Design of a Hybrid Light Guiding Plate With High Luminance for Backlight System Application

Jui-Wen Pan and Ya-Wen Hu

***Abstract*—We proposed a novel backlight system, which consisted of a hybrid light guide plate (LGP) and one diffuser sheet. The hybrid LGP contains a flat plate without any microstructures and one layer of optically patterned film (OPF). Comparing with the conventional edge-lit backlight system, the on-axis luminance could be improved to 6.1× by using the novel backlight system and the half-luminance angle decreased from 21 deg to 10 deg in vertical direction, and decreased from 21 deg to 6 deg in horizontal direction. At the same time, this design also achieved a uniformity of illumination of 89%. The design can predigest the fabrication and reduce the number of components. Moreover, since the microstructures arrangement was periodical, user could use light-emitting diodes (LEDs) on the both sides. When user turned on both side LEDs, the on-axis luminance were improved 1.7× comparing with turning on single side LEDs.**

***Index Terms*—Illumination design, light-emitting diodes (LEDs), micro-optics, microstructure fabrication, optical systems design.**

I. Introduction

THE backlight system for liquid crystal displays (LCDs) applications has developed in the recent years. Due to the advantages of LCD, such as low power consumption, long life, small size, and light weight, LCD has gradually replaced the traditional cathode ray tube (CRT) monitors. Because of the LCD's characteristics, backlight system is also suitable to be used in personal products, such as cell phones, digital cameras, and notebook computers. For more effective use of energy, improving the optical efficiency and collimation of backlight system are the emphasis.

The conventional backlight system collimates the rays by adding two crossed prism sheets for two directions [1]. However, adding the prism will cause more Fresnel loss. Thus, for reducing the energy loss and predigesting the structure of whole backlight system, many researches proposed a LGP with the microstructures [2], [3]. For example, some designs used the V-cut microstructures on the LGP to achieve the high collimation. However, the V-cut can collimate only one-directional rays. There still must be added one prism sheet to collimate another one-directional rays [4]. In addition, according to the previous researches of LGP with the microstructures, we can find that many designs of microstructures are unsymmetrical [5] and usually distributed unevenly on LGPs [6]–[8] for uniform illumination. To manufacture the unsymmetrical and aperiodical microstructures need accurate alignment technology, thus the fabrication is more expensive and complex than the microstructures which are symmetrical and periodical. Moreover, the LEDs also cannot be used at both sides since the whole structure is not symmetrical.

In this paper, we proposed a novel design of backlight model to improve above disadvantages. The novel backlight system is consisted of a hybrid LGP and only one diffuser sheet to reduce the flaws. The hybrid LGP contains a flat plate to guide rays and an optically patterned film (OPF) to collimate and uniform rays. Comparing with the conventional backlight system, the optical efficiency remained the same values and the on-axis luminance improved to 6.1-times by using the novel backlight system. The half-luminance angle was 6 deg in horizontal direction and 10 deg in vertical direction. This novel design successfully predigests the structure of whole backlight system and improves the collimation. Moreover, the whole structure of the novel LGP we proposed is symmetrical, therefore the LEDs can be used at both side. When we not need high-brightness, the LEDs can be turned on only at one side, this condition is the "power-saving" mode. The LEDs also can be turned at both side, this condition is the "high brightness" mode. In the high brightness mode, the on-axis luminance was improved to 1.7-times comparing to the power-saving mode.

II. Working Function of the Hybrid LGP

For high collimation, we proposed a novel hybrid LGP as shown in Fig. 1. The hybrid LGP consists of a flat plate and an OPF. We use the same material for the flat plate and the OPF to avoid the Fresnel loss. The top and the bottom surface of the OPF have periodical microstructures [9]. The bottom microstructures on the OPF are contacted with the top surface of the flat plate [10]. We defined the contact surfaces of the flat plate and the bottom microstructures on the OPF as area A. Fig. 1 also shows the schematic of the ray paths in the hybrid LGP. In Fig. 1(a), as the rays entered the flat plate, the rays would be reflected by total internal reflection (TIR). The rays would continue guiding in the flat plate until rays stroke area A as shown in Fig. 1(b). Because the materials of the flat plate and the OPF are the same, the rays would not guide in the flat plate but enter the OPF. After the rays entered the OPF from the area

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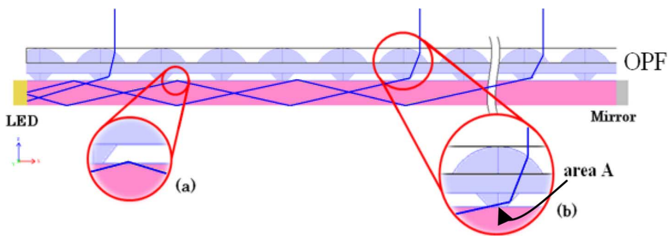

Fig. 1. (a) Rays entered the flat plate and would be reflected by TIR (b) Condition after the rays entered the OPF from the contact surfaces.

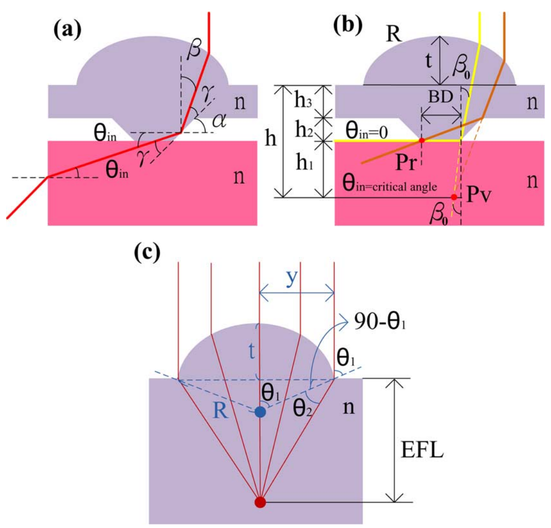

Fig. 2. (a) Ray paths in the OPF. (b) Virtual emission point (c) Focus length of the spherical microstructures.

A and stroke the side surface of the bottom microstructures, the direction of rays would be changed to the top of the OPF by TIR. Finally, the rays would be collimated by the top spherical microstructures.

III. Principle of Ray Paths

The rays guided in the flat plate until they stroke the contact surfaces of the flat plate and the bottom microstructures on the OPF. Then, the rays entered the OPF and the rays would be reflected by the side of the bottom microstructures as shown in Fig. 2(a). The relationships are described as follows:

$$\gamma = \alpha - \theta_{\rm in}, \quad \text{for } 0 \leq \theta_{\rm in} \leq \sin^{-1}(1/n) \; \text{(Critical angle)} \tag{1}$$

$$\alpha + \beta + \gamma = 90^\circ \tag{2}$$

$$\begin{aligned} \beta &= 90^\circ - \alpha - \gamma \\ &= 90^\circ - \alpha - (\alpha - \theta_{\rm in}) \\ &= 90^\circ - 2\alpha + \theta_{\rm in}. \end{aligned} \tag{3}$$

Then we described the two extreme rays ($\theta_{\rm in} = 0^\circ$ and Critical angle) reflected by the side of bottom microstructures in Fig. 2(b). We extended the two reflected rays to find their crossing point, and we could get the virtual emission point ($\rm P_v$). All rays could be regarded as transmitting from the virtual emission point. According to theory of mirror, the virtual emission point appeared to be the same distance from the mirror surface as the real emission point ($\rm P_r$). Thus, we could derive $\rm h_1$

$$d = BD \tag{4}$$

$$h_1 = d\cos(\beta_0), \quad \beta_0 = 90^\circ - 2\alpha. \tag{5}$$

We defined the distance between the virtual emission point and the top spherical microstructures as h, and h_2 and h_3 are the height of the bottom conical microstructures and the OPF without microstructures. The relationship between h_1, h_2, h_3, and h is shown in the following equation:

$$h = h_1 + h_2 + h_3. \tag{6}$$

Next, Fig. 2(c) shows the focus and the effective focus length (EFL) of the top spherical microstructures. According to theory of a focusing lens, the rays transmitting from the focus would be collimated to parallel light. Thus, as the virtual emission point coincided with the focus of the top spherical microstructures, the collimation is the best. According to Snell's law, we can derive the *EFL* by the following equation:

$$\sin(\theta_1) = n_2 \sin(\theta_2)[11] \tag{7}$$

$$\cos(\theta_1) = (R - t)/R \tag{8}$$

$$\text{EFL} = y \times \tan(90 - \theta_1 + \theta_2). \tag{9}$$

In order to match the EFL, we must design the radius of the top spherical microstructures to coincide the focus with the $\rm P_v$ for a determined height of the bottom conical microstructures (h2) and the OPF without microstructures (h3). In this condition, we could get the best collimation.

$$\text{EFL} = h. \tag{10}$$

IV. Conditions of the Novel Backlight System

According to the above introduction, the schematic of the novel backlight system is shown in Fig. 3. There are 18 LEDs (Nichia NESW155T) [12] as light source. These LEDs were the typically Lambertian light source. We called the surface of LGP near light source as incident surface and the opposite surface as far surface. A mirror is located at the far surface for enhancing the light efficiency.

The material of the LGP we use is Poly(methyl methacrylate) (PMMA), and the OPF is the same material to avoid Fresnel loss. The top and the bottom surface of the OPF have periodical microstructures. The bottom microstructures are conical and the top microstructures are spherical. At the beginning, we determine the inclined angle (α) of the bottom conical microstructures is 51.34° [13]. By the above equation and simulation, we get the appropriate conditions. The bottom conical microstructures' bottom diameter (BD) is 0.042 mm, top diameter (TD) is 0.122 mm, and height (h2) is 0.05 mm. The thicknesses of LGP and OPF (h1) are severally 1.4 mm [4] and 0.16 mm [14]. According to the (10), we have to match the EFL and the h ($h_1 + h_2 + h_3$). We thus derived the top spherical microstructures' radius (R) is 0.15 mm and thickness (t) is 0.09 mm. The microstructures are distributed evenly in an area of 136.1 mm by 236 mm.

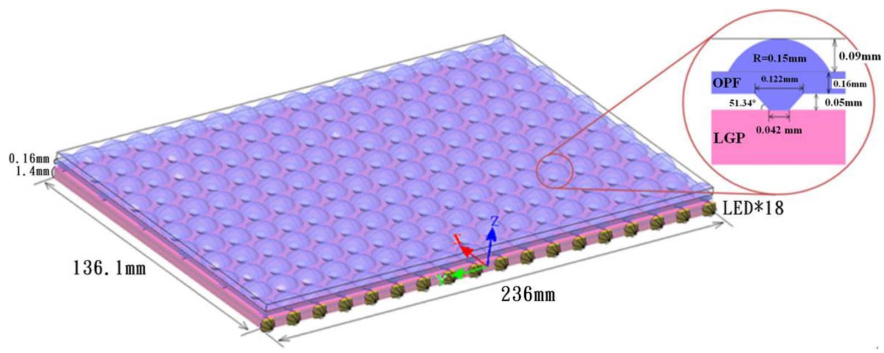

Fig. 3. Condition of each component and microstructure in the novel hybrid backlight system.

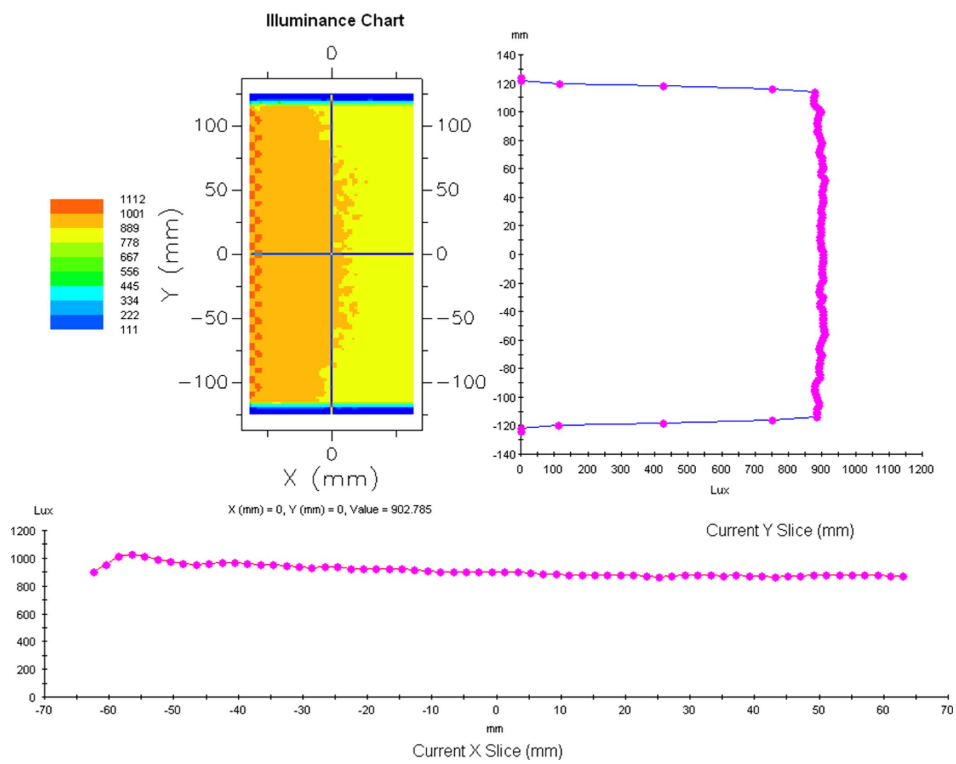

Fig. 4. Illumination of the novel backlight system with one diffuser. It looks good illumination uniformity.

V. Optical Simulation

The novel backlight system was constructed by LightTools[1]. For reducing the visual impact of microstructures, there must be added one diffuser sheet to reduce the flaws. The illumination chart of this novel backlight system is shown in Fig. 4, and the uniformity of the novel backlight system was 89% under nine points measuring method [15]. Fig. 5 is the intensity chart of the novel hybrid LGP with one diffuser sheet. The original half-luminance angle was 6 deg in horizontal direction and 10 deg in vertical direction.

VI. Comparison With the Different Backlight Systems

We used the conventional backlight system as our comparing target. The model of the conventional backlight is

[1]Optical Research Associates (ORA). [Online] Available: http://www.opticalres.com

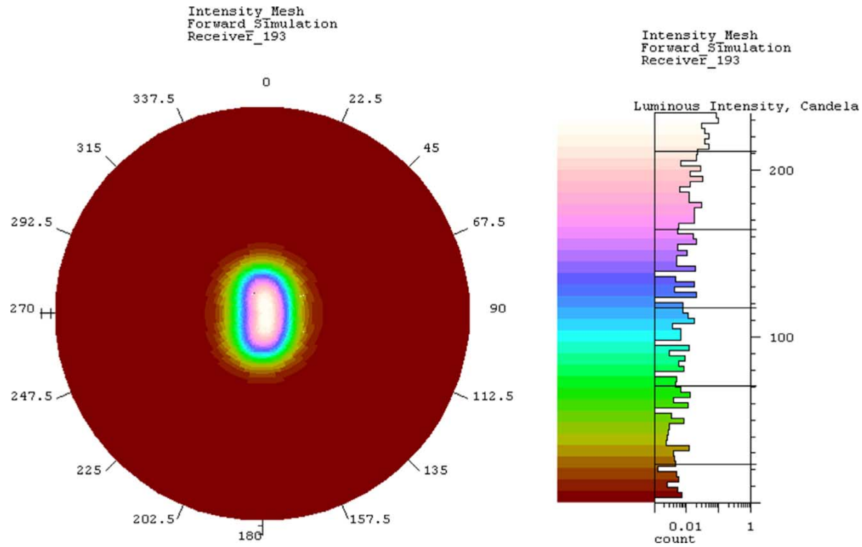

Fig. 5. Intensity chart of the novel hybrid LGP (with one diffuser sheet).

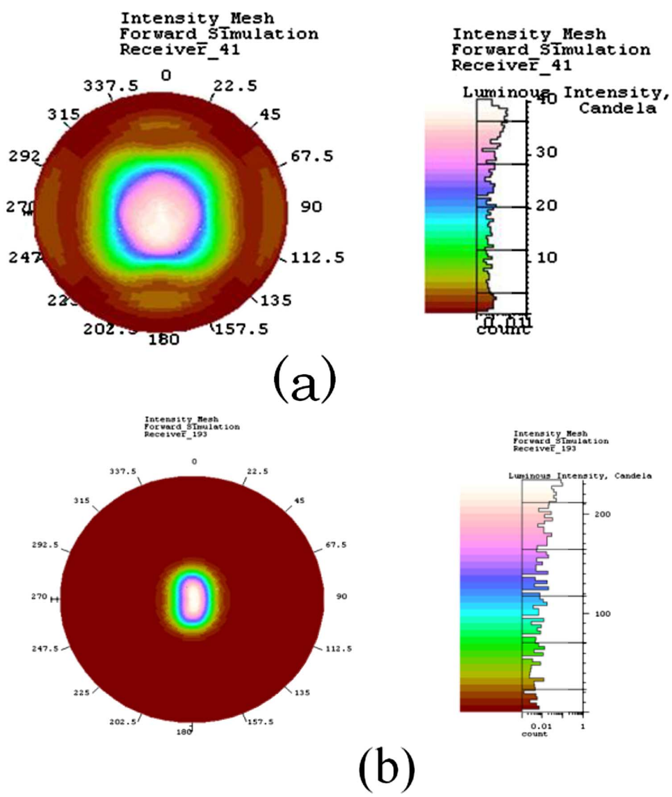

Fig. 6. Intensity charts of (a) the conventional backlight system and (c) the novel backlight system we proposed (with one diffuser sheet).

N101L6-L0B[2]. This backlight system is widely used for the laptops in the world. Fig. 6 shows the intensity charts of the two backlight systems.

The dependence of the normalized luminance and the off-axis angle are plotted as Fig. 7. We normalized the luminance data by the on-axis luminance of the conventional backlight system. Comparing with the conventional backlight system, the on-axis luminance of the novel backlight system proposed in this paper was increased to 6.1×. The half-luminance angle decreased from 21 deg to 10 deg in vertical direction, and decreased from 21 deg to 6 deg in horizontal direction. Thus in this novel backlight system we proposed, the on-axis luminance was significantly improved and the half-luminance angle decreased both in vertical and horizontal direction. At the same time, the number of optical sheets was decreased from 5 to 1. There was a comparison for the number of optical sheets, the normalized on-axis luminance, and the half-luminance angle in Table I.

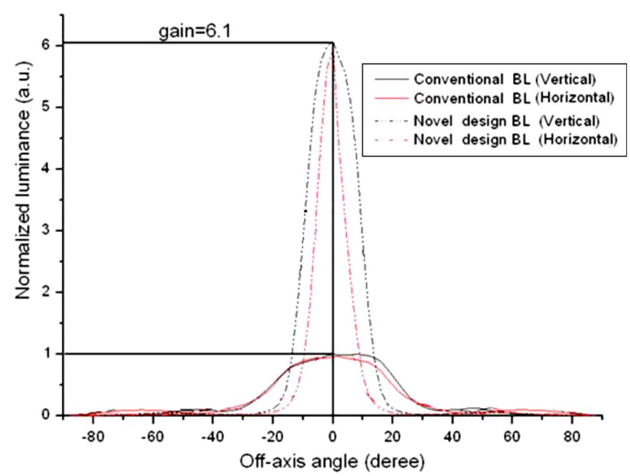

Fig. 7. Comparison between the Novel, V-cut and the Conventional Backlight system.

VII. Tolerance Analysis of Optically Patterned Film

The novel hybrid LGP has the straight ray direction and the high collimation as the virtual emission point coinciding with the focus of the top spherical microstructures. However, there will be errors existing in the manufacturing alignment process. The errors will cause the differences between the product and our design. Furthermore, the errors will affect the result of the

[2]Chimei Innolux Corporation. [Online] Available: http://www.deaking.cn/uploadfile/N101L6-L0B.pdf

TABLE I
THE COMPARISON BETWEEN THE CONVENTIONAL, V-CUT, AND NOVEL BACKLIGHT SYSTEM

	Number of reflector	Number of prism	Number of diffuser	Normalized on-axis luminance	Half-luminance angle (V/H)	Normalized optical efficiency
Conventional design	1	2	2	1.0	21° /21°	1.0
Novel design	0	0	1	6.1	10° /6°	1.0

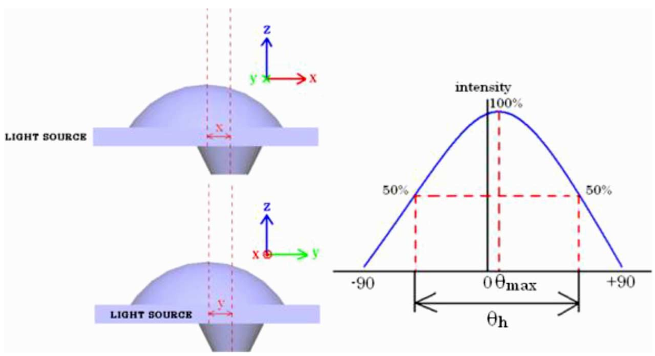

Fig. 8. Schematic of x, y, $\theta_{\max}$ and θ_{h}.

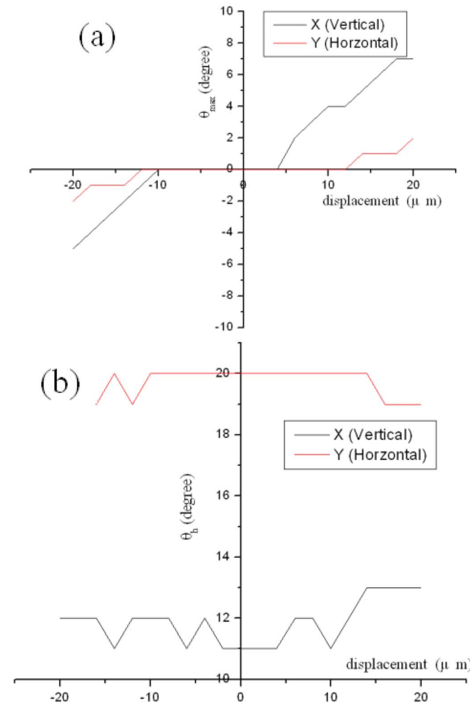

Fig. 9. (a) Relation between x, y, and $\theta_{\max}$ (b) Relation between x, y, and θ_{h}.

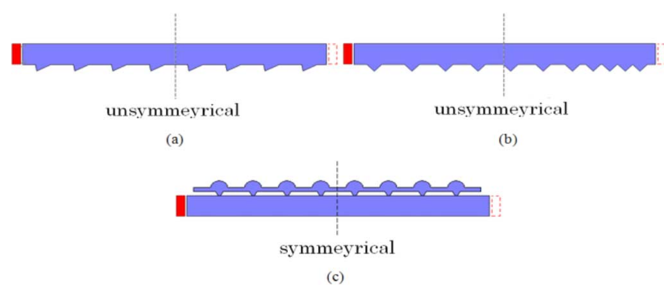

Fig. 10. An LGP with (a) unsymmetrical or (b) aperiodical microstructures is unsymmetrical in vertical direction. (c) Proposed LGP is symmetrical in vertical direction.

rays' direction and the collimation.[3]. Thus, we have to analysis the impact of the microstructures' alignment on the intensity result.

In Fig. 8, the parameter of x and y is defined as the displacement between the center of the bottom conical microstructures and the center of the top spherical microstructures in vertical and horizontal direction separately. The $\theta_{\max}$ is the degree value as the intensity reaches the maximum value, and the θ_{h} is the absolute value of the two degree values' subtraction as the intensity decreased to 50% of the maximum value. We simulated the x and y from $-2\ \mu$m to $+20\ \mu$m and observe changes of the $\theta_{\max}$ and the θ_{h}.

Fig. 9 is the diagram between x, y, θ_{h}, and $\theta_{\max}$. An appropriate backlight system must have the straight main ray direction. If the main ray directions are straight, the $\theta_{\max}$ will be 0°. From Fig. 9(a), the $\theta_{\max}$ was 0° as x was in -10 to 4 μm and y was in -12 to 12 μm. In this range, the main ray direction of the novel backlight system was straight. Then we can find the tolerance was higher in the horizontal. Because the intensity of edge-lit light source is not consistent in vertical and horizontal direction, the tolerance of the two directions is different. Observing from Fig. 9(b), the value of θ_{h} was about 11° to 13° and 19° to 20° in vertical and horizontal direction separately. If the collimation is high, the θ_{h} will be small. We could find there is little change in θ_{h} as x and y in this range of $\pm 20\ \mu$m. This means in this range, the tolerance has little affection for the collimation.

VIII. BOTH SIDE LIGHT SOURCE IN THE BACKLIGHT SYSTEM

According to many studies, there are many designs of microstructures are unsymmetrical [5] and usually distributed unevenly on LGPs [6]–[8] for uniform illumination. To manufacture the unsymmetrical and aperiodical microstructures need accurate alignment technology, thus the fabrication is more expensive and complex than the microstructures which are symmetrical and periodical.

We called the surface of LGP near light source as incident surface and the opposite surface as far surface. Because the whole LGP with unsymmetrical or aperiodical microstructures is unsymmetrical in vertical direction as shown in Fig. 10(a), (b) and the microstructures are designed for the left light source, the LEDs cannot used at far surface to get the same result as the LEDs used at incident surface. In this paper, the microstructures we designed on the OPF are symmetrical and periodical. Thus, the whole LGP is symmetrical in vertical direction as shown in Fig. 10(c) and the LEDs can be used at the far surface to get the same result as the LEDs used at incident surface. The LEDs can be used at both incident surface and far surface.

We used LightTools to simulate the novel backlight system with both side light source, and observing from the Fig. 11, the uniformity of the novel backlight system with the both side

[3]Industrial Technology Research Institute (ITRI). [Online] Available: http://www.itri.org.tw/eng/

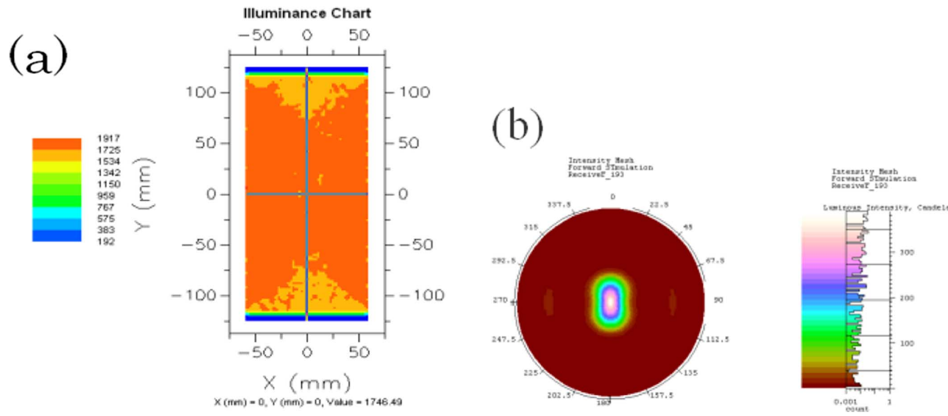

Fig. 11. (a) Illumination and (b) intensity charts of the novel backlight system with both sides light.

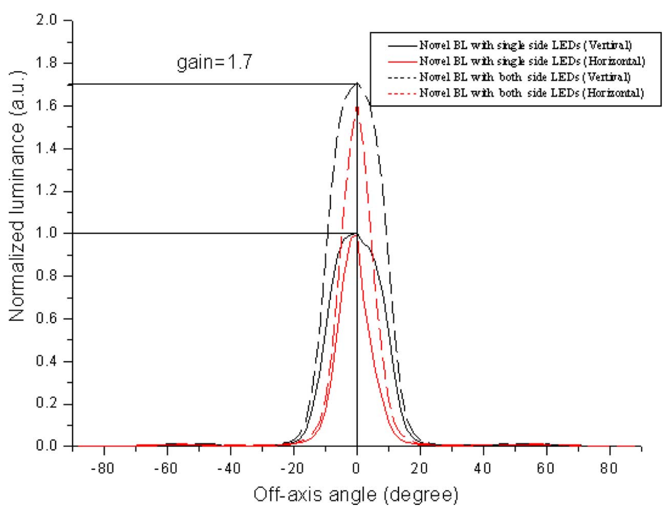

Fig. 12. Normalized comparison chart of luminance between the novel backlight systems module with single and both side LEDs.

LEDs was 96.5% by nine points measuring method. From the Fig. 13 we can find the on-axis luminance was improved to 1.7 times comparing with using the single side source.

If we do not need "high-brightness", the LEDs can be turned on only at one side, and this condition is the "power-saving" mode. As the LEDs are turned on at both sides, we can get the "high brightness" mode with the high collimation and uniformity of illumination. The user can choose the different mode for different needs to avoid energy waste.

IX. Conclusion

In this paper, the design decreased the number of optical sheets from 5 to 1 and achieved 89% uniformity. The optical efficiency had been remained the same values and the on-axis luminance improved to 6.1-times comparing with conventional backlight system. The half-luminance angle decreased from 21 deg to 10 deg in vertical direction, and decreased from 21 deg to 6 deg in horizontal direction. Because this novel backlight system has high on-axis luminance, it is suitable to be used in some products which require high brightness, such as small size laptops, tablet PC, and 3D displays module. At the same time, it also can be applied for anti-peep due to the high collimation. In addition, this novel backlight system can be used in two modes by turning on single or both side LEDs. The user can choose the "power-saving" mode or the "high brightness" mode for different needs to avoid energy waste.

References

[1] S. Kobayashi, S. Mikoshiba, and S. Lim, LCD Backlights 2009.

[2] D. Fen, Y. Yan, X. Yang, G. Jin, and S. Fan, "Novel integrated light-guide plates for liquid crystal display backlight," *J. Opt. A: Pure Appl. Opt.*, vol. 7, pp. 111–117, 2005.

[3] J. H. Lee and J. B. Yoon, "A novel LCD backlight unit using a light-guide plate with high fill-factor microlens array and a conical microlens array sheet," in *Soc. Inf. Display Symp. Dig. Tech. Papers.*, 2007, vol. 38, pp. 465–468.

[4] J. W. Pan and C. W. Fan, "High luminance hybrid light guide plate for backlight system application," *Opt. Express*, vol. 19, pp. 20079–20087, 2011.

[5] K. Käläntär, S. Cho, and H. O. Shi, "A directional backlight with narrow angular luminance distribution for widening viewing angle of a LCD with a front-surface-light-scattering film," *J. Soc. Inf. Display*, vol. 20, pp. 133–142, 2011.

[6] C. H. Chien and Z. P. Chen, "Fabrication of a novel integrated light guiding plate by microelectromechanical systems technique for backlight system," *J. Microlith., Microfab., Microsyst.*, vol. 5, pp. 0430111–0430116, 2006.

[7] 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.

[8] J. C. Yu and P. K. Hsu, "Integration of stamper fabrication and design optimization of LCD light guides using silicon-based microfeatures," *Microsyst. Technol. DOI*, vol. 16, pp. 1193–1200, 2010.

[9] R. Winston, J. C. Minano, and P. Benitez*, Nonimaging Optics*. New York: Academic, 2004.

[10] A. Agasawa, T. Eguchi, Y. Sanai, and K. Fujisaw, "Ultra slim and bendable system with a unified component for liquid crystal applications," *Opt. Rev.*, vol. 15, pp. 38–43, 2008.

[11] *Modern Optical Engineering*. New York, NY, USA: McGraw Hill, 2008.

[12] Nichia NESW155T Website [Online]. Available: http://www.nichia.co.jp/specification/en/product/led_library/NESW155T-E.pdf

[13] J. H. Lee, H. S. Lee, B. K. Lee, W. S. Choi, H. Y. Choi, and J. B. Yoon, "Simple liquid crystal display backlight unit comprising only a single-sheet micropatterned polydimethylsiloxane (PDMS) light-guide plate," *Opt. Lett.*, vol. 32, pp. 2665–2667, 2007.

[14] "3M display solution in tablet and notebook," [Online]. Available: http://solutions. 3m.com/wps/portal/3M/en_US/NA_Optical/Systems/Technology/DisplayFilms/

[15] *Data Projection Equipment and Large Screen Data Displays - Test Methods and Performance Characteristics*, ANSI IT7.215-1992, American National Standards Institute (ANSI), 1992 [Online]. Available: http://www.ansi.org

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