Polarization-Preserving Light Guide Plate for a Linearly Polarized Backlight

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***Abstract*—We analyze the polarization-preserving property of two conventional edge-lit light guide plates (LGPs) based on scattering dots and refractive microgrooves and find that these two structures almost completely depolarize the incident linearly polarized light. We then propose a new edge-lit LGP based on total internal reflection (TIR). Simulation results show that such a TIR-based LGP can largely preserve the polarization state of the incident linearly polarized light. The polarization efficiency is 77.2%. By incorporating a linearly polarized LED to our proposed LGP, the overall optical gain is 1.54 compared with the backlight system with an unpolarized LED. At on-axis, the luminance is 2.4× higher. Because the output light is concentrated near the surface normal direction, no additional brightness enhancement film is needed. This polarization-preserving LGP enables a polarized or partially polarized LED backlight to be used, which in turn greatly enhances the optical efficiency of a LCD.**

***Index Terms*—Light guide plate, liquid crystal display (LCD).**

I. Introduction

LOW power consumption is a critical issue for all the display devices, including liquid crystal displays (LCDs) [1], [2]. For smartphones and tablets, low power consumption leads to a long battery life. For large screen TVs, Energy Star 6 sets a challenging goal for a 60-inch TV to be lower than 100 W, and beyond 90-inch the maximum power consumption is clamped at 115 W. However, the state-of-the-art 60-inch high definition (1920 × 1080) LCD TV consumes ~200 W, which is twice higher than the targeted value. This problem is amplified as the panel size or resolution increases. Therefore, reducing power consumption is an urgent issue.

Several approaches have been proposed to improve the optical efficiency of an LCD system. For examples, using a more efficient backlight [1], [3], recycling backlight with a reflective polarizer [4], [5], multi-primary colors [6], and field sequential colors with red, green and blue light emitting diodes (LEDs) [7]–[9], just to name a few. Different approaches have different merits and challenges.

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Most LCDs require two crossed linear polarizers in order to obtain high contrast ratio. A conventional backlight source is randomly polarized, thus in the most ideal case only 50% of the backlight can pass through the polarizer. A LED with linearly polarized emission has potential to double the optical efficiency of an LCD. Several approaches, such as crystal growth along nonpolar or semipolar orientation [10], [11], and embedding LED with an interior or exterior wire-grid polarizer [12], [13], have been proposed to realize a linearly or partially polarized LED. Although it is still in developmental stage, such a linearly polarized light source could become available in the near future.

However, even with a perfect linearly polarized LED the incident light could still be depolarized during propagating in the light guide plate (LGP) or other optical films. This depolarization effect could severely compromise the benefit of the polarized light source. Such phenomenon is significant in conventional edge-lit LGPs [14]. Some LGPs with polarization preserving feature have been proposed, e.g., using a sub-wavelength polarization separating grating [15], [16] or selective reflection on the interface between isotropic and anisotropic layers [17], [18]. However, the former requires a high precision nanofabrication technique, while the later limits the selection of LGP material. Moreover, both approaches are not cost effective and difficult for mass production.

In this paper, we first analyze the polarization efficiency of two commonly employed LGPs: Type-I with scattering dots and Type-II with refractive microgrooves. From the lessons learned, we then propose a Type-III LGP based on total internal reflection (TIR), which exhibits a much weaker depolarization effect. After a linearly polarized light passing through the TIR-LGP, the polarization efficiency can still keep 77.2%. In comparison with Type-I and Type-II, our TIR-LGP shows a 2.4× higher on-axis luminance for a linearly polarized incident light. As a result, no brightness enhancement film (BEF) is required. The advantages of our Type-III LGP would manifest once the partially polarized or linearly polarized light source is available.

II. System Configuration

Fig. 1 depicts the structure of a typical edge-lit backlight system in our simulation. It consists of a LED array, input linear polarizer, LGP, output linear polarizer, and the observation plane. Our simulation is based on the LightTools software [19]. The LED array contains five LEDs arranged in parallel on the left edge of the LGP. Each LED is a typical planar Lambertian source with directivity $(2\theta^{1/2})$ of 120° and has a luminous flux of 2 lm. Because the software does not allow us to identify the polarization state of the light source, we intentionally insert

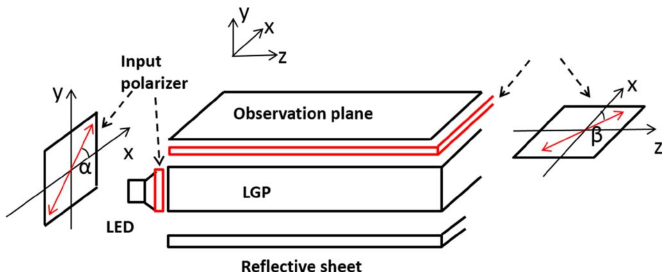

Fig. 1. Schematic of the light source and edge-lit type LGP.

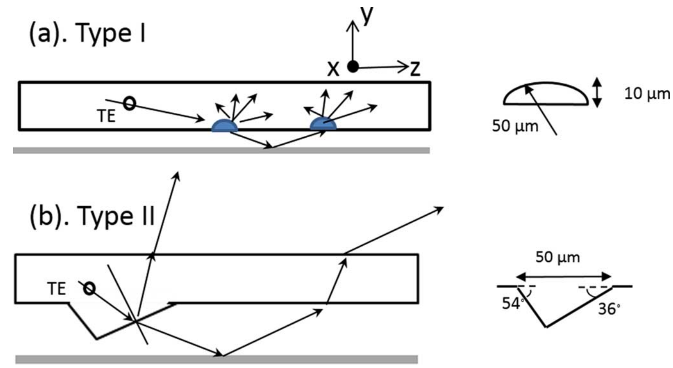

Fig. 2. Schematic and ray tracing of (a) Type-I LGP, and (b) Type-II LGP. The inset shows the geometrical parameter of each light extracting microstructure.

a linear polarizer in front of the LGP to define the input polarization. In practice this polarizer is not needed when using a polarized light source. During simulation, we assume the LGP size is 60 mm * 40 mm * 3 mm, and is made of PMMA with refractive index $\mathrm{n} = 1.49$. The bottom reflector sheet has 95% reflectivity and 5% absorption. There is also a frame encircles the LGP with 85% reflectivity. After the light is incident from the left side, it is confined by TIR while propagating in the LGP. Once the TIR condition is broken by certain microstructure, the light will leak out from the top surface. Through this process the edge-lit LGP can convert the linear array light source into planar emittance. An output polarizer is laid on top of the LGP for analyzing the output polarization. An observation plane is set above the output polarizer to record the spatial illuminance distribution of the output light.

In our design, there are two important characteristics that define the quality of LGP: 1) Polarization efficiency defined as $\Phi_{\mathrm{pol}}/\Phi_{\mathrm{total}}$: Here Φ_{total} is the total output light flux and Φ_{pol} is the light flux passing through the output polarizer and reaching the LCD panel. During each simulation Φ_{pol} is recorded with the insertion of output polarizer, and Φ_{total} is obtained without the output polarizer. 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 to certain degree so that the polarization efficiency can hardly reach unity. Our objective is to design a LGP with high polarization efficiency. 2) Spatial illuminance uniformity defined as $\mathrm{I_{min}}/\mathrm{I_{max}}$: Here $\mathrm{I_{min}}$ and $\mathrm{I_{max}}$ stand for minimum and maximum spatial illuminance, respectively. A desired LGP should also keep good spatial illuminance uniformity.

As Fig. 1 shows, the transmission axis of the input polarizer and output polarizer makes an angle α and β with respect to x axis. The input polarizer sets the polarization direction of the LED irradiance, while the output polarizer controls the polarization of output light which will eventually enter the LCD. The transmission axis direction greatly affects the final output irradiance. As a special case when $\alpha = 0$ and $\beta = 0$, both input and output beams are actually TE polarized in the cross section plane of the LGP ($y - z$ plane). In our simulation we find this setting leads to maximum light output, so we will keep this configuration throughout the paper.

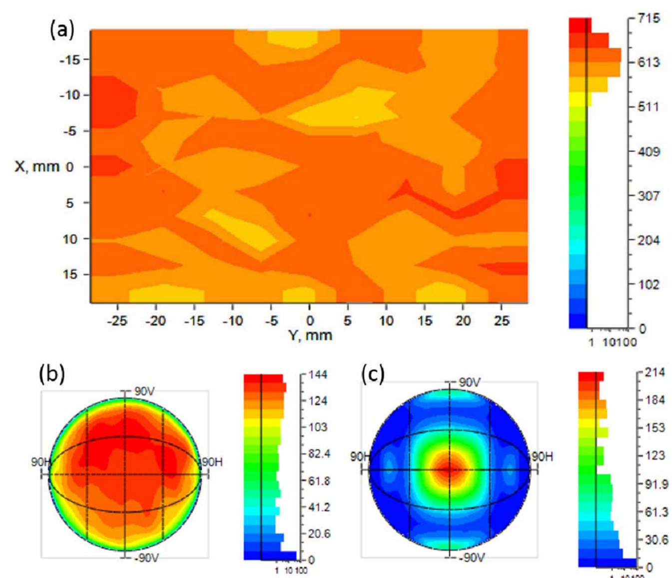

Fig. 3. (a) Simulated spatial illuminance of type-I LGP with dotted microstructure, (b) angular light distribution of LGP alone, and (c) angular light distribution of the LGP with two crossed BEFs.

III. Depolarization Effect in a Conventional LGP

Let us first analyze the polarization efficiency of two conventional LGPs: Type-I has dotted microstructure printed on its bottom surface, and Type-II has microgroove microstructure on the bottom surface, as Fig. 2 depicts. The microdot structures of Type-I LGP (Fig. 2(a)) have uniform size: radius $\mathrm{r} = 50\ \mu$m and height $\mathrm{h} = 10\ \mu$m. Each microdot acts as a Lambertian scatter. An optimal distribution pattern is obtained by the backlight pattern optimization module in LightTools software [19].

Fig. 3(a) shows the simulated spatial illuminance distribution of Type-I LGP. Its uniformity is 79.8%. Fig. 3(b) shows the simulated angular luminance distribution for the entire light emitting area. Because the light emits from LGP with broad angular range so the on-axis luminance is low. In order to boost the on-axis luminance, two crossed BEFs should be laminated on top of the LGP. Fig. 3(c) shows the resultant angular luminance. Most of light is now preferentially emitted around the surface normal direction so that the on-axis luminance is increased.

TABLE I
SPATIAL ILLUMINENCE AND POLARIZATION EFFICIENCY OF TYPE-I LGP

	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%

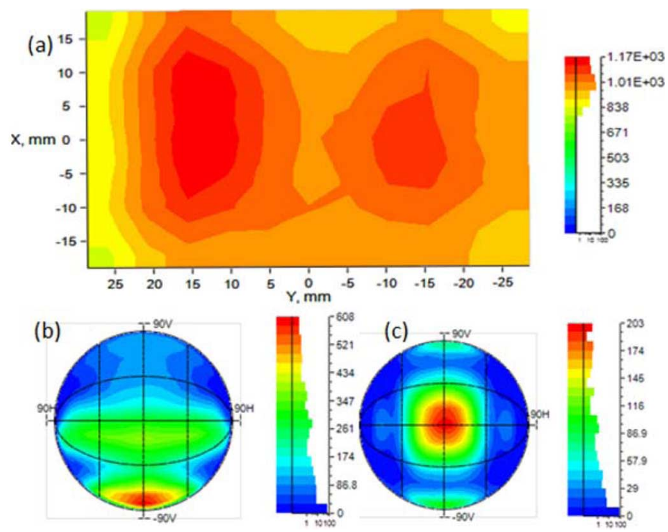

Fig. 4. (a) The spatial illuminance of Type-II LGP with V-groove microstructure, (b) Angular luminance distribution of the LGP, and (c) Angular luminance distribution of the LGP with two crossed BEFs.

Table I lists the polarization efficiency of Type-I LGP. Here, we assume each LED emits 2 lm. The light output from a bare LGP has total illuminance of 1109.1 lux, in which 614.2 lux is TE polarized. Therefore, the polarization efficiency for TE wave is 55.4%. After inserting the BEF, light is recycled between BEF and LGP, and some light is lost during this process due to absorption. The total light output drops to 702.1 lux, while TE polarized light is 354.5 lux, so the polarization efficiency declines to 50.5%. To verify whether this depolarization effect is general, we also studied dotted microstructure with different geometrical shape and pattern distribution. For all the patterns studied, the polarization efficiency is always less than 55%. Therefore, Type-I LGP greatly depolarizes the light. A linearly polarized input light would become almost unpolarized after propagating through the Type-I LGP. The detailed mechanisms will be explained later.

Fig. 2(b) shows the Type-II LGP structure with microgrooves on the bottom surface. Each microgroove has dimension of 50 μm. These microgrooves are arranged with Bezier's distribution for achieving high spatial illuminance uniformity [19]. Fig. 4(b) shows the simulated angular luminance distribution for the entire light emitting area, and the calculated uniformity is 70.2%. The angular luminance distribution is displayed in Fig. 4(b), indicating most lights exit from the LGP at a large angle. This oblique luminance is not favorable for LCD's contrast ratio. Therefore, crossed BEFs is required in order to steer the light path toward the surface normal direction. The resultant angular luminance is shown in Fig. 4(c).

Table II lists the polarization efficiency of Type-II LGP. For a bare Type-II LGP, the emitted light has total illuminance of

TABLE II
SPATIAL ILLUMINNCE AND POLARIZATION EFFICIENCY OF TYPE-II LGP

	Illuminance (lux)		Polarization efficiency
	Total	TE component	
Type-II LGP	1425.3	1013.4	71.1%
Type-II LGP with BEF	830.8	445.6	51.7%

1425.3 lux, while the illuminance for TE component is 1013.4 lux. The polarization efficiency is 71.1%, which is much higher than that of Type-I. However, after inserting the BEFs, the polarization efficiency of TE drops to 51.7%. Although a bare Type-II LGP could partially preserve the light polarization state, after traversing the BEFs the light would be depolarized.

A simple ray tracing can explain the origin of the depolarization. As indicated in Fig. 2(a), several mechanisms could lead to depolarization in Type-I LGP. 1) The dotted microstructure would scatter the incident light into different directions; each scattered wave experiences a different phase change and propagate towards different directions. The total scattered wave is the summation of each individual wave and it could become partially polarized. 2) For a TE-wave travelling in the LGP cross section plane ($y-z$ plane), the microstructure could scatter the light into different directions and most of the rays would scatter out of $y-z$ plane. Since the polarization direction is perpendicular to the light propagation direction, the polarization state would rotate with light propagation direction and is no longer a TE wave in the $y-z$ plane. 3) Light could experience multiple scattering during propagation, and each scattering would average out the light polarization into different directions. Thus, the outgoing light could become unpolarized after exiting from type-I LGP.

On the other hand, Type-II LGP uses refraction instead of scattering for light guiding. As shown in Fig. 2(b), after the incident light hits the microgroove, the ray is split into two parts: transmissive and reflective. Compared with scattering, there is fewer ray-splitting so that the depolarization effect is less significant. Therefore, Type-II LGP has a higher polarization efficiency than Type-I. However, for ray propagating out of $y-z$ plane, there is still polarization rotation effect which induces a certain degree of depolarization. On the v-cut interface the transmission is higher than reflection, so the majority of light would transmit and finally exit at a large angle, as indicated in Fig. 2(b). An extra BEF is required to boost the on-axis illuminance. In addition to LGP, BEF is another source of depolarization. It deflects the ray propagation direction, which in turn will rotate accordingly. As the light propagates between BEF and LGP, it is depolarized.

IV. POLARIZATION-PRESERVING LGP

Through analyzing the origin of depolarization, we learn some lessons for designing a polarization-preserving LGP. 1) It is much better to use refraction instead of scattering to guide light. 2) Splitting light path would inevitably induce depolarization, and therefore it is better to utilize TIR to avoid the light path splitting. And 3) LGP is preferred to have strong on-axis luminance; under this circumstance BEFs are not needed and the associated depolarization could be avoided. Based on these

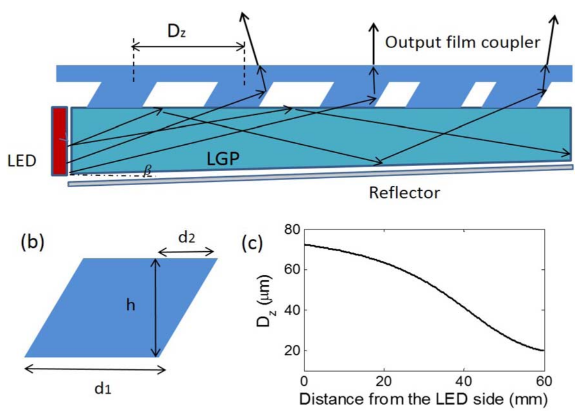

Fig. 5. (a) Schematic drawing of the proposed Type-III LGP consisting of a main body and an output film coupler. (b) Geometry of the parallelogram prism, and (c) Relationship between Dz and the distance to LED. The distribution of microstructure follows a Bezier distribution.

principles, here we propose a new LGP (Type-III) that has much lower depolarization effect.

Fig. 5(a) shows the structure of Type-III LGP. The main body of LGP has a wedge shape with inclination angle $\beta = 1^\circ$. Simulation proves the wedged LGP has higher illuminance than the rectangular LGP. In our Type-III LGP, there is no any microstructure on the bottom or top surface of the main body. Light is extracted by an output film coupler. The film coupler 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. 5(a). Before the light hits the contact region, it will continue to propagate 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, which in turn is deflected toward the surface normal. The amount of light that can be coupled out is governed by the bottom width of the prism surface, and the angular distribution can be controlled by the slope of the prism.

Each microstructure has a parallelogram shape and its basic unit is shown in Fig. 5(b). Each microstructure has the following geometry parameters: $\mathrm{h} = 12\ \mu\mathrm{m}$, $\mathrm{d_1} = 16\ \mu\mathrm{m}$, $\mathrm{d_2} = 8\ \mu\mathrm{m}$. The geometry is specially designed to optimize the on-axis luminance. $\mathrm{D_z}$ represents the separation between each microstructure; it follows a Bezier distribution. The control parameter of the Bezier distribution is modified many times until a uniform distribution is obtained. Fig. 5(c) shows the variation of $\mathrm{D_z}$ as a function of distance to the LED side. Near the LED side the input illuminance is stronger, so we intentionally enlarge the interval between microstructures to lower the light extraction. On the far side, the LED illuminance is weaker so we increase the microstructure density in order to extract more light. Fig. 6 shows the simulated spatial distribution at the output coupler. A reasonably good spatial uniformity (76.8%) is achieved.

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 a gain factor of 1.54 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 out. 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. 7(a) depicts the light paths of two rays with different propagation directions. The parallelogram prism is a one dimensional structure, which can only control 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 would still exit the LGP at an oblique angle. We calculate the angular distribution of the light output from the entire light emitting area. The angular distribution of the total light output is only confined along the horizontal direction, as sketched in Fig. 7(b). We also test the angular distribution at several different points on the observation plane, and find that the angular distribution is quite uniform at different positions. The total light output can be split into TE and TM components. Their angular distribution is shown in Figs. 7(c) and (d), respectively. It is obvious that the TE component mainly concentrates near the axial region, while the TM component predominantly spreads out at off-axis. For display applications, only TE component can pass through the output polarizer and reach the LCD panel. Its luminance is already on axis so that no extra BEF is needed.

In Fig. 7(a), ray A would maintain its polarization direction while the polarization state of ray B would inevitably rotate following the variation of propagation direction. For skew rays this effect could be significant. As a result, when viewed from the off-axis direction where skew rays dominate, TE component [Fig. 7(c)] decreases while TM component [Fig. 7(d)] increases. This is the primary source of depolarization in type-III LGP. On the other hand, the on-axis emission is less affected by the polarization rotation effect. As Fig. 7(c) shows, the majority of on-axis light intensity is TE polarized. Therefore, the polarization efficiency for the on-axis light could be very high.

To validate this hypothesis, we simulate the on-axis angular luminance along the vertical direction. Calculation is performed for both unpolarized light and TE polarization. Fig. 8(a) shows the angular luminance from LGP with an unpolarized light source. Different types of LGPs are represented with different colors. Type-III LGP has on-axis luminance of 292 nits: it is $\sim 1.4\times$ higher than that of Type-I and Type-II. This is because Type-I and Type-II LGPs require extra BEFs. When the light recycling takes place between BEFs and LGP, some energy is lost due to absorption and scattering.

Fig. 8(b) shows the angular luminance for TE polarization. The luminance of Type-I and Type-II LGPs maintains at almost the same level as compared to the unpolarized case. This is because Type-I and Type-II LGPs tend to depolarize the light so that the benefit of using a linearly polarized light source is compromised. On the other hand, the luminance from Type-III LGP increases to 590 nits, which is $2.4\times$ higher than that of Type-I and Type-II. Compared to an unpolarized light, Type-III LGP has $1.7\times$ higher luminance. Type-III LGP is much more efficient for a linearly polarized backlight. This is because Type-III LGP not only effectively preserves the TE polarization, but also

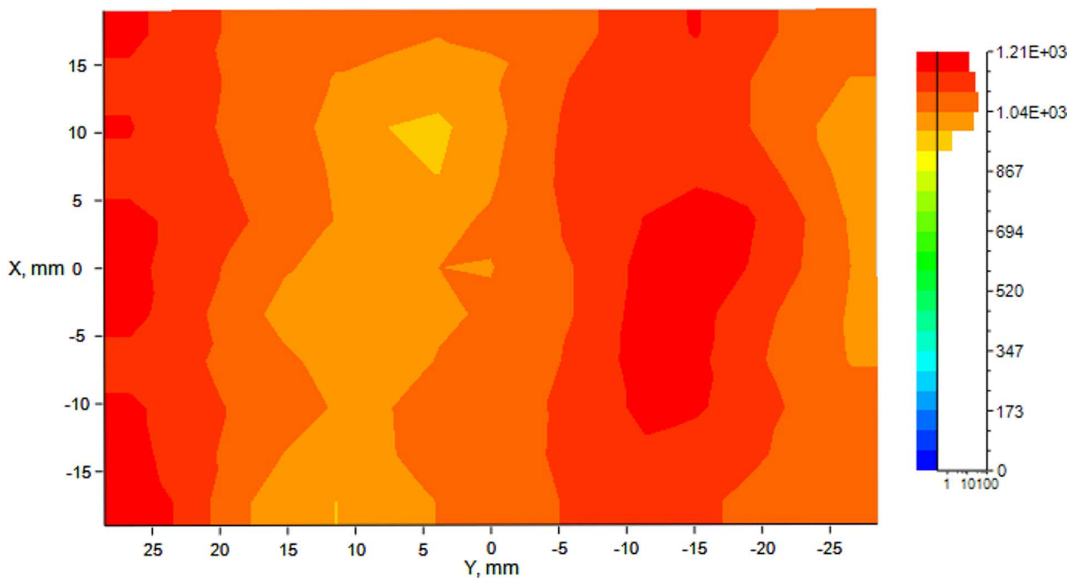

Fig. 6. Simulated spatial illuminance distribution of Type-III LGP.

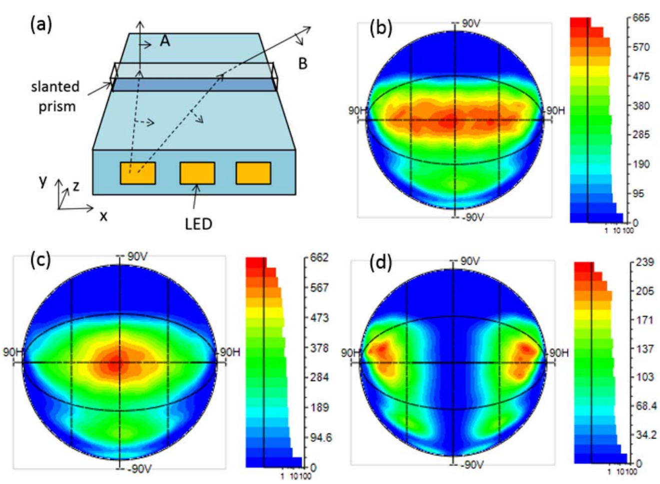

Fig. 7. (a) Light paths of two rays with different propagation directions, (b) Angular distribution of the total output light, (c) Angular distribution of the output light with TE component, and (d) Angular distribution of the output light with TM component.

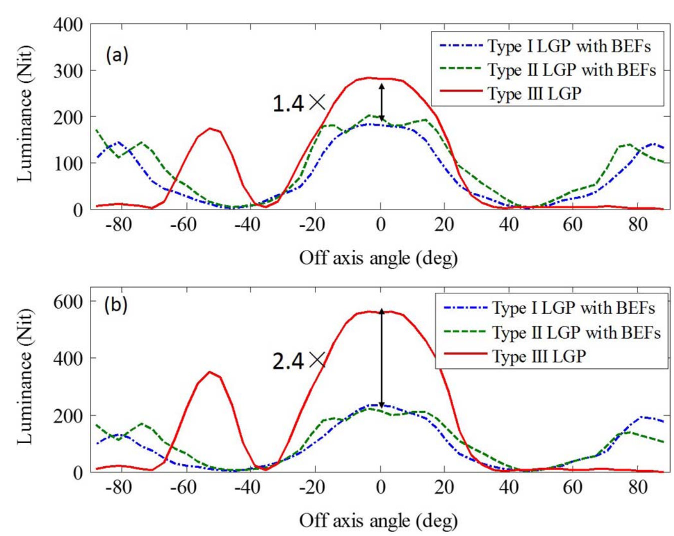

Fig. 8. (a) Angular luminance as a function of off-axis angle for the three LGPs under an unpolarized light, and (b) Angular luminance as a function of off-axis angle for the three LGPs with TE polarization. Off-axis angle is measured along the vertical direction.

preferentially emits the TE light towards the surface normal direction.

The newly proposed LGP can also be modified to provide luminance with large angular distribution. As shown in Fig. 9(a), there are a group of parallelogram microstructures on the bottom surface of the output film coupler. Each microstructure has the same height and bottom width, e.g., $\mathrm{h} = 12\ \mu\mathrm{m}$ and $\mathrm{d}_1 = 16\ \mu\mathrm{m}$. But they have different slope: from left to right, $\mathrm{d}_2 = 6.5\ \mu\mathrm{m}$, $8.0\ \mu\mathrm{m}$ and $9.5\ \mu\mathrm{m}$, respectively. Each microstructure will guide the light towards different direction. Fig. 9(c) shows the angular distribution of the modified LGP structure. Compared to Fig. 9(b), it has much wider angular distribution. The illuminance of the modified LGP structure is 1313.3 lux and the TE component is 976.1 lux, so the modified LGP still maintains reasonably good polarization efficiency (74.3%). This modified LGP design is more favorable to TV applications as it provides a sufficiently wide viewing angle.

The results presented above are for a perfectly TE polarized light, i.e., the TE/TM ratio approaches infinity. Under such a circumstance, Type-III LGP can reach 77.2% polarization efficiency. Next, we investigate the effect of a partially polarized light source, in which the polarization efficiency is expected to decrease. Fig. 10 depicts the polarization efficiency as a function of TE/TM ratio of the light source (blue solid line). If the light source has a TE/TM ratio of 5, then the polarization efficiency is 68.0%. As the TE/TM ratio increases to 22, the polarization efficiency reaches 75% and then gradually saturates. Recently, semipolar InGaN LEDs with TE/TM ratio of 9 have been reported [11]. GaInN LED embedded with sub-wavelength wire-grid polarizers can have polarized emission with TE/TM over 49 [12]. For these two types of polarized light sources,

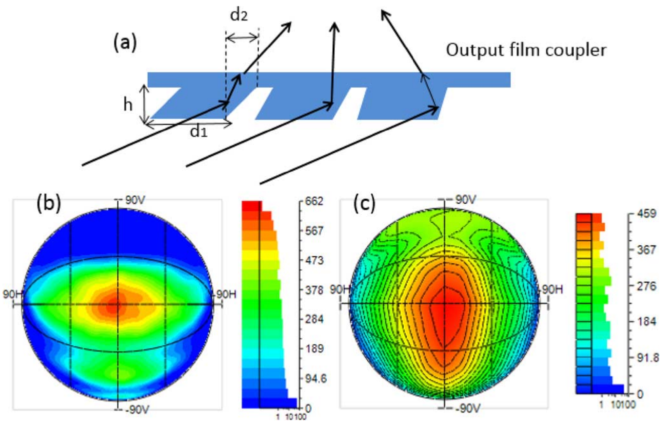

Fig. 9. (a) Light path of three rays passing through a group of microstructures with different slopes, (b) Angular distribution of TE component when all the microstructures have the same slope (same as Fig. 7(c)), and (c) Angular distribution of the TE component for the structure with different slopes shown in Fig. 9(a).

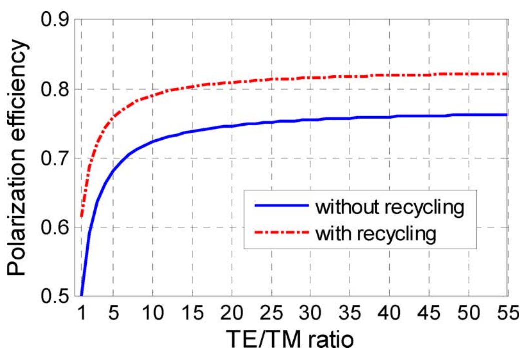

Fig. 10. Simulated polarization efficiency as a function of TE/TM ratio of the input light source.

the polarization efficiency of Type-III LGP reaches 73.2% and 77.0%, respectively.

Finally, we consider the polarization recycling effect. In the above simulations, we assume the output polarizer is absorption type. This polarizer can be replaced with a reflective one, such as 3M's dual brightness enhancement film (DBEF) [4], [5]. Such a reflective polarizer transmits TE while reflecting TM. The reflected TM becomes partially polarized during recycling process and is then sent back to the polarizer. As a result, part of the unused light can be recovered after several cycles. To simulate the polarization recycling effect, we replace the output polarizer as shown in Fig. 1 with a virtual reflective polarizer, which transmits the TE polarized light while reflects the TM polarized light. The polarization recycling effect for different types of LGPs is simulated and the results are listed in Table III. For Type-I and Type-II LGPs, their polarization efficiency is increased to 69% and 71.2%, respectively, when introducing polarization recycling. This polarization efficiency is still inferior to our Type-III LGP without polarization recycling. After polarization recycling, the polarization efficiency of Type-III LGP can reach 82.2%. The recovery ratio of unused light is not very high because there is less TM wave which can be recycled and the type-III LGP tends to maintain polarization. By integrating LGP with an efficient broadband polarization convertor [20], [21], the polarization efficiency can be further improved.

TABLE III
COMPARISION OF DIFFERENT TYPES OF LGP WITH AND WITHOUT POLARIZATION RECYCLING

	Polarization efficiency without recycling	Polarization efficiency with recycling
Type-I LGP+BEFs	50.5%	69%
Type-II LGP+BEFs	51.7%	71.2%
Type-III LGP	77.2%	82.2%

V. CONCLUSION

We have analyzed the polarization properties of edge-lit LGP. The depolarization effect in a conventional LGP is studied and its origins explained. A new polarization-preserving LGP is proposed to boost energy efficiency. This LGP exhibits several attractive features: 1) High polarization efficiency (77.2%), which is $1.46\times$ higher than an unpolarized light. 2) The on-axis luminance is $2.4\times$ 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.

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