Current Optics and Photonics
Vol. 1, No. 2, April 2017, pp. 101-106
ISSN: 2508-7266(Print) / ISSN: 2508-7274(Online)
DOI: https://doi.org/10.3807/COPP.2017.1.2.101

Optimization of Ultrathin Backlight Unit by Using a Tapered Light Guide Film Studied by Optical Simulation

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(Received January 10, 2017 : revised February 14, 2017 : accepted February 20, 2017)

Optical structures of a tapered ultra-thin light guide film (LGF) were optimized by optical simulation for increasing coupling efficiency between light sources and the LGF. A serration pattern on the entrance side surface could provide a comparable coupling efficiency to that of the conventional LGF where a linear, asymmetric prism array was formed on the taper surface. Several micro-patterns were applied to the top and/or bottom surface of the LGF for achieving better luminance property, and it was found that an optimized micro-pyramid pattern exhibited the highest average luminance together with satisfactory luminance uniformity.

Keywords : Light guide film, Coupling efficiency, Taper, Serration, Optical simulation
OCIS codes : (120.2040) Displays; (150.2950) Illumination

I. INTRODUCTION

Liquid crystal displays (LCD) are widely used in display applications from mobile phones to large-size flat panel displays. LCD is a non-emissive display, which means it is necessary to adopt independent light sources called back-light units (BLUs). While direct-lit BLUs are traditionally adopted in large-size LCDs, edge-lit BLUs are used for both small-size and large-size LCDs. In edge-lit BLUs, white light emitting diodes (LEDs) are attached on one or two side surfaces of a light guide plate (LGP), which guides the light for homogeneous illumination via total internal reflection (TIR). Scattering patterns formed on the backside of LGPs direct the guided light toward the LCD panel. Many theoretical and experimental efforts have been made for the improvement of LGP technology since it plays the most important role in the edge-lit BLUs [1-12].

Recent technological achievements have made it possible to develop ultra-slim mobile LCDs. Recently, slim BLUs with a thickness smaller than 0.3 mm have been under development for mobile applications. This thickness is even smaller than that of typical LEDs, which is usually 0.4 mm. It is necessary to input more light from LEDs into the light guide film (LGF), but significant coupling loss is inevitable due to the thickness difference between the LEDs and the LGF. Figure 1(a) demonstrates this situation, where part of the light emitted from LEDs is lost due to the thickness difference between the LED and the flat-type LGF. Accordingly, optimization of the optical structure of the LGF is necessary to reduce this coupling loss. Figure 1(b) shows that a tapered shape at the incident side surface of the LGF is one of the designs to increase the coupling efficiency. However, some light may leak out from the upper inclined surface of the tapered part, the angle of which should be optimized to reduce this coupling loss. Extensive efforts are under way for developing optimized taper shape to reduce the coupling loss in ultra-slim BLUs for mobile applications.

Figure 2 shows one of the efforts to increase the coupling efficiency, where symmetric patterns are formed on the taper surface with respect to the LED location. Figure 2(a) exhibits the conventional case where the taper surface is flat. The cross-section shows that the rays emitted from LEDs are partially transmitted due to the failure of total

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internal reflection. Figure 2(b) shows a linear, asymmetric prism array (called a LAPA pattern) formed on the taper surface symmetrically with respect to the LED location. This pattern, suggested by a Japanese company Omron [13], is known to increase the coupling efficiency of the LGF. In conventional taper structure shown in Fig. 2(a), some of the rays meeting the taper surface exhibits incident angles smaller than the critical angle, resulting in low coupling efficiency. On the other hand, more rays tend to be guided

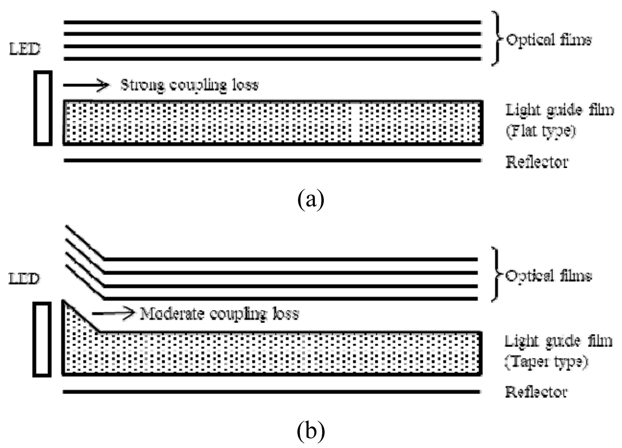


FIG. 1. (a) A thin BLU using a flat light guide film where substantial coupling loss occurs due to the difference in the thickness between LEDs and LGF; (b) A thin BLU using a flat light guide film with tapered end where moderate coupling loss occurs.

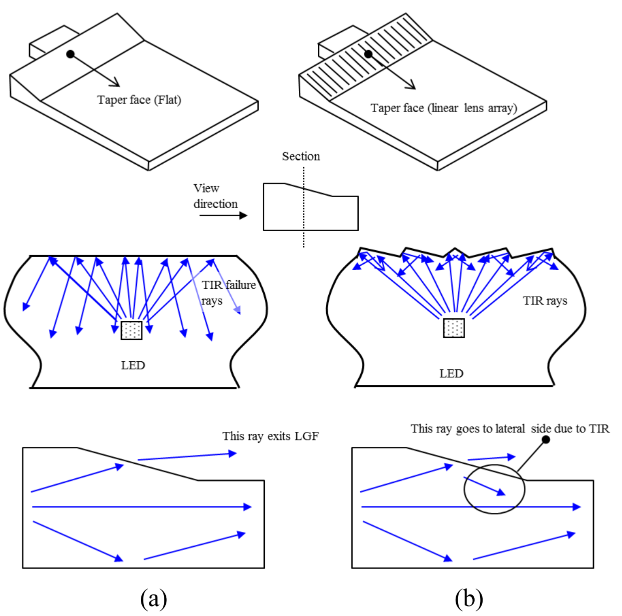


FIG. 2. (a) A LGF with a flat taper face together with two cross sections showing that part of the rays exit the LGF due to the failure of TIR; (b) An LGF with a taper face having a linear asymmetric prism array together with two cross sections showing part of the rays go to lateral sides in the LGF due to TIR.

in the LGF via TIR due to the optimized inclination of the prism pattern, because inclined surfaces of the LAPA pattern are effective in making the incident angles of the rays striking the taper surface larger than the critical angle. The lower figure in Fig. 2(b) shows a schematic side view where part of the rays incident onto the tapered regions with the LAPA pattern are reflected back into the LGF. The imprinting method has been suggested to be a suitable process for fabricating the LGF shown in Fig. 2(b), which, however, has some drawbacks such as overflow.

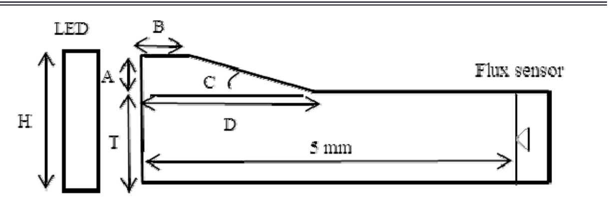
In this paper, we present a new optical structure for the tapered LGF for increasing the coupling efficiency. In this new structure, there is no pattern on the taper surface, while the other taper dimensions are optimized. Moreover, serration pattern is applied to the side (entrance) surface of the LGF. The combination of the serration pattern and the taper structure is helpful in increasing the coupling efficiency. In addition, a micro-prism pattern is suggested for high-luminance applications.

II. SIMULATION

A light guide plate with a dimension of 155×200 mm^2 was constructed, and 36 LEDs were placed with a pitch of 5 mm along the longer side of LGP. Polycarbonate (PC) was assumed for the LGP material, the refractive index of which was calculated by using the Laurent dispersion formula. The emitting area of each LED was 3.6×0.4 mm^2, and the distance between the LED and the entrance surface of LGP was 0.1 mm. The emitting spectrum of these white LEDs was a typical one consisting of a sharp blue peak at ~450 nm from the blue chip and a broad yellow peak at ~580 nm emitted from yellow phosphors.

Table 1 includes a cross-sectional shape of the tapered LGP along with five parameters some of which should be

TABLE 1. Dimensions of the taper region and LED to be optimized for efficient light coupling



Parameter			Range of Parameter value
A	mm	Taper thickness	Fixed as 0.15 mm
B	mm	Taper top width	0, 0.5, 1.0, 1.5, 2.0, 2.5 mm
C	degree	Taper angle	1~40 degree
D	mm	Taper bottom width	D=B+A · tan (π/2−C π/180)
T	mm	Film thickness	Fixed as 0.23 mm
H	mm	LED height	Fixed as 0.40 mm

optimized, i.e., taper thickness A, top width of the taper region B, taper angle C, bottom width of the taper region D (which is determined in terms of the values of B and C), and the film thickness T. The thickness of the LGF and the taper region, denoted as T and A, were fixed as 0.23 mm and 0.15 mm, respectively, in this simulation study. The height of the emitting area of the LED, denoted as H, was fixed as 0.4 mm. The emitting distribution of the LED was assumed to be Lambertian. A flat illumination detector was placed vertically in the LGF at a distance of 5 mm from the entrance surface, and the coupling efficiency was calculated to be the ratio of the flux on the detector to the total flux emitted from the LED. In the simulation, the two parameters B and C were changed in a certain range as shown in Table 1. Commercial software (LightTools, ORA Co.) was used as a ray-tracing simulator.

Figure 3 shows the dependence of the coupling efficiency on the taper angle C and the top width B. The coupling efficiency decreases slightly as the taper angle increases from 1 to 13° and then decreases substantially beyond the taper angle of 13°. This is natural because the incident angle of the light striking the taper surface becomes larger as the taper angle C increases, making more rays leak out through the taper surface that do not meet the condition of TIR. The extended view on the lower figure shows that the coupling efficiency is not sensitive to the top width B except for the case of B=0 mm. The optimized taper angle and the top width are found to be 4° and 0.5 mm, respectively, which lead to the coupling efficiency of 64.4%.

As a next step, a serration-type prism pattern was formed on the entrance surface of the LGF as shown in Fig. 4. This serration pattern disperses the rays along the horizontal direction, as schematically shown in Fig. 4. This redirection in turn increases the incident angle of the rays striking the taper surface effectively and reduces the probability of the failure of TIR. Table 2 shows dimensions of the serration pattern and the taper region, which should be optimized for efficient light coupling The apex angle θ of the vertically-aligned prism array was changed in the range from 20 to 120°, while the serration width P was fixed as 0.02 mm, as shown in Table 2. Figure 5 shows the dependence of the coupling efficiency on the apex angle of the serration pattern for four taper structures where the top width was fixed as 0.5 mm and the taper angle was changed in the

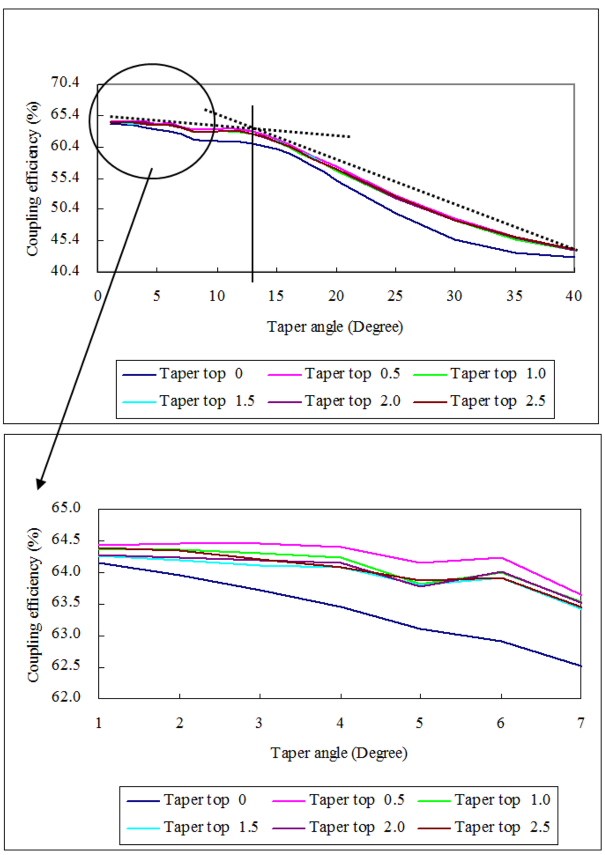


FIG. 3. The dependence of the coupling efficiency on the taper angle and the taper top width. The lower figure is the extended view of the part of the upper figure as shown in the figure.

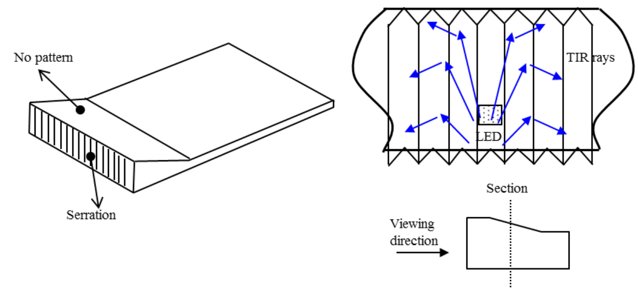
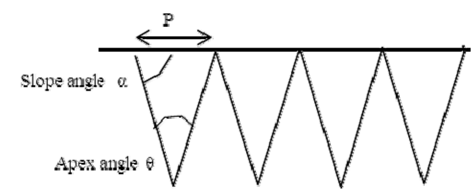


FIG. 4. The serration pattern applied to the entrance side surface of the LGF. The right figure shows a schematic view for the rays dispersed by the serration pattern horizontally.

TABLE 2. Dimensions of the serration pattern and the taper region of the LGF



Parameter			Range of Parameter value
θ	degree	Serration apex angle	20-120 degree ($\alpha=90-\theta/2$)
P	mm	Serration width	0.02
A	mm	Taper thickness	Fixed as 0.15 mm
B	mm	Taper top width	0, 0.5, 1.0, 1.5, 2.0, 2.5 mm
C	degree	Taper angle	1~40 degree
D	mm	Taper bottom width	D=B+A · tan ($\pi/2-C\ \pi/180$)
T	mm	Film thickness	Fixed as 0.23 mm
H	mm	LED height	Fixed as 0.40 mm

range from 1 to 4°. For all cases, the coupling efficiency became maximum at the apex angle of 40°, resulting in the coupling efficiency of 68.7% at the condition of the taper angle of 4°. This amounts to approximately 6.7% increase in the coupling efficiency compared to the case without the serration pattern on the entrance side surface.

It would be interesting to compare the present coupling efficiency with the previous results obtained from the LAPA pattern formed on the taper surface. Table 3 summarizes the results on the coupling efficiency for the three cases discussed above. In the case of the LAPA pattern shown in Table 3, one side angle α_1 was fixed to be 15° and the other angle α_2 was changed between 55~65°. The obtained maximum coupling efficiency was 67.8% at α_2=57°, which is comparable to that obtained from the LGF (68.7%) with a serration prism pattern on the entrance side surface. This result shows that inscribing appropriate patterns on the entrance surface may replace the role of another pattern formed on the taper surface showing a comparable coupling efficiency.

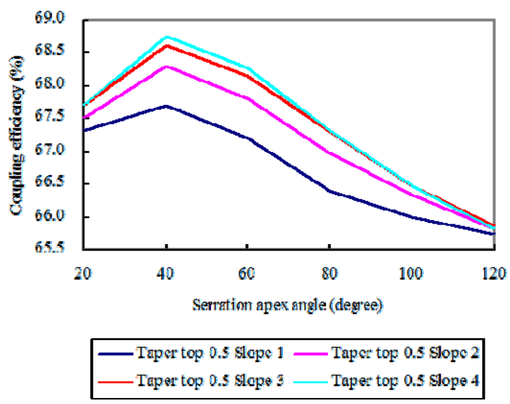


FIG. 5. The dependence of the coupling efficiency on the apex angle of the serration pattern and the taper slope angle at a fixed taper top width of 0.5 mm.

III. RESULTS AND DISCUSSION

Various micro-patterns have been applied to the upper and/or lower surface(s) of the light guide plate for adjusting the luminance distribution and increasing the overall efficiency of backlights [2, 11-12]. As a typical light-extraction component, diffusely reflecting dot patterns are formed on the bottom surface for redirecting the guided light toward the LCD panel. The diffuse nature of the scattering dots inevitably necessitates several optical films on the LGF for realizing homogeneous and collimated light. A diffuse film, one or two prism films, and a protection film are placed over the LGF in general [1].

As light-extraction structures, micro-patterns were considered and optimized on both upper and lower surfaces of LGFs in this study. Figure 6 shows two micro-patterns, the V-cut pattern on the upper surface and the micro-pit pattern on the lower surface of the LGF. The width and the depth of the V-cut pattern were 10 μm and 3 μm, respectively. The pitch for this pattern was 25 μm. The diameter and the height of the micro-pit pattern negatively inscribed into the lower surface of the LGF were 50 μm and 3 μm, respectively. Another micro-pattern on the lower surface of the LGF was a pyramidal extraction pattern negatively inscribed

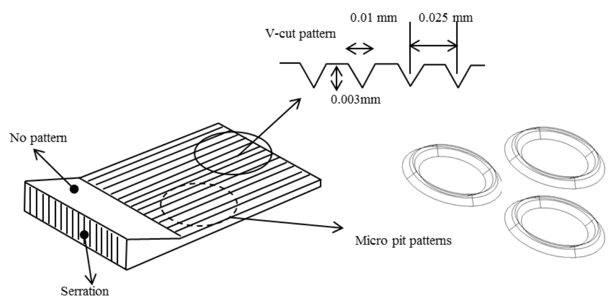
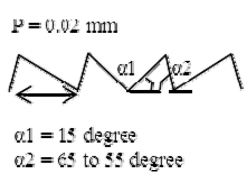
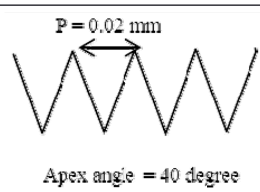


FIG. 6. V-cut and micro-pit extraction patterns on a tapered light guide film with a serration pattern on the side surface.

TABLE 3. Comparison of the coupling efficiency of three conditions for the LGF

Parameter	Taper without any pattern	Taper with the LAPA pattern	Taper with serration prism pattern
A (mm)	0.15	0.15	0.15
B (mm)	0.5	0.5	0.5
C (degree)	4	4	4
D (mm)	2.645	2.645	2.645
Pattern	None	LAPA pattern on the taper surface	LAPA prism on the entrance side surface
Pattern shape	None		
Coupling efficiency	64.4%	67.8%	68.7%

into the film as shown in Fig. 7. These micro-pit and micro-pyramid patterns were randomly arranged and optimized for achieving satisfactory uniformity over the LGF. The optimized number of patterns per unit area as a function of the distance from the LEDs is shown in Fig. 8. These patterns can be formed by using a laser machining process. For example, these patterns can be made on stainless steel by using a Nd:YAG laser. This master mold can be used to engrave these micro-patterns on the LGP.

In addition to the LGF, conventional optical films were stacked, i.e., a low-haze diffuser film, two crossed prism films and a protection film were placed sequentially on the LGF. Figure 9 shows the colored on-axis luminance distribution on the backlight with the serration pattern on the entrance surface and the micro-pyramid pattern on the lower surface of the LGF. The 9-point luminance uniformity is estimated to be approximately 80%, that is, satisfactory luminance uniformity could be achieved by optimizing the distribution of the micro-pyramid pattern. Table 4 compares relative average luminance and luminance uniformity for four cases with different combinations of micro-patterns. Note that there was no pattern on the tapered surface for these four cases in Table 4. The combination of the V-cut pattern on the upper surface and the micro-pit pattern on the lower surface without any serration pattern is a reference design (Case 1). The luminance uniformity of this design is ~77%. If the V-cut pattern is removed from the top surface of the LGF (Case 2), the average luminance decreases by ~12% compared to that of the reference design. This indicates that the V-cut (or other) pattern on the top surface of the LGF is necessary to increase the average luminance. On the other hand, the serration pattern on the side entrance surface of the LGF may be adopted instead of the V-cut pattern for enhancing coupling efficiency and thus the average luminance (Case 3). In this case, the average luminance and the luminance uniformity are comparable to those of the reference case. Finally, the micro-pit pattern may be replaced with the micro-pyramid pattern for further increasing the average luminance. The resulting average luminance of the last design (Case 4) is higher than that of the reference case by ~12% together with a bit larger luminance uniformity.

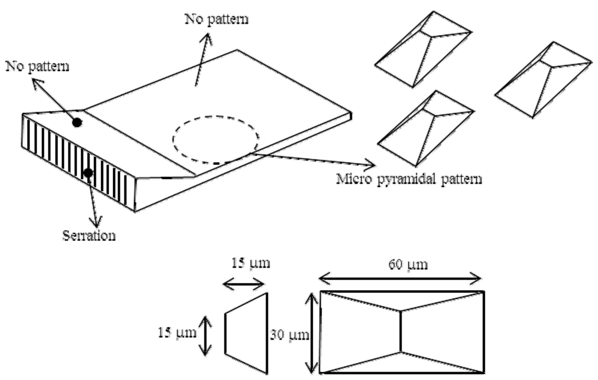


FIG. 7. A pyramid extraction pattern on a tapered light guide film with a serration pattern on the side surface.

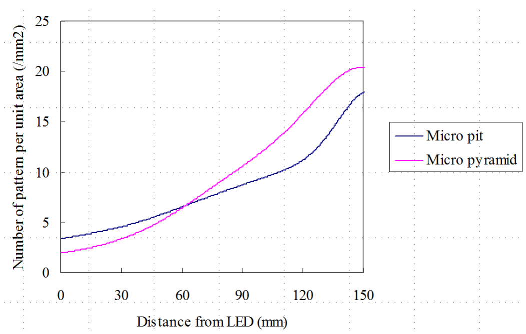


FIG. 8. Optimized number density of the two patterns as a function of the distance from the LEDs.

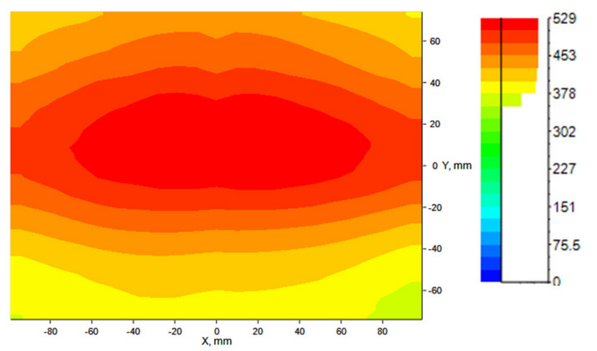


FIG. 9. The on-axis luminance distribution on the backlight with the serration pattern on the entrance surface and the micro-pyramid pattern on the lower surface of the LGF.

TABLE 4. Comparison of luminance characteristics of four cases

	Case 1 (Reference)	Case 2	Case 3	Case 4
Coupling face pattern	None	None	Serration prism	Serration prism
Top extraction pattern	V-cut	None	None	None
Bottom extraction pattern	Micro pit	Micro pit	Micro pit	Micro pyramid
Relative average luminance	100%	87.7%	99.2%	111.7%
Luminance uniformity	77%	75%	78%	80%

IV. CONCLUSION

A new optical structure was studied to increase the coupling efficiency between light sources and a light guide film having a taper structure at the entrance part of the film. We found that the traditional linear, asymmetric prism array formed on the taper surface could be replaced by a serration pattern on the entrance side surface with a comparable coupling efficiency of ~69%. The coupled light could be extracted out toward the top surface of the LGF via upper and/or lower micro-patterns such as micro-pit and micro-prism patterns. The micro-prism pattern negatively inscribed into the bottom surface of the LGF was found to be the most effective design from the viewpoint of average luminance together with satisfactory luminance uniformity.

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