A Novel Architecture for Autostereoscopic 2D/3D Switchable Display Using Dual Layer Strip Patterned OLED Backlight Module

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***Abstract*—A novel backlight module that integrates dual layer strip patterned organic light emitting diode (DLSP-OLED) for 2D/3D switchable display was demonstrated. The DLSP-OLED functions as a parallax barrier in 3D mode and a planar light source in 2D mode. The results indicated that the backlight module with a thin form factor ($\sim$1.1 mm) can achieve uniformity of 91% in 2D mode, and increased optical efficiency by a factor of 2.8 with a crosstalk of less than 6% in 3D mode, compared with the conventional 2D/3D switchable display. A fast switching rate ($<$1 ms) with simple operation can eliminate the visual fatigue caused by flicker during the switching. In addition, this configuration can function localized 3D display by modulating the DLSP-OLED individually.**

***Index Terms*—Crosstalk, DLSP-OLED backlight, localized 3D, optical efficiency, 2D/3D switchable display.**

I. Introduction

THREE-DIMENSIONAL (3D) display is becoming popular [1]. Nowadays, people enjoy seeing 3D films, while others still prefer 2D images. Therefore, 2D/3D switchable display is a good feature to meet consumers' various needs.

Typical 2D/3D switchable displays can be classified into two general categories, namely, by backlight module design and by liquid crystal (LC) components, which including LC barrier and LC lenticular. The LC barrier type technologies such as the wire grid polarizer [2] and the shifted Indium Tin Oxide(ITO) electrode structure [3] show some notable success for short viewing depth, thin form factor, and variable viewing zones, but with the major drawback of low brightness owing to light absorption by LC barrier [4]–[6]. The LC lenticular types exhibit the merits of high transmittance and possibility of using similar fabrication process of conventional LC displays [7]–[11]. Nonetheless, due to the non-ideal refractive index distribution of LC lens, the high crosstalk is still a major issue, hindering it from commercial applications. Moreover, various optical designs on backlight module have been reported with the benefits of cost and fabrication. However, the thickness of proposed structures cannot be largely reduced due to their dual-layer light guide plates [12]–[15]. On the other hand, OLEDs are promising for future displays owing to unique properties of self-emission, light weight, high luminance, wide viewing angle, and fast response [16]–[18].

We demonstrate a novel DLSP-OLED backlight module of high optical efficiency, low crosstalk, fast switching, and thin form factor for 2D/3D switchable display. Besides, the DLSP-OLED backlight module is potential for localized 3D display application.

II. Design Principle

In a conventional 2D/3D switchable display with an absorption-type parallax barrier system (e.g., LC barrier type), two major factors affect the optical efficiency. The most crucial factor is barrier absorption, which only allows a part of the incident light to pass through and absorb the rest. Moreover, the aperture ratio of the barrier limits optical efficiency significantly. In order to suppress the crosstalk, reducing the aperture ratio of the parallax barrier is a plausible method, often at the expense of optical efficiency. Consequently, the optical efficiency in 3D mode is often less than 40% in two-view system and even lower in multi-view system [6]. Therefore, to improve the optical efficiency is a critical issue.

A DLSP-OLED backlight module comprising dual layer strip patterned OLED with two glass substrates and a thin-film encapsulation (TFE) layer, is proposed to enhance the optical efficiency. The proposed structure of DLSP-OLED backlight module is shown in Fig. 1.

Some special designs have been employed to improve the optical efficiency in this configuration. The absorption type barrier (e.g., LC barrier type) is replaced by the reflection type (cathode of DLSP-OLED) with the high reflective index material, which can effectively reflect lights back to glass substrate for recycling. The bottom layer OLED are patterned as the strip type and only in locations corresponding to the slits of the parallax barrier to extract more rays from backlight, as shown in Fig. 2. Moreover, based on micro-cavity effect, the structure of bottom

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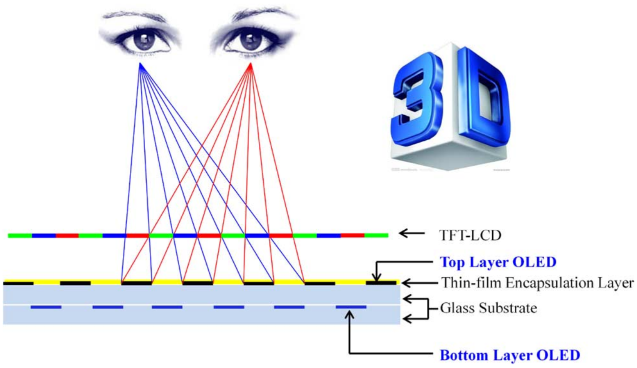

Fig. 1. The configuration of DLSP-OLED backlight module.

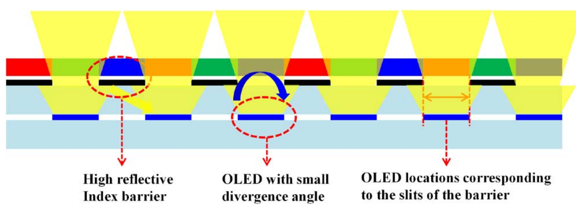

Fig. 2. Improving the optical efficiency in 3D mode.

TABLE I
OPERATING MODES AND FUNCTIONS OF DLSP-OLED

	2D Mode	3D Mode
Top layer OLED	**ON** (Light Source)	**OFF** (Parallax Barrier/ Reflective Film)
Bottom layer OLED	**OFF** (Reflective Film)	**ON** (Light Source)

layer OLED has been optimized so that the angular distribution can be compressed compared with the Lambertian distribution. Consequently, more rays can be converged to the slits, resulting in a higher light out-coupling. In this case, the optical efficiency of the DLSP-OLED backlight module can effectively increase in 3D mode.

The cornerstone of the backlight module is DLSP-OLED, which plays different roles in different modes. The different operating modes and functions of DLSP-OLED are summarized in Table I. In addition, the fast switching rate (<1 ms) between 2D and 3D mode by alternating the different light sources can decrease the visual fatigue caused by flicker during the switching.

III. RESULTS AND DISCUSSION

A prototype was fabricated to demonstrate the effect of the DLSP-OLED structure, as illustrated in Fig. 3. Based on the fundamental principle of binocular parallax, the parameters of the backlight module are summarized in Table II. The proposed thin-film encapsulation (TFE) layer was replaced by a thin cover glass to simplify the fabrication and protect the DLSP-OLED. It should be noted that though replacing the TFE layer with a thin glass, the total thickness of the DLSP-OLED backlight module (1.1 mm) was still much thinner than others (2–3 mm) [12], [13].

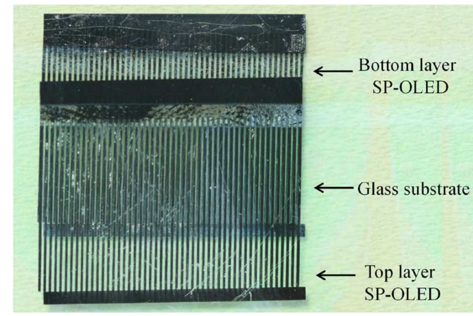

Fig. 3. Prototype of the DLSP-OLED backlight module.

TABLE II
PARAMETERS OF THE HYBRID BACKLIGHT MODULE

View points	2
Backlight dimensions (mm)	20*20*1.1
Width of sub-pixel (μm)	149.9
Width of strip patterned OLED top/bottom (μm)	150/150
Width of slit (μm)	150
Thickness of OLED glass substrate top/bottom (mm)	0.4/0.4
Thickness of cover glass (mm)	0.3
OLED emission type	Top emission
Best viewing distance (cm)	34.5

The system form factor can be further reduced by using TFE layer, which is benefit for light weight in mobile device.

The optical efficiency in 3D mode for a hybrid backlight combining a single layer strip patterned OLED and a normal LGP with special designed patterns on bottom surface is compared. The locations of special designed patterns are the same with the bottom layer SP-OLED and the dimensions of the special patterns have been optimized in hybrid backlight. The optical efficiency with five different structures of backlight modules were obtained by ray tracing software LightTools and the simulation results are illustrated in Table III.

Compared with the five types A, B, C, D and E, the results are obtained as follows:

A-B: The reflection-type barrier can increase the efficiency by more than 20%, implying that the absorption-type barrier is a major issue of low optical efficiency in barrier-type system.

B-C: The optical efficiency of Type C is largely enhanced by more than 35% with the aid of the reflection-type barrier and strip-type micro-prisms. Compared with strip-type scattering patterns, the strip-type micro-prisms can further improve the optical efficiency because the former simply diffuses the rays without controlling the directions of light transmission, whereas the latter controls the rays in a precise manner and guides the rays to the barrier slits.

TABLE III
DIFFERENT TYPES OF BACKLIGHT MODULE

Type	A Conventional (LGP+LC barrier)	B Hybrid (LGP+SP-OLED)	C Hybrid (LGP+SP-OLED)	D DLSP-OLED	E DLSP-OLED
Barrier Type	Absorption	Reflection	Reflection	Reflection	Reflection
Features	LC barrier	Strip-type scattering patterns on LGP	Strip-type micro-prisms on LGP	Lambertian distribution (Both T/B layer OLED)	Lambertian (T-layer) Micro-cavity (B-layer)
Optical Efficiency (%)	34	55	69	80	94

LGP: Light guide plate.

C-D: Type D has a higher light out-coupling than LGP owing to the fact that the rays are less trapped in glass substrate of DLSP-OLED backlight. Thus, the DLSP-OLED backlight shows improved optical efficiency than that of the hybrid structure.

D-E: The DLSP-OLED backlight with micro-cavity can further enhance the optical efficiency due to their smaller full width at half maximum (FWHM) to couple more rays to the slits of the barrier. It almost has the same efficiency compared with the conventional 2D/3D switchable display with LC lens type [7].

The optical properties such as crosstalk, uniformity of spatial luminance, and light divergence angle are commonly used to evaluate the performance of 2D/3D switchable display. For 3D effect, the crosstalk, which is defined as the peak light intensity of one parallax ray divided by the total light intensity at the same position, is an important factor. We measured the luminance distribution of the backlight in different positions by spectro-radiometer (CS-2000) for calculating the crosstalk. As shown in Fig. 4, the crosstalk is minimized less than 6% at the best viewing position, which is much lower than tolerable level [6]. Consequently, not need to reduce the aperture ratio of parallax barrier for low crosstalk at the expense of optical efficiency.

The spatial luminance distributions were measured to evaluate the uniformity of the novel backlight in 2D mode, as shown in Fig. 5. The uniformity is defined as the minimum luminance divided by the maximum luminance. The results reveal that a high uniformity of 91% is obtained with the novel backlight module. The mura effect can be observed at the edge of the backlight due to the non-uniform current density distribution, which can be eliminated by optimizing the electrodes of SP-OLED. Thus, the active area can be enlarged and the utilization of the backlight can be further increased.

The light distribution was measured to evaluate the viewing angle of the backlight as illustrated in Fig. 6. These results demonstrated that the novel backlight module offered the same functionality as a conventional 2D display when only top layer OLEDs are switched on in 2D mode. Besides, the angular distribution of bottom layer OLED is smaller than that of the conventional one for increasing the optical efficiency in 3D mode.

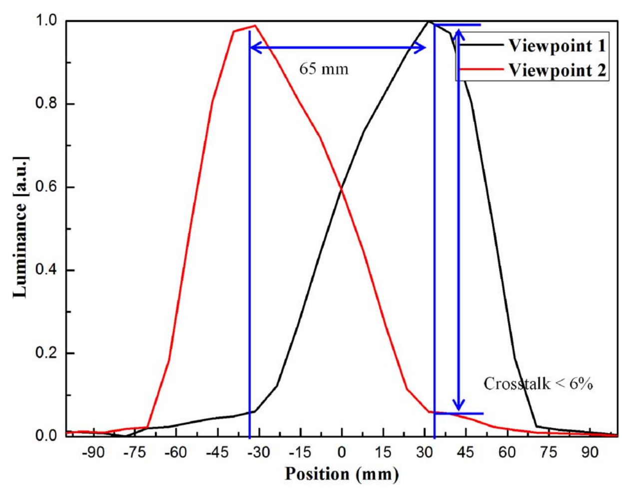

Fig. 4. Light distribution at viewing plane for two-view autostereoscopic 3D display.

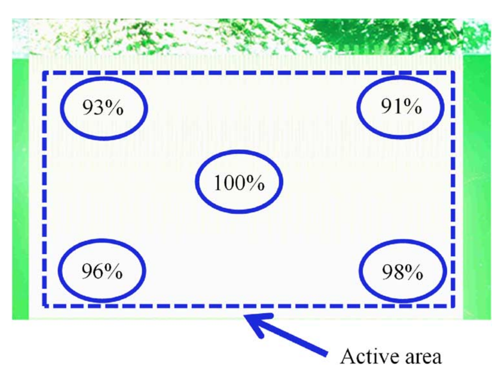

Fig. 5. The spatial luminance distributions of the backlight.

The trend of bottom OLED FWHM v.s. 3D cross-talk were simulated by the ray tracing software Lighttools and the result is shown in the Fig. 7 below:

The simulation results indicated that the crosstalk varied slightly with the increasing the FWHM of bottom OLED when the FWHM is larger than ± 30 deg.. On the other hand, as the FWHM of bottom OLED reduced to ± 20 deg., the high directional light source cannot result in 3D effect.

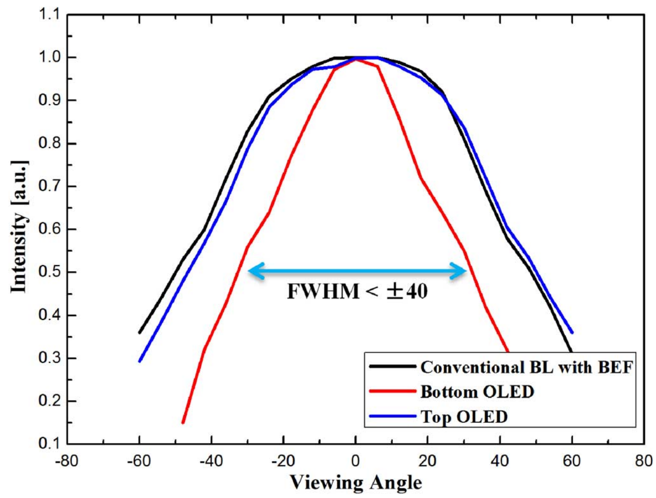

Fig. 6. The light divergence angle of the DLSP-OLED.

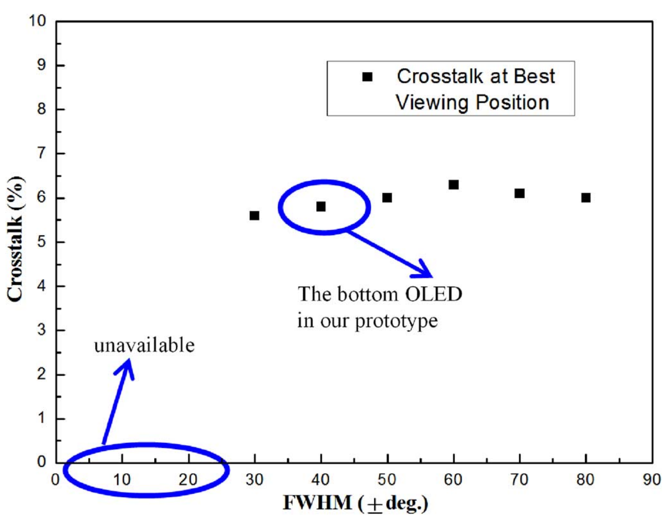

Fig. 7. FWHM of bottom OLED v.s. 3D crosstalk.

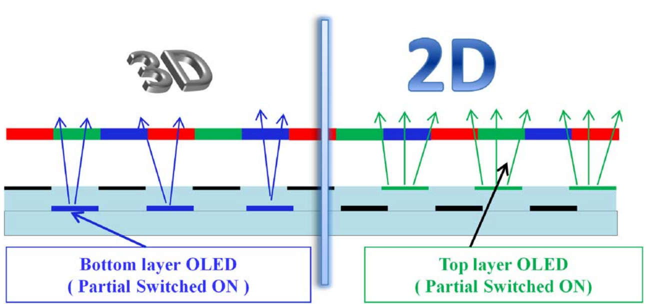

Fig. 8. Backlight operated in a localized 3D mode.

This novel configuration shows a potential application for a localized 3D display in landscape mode. This function can be yielded by illuminating partial bottom layer OLEDs for 3D effect and partial top layer OLEDs for 2D effect in their specific regions, respectively, as illustrated in Fig. 8. The parallax images are required in 3D regions and only single image is needed in 2D regions. Thus, the localized 3D display can apply 2D scripts and 3D images simultaneously by modulating the DLSP-OLED individually.

IV. Conclusion

We demonstrated a DLSP-OLED backlight module for autostereoscopic 2D/3D switchable displays, whose optical efficiency in 3D mode increase by a factor of 2.8 compared to the conventional 2D/3D display. The backlight with a thin form factor (<1.1 mm) shows the merits of high uniformity (>91%), low crosstalk (<5%) and fast switching rate (<1 ms). In addition, a localized 3D display can be obtained with a simple operation, to meet consumers' various demands. As a consequence, the DLSP-OLED backlight module is potential for future display applications.

References

[1] B. Javidi and F. Okano, *Three-Dimensional Television, Video, Display Technologies*. New York, NY, USA: Springer, 2002, p. 461.
[2] D. H. Kang, B. S. Oh, J. H. Oh, M. K. Park, H. J. Kim, S. M. Hong, J. Ho Hur, J. Jang, S. J. Lee, K. H. Lee, and K. H. Park, "Auto-stereoscopic TFT-LCD with LC parallax barrier on wire grid polarizer," in *SID Symp. Dig.*, 2009, vol. 40, pp. 344–347.
[3] K. Kang, S. Park, S. Hwang, J. Yoon, D. Hwang, S. Moon, A. Cho, T. Park, and Y. Kim, "LC barrier with a shifted ITO electrode structure for additional sweet spots," in *SID Symp. Dig.*, 2012, vol. 43, pp. 1061–1064.
[4] J. Y. Son, V. V. Saveljev, J. S. Kim, S. S. Kim, and B. Javidi, "Viewing zones in three-dimensional imaging systems based on lenticular, parallax-barrier, microlens-array plates," *Appl. Opt.*, vol. 43, pp. 4985–4992, 2004.
[5] W. Mphepö, C. L. Wu, S. C. Chuang, Y. P. Huang, C. H. Chen, and H. P. D. Shieh, "High transmittance LC pixel design for multi-view 3D mobile display," in *SID Symp. Dig.*, 2008, vol. 39, pp. 1967–1970.
[6] W. Mphepö, Y. P. Huang, and H. P. D. Shieh, "Enhancing the brightness of parallax barrier based 3D flat panel mobile displays without compromising power consumption," *J. Display Technol.*, vol. 6, no. 2, pp. 60–64, Feb. 2010.
[7] G. J. Woodgate and J. Harrold, "High efficiency reconfigurable 2D/3D autostereoscopic display," in *SID Symp. Dig.*, 2003, vol. 34, pp. 394–397.
[8] H. K. Hong, S. M. Jung, B. J. Lee, H. J. Im, and H. H. Shin, "Autostereoscopic 2D/3D switching display using electric-field-driven LC lens (ELC lens)," in *SID Symp. Dig.*, 2008, vol. 39, pp. 348–351.
[9] J. G. Lu, X. F. Sun, Y. Song, and H. P. D. Shieh, "2-D/3-D switchable display by Fresnel-type LC lens," *J. Display Technol.*, vol. 7, no. 4, pp. 215–219, Apr. 2011.
[10] C. W. Chen, Y. C. Huang, and Y. P. Huang, "Fast switching Fresnel liquid crystal lens for auto-stereoscopic 2D/3D display," in *SID Symp. Dig.*, 2010, vol. 41, pp. 428–431.
[11] G. Hamagishi, "Analysis and improvement of viewing conditions for two-view and multi-view displays," in *SID Symp. Dig.*, 2009, vol. 40, pp. 340–343.
[12] K. W. Chien and H. P. D. Shieh, "Time-multiplexed three-dimensional displays based on directional backlights with fast-switching liquid-crystal displays," *Appl. Opt.*, vol. 45, no. 13, pp. 3106–3110, 2006.
[13] C. H. Chen, Y. C. Yeh, and H. P. D. Shieh, "3-D mobile display based on moiré-free dual directional backlight and driving scheme for image crosstalk reduction," *J. Display Technol.*, vol. 4, no. 1, pp. 92–96, Mar. 2008.
[14] M. Minami, K. Yokomizo, and Y. Shimpuku, "Glasses- Free 2D/3D switchable display using a unique light guide," in *SID Symp. Dig.*, 2011, vol. 42, pp. 468–471.
[15] W. Mphepö, Y. Li, M. J. Liu, Y. M. Liu, and J. Y. Gao, "Switchable 2D/3D display using prism conversion module," in *SID Symp. Dig.*, 2012, vol. 43, pp. 33–35.
[16] Y. Kim and C. S. Ha, *Advances in Organic Light-Emitting Device*. Dürnten, Switzerland: Trans Tech Publ. Ltd., 2008.
[17] A. Misra, P. Kumar, M. N. Kamalasanan, and S. Chandra, "White organic LEDs and their recent advancements," *Semicond. Sci. Technol.*, vol. 21, no. 7, pp. 35–47, 2006.
[18] K. Y. Peng, C. C. Lin, C. T. Lee, and C. I. Wu, "Enhanced hole-injection in organic light-emitting devices by utilizing F4-TCNQ and the interface analysis by ultraviolet photoelectronspectroscopy," in *Proc. IDW*, 2006, pp. 1279–1281.

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