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Optical Characterization and Manufacturing of an Optical Plate for Increasing Light Efficiency of LED Systems

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*The use of an optical plate to enhance light efficiency of LED systems was suggested. The optical plate technology indicates that polymeric optical plates having optical patterns on themselves are placed on LED systems. We designed and manufactured an optical plate that enhance light efficiency, and verified its optical characteristics in this study. The shape and the size of the spherical lens patterns were designed based on the lens formula including the refraction indices of air and PMMA, thickness of the optical component and the optical distance. To manufacture the optical plate having the designed spherical lens patterns, a metal mold was machined by ultra-fine punching machining technology. Using the ultra-fine punching machining system, spherical lens patterns with 0.45 mm in height, 1.15 mm in diameter were successfully machined on the top of a mold of 90 * 60 mm2 size. Using the machined mold and transparent PMMA, an optical plate with the spherical lens patterns was molded by injection molding technology. The optical plate was placed on the LED system, and the luminance was measured with and without the optical plate, and as a result the average and the maximum intensity increased by 1.4 times and 1.3 times respectively.*

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NOMENCLATURE

n = refractive index
f = focal length
d = thickness of a medium
R = radius of the spherical lens

1. Introduction

The movement to discard light bulbs with poor luminance efficiency is rapidly spreading across the globe due to the energy saving policy that targets reduction of CO_2 emission which causes the greenhouse effects. LED (Light Emitting Diode), which has a long life, high luminance efficiency and no toxic material, is expected to become an environment-friendly alternative for the existing light sources. Following the commercialization of LCD TVs that use the LED BLU (Backlight Unit),[1] the demands for LED are arising. Despite of its benefits, LED's high price compared to the those of the existing light sources makes it difficult to use LED as a main light source of display products and lighting equipments. If less number of LEDs can be used maintaining the same brightness and light uniformity as in the case of many LEDs, it will significantly reduce price of LED systems. This study introduces the idea of an optical plate that can enhance the brightness in spite of reducing the number of LEDs used in LED systems. Furthermore, the optical plate was manufactured and its optical characteristics were measured.

2. Methods to Increase Light Efficiency of LED Systems

2.1 Previous studies

The best method to reduce the number of LEDs is to enhance light efficiency by gathering more light from LEDs. The most well-known method is to use optical sheets with a set of engraved patterns in order to control light path.[2,3] Diffusion sheets which enhance the uniformity

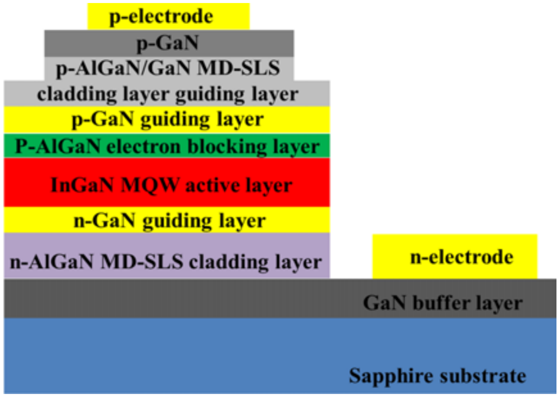

Fig. 1 A general structure of a typical LED

of viewing angle or the light diffusion area, and prism sheets which improve the overall brightness by gathering light to normal direction are commonly used.[4] Another method that is being extensively investigated is the one that uses aspherical lenses.[5-7] This method includes designing a lens that can diffuse the LED light and inserting the lens directly on the LED systems. Many companies are developing aspherical lenses, however, it is hard to machine the metal mold to have aspherical shape. The other method involves direct patterning on the LED light sources.[8,9] As shown in Fig. 1, an LED has lamination structure of various layers. Etching or laser technique is used to engrave a certain type of desired patterns on each substance before layering.

All of the methods need multiple processes that require a large amount of time and cost. For example, optical sheets require a roll mold to print patterns and much time to optimize the roll printing processes.[10] Moreover, diffusion sheets, incurs huge optical loss in spite of improving the brightness uniformity.[11-13] When using aspherical lenses, manufacturing of a lens mold is too difficult.[14,15] Ultra-precision turning machine must be used to produce the aspherical lens mold, and even if such a ultra-fine machine is used, there is a high chance to generate machining error. Lastly, direct patterning on LED involves micro etching laser technique, which requires high cost, that makes it hard to implement for commercial products. Thus, this study suggests an optical plate, which has simple manufacturing process and offers flexible pattern sizes.

2.2 Optical plate

Using on optical plate to enhance light efficiency of LED system was recently suggested.[1] The optical plate technology is producing a polymeric substrate having optical lenses or patterns on the surface and placed on the top of LED system as shown in Fig. 2.

Additionally, this method allows customized patterns designed based on to give different functions of the LED systems. The method also requires relatively simpler processes compared to the other light enhancement methods, and thus, and time can be saved. For example, if the final product requires optical property that concentrates light, the pattern can be designed to focus light and if the final product requires optical property that diffuses light, the pattern can be designed to disperse light.

In this study, spherical lens patterns that are advantageous to gather light were investigated for enhancing light efficiency of on LED system.

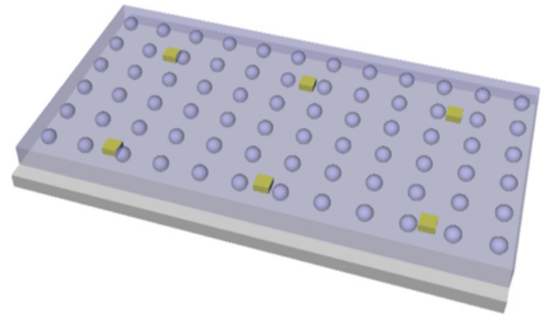

Fig. 2 A schematic diagram of an optical plate

The size of the spherical lens patterns can be determined using the lens formula. The core technology of manufacturing the optical plate is to machine the designed patterns on its surface to make mold. The spherical lens patterns are much easier to be machined than the aspherical lens patterns. Using the machined mold and a polymeric material, the optical plate can be molded by the injection molding technology. Then, the molded optical plate with the spherical lens patterns is placed on the top of the LED systems, enhancing the efficiency by controlling the light path.

3. Design and Optical Simulation of Spherical Lens Patterns on an Optical Plate

The spherical lenses were designed based on the lens formula in Eq. (1).

$$\frac{n_1}{d_1}+\frac{n_2}{d_2}=\frac{1}{f} \tag{1}$$

n : refractive index, d : thickness of a medium, f : focal length

PMMA was used as a material of the plate. The first medium was PMMA and the second was air. Thus, n_1 and n_2 were 1.49 and 1.00 respectively. The thickness of the PMMA was 2 mm and the distance between the spherical lens and the cover of the LED system was 15 mm. The radius of the spherical lenses has a relationship to the focal length as presented in Eq. (2). R_1 was 0.6 mm, while R_2 was infinite because the second substrate was flat.

$$\frac{1}{f}=(n_1-n_2)\left(\frac{1}{R_1}-\frac{1}{R_2}\right) \tag{2}$$

n : refractive index, R : radius of spherical lens

The spherical lens patterns, as shown in Fig. 3, were designed to have 5×5 arrays based on the size of the LED system. The focal length is always same if the spherical lens patterns have the same curvature as the calculated radius. Therefore, the height and the length of the spherical lens patterns were determined 0.6 mm and 1.2 mm, respectively. Optical simulations were conducted based on the designed spherical lens patterns using a commercial software (ZEMAX). The light source showed Lambertian distribution. The size of the LED chip was 0.8 mm * 0.8 mm.

We designed spacing between the lenses. The spacing between the lenses is required for the machining. If there is no spacing between the

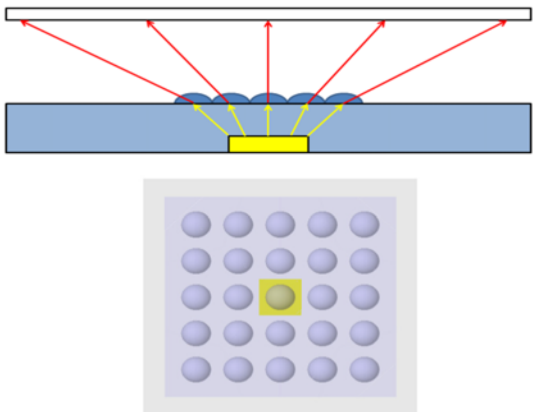

Fig. 3 A schematic diagram of an optical plate designed in this study

lenses, the lens that is machined earlier could be deformed unintentionally. This is due to the plastic deformation around the lens during the machining. For this reason, we conducted a punching machining and confirmed that the optimum spacing between the lenses was 0.1mm. The simulation with 0.1mm spacing also yielded the best result of light distribution. It takes a lot of time to simulate an LED system having a lot of LEDs. Instead of, we adapted side mirrors to the optical simulations which can give an effect of successive of LEDs in order to save simulation time. The results of the optical simulations without the spherical lens patterns on the surface of the optical plate were presented in Fig. 4(a) and Fig. 5(a). The results show that the area surrounding the LED light source appears brighter than the rest of the area. Radiance decreased rapidly with the lateral distance from on LED. In order to make this system have a high radiance, additional LEDs should be placed between the existing LEDs or additional optical sheets should be required. On the other hand, when there is an optical plate having spherical lens patterns, radiance becomes higher around the LED as shown in Fig. 4(b), 5(b). Moreover, radiance in other areas is also higher. The maximum radiance directly above the LEDs with the spherical lens patterns was 1.8 times higher than the maximum value without the spherical lens patterns. The average radiance also increased by 1.7 times after implementing the spherical lens patterns. This proves that the use of optical plate with spherical lens patterns can enhance light efficiency of LED systems and decrease the number of LEDs.

4. Manufacturing and Optical Characteristics of an Optical Plate

A metal mold was machined in order to manufacture the optical plate having the spherical lens patterns after the optical simulation. Fig. 6 shows the ultra-fine punching machining system used in this study. This system was designed to conveniently create spherical lens patterns. The system's X, Y, Z axes are driven by a micro linear motor and the each axis has stroke of 200 mm, 200 mm, and 70 mm respectively.

The spherical lens patterns were machined using the cam axis. The size of the spherical lens patterns can be controlled by changing the rotation angle of the cam axis. A tungsten carbide tool in a spherical shape with the radius of 6 mm was used, and a 90 * 60 mm^2 brass mold

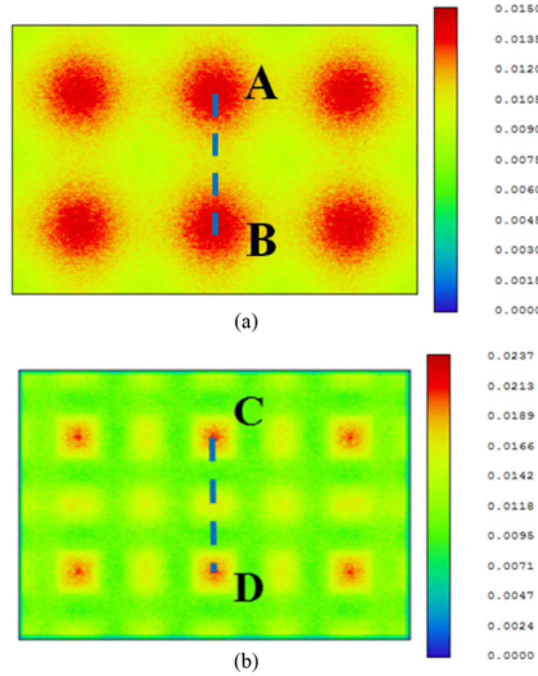

Fig. 4 Radiance by optical simulations (a) without spherical lens patterns and (b) with spherical lens patterns

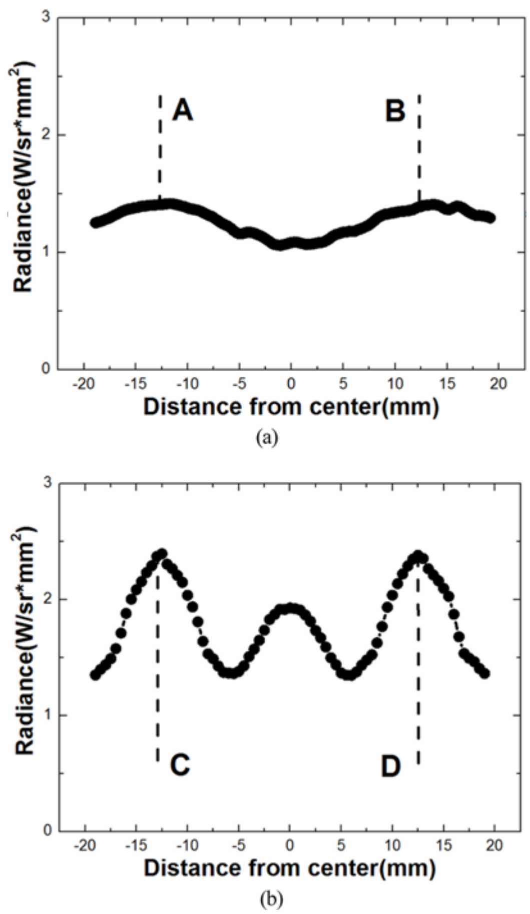

Fig. 5 Distribution of predicted radiance by optical simulations (a) without the spherical lens patterns and (b) with the spherical lens patterns

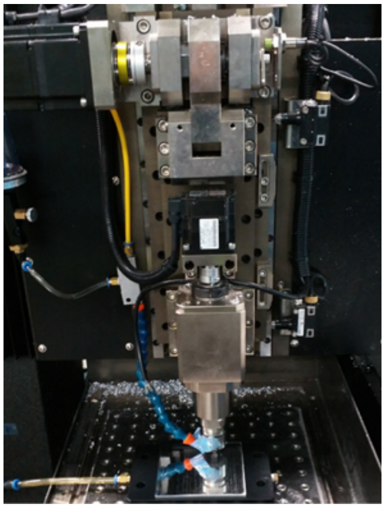

Fig. 6 An ultra-fine punching machining system

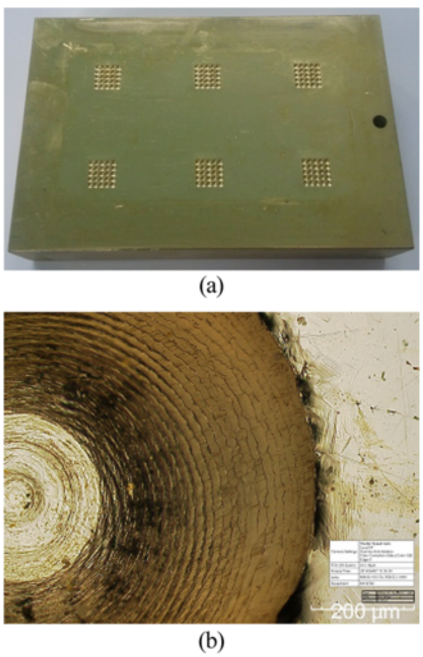

Fig. 7 (a) The overall view of the machined metal mold and (b) the magnified view of the machined spherical lens pattern

was used. The brass mold was annealed to reduce the pile-up which generates inhomogeneous plastic deformation around the spherical lens patterns. The manufacturing speed of the cam axis was 360°/s and the acceleration and the deceleration speed were 80 ms.

The machined metal mold is present in Fig. 7(a). The shape of the machined spherical lens pattern was measured by an 3D optical microscope as shown in Fig. 7(b). The machined spherical lens pattern had the height of 0.45 mm and the diameter of 1.15 mm. The measured shape of the machined spherical lens pattern was a part of a hemisphere of 0.6 mm diameter.

Using transparent PMMA and the machined mold, an optical plate with the spherical lens patterns was molded by injection molding technology. The injection direction, the injection speed, and the mold

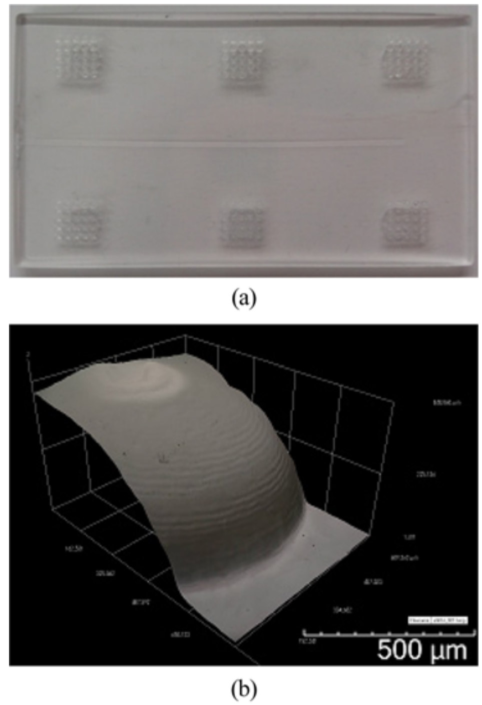

Fig. 8 (a) The overall view of the injection molded optical plate and (b) the magnified view of the molded spherical lens pattern

temperature were optimized to prevent the short shot at the upper part of the spherical lens patterns. The molded optical plate is shown in Fig. 8(a). The molded spherical lens patterns were also measured by the 3D microscope and shown in Fig. 8(b). The spherical lens patterns had the height of 0.41 mm, little lower than the machined mold, and the diameter of 1.15 mm.

The molded optical plate was placed on the top of on LED system and luminance distribution was measured. We built the LED system to have 15 mm distance between the optical plate and the cover of the LED system, which was same as the simulation model in Fig. 3. A commercial optical system (Prometric, Radiant Inc) was used to measure the optical characteristics.

The measured results are presented in Figs. 9 and 10. The overall luminance of Figs. 9(b) and 10(b) is higher than the luminance of Figs. 9(a) and 10(a) as the same as shown in Figs. 4(a) and 4(b). This means that the optical plate with the spherical lens patterns enhances light efficiency of the LED systems. The maximum value of the luminance increased by 1.3 times and the average luminance increased by 1.4 times than that of no spherical lens patterns. If there is no spherical lens pattern, much light loss would be occurred by total reflection.

More light could penetrate the optical plate by virtue of the spherical lens patterns, and it increased the maximum and the average luminance. However, the increasing rate of the maximum luminance was lower than the predicted rate from the optical simulations. Also, the simulation showed relatively high luminance between two LEDs, while, the measurement did not. The major difference between the simulations and the experiments was whether side mirrors were adapted or not. Side mirrors could not be installed in the experiments because a prototype of LED systems was used in this study. In order to confirm the effects of the side mirrors, we conducted an optical simulation of

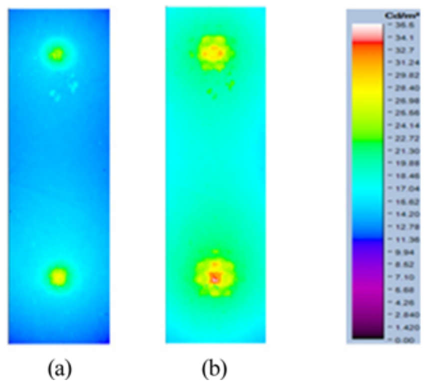

Fig. 9 Measured luminance (a) without the spherical lens patterns and (b) with the spherical lens patterns

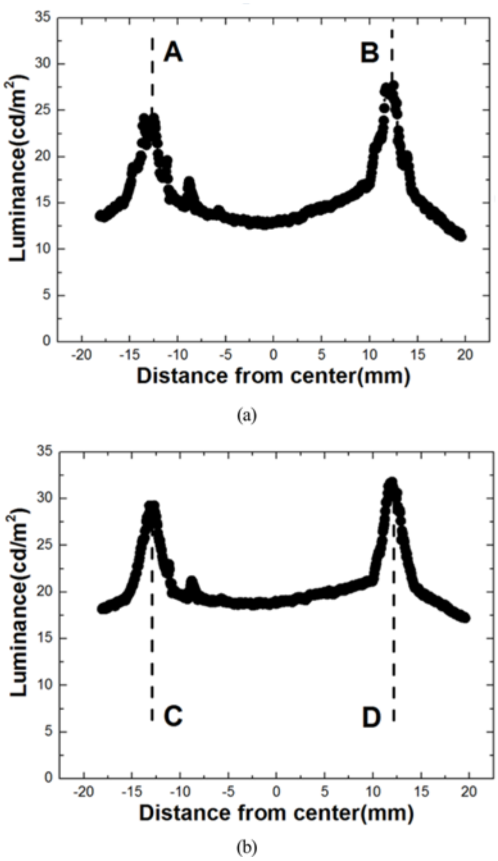

Fig. 10 Distribution of measured luminance (a) without the spherical lens patterns and (b) with the spherical lens patterns

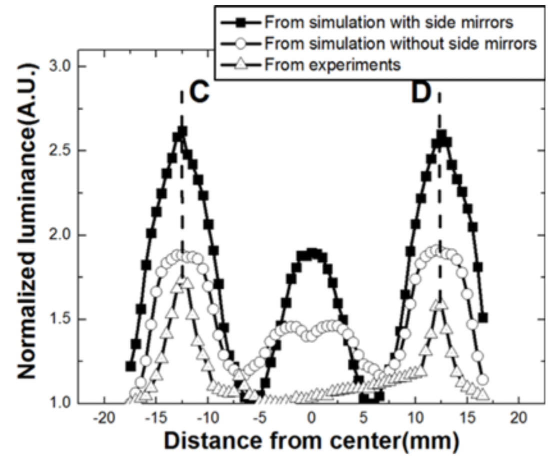

Fig. 11 Comparison of luminance distributions varied by side mirrors

LED systems without side mirrors. In this study, the light having a single wavelength was used in the optical simulation, it can also be regarded as luminance ($cd/m^2 = lm/sr*m^2$). Therefore, we compared the simulation results with the experiment results using normalized luminance in Fig. 11. The results of the simulation showed that the maximum luminance with the spherical lens patterns was 1.4 times higher than that without the spherical lens patterns. This increasing rate of the optical simulation without side mirrors approached to that of the experiments much. This tendency was shown in Fig. 11. The normalized maximum luminance without side mirrors was closer to that of the experiments. The luminance between two LEDs also fell to the value of the experiments as shown in Fig. 11. Thus, we could conclude that side mirrors affect the increasing rate of the maximum luminance and the relatively high luminance between two LEDs.

The side mirrors can give the same effect as in infinitely successive LEDs like a fractal, which can save optical simulation time. Also, the side mirrors increase light efficiency by reflecting and recycling the lights that escape to the side directions. Therefore, the light emitted to the side directions was lost in the experiments without side mirrors, and it made the luminance between two LEDs lower than the predicted values of the optical simulations. The results from simulation without side mirror, the graph had some ripples in the middle in Fig. 11 though there was no ripple in the experimental results. The height of the manufactured lenses were smaller than the lenses designed in the simulations. The lower height of the manufactured lenses could make less concentrated effects than the simulation.

5. Conclusions

In this study, the optical plate technology is proposed, designed and manufactured, to enhance light efficient of LED systems. We can summarize like following:

(1) An optical plate with spherical lens patterns was designed using the lens formula, and the characteristics were predicted by optical simulations.

(2) Using an ultra-fine punching system, the spherical lens patterns with 0.45 mm of height and 1.15 mm of width/length was successfully machined on the top of a mold with 90×60 mm^2 size. Using the machined mold, the spherical lens patterns with 0.4 mm of height, 1.15 mm of width/length was successfully molded on the top of the optical plate by injection molding method.

(3) When the molded optical plate was placed on an LED system, the maximum luminance and the average luminance were improved by 1.3 times and 1.4 times, respectively.

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