Novel buried inverse-trapezoidal micropattern for dual-sided light extracting backlight unit

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Abstract: We devised a novel buried inverse-trapezoidal (BIT) micropattern that can enable light extracting to both front and back sides of the backlight unit (BLU). The proposed BLU comprised of only a single-sheet light-guide plate (LGP) having the BIT micropatterns only on the top surface of the LGP. The proposed BLU shows normal directional light emitting characteristics to both the front and back sides of the LGP and successfully acts as a planer light source for a dual-sided LCD. The proposed BLU has the potential to dramatically reduce the thickness, weight and cost of the dual-sided LCD thanks to its single-sheet nature.

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1. Introduction

A dual-sided liquid crystal display (LCD) is a display device for delivering information to both front and back sides of the display simultaneously, and is able to display a great deal of information in a limited space, which is suitable for mutual communication. Conventionally, the dual-sided LCD has been made by attaching two single-sided LCDs back-to-back and is

used in large display applications [1]. However, recently, it has been applied to portable information display devices such as mobile phones, laptops and tablet PCs, and consequently there is a growing need for a thinner, lighter and cheaper dual-sided LCD system.

The primary obstacle to achieving these features is the backlight unit (BLU). The BLU is needed to supply white light to the two LCD panels, but in this configuration it consists of too many optical sheets, including the light-guide plate (LGP), prism sheets, diffuser and reflective sheets. Thus, the BLU accounts for a significant portion of the thickness, weight and cost of the dual-sided LCD. Therefore, many studies have been aimed at reducing the number of optical sheets in the BLU [2–4]. Previous studies have removed the duplicate LGP and reflective sheets of a conventional dual-sided LCD by using a sheet of dual-sided light emitting LGP. However, previous LGPs have not shown vertical directionality of the extracted light solely, therefore, in spite of these partial successes, it is still a challenging issue to eliminate the prism sheets, which are used for light collimating.

In order to realize an ultimately simple backlight system for a dual-sided LCD, we devised a novel light-extracting microstructure based on a previous study where *Lee et al.* developed a single-sheet unidirectional BLU using protruding inverse-trapezoidal (PIT) microstructures [5]. The PIT structure has an inverse-trapezoidal cross-sectional shape and its unique feature is its negatively slanted sidewall. The negatively slanted sidewall reflects light by total internal reflection (TIR) and illuminate to certain direction, thus directionality can be controlled by the inclined angle of the sidewall [6]. However, the PIT microstructure only provides one directional light extraction; therefore it cannot be used directly in a dual-sided light emitting BLU.
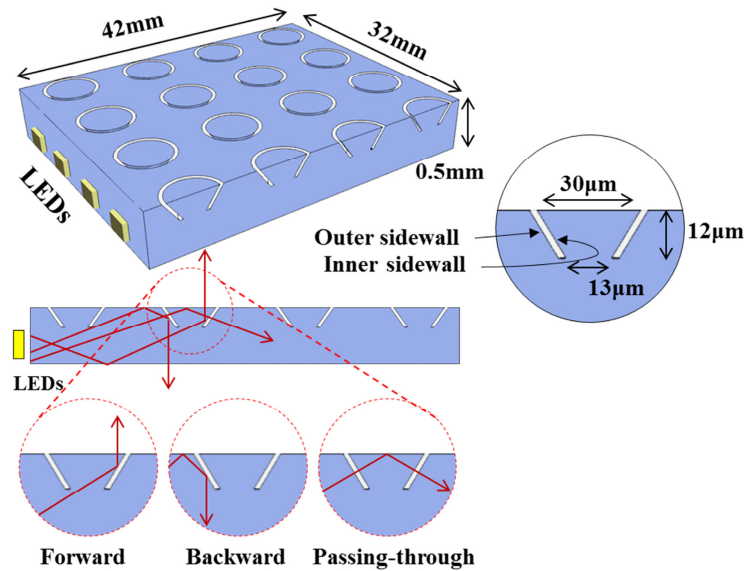

Fig. 1. Schematic of the proposed dual-sided light emitting BLU and its optical light-path. The buried inverse-trapezoidal (BIT) microstructures in the figure are exaggerated in size and spacing for viewing purposes. The propagating light inside of the LGP can be extracted to both forward and backward directions by the total internal reflection that occurs at the inner or outer sidewall of the BIT microstructures.

Here, inspired but distinctively different from the previous study, we propose a buried inverse-trapezoidal (BIT) microstructure only on one surface, for the first time, that can enable dual-sided light extraction in a single-sheet LGP for a dual-sided LCD. By introducing a unique inclined air-gap structure, the proposed BIT microstructure gives not only vertical directionality to the light, but also includes a dual-sided light extraction characteristic [7].

2. BIT microstructure and BLU design

2.1. Overall scheme of the proposed BLU

The features shown in Fig. 1 illustrate the scheme of the proposed BLU having the proposed BIT micropatterns only on the top surface of a single-sheet LGP which is made of polydimethylsiloxane (PDMS). LEDs are placed on either side of the LGP as light sources. The light propagates inside of the LGP by TIR from the LEDs. A portion of this light can go out of the LGP through the output coupling BIT microstructure. The BIT microstructure has an inverse-trapezoidal cross-sectional shape surrounded by an inclined air-gap placed between the BIT microstructure and the LGP body. This air-gap forms two PDMS/air interfaces at both outer and inner sidewalls, as shown in Fig. 1. Since TIR occurs when the light is going from a higher refractive index material (PDMS in this case) to a lower refractive index material (air in this case), there are three kinds of light paths in the BIT microstructure: forward extraction, backward extraction and passing-through [insets of Fig. 1].

Forward extraction occurs when the traveling light is reflected to an inner sidewall by TIR. At this point, the directionality of the extracted light is controlled by the incident angle of the sidewall. This is similar to the output coupling mechanism of the previous PIT microstructure. In contrast to forward extraction, the backward extraction and passing-through paths are unique characteristics of the BIT microstructure due to the existence of the air-gap. When the light reaches the outer sidewall, if the incident angle to the outer sidewall is larger than the critical angle of the PDMS/air interface, TIR occurs and the light goes toward the backward direction of the LGP. If instead the incident angle to the outer sidewall is smaller than the critical angle, the light passes through the air-gap.

2.2. Design of the microstructure: angle of the sidewall

The direction of the forward or backward extracted light depends on the inclined sidewall angle of the BIT microstructures, as shown in Fig. 2. In case of the forward light extraction, the incident angle θ_i of the light that hits the inner sidewall of the air-gap can be expressed as:

$$\theta_i = \theta_s - \theta_t \tag{1}$$

where θ_s is the sidewall angle and θ_t is the propagating angle of the traveling light inside the BLU. From Eq. (1), the angle of the forward extracting light θ_f is:

$$\begin{aligned} \theta_f &= \theta_i + \theta_s \\ &= 2\theta_s - \theta_t \end{aligned} \tag{2}$$

Likewise, the angle of the backward extracting light θ_b is expressed by:

$$\theta_b = 2\theta_s - \theta_t \tag{3}$$

From Eqs. (2) and (3), it is interestingly noted that the forward and backward extracted lights have the same directionality. Thanks to this symmetry, it is possible to design the BIT microstructure that can extract the light vertical to both forward and backward directions simultaneously.

Figure 3(a) shows the simulation result displaying how the forward light is extracted depending on the sidewall angle θ_s obtained by LightTools® optical simulator. In the simulation 6 LEDs having the Lambertian luminance distribution was used as the light sources. As can be seen in Fig. 3(a), the sidewall angle of 55° can be optimally chosen for the BIT microstructure to achieve the vertical forward light extraction. Also, Fig. 3(b) shows the simulation result exhibiting the forward and backward light extraction behavior when the sidewall angle was optimally set to 55°, from which it is noted that the designed BIT structure successfully extracts light equally to both forward and backward directions all vertically.
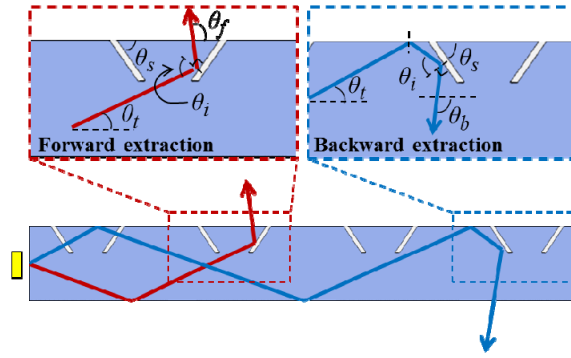
Fig. 2. Relationship between the forward and backward extracting light angles (θ_f and θ_b) and the sidewall angle (θ_s) of the BIT microstructures. Interestingly, the forward and backward extracted lights have the same directionality ($\theta_f = \theta_b$).
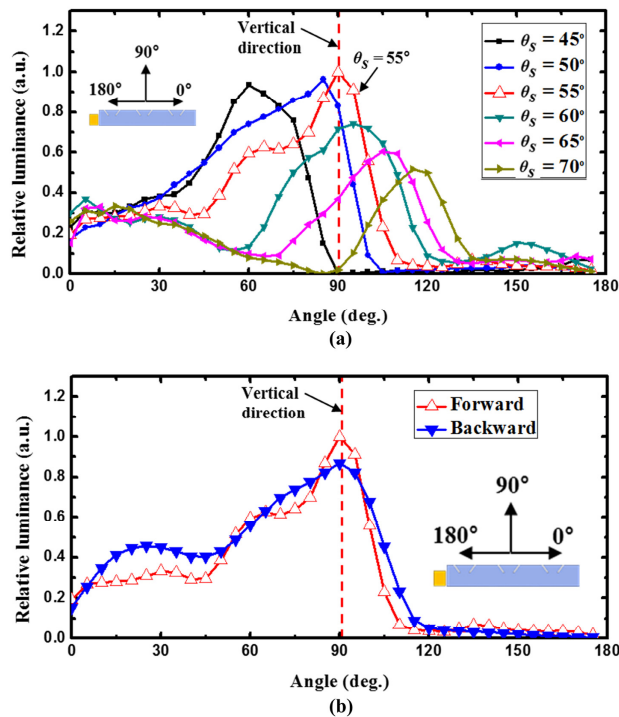

Fig. 3. Simulation results of the forward and backward angular luminance distribution. (a) Forward luminance with respect to the sidewall angle θ_s of the BIT microstructures and (b) the forward and backward luminances when θ_s was optimally set to 55°.

2.3. Design of the microstructure: thickness of the air-gap

The air-gap surrounding the BIT structure is essential to make the forward and backward light extractions possible. In order to choose a proper thickness of the air-gap, we investigated the air-gap thickness effect to the light output coupling efficiency. Figure 4 shows the possible optical loss paths caused by the air-gap structure, shown as the solid lines. The original contributing light paths are drawn with the dotted lines. If the air-gap is negligible, there are only contributing light paths as shown with the dotted lines in Fig. 4. However, in practice, the light can be refracted to escape from the BLU with unintended angle through an interface

between the PDMS body and the air-gap [red solid line in the upper left inset in Fig. 4]. Moreover the valley floor of the air-gap screens and disrupts TIR at the inner sidewall of the air-gap [blue solid line in the upper right inset in Fig. 4]. These two unexpected light paths cause leakage of lights, or reduce light output coupling efficiency of the BIT structures.
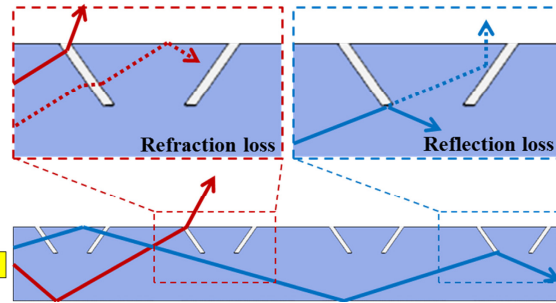

Fig. 4. Possible optical loss paths caused by the air-gap surrounding the BIT structure (all solid lines). The original contributing light paths are drawn with the dotted lines. Upper left inset shows the refraction loss and upper right inset indicates the reflection loss.
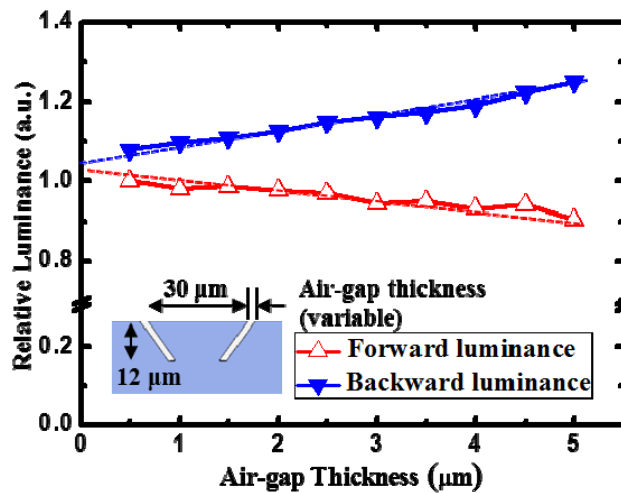

Fig. 5. Simulated forward and backward luminances with respect to the air-gap thickness.

Figure 5 depicts a graph of the simulated forward and backward luminances as the air-gap thicknesses varies. The dimensions of the BIT structure were constant (inset of the graph) except the air-gap thickness. As can be seen in Fig. 5, the forward luminance decreases as the air-gap becomes thicker. On the other hand, the backward luminance increases as the air-gap becomes thicker since the thicker air-gap makes the larger reflective area of the outer sidewall for the backward luminance. According to the simulation result, thinner air-gap is more preferential to minimize the light leakage in the forward luminance as well as to equalize the forward and backward luminances. The dotted lines in Fig. 5 show that if the thickness of the air-gap reaches to almost zero, the forward and backward luminances become identical because the reflecting areas of the outer and inner sidewalls are the same with each other and the optical loss paths turn out to be negligible.

2.4. Optical simulation results

The designed BIT microstructure has a top diameter of 30 μm, a bottom diameter of 13 μm, a height of 12 μm, and a sidewall angle of 55°. The sidewall angle was optimally chosen to obtain vertical directional light extraction in both the forward and backward directions. The

thickness of the air-gap is 1.5 μm considering fabrication capability. The BIT microstructures are distributed in an area of 42 × 32 mm (2-inch diagonal length) and their pitches are gradually decreased as going far from the LEDs for uniformity of spatial luminance.
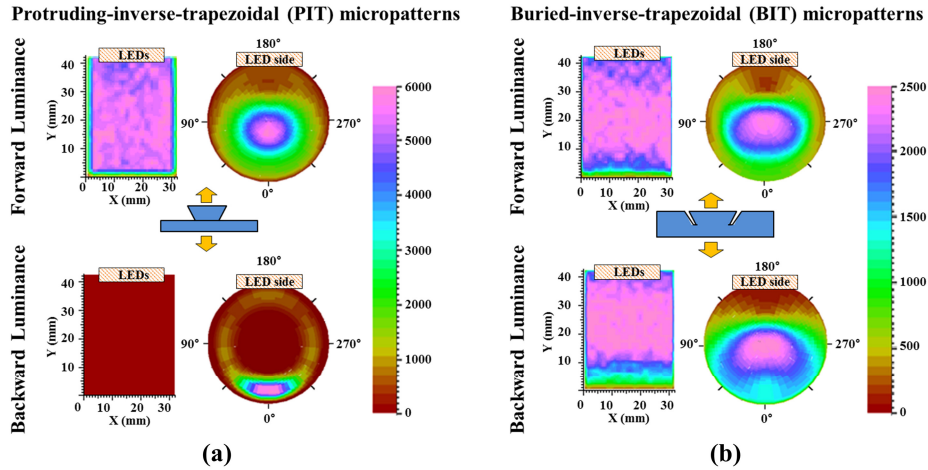

Fig. 6. Simulation results of the spatial and angular luminance distributions of the front and back sides of (a) the previous protruding inverse-trapezoidal (PIT) micro-patterned LGP and (b) the proposed buried-inverse-trapezoidal (BIT) micro-patterned LGP.

The optical properties of the proposed LGP were simulated by optical simulator and Fig. 6 shows the result. To confirm the effect of the inclined air-gap surrounding the BIT microstructure, we compared the optical properties of the LGP having BIT microstructures with those of the LGP having PIT microstructures which do not have the surrounding air-gap. As shown in Fig. 6(a), the LGP with PIT microstructures exhibited an average vertical luminance of 5027 cd/m^2 in the forward direction and negligible luminance in the backward direction. On the other hand, the proposed LGP including the BIT pattern emitted light to both forward and backward directions with 2194 cd/m^2 and 2164 cd/m^2 on average, respectively, as shown in Fig. 6(b). For both the PIT and BIT microstructures, the extracted light was perpendicular to the surface of the LGP, as can be seen in each angular distribution chart. These results indicate that the proposed LGP having the BIT microstructures is best suited to a single-sheet BLU for the dual-sided LCD.

3. Fabrication process

In order to demonstrate the proposed BLU, we fabricated a polydimethylsiloxane (PDMS) LGP having the BIT microstructures only on one surface. The fabrication process of the proposed LGP is illustrated in Fig. 7. The overall process is divided into three steps: photoresist mold fabrication [Fig. 7(a)-3(b)], Ni mold fabrication [Fig. 7(c)-7(f)], and PDMS replication process [Fig. 7(g) and 3(h)].

First, as a seed metal layer for electroplating, Ti (500 Å) and Au (1000 Å) were deposited on the cleaned Si wafer by means of thermal evaporation. Then, 12 μm-thick positive photoresist AZ50XT (Clariant, Co. Ltd.) was spin-coated. On top of the photoresist, a metal mask made of Cu thin film was formed for self-aligned diffuser lithography (SADL) [8]. During the SADL process, an opal diffuser plate (NT02-149; Edmund Optics, Co. Ltd) and water were inserted between the UV light source and the Cu self-aligned mask. The UV light was scattered and spread by the diffuser plate [Fig. 9(a)]; therefore, a photoresist mold having truncated-conical micro-holes array was formed after UV exposure and development [Fig. 9(b)]. Since the type of the diffuser plate and the index-matching liquid defines the side angle

of each hole, the opal diffuser plate and deionized water were selected deliberately in this fabrication process to make the optimized side angle of 55 ° [6, 9].
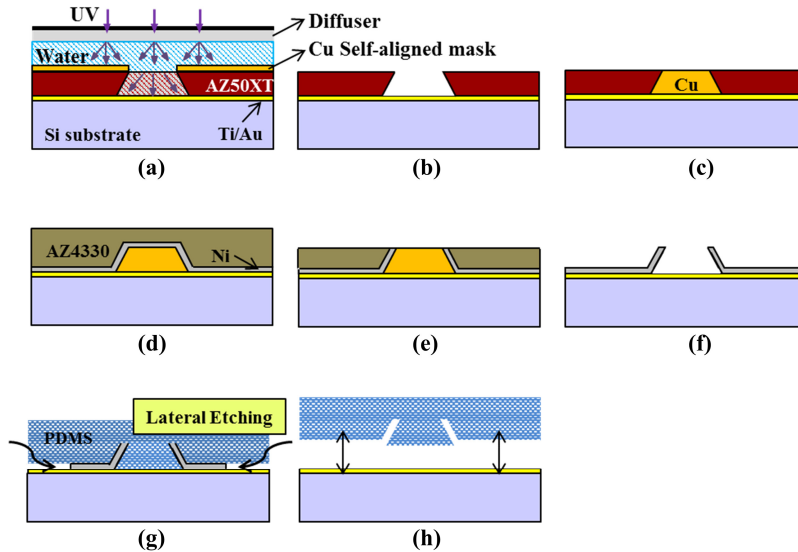

Fig. 7. Overall fabrication process of the proposed single-sheet dual-sided light extracting PDMS LGP. (a) Self aligned diffuser lithography (SADL) process on the Ti (500 Å)/Au (500 Å) deposited Si wafer. (b) Photoresist development to form hollow truncated-conical photoresist mold. (c) Cu electroplating for making a truncated-conical shape (d) Ni electroplating for forming a metallic shell mold and photoresist coating for protecting the microstructures during CMP. (e) Ni CMP process to open up the cap of the shell. (f) Etching out the Cu structure. (g) PDMS curing and removing the metallic shell mold. (h) Separation of the PDMS LGP.

After the SADL process, 12 μm-thick Cu microstructures were grown by electroplating. Being guided by the shape of the photoresist mold, the Cu microstructures have a truncated-conical shape with the optimized side angle. Next, the photoresist mold was removed and 1.5 μm-thick Ni was electroplated on the whole surface. In order to make metallic shell microstructures, the top most plane of each of the Ni microstructures was removed by chemical mechanical polishing (CMP) [Fig. 7(e)]. In order to protect the Cu microstructures from physical damage during CMP [10], an AZ4330 (Clariant, Co. Ltd.) photoresist layer was blanket deposited and baked before the CMP process [Fig. 7(d)]. Then, the photoresist protector and the Cu microstructures were selectively removed to complete the metallic shell microstructures, made of 1.5μm-thick Ni [Fig. 7(f)].

In order to form the PDMS LGP, the compound of PDMS base and curing agent were mixed and spun on the metallic shell mold and cured at 85 °C for 1.5 hours. Finally, the PDMS LGP was peeled-off from the substrate by etching out the metallic shell mold laterally [Fig. 7(g) and 7(h)]. The metallic shell mold etching process is adopted here for preventing mechanical damages in the PDMS microstructures during the peel-off process. However, with improved dimensional designs such as widening neck of the inverse-trapezoidal microstructures, it is possible to peel-off the PDMS LGP directly from the metal mold without metal etching, which makes the metal mold re-usable and alleviates process complexity and cost, accordingly.
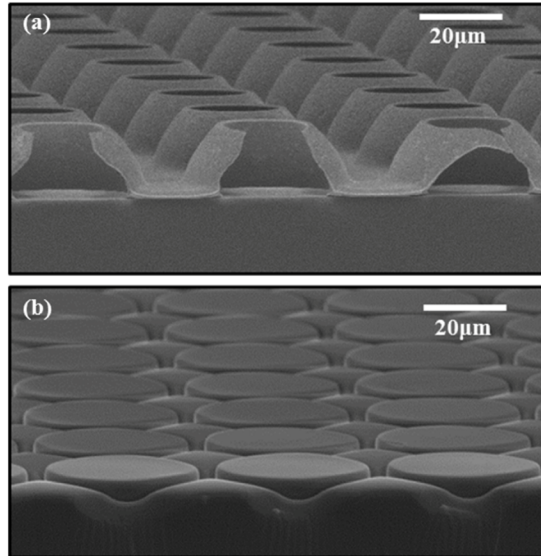
Fig. 8. Scanning electron microscope (SEM) images of (a) the hollow metallic (Ni) micro-shell array, and (b) the fabricated PDMS LGP having BIT microstructures.

Figure 8(a) and 8(b) show the scanning electron microscope images of the fabricated metallic shell mold and the PDMS LGP, respectively. Figure 8(a) was taken after the step shown in Fig. 7(f), and Fig. 8(b) was obtained after the whole process. Notwithstanding the metal shells were very thin (1.3 μm), they were all well-formed without any distortion [Fig. 8(a)]. The metallic shell mold sizes were 13.5 μm in the top diameter, 29 μm in the bottom diameter, and 13 μm in the shell height; all are close to the designed dimensions. The top diameter of the PDMS BIT microstructure shown in Fig. 8(b) was 28.5 μm, which is very close to the bottom diameter of the metal shell mold, which indicates that PDMS shrinkage during thermal curing at 85 °C was insignificant [11]. The diagonal length was 2-inch. The thickness of the fabricated PDMS LGP (which equals the entire thickness of the BLU) was nearly 500 μm, facilitating input light coupling with LEDs. If required, the BLU thickness can be reduced by changing the spin-coating condition.

4. Results and discussions

The performance of the fabricated single-sheet BLU was investigated using a spectroradiometer (CS-2000, Konica Minolta). Six LEDs were used as a light source and they were placed in the position illustrated. As a control sample, a BLU having the PIT microstructures was also tested. The pattern distribution of the two LGP samples was inevitably different since the light extraction efficiencies of the BIT and PIT microstructures are not the same; therefore, pattern distribution for uniform luminance was different accordingly. In this case, the pattern distribution of the PIT microstructures was denser.

Figure 9 shows the optical characteristics of the two LGPs. L_f and L_b denote the values of the forward luminance and backward luminance at each position, respectively, all vertical to the BLU surfaces. Figure 9(a) depicts the ratio of L_b to L_f at six positions of two BLUs: 100% means the backward luminance is equal to the forward luminance at that position. As shown in the graph, the proposed dual-sided BLU extracted light to both-surfaces with a very similar amount (L_b was 96.9% of L_f, on average). On the other hand, the BLU patterned with PIT microstructures extracted only a minimal amount of light to the backside surface (L_b was 11.8% of L_f, on average).
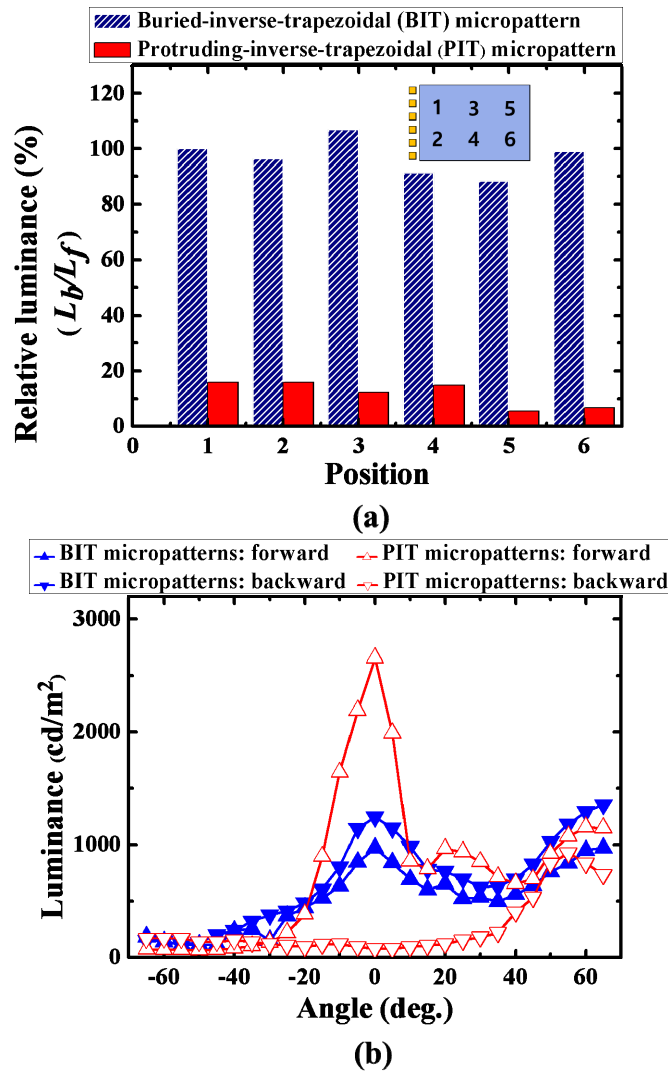
Fig. 9. Optical characteristics of the fabricated BLUs: one BLU has BIT microstructures and the other BLU has PIT microstructures. (a) Ratio of the backward luminance (L_b) to forward luminance (L_f) of the two BLUs in six positions, and (b) angular luminance distribution of the two BLUs at the center position.

The angular luminance distribution at the center position of the two BLUs is illustrated in Fig. 9(b). Figure 9(b) shows that the sum of the forward and backward luminance of the BIT patterned BLU at the center position is similar to the forward luminance of the PIT patterned BLU. This is consistent with the simulation result. Note that asymmetry in luminance away from the BLU center is originated from the fact that the light source is located in only one side and there are some light leakages in the BIT micropatterns owing to light refraction at the air-gap structure and imperfection in the surface such as defects and roughness. The pattern shape and distribution were not optimized perfectly here; therefore, further improvements in the angular and spatial luminance uniformity are possible.

5. Conclusion

In this work, we proposed the novel BIT microstructure which makes possible a dual-sided light extracting single-sheet and single-side-patterned BLU. Thanks to the unique structure of the BIT patterns with the carefully-designed surrounding air-gap, the proposed single-sheet BLU successfully extracted light in both forward and backward directions with almost equal luminance amounts. Both forward and backward angular distributions showed maximum light extraction at the vertical direction with no additional optical sheets such as prism sheets. Thanks to the single sheet nature of the proposed BLU, total thickness of the BLU was 500 μm which is the smallest value compared with that of the previous dual-sided BLUs. The results indicate that the proposed BLU can be favorably applied to ultimately thin, light-weight, and cost-effective dual-sided LCDs.

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