High directional backlight using an integrated light guide plate

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Abstract: A high directional backlight system that combined a composite microstructure light guide plate (LGP) with a collimated light source was proposed for eco-displays. The collimated planar light was expanded from a point light source and guided towards the normal direction by utilizing the micro-prism array on LGP. High uniformity of spatial luminous, 91%, with a narrow viewing cone of ± 4° can be achieved without additional optical films. Moreover, compared to the conventional backlight, only 5% of power consumption was needed to keep the same luminance, hence, the optical efficiency increased by a factor of 1.47.

OCIS codes: (080.2740) Geometric optical design; (230.3990) Micro-optical devices; (230.4000) Microstructure fabrication; (220.4830) Systems design.

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1. Introduction

Liquid crystal displays (LCDs) are currently dominating the display market due to their thin form factor and light weight. As the demand of green technologies in power saving and image quality enhancement, backlighting technologies have recently been advanced remarkably. A typical edge-type backlight with several optical films such as brightness enhancement film (BEF)-dual brightness enhancement film (DBEF) -diffuser and reflector consumes more than 60% of the total power consumption in LCD modules, with its obvious drawback, such films increase costs and lower optical efficiencies. Hence, many studies have been reported to improve the optical efficiency for device usage [1, 2]. Therefore, directional backlight system with fewer optical films added is of highly attractive.

Several types of backlights with high optical efficiency were reported, to replace the conventional ones. IBM used diffractive grating and multi-index materials to control the light angular distribution of entering the microstructures, but the high cost hindered their widely application [3–6]. Kodak used a dual-turning film to collimate the light which needs precise alignment [7]. Käläntär et al proposed a monolithic block-wise functional light guide combined with an inverted prism to get the high directional backlight [8–10]. In order to keep the high uniformity spatial luminous, the contours of micro-structures on “block-wise functional” LGP vary gradually which lead to a complicated fabrication process. Togaya et al have reported a backlight system using a highly scattering optical transmission (HSOT) polymer of high quality [11]. But LGPs in these systems cannot control the illumination angle. Recently, Okumura et al have reported a highly efficient HSOT backlight system without optical sheets which can control the light directly into the front direction, but the LGP based on micro-prism structures is made of a HSOT polymer, not a traditional acrylic material, polycarbonate (PC) material, or polymethyl methacrylate (PMMA) material [12]. Moreover, most of the technologies mentioned above have the same issue that only one direction of the rays can be compressed with the FWHM $\pm$ 10°~ $\pm$ 20°, but the light leakage still exists in the other direction.

In this paper, we demonstrate a backlight system of high optical efficiency and uniformity, narrow viewing cone in dual directions and compact form factor without using optical films. Besides, compared with the conventional backlight system, the power consumption of the backlight module was much lower at the same luminance.

2. Design principle

In spite that LEDs are widely used as the light source for backlight in LCDs, the conventional LED with Lambertian angular distribution is not suitable for narrow viewing angle backlight design in eco-displays [7–9]. Thus, the collimated light source becomes a good candidate for the direction-dependent-displays. In the system, a collimate point light source is expanded to a planar light source without changing the high directional character. The proposed structure of high direction backlight system with isometric, top, and front views are shown in Fig. 1.

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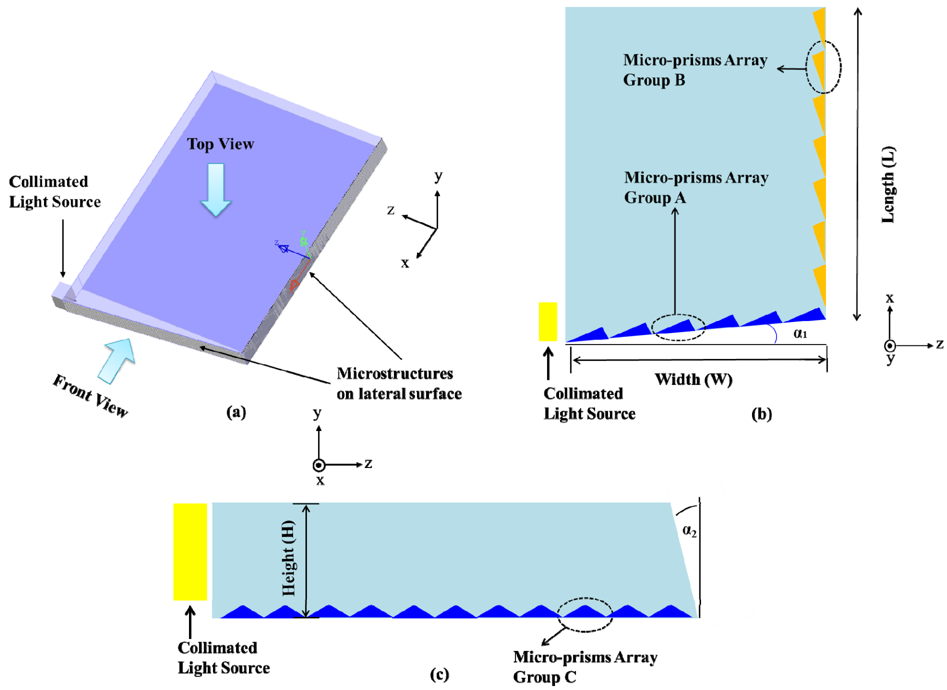

Fig. 1. Sketch of backlight in different viewing angle (a) Isometric, (b) top, and (c) front view.

The backlight system includes two parts: an integrated LGP and a collimated light source located at the corner of LGP, as shown in Fig. 1(a). The micro-prism array with silver reflective film coated which can be divided into three groups were located on the lateral and bottom surface of LGP, as shown in Figs. 1(b) and 1(c).

In x-z plane, the LGP is not rectangle but incline to z-axis with an angle of α_1. Figure 2(a) illustrates the process of light propagation in the x-z plane: According to the total internal reflection (TIR) theory, the incident light propagating alone z-axis is reflected twice by the micro-prism arrays which function as transferring a point light source to a line light source. In y-z plane, the right surface of LGP also inclines to y-axis with an angle of α_2. The lights reflected by group B (micro-prism array with yellow color in Fig. 2(a)) propagating alone negative z-axis with a tilt angle φ, are reflected toward the normal direction by the micro-prisms of group C on bottom surface of LGP as illustrated in Fig. 2(b). Therefore, a line light source is expanded to a planar light source. Compared with conventional backlight with LEDs, rays propagating in novel LGP with only three reflections have been almost totally coupled out without scattering or trapping in LGP, which much improves the optical efficiency.

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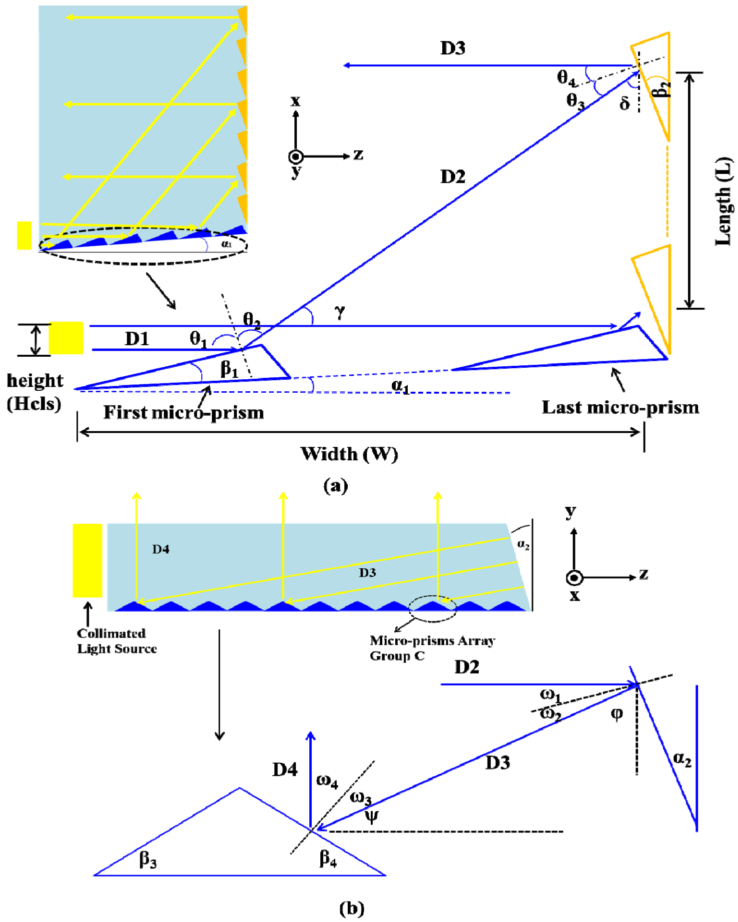

Fig. 2. Light propagation in LGP in (a) x-z and (b) y-z plane.

According to the geometrical optics, the parameters of LGP can be deduced by the following Eqs. (1) and (2):

In x-z plane:

$$\begin{aligned} &\alpha_1 = \tan^{-1}(\mathrm{H_{cls}} / \mathrm{W}) \\ &\gamma = \tan^{-1}(\mathrm{L} / \mathrm{W}) \qquad \delta = \tan^{-1}(\mathrm{W/L}) \\ &\theta_1 = \theta_2 = (180 - \gamma) / 2 \qquad \theta_3 = \theta_4 = (90 - \gamma) / 2 \\ &\beta_1 = 90 - \alpha_1 - \theta_1 \qquad \beta_2 = 90 - \delta - \theta_3 \end{aligned} \tag{1}$$

In y-z plane:

$$\begin{aligned} &\varphi = \tan^{-1}(\mathrm{W/ H}) \qquad \varphi = \tan^{-1}(\mathrm{H/ W}) \\ &\omega_1 = \omega_2 = (90 - \varphi) / 2 \qquad \omega_3 = \omega_4 = (90 - \psi) / 2 \\ &\alpha_2 = 90 - \varphi - \omega_2 \qquad \beta_3 = \beta_3 = 90 - \psi - \omega_3 \end{aligned} \tag{2}$$

where, $\mathrm{H_{cls}}$ is the height of collimated light source, H, L, and W is the height, length, and width of the LGP respectively, as shown in Fig. 2.

3. Results & discussion

In order to verify the effect of the proposed structure, the 3D geometric model of the backlight module was built by the commercial software, Light tools 7.2, which employs the

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Monte Carlo method [13, 14]. The simulation results showed that the optical efficiency of conventional backlight was of 65% as well as the novel backlight was of 96% which increased by a factor of 1.47. According to the P. Bouguer Law, it can be explained by the following Eq. (3) [15]:

$$I \propto \left|E_0\right|^2 e^{-2n\kappa x/c} \tag{3}$$

where, E_0 is amplitude of incident rays, n is refractive index and κis attenuation index, x is optical path distance in LGP and c is light speed in a vacuum.

As lights propagate in an attenuation medium, the light intensity decreases gradually according to the optical path length. In conventional backlight, the optical path length in LGP is quite long due to the lights are simply diffused by the scatterings dots without controlling the directions of light transmission. However, the novel proposed structure induced the rays coupled-out with only three reflections, which greatly reduces the optical path in LGP. More importantly, due to the random scattering, lots of rays cannot be extracted from the LGP according to the TIR (total internal reflection) law in conventional backlight. Alternatively, the novel structure controlled the collimated rays more precisely and guided them out from LGP. Besides, in order to achieve high uniformity of spatial luminance distributions, the scatter points of conventional LGP are only covered a part of bottom surface resulting in the energy loss. The micro-prisms on novel backlight array are arranged much more compact to suppress the light leakage. The simulation results in Table 1 demonstrated that the configuration could improve the optical efficiency. The luminous flux of the backlight which is an important factor to evaluate the power consumption can be approximate calculated by doing the integral of intensity according to their viewing angle as the following Eq. (4):

$$L = \iint I(\Omega) \bullet d\Omega \tag{4}$$

where L is the luminous flux, I is the light intensity, $d\Omega$ is the solid angle.

The light intensity (cd) is normalized to keep the same luminance (cd/m^2) at the normal direction for both of the backlights (novel and conventional BL), as shown in Fig. 3. Due to the energy only need to be afforded to the normal direction in novel backlight as well as to a wide direction in conventional backlight, the novel backlight can achieve a luminance at a 10035 cd/m^2 with 5 lumens while the conventional backlight needs 103 lumens to keep the same luminance." It indicated that the novel backlight needs only 5% of power consumes to keep the same luminance in normal viewing angle, as compared with conventional backlights.

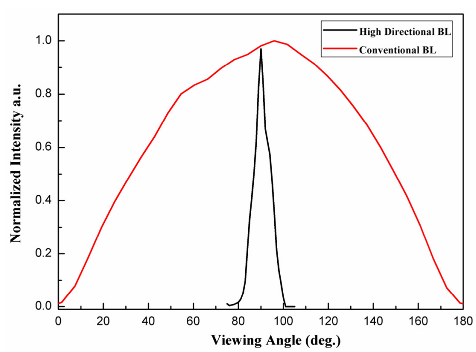

Fig. 3. Light intensity distribution in different viewing angle.

The luminance spatial distribution of the backlight with different size dimensions for micro-prisms varied between 10 and 550μm were also simulated by Lighttools. As the pitch of micro-prisms increasing from 25 to 450μm, the backlight can keep a luminance spatial distribution of 83% as minimum which shown in Fig. 4.

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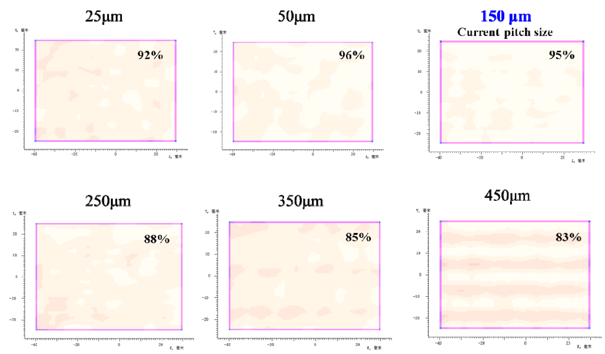

Fig. 4. Luminance spatial distribution with different size dimensions of micro-prisms.

However, as shown in Fig. 5, the luminance spatial distribution decreased greatly with 10μm pitch size due to the profile of micro-prism had been changed, most of lights were diffused by the vertex angle which was not as sharp as pre-design and caused the non-uniformity.

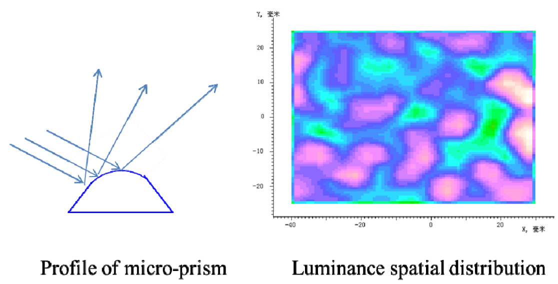

Fig. 5. The profile of micro-prism with 10μm pitch size of and the luminance spatial distribution.

On the other hand, the luminance spatial distribution formed the bright/dark patterned distribution periodically with the 550μm pitch size due to the pitch size was too large to keep the high uniformity as shown in Fig. 6. In conclusion, the dimension of micro-prisms should be optimized to achieve high uniformity and 150μm pitch size of micro-prisms was used to fabricate our prototype.

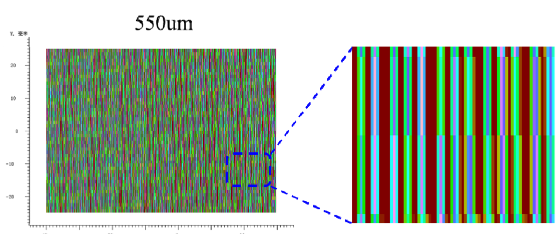

Fig. 6. The luminance spatial distribution with a 550μm pitch size.

By geometrical optics and equations in last section, a prototype was fabricated by widely used process in display industry [16]. The micro-prism array's profiles of each group were measured, as shown in Figs. 7(a)-7(d). The parameters of the backlight system were calculated and listed in Table 1.

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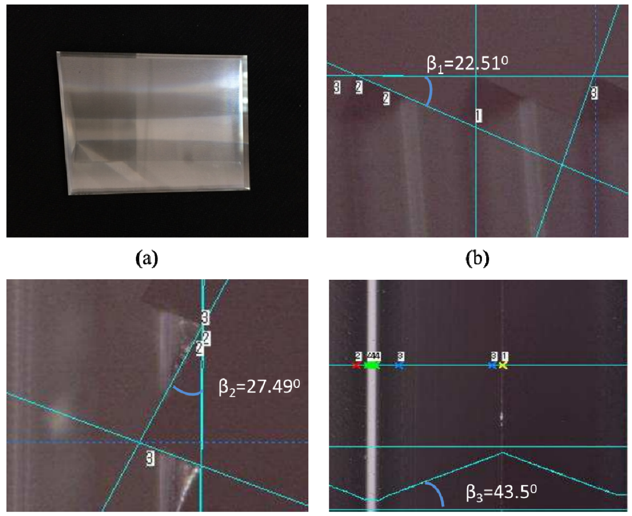

Fig. 7. Prototype of backlight & group of micro-prism array (a) general view, (b) group A, (c) group B, and (d) group C.

Table 1. Parameters of light guide plate

Material / Refractive Index	PMMA / 1.49
Backlight Dimension (L*W*H)(mm)	84*59*6
α_1 /α_2 (deg.)	5 / 22.5
β_1 / β_2 (deg.)	22.5 / 27.5
β_3 / β_4 (deg.)	43.5 / 43.5

The red laser (λ = 533nm) with uniform light intensity was employed as the collimated light source. We measured the luminance distribution of the backlight in different positions by a spectro-radiometer (CS-2000) for calculating the spatial luminance distributions of light source and backlight as illustrated in Figs. 8(a) and 8(b), respectively. The uniformity, defined as the minimum luminance divided by the maximum luminance, were 98% of light source and 90% of the LGP (5 points). Theoretically, the micro-prism array on LGP just extends a point light source to a planar light source without changing its uniformity. Nevertheless, the different optical path lengths of the incident rays result in the uniformity of backlight is not as high as the light source, as shown in Fig. 8(b). The typical optical path length in LGP for all the incident rays can be approximately described as: $L_{optical\ path\ length} = D_1 + D_2 + D_3 + D_4$, as show in Figs. 2(a) and 2(b). According to the P. Bougure Law, in an isotropic attenuation medium, the light intensity decreases simultaneously with the same optical path length (total path of $D_1 + D_2 + D_4$ is almost the same), but with variable in D_3. Therefore, it can be inferred that the non-uniformity of the emergent light is related to the different path length of D_3, moreover, the longer path length D_3 is, the lower light intensity is, which is consistent with our measurement results as illustrated in Fig. 8(b).

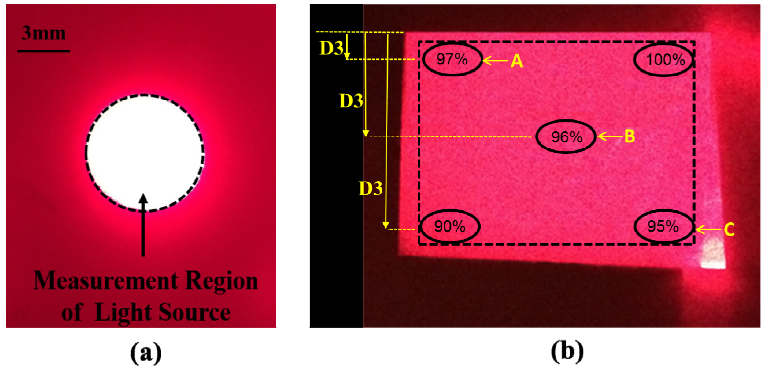

Fig. 8. The spatial luminance distributions of the backlight (a) light source and (b) light guide plate.

The angular distribution is a key parameter for high directional backlight. The characteristics with different positions on LGP (Points A-C in Fig. 8 (b)) are depicted in Fig. 9(a). The angular distributions in dual directions of point A are shown in Fig. 9(b). These results demonstrated that the backlight can offer ± 4° of FWHM on both directions. Ideally, the micro-prism array can keep the high direction without distortion (FWHM< ± 1°) but several factors cause the angular distribution to be extended. One of the most critical factors is the apex scattering of the micro-prism, which has a deflection with radius of 5μm but not as sharp as ideal, as shown in Fig. 10. Besides, surface irregularities and mis-machining tolerance in fabrication process also result in the slightly lager angular distribution. Compared with the prior-arts [3–12], the novel architecture can compress lights in dual directions with high collimation (from FWHM ± 10°~ ± 20° to ± 4°). Moreover, no additional optical film needed, thus, compact form can and benefit mass production and cost.

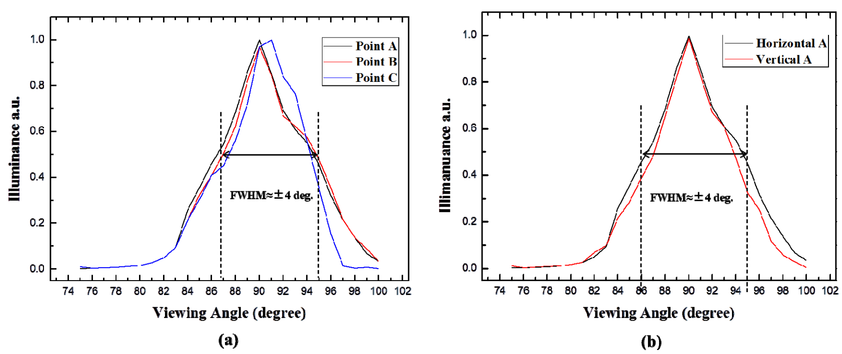

Fig. 9. Angular distributions of (a) different points and (b) in dual directions of point A.

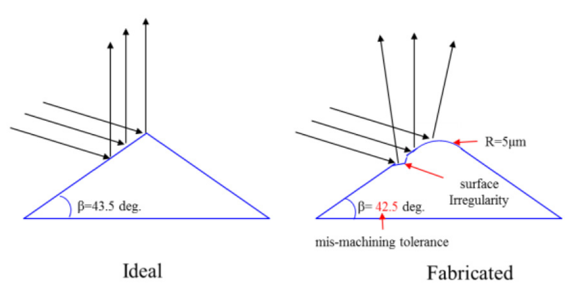

Fig. 10. The profile of micro-prism ideal vs. fabricated one.

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4. Conclusions

The high directional backlight with special designed microstructures and a collimated light source was demonstrated for the applications of eco-displays. Compared with the conventional backlight module, the novel configuration can achieve high uniformity (>90%) with the optical efficiency increased by a factor of 1.47. It can offer FWHM at ± 4° in dual directions with low power consumption (5% power consuming of conventional backlight) at the same luminance. As a consequence, the backlight is potential for high efficient eco-display applications.

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