Enhancing LCD Optical Efficiency with a Linearly Polarized Backlight and Polarization-preserving Light Guide Plate

Zhenyue Luo,* Yu-Wen Cheng, and Shin-Tson Wu***
*College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816, USA
** Display Technology Center, Industrial Technology Research Institute, Hsinchu, Taiwan 310

Abstract

We propose a new polarization-preserving edge-lit light guide plate (LGP) based on total internal reflection. Our simulation results show that such a LGP exhibits several attractive features: 1.54X higher polarization efficiency, 2.4X higher on-axis luminance, and no need for a brightness enhancement film. When integrated with a linearly polarized LED array, the LCD optical efficiency can be enhanced dramatically and its power consumption can meet the challenging goal set by Energy Star 6.

1. Introduction

Reducing power consumption is an urgent issue for LCD industry to meet the challenging goal set by Energy Star 6. A high contrast LCD utilizes two crossed linear polarizers, but most of present backlight sources are unpolarized. As a result, about 50% of the backlight is absorbed by the linear polarizer. To mitigate this absorption loss, linearly or partially polarized LEDs have been considered [1-3]. However, conventional edge-lit light guide plate (LGP) significantly depolarizes the light polarization state, which in turn compromises the benefits of polarized LEDs [4]. Some LGPs with linearly polarized light emission have been proposed, but they either rely on complicated nano-grating [5] or require highly anisotropic material [6]. Those LGPs are not cost effective and difficult for mass production.

In this paper, we propose a novel polarization preserving LGP based on total internal reflection (TIR). It exhibits several attractive features: 1) High polarization efficiency (77.2%), which means 1.54X optical gain compared to conventional LGPs, 2) 2.4X higher on-axis luminance when illuminated by a linearly polarized light, 3) No need for a brightness enhancement film (BEF), and 4) Simple structure which is favorable for mass production. The advantages of this novel LGP would manifest once a partially polarized or linearly polarized light source is available in the near future.

2. Depolarization effect of conventional LGP

Figure 1 depicts a typical edge-lit backlight system under investigation. Five LEDs are aligned on the left side of LGP, each LED is a typical planar Lambertian source with directivity (2θ ½) of 120° and has a luminous flux of 2 lm. We intentionally insert the input polarizer to simulate the ideal linearly polarized illuminance. In real application this polarizer is not needed when using a polarized light source. The dimension of LGP is 60-mm x 40-mm x 3-mm, and the material is PMMA (n=1.49). An output polarizer is laid on top of the LGP for analyzing the output polarization. The transmission axis of the input polarizer and output polarizer makes an angle α and β with respect to *x* axis. As a special case when $\alpha=0$ and $\beta=0$, both input and output beams are x polarized and is TE wave regarding to the LGP cross-section plane (y-z plane). In our simulation we find this setting leads to maximum light output, so we keep this configuration throughout the paper.

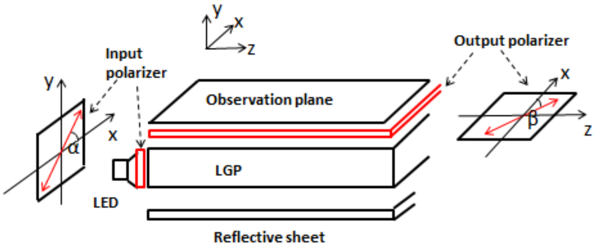

Figure 1. Schematic of the light source and edge-lit type LGP.

The polarization efficiency is defined as Φ_{pol}/Φ_{total}, where Φ_{total} is the total output light flux from LGP and Φ_{pol} is the flux of polarized light component that can be utilized by LCD. Φ_{pol} and Φ_{total} are recorded with and without output polarizer respectively. For an unpolarized incident light, the output light from LGP remains unpolarized so the polarization efficiency is only 50%. For a linearly polarized input light, if the LGP can ideally preserve the polarization, then the polarization efficiency should be 100%. In reality, a LGP would inevitably depolarize the light so that the polarization efficiency can hardly reach unity. Our objective is to design a LGP with high polarization efficiency.

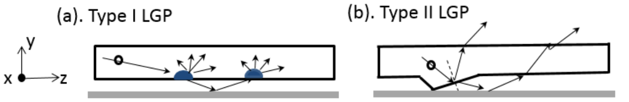

Figure 2. Schematic and ray tracing of (a) Type-I LGP and (b) Type-II LGP.

Table I. Spatial illuminance and polarization efficiency of different type LGPs.

	Illuminance (lux)		Polarization efficiency
	Total	TE component	
Type-I LGP	1109.1	614.2	55.4%
Type-I LGP with BEFs	702.1	354.5	50.5%
Type-II LGP	1425.3	1013.4	71.1%
Type-II LGP with BEFs	830.8	445.6	51.7%
Type-III LGP	1358.3	1049.1	77.2%.

We first evaluate two types of conventional LGPs. Their structures are shown in Fig. 2 and performances are summarized in Table I. Type-I LGP has dotted microstructure printed on its bottom surface and use scattering to extract the light. Each scattering process would average out the light polarization into different directions, therefore after multiple scattering the light is completely depolarized and Type-I LGP has very low polarization efficiency (55.4%). Type-II LGP has v-groove structure and uses refraction for light extraction. Refraction reduces depolarization due to fewer ray-splitting. Therefore, a bare Type-II LGP has relatively high polarization efficiency (71.1%).

Moreover, both Type-I and Type-II LGPs require BEFs to boost the on-axis luminance. BEFs also induce significant depolarization by splitting the ray and deflecting the propagation direction. After considering the BEF effect, the polarization efficiency of Type-I and Type-II LGPs drop to 50.5% and 51.7%, respectively. Therefore, a polarized light would become almost unpolarized after passing through the backlight system and there is no advantage of using a linear polarized light source.

3. Polarization-preserving LGP

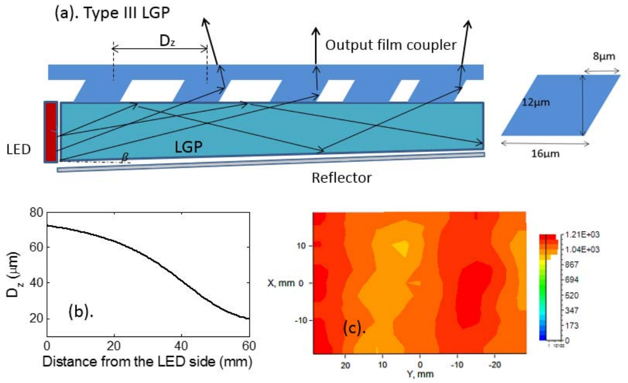

Figure 3. (a) Schematic drawing of Type-III LGP, (b) Relationship between D_z and the distance to LED, and (c) Spatial illuminance distribution.

To solve this problem, we propose a new LGP (Type-III) shown in Fig. 3(a). It consists of the LGP main body and an output film coupler. The LGP main body has a wedged shape with flat top and bottom surface. Light is extracted by the output film coupler, which has one dimensional array of parallelogram prism on the bottom surface and is in contact with LGP. To illustrate the working principles, we draw four rays in Fig. 3(a). Before the ray hits the contact region, it continuously propagates within the LGP under TIR confinement. After the ray hits the contact region, it experiences another TIR on the slope surface of the slanted prism and is deflected toward the surface normal. The geometry and slope of the prism is designed to guide the emitting light along the surface normal direction. The interval between each microstructure D_z should be optimized in order to achieve a good spatial uniformity. After optimization, a reasonably good spatial uniformity (76.8%) is obtained.

For Type-III LGP, the illuminance of total light output is 1358.3 lux and the TE component is 1049.1 lux, so the corresponding polarization efficiency is 77.2%. In comparison with an unpolarized light source that has 50% polarization efficiency, our Type-III LGP has 1.54X gain in polarization efficiency. This high polarization efficiency originates from two unique guiding mechanisms: 1) it uses TIR to control the light propagation in the LGP, and 2) it also uses TIR to extract light. For each TIR, both TE and TM components have the same reflection coefficient and there is no beam splitting, therefore the associated depolarization is suppressed.

Next, we analyze the angular light distribution for Type-III LGP. Fig. 4(a) traces two typical TE polarized ray with different propagation directions. The parallelogram prism is a one dimensional structure and only controls the angular luminance along one direction. Ray A propagating in the y-z plane could be extracted toward the surface normal, while a slanted ray B propagating off the y-z plane still exits the LGP at an oblique angle. The angular distribution of the total light output is only confined along the horizontal direction, as sketched in Fig. 4(b). The on axis light emission is mainly constitute by Ray A, which keeps the polarization after refraction, while ray B dominates the off axis illumination and can be preserve the initial polarization due to polarization rotation effect during refraction. As a result, the angular distribution of TE component (Fig. 4(c)) mainly concentrates near the axial region, while the TM component (Fig. 4(d)) predominantly spreads out at off-axis. For display applications, only TE component is utilized. Its luminance is already on axis so we do not need a BEF. This is beneficial for reducing the cost and weight of the backlight system.

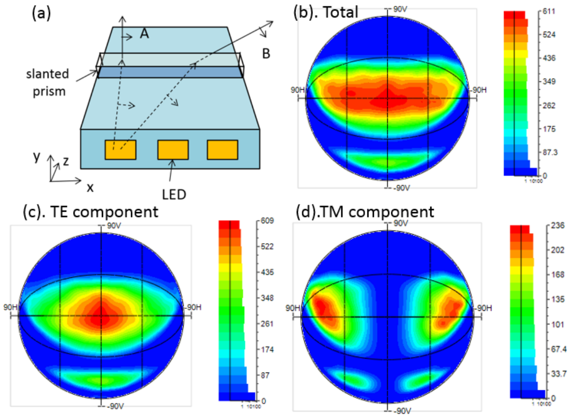

Figure 4. (a) Light paths of two rays with different propagation directions, (b) Angular distribution of the total output light, (c) Angular distribution of the output light with TE component, and (d) Angular distribution of the output light with TM component.

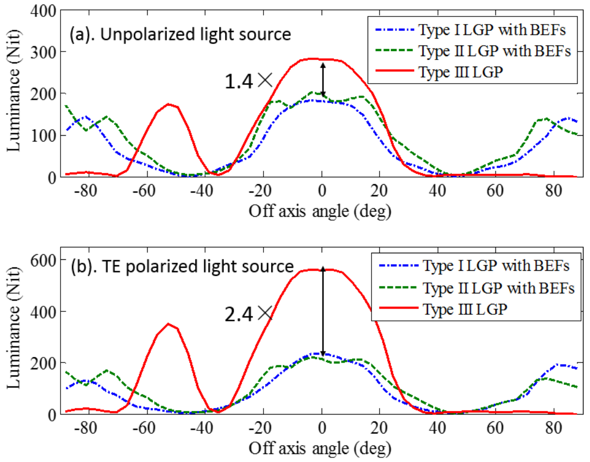

Figure 5. Angular luminance as a function of off-axis angle for the three LGPs when illuminated by (a) unpolarized light and (b) TE polarized light with half intensity. Off-axis angle is measured along the vertical direction.

Fig. 5 compares the on-axis luminance between different types of LGPs. Type-III LGP exhibits ~1.4X higher on-axis luminance under unpolarized light illumination and ~2.4X higher on-axis luminance under TE polarized light illumination. This advantage comes from: 1) Type-III LGP does not require BEFs, which introduces absorption/scattering during light recycling. 2) Type-III LGP not only efficiently preserves the light polarization, but also preferentially guides the light through on-axis direction. Type-III LGP can effectively reduce the power consumption of a backlight system.

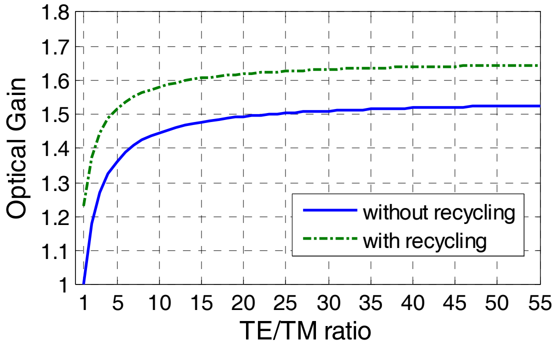

Figure 6. Optical gain as a function of TE/TM ratio of the input light source.

The proposed LGP is efficient even for partially TE polarized light. We define the optical gain as the ratio of LGP polarization efficiency to that of unpolarized light (50%), and calculate the optical gain as a function of TE/TM ratio. As Fig. 6 depicts, the optical gain increases rapidly as TE/TM ratio improves and gradually saturates as the TE/TM ratio exceeds 20:1. Currently, semipolar InGaN LEDs can achieve TE/TM ratio of 9 [2] and GaInN LED embedded with sub-wavelength wire-grid polarizers can have TE/TM ratio over 49 [3]. For these two types of polarized light sources, Type-III LGP still has considerable high optical gain of 1.45X and 1.53X, respectively. Thus, it can be integrated with a linearly or partially polarized LED array to significantly boost the optical efficiency.

Table II. Comparison of different LGPs with and without polarization recycling

	Optical gain without recycling	Optical gain with recycling
Type-I LGP+BEFs	1.01X	1.38X
Type-II LGP+BEFs	1.03X	1.42X
Type-III LGP	1.54X	1.64X

To further improve the optical gain, we also calculate the polarization recycling effect [9] for various types of LGP and summarize the results in Table II. The optical gain of Type-I and Type-II LGPs increases to 1.38 and 1.42 after introducing polarization recycling, but they are still inferior to our Type-III LGP without polarization recycling. With polarization recycling, the Type-III LGP can achieve 1.64X optical gain. We can expect even better results when combining Type-III LGP with efficient broadband polarization convertor [10, 11].

4. Conclusion

We proposed a new polarization-preserving LGP to boost the optical efficiency of LCDs. This LGP exhibits several attractive features: 1) High polarization efficiency (77.2%), which is 1.54X optical gain compared to unpolarized light. 2) The on-axis luminance is 2.4X higher than that of a conventional LGP when a linearly polarized light is used. 3) The light output is mainly on axis, so no extra BEF is required. 4) It does not require complex nano-grating or anisotropic material, and is therefore more favorable for mass production. All these characteristics make the proposed LGP attractive for low power LCD applications.

5. References

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