent plate and OLED panels, and adopting an additional pixel line on the lower OLED panel.

3. Prototype fabrication & Evaluation

From these results we designed a new foldable AMOLED display. Each AMOLED panel is made by general top-emission AMOLED panel fabrication process except for the encapsulation step. Thin film encapsulation process was made by forming alternative organic and inorganic layers on AMOLED panels. The entire film layer thickness is about several ㎛ and the thickness of AMOLED panel 1 is slimmed down to 0.05mm. This thin AMOLED panel 1 is emerged to transparent plate in order to eliminate the lateral air gap. This transparent plate consisted of silicone rubber which has good elasticity. On this transparent plate a flexible optical film is introduced to prevent the reflection by incident lights. Fig. 9 shows the schematic side view of foldable OLED display.

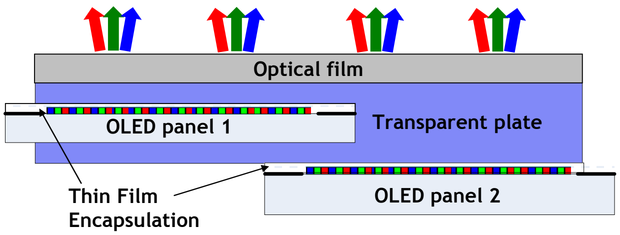


Figure 9. Schematic side view diagram of foldable display

The photographic images of our prototype are shown in Figure 10 and a brief specification is in Table 1. This prototype shows a faint shadowing seam line in the normal direction view and both oblique direction views. This weak seam line might be the influence of misaligned semitransparent cathode layers of OLED panel 1.

Figure 10. Photographic images of prototype at left oblique, normal and right oblique direction

Display specifications	
Type	Active Matrix OLED
Active Size	107.0 mm [V] x 172.8 mm [H] (5.4 inch diagonal)
Number of pixels	480xRGBx270
Resolution	138ppi
Pixel Size	186 um [V] x 186 um [H]
Aperture ratio	40.6 %
Encapsulation	Thin film encapsulation
TFT structure	LTPS (Top Emission)

Table 1. PROTOTYPE DISPLAY SPECIFICATIONS

The effect of improvements which are predicted by simulation study is shown in fig 11. Figure 11 (a) is the luminance cross-section graphs of the previous foldable display and (b) is that of new one. This graph shows that the two seam lines are almost eliminated on our new prototype.

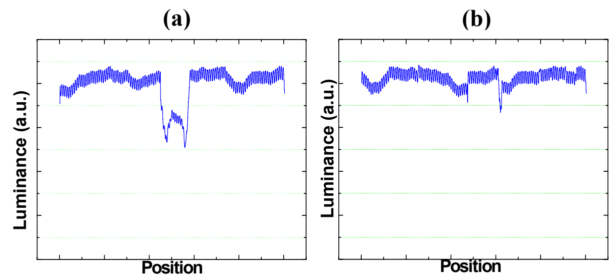


Figure 11. Luminance cross-section graph of whole display

Because the rotating axis is located in the middle of elastic part (Fig 9), this structure has high reliability against repeated folding-unfolding action. During one AMOLED panel is folded onto another AMOLED panel, no rigid optical or electrical part is folded. We confirm that our prototype was normal operation after 10,000 times folding. The successive folding still shots are shown in Fig 12.

Figure 12. Successive still shots of prototype display unfolding.

4. Conclusion

Through computer simulations and prototype fabrication, we confirm the feasibility of seamless foldable OLED displays. Our prototype offers seamless image viewing and reliable device structure. It also displays high speed moving images which is not possible in previous foldable displays. In addition, the mass-production possibility of our foldable display is high, due to its use of already commercial AMOLED panels. This novel seamless displaying technology can be applied not only to foldable displays, but also to large size tiled displays.

5. References

[1] Hyung Kyu Lim, International Solid State Circuit Conference proceeding, p. 18, San Fransisco, IEEE (2008)

[2] Nam-Seok Lee, et al., Society of Information Display digest, p 546, (2002)

[3] HongShik Shim, et al., Society of Information Display digest, p 518, (2008)

[4] HongShik Shim, et al., International Display Workshop proceeding, p 173, (2008)