Light-guide plate using periodical and single-sized microstructures to create a uniform backlight system

Jui-Wen Pan[1,2,3,*] and Ya-Wen Hu[1]

[1]*Institute of Photonic Systems, National Chiao Tung University, Tainan City 71150, Taiwan*

[2]*Biomedical Electronics Translational Research Center, National Chiao Tung University, Hsin-Chu City 30010, Taiwan*

[3]*Department of Medical Research, Chi Mei Medical Center, Tainan 71004, Taiwan*

*Corresponding author: juiwenpan@gmail.com

Light-guide plates (LGPs) with aperiodic or size-varied microstructures are widely used in edge-lit light-source backlight systems for their high uniformity. In this Letter we designed a LGP with periodic and single-sized microstructures and analyzed the relationship between the holistic arrangement density of the microstructures and the uniformity. By controlling the holistic arrangement density of the microstructures, the uniformity could also be increased.   © 2012 Optical Society of America

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A complete backlight system includes a light source, light-guide plate (LGP), and some optical films [1]. In this system, the LGP plays a very important role for transporting rays evenly from the light source to the observer. After the rays from the light source enter the LGP, they will be guided in the LGP due to total internal reflection (TIR) in the edge-lit light-source backlight system. These rays cannot escape the LGP. Therefore, in addition to using wedged plate, many studies have proposed the design of a rectangle LGP with microstructures [2–4]. As the rays strike the microstructures on the LGP, the ray paths will be changed. The rays will thus escape the LGP and can be received by the observer. Because only the rays which strike the microstructures can escape the LGP, the light extraction conditions can be grasped by controlling the shape, size, and arrangement of the microstructures. Closer to the light source, the intensity of light in edge-lit sources backlight systems is relatively strong. In order to produce uniform light extraction, most researchers have used the two common methods: (1) changing the size of the periodic arrange microstructures [5,6] or (2) changing the partial arrangement density of the single-sized microstructures [7,8]. As the intensity decreases, with the first method, the size of the microstructures gradually increases, and with the second method, improvement of the partial arrangement density of the microstructures increases the probability of the rays striking the microstructures. In this way, the LGP can achieve good uniformity. However, more complex technology is required for the production of size-varied or aperiodic arrangements of microstructures. In contrast, single-sized and periodic arrangements of microstructures have many benefits, for example, their productions are simpler and the user can place a light source on either side. Therefore, we wanted to use a single-sized and periodic arrangement microstructure with high uniformity.

In this Letter we proposed an LGP with single-sized cylindrical and periodic microstructures as shown in Fig. 1. Once the rays strike the microstructures, they can escape the LGP, as shown in Fig. 1(a). The remaining rays will continue passing in the LGP due to the TIR,

as shown in Fig. 1(b). Thus, the uniformity of light extraction is related to the holistic arrangement density of the microstructures. In the following we explore the relationship between the holistic arrangement density of the microstructures and the uniformity.

In order to facilitate the analysis, we regard the LGP as being composed of m elements, as shown in Fig. 2(a), and analyze the ray path and the efficiency of the light extraction for each element. Then, we can derive the whole light distribution of the LGP. In the beginning, the thickness of each element is defined as t, and the length of each element is defined as $t/\tan\theta c$ (θc is the critical angle). as shown in Fig. 2(b). Because we only discuss the one-dimensional (1D) direction of the light distribution in this Letter, the width is ignored. The $t/\tan\theta c$ is selected as the length of each element since the ray will strike the top surface less than, or equal to, one time in this length. The value could make our analysis more convenient.

After the rays enter the first element of the LGP, we regard the surface where the rays enter as the light-emitting surface. The luminous energy is defined as S_1, and the probabilities of rays striking the top and the bottom surface are defined as P_t and P_b severally, as shown in Fig. 3. Because the microstructures are only
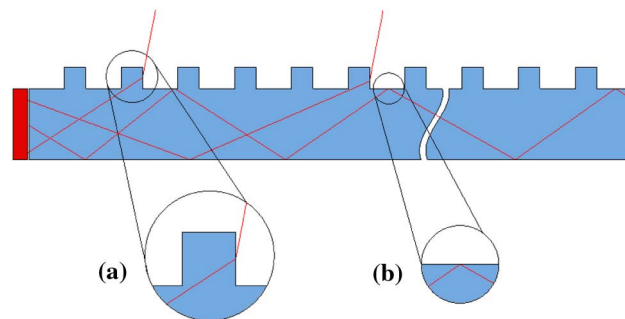

Fig. 1.   (Color online) LGP with single-sized cylindrical and periodic microstructures: (a) rays strike the microstructures and then escape the LGP and (b) remaining rays are guided in the LGP by the TIR.
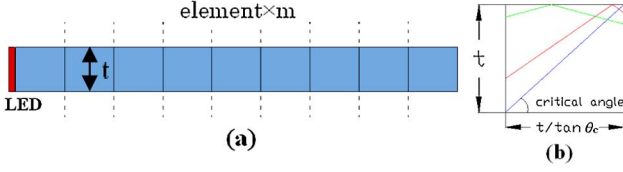
Fig. 2. (Color online) (a) Proposed LGP composed of m elements and (b) structure of each element.

on the surface of the LGP, we needed the probability of rays striking the top surface, P_t. Then, the proportion of the microstructures' bottom area (a), accounting for the area of the whole top surface (A), is P_a as shown in Fig. 3. The value of P_a is associated with the holistic arrangement density and the size of the microstructures. Because only the rays that strike the microstructures can escape the LGP, P_a can also be regarded as the probability of light extraction at the top surface. Therefore, we can obtain the probability for light extraction of the first element (P) and the amount of light extraction (E_1) using Eqs. (1) and (2):

$$P = P_t \times P_a, \qquad (1)$$

$$E_1 = P \times S_1. \qquad (2)$$

The rays leaving the first element enter the second element, thus we similarly regard the surface the rays enter as the light-emitting surface, and the luminous energy as S_2:

$$S_2 = S_1 - E_1 = S_1 - P \times S_1 = (1 - P) \times S_1. \qquad (3)$$

Subsequently, light extraction (E_2) can be derived:

$$E_2 = P \times S_2 = P \times (1 - P) \times S_1. \qquad (4)$$

Thus, the relationship between E_n, S_1, and P is shown in Eq. (5) and Fig. 4:

$$E_n = P \times (1 - P)^{n-1}, \qquad 1 \le n \le m. \qquad (5)$$

The path that the rays pass from, the first element to the mth element, is called the first path. If a mirror with the reflectivity R is added at the end of the LGP, the rays will be reflected back to the LGP. The rays reflected by the mirror enter the $((m+1)$th element and continue passing through the LGP until leaving the $2m$th element. This path is called the second path. From Eq. (5) we are able
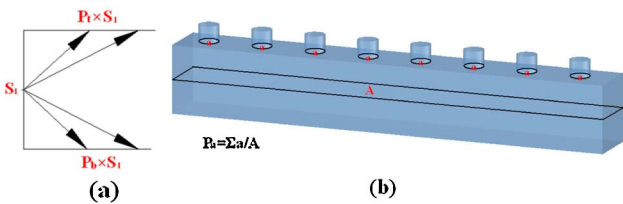

Fig. 3. (Color online) (a) We define the probabilities of rays striking the top and the bottom surface as P_t and P_b (b) and the proportion of the microstructures' bottom area (a) accounting for the area of the whole top surface (A) as P_a.
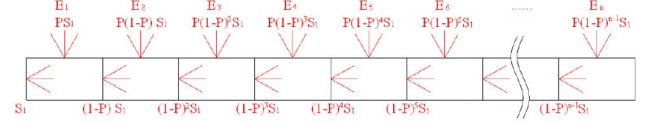

Fig. 4. (Color online) Schematic diagram of E_n.

to derive that $E_n > E_{n+1}$. Because the directions of the first and the second path are opposite, the summation of two paths can be averaged as shown in Fig. 5. The LGP with single-sized and periodic arrangements of microstructures can still achieve high uniformity.

The light extraction summation of two paths (E'_n) is

$$E'_n = P \times (1 - P)^{n-1} \times S_1 + R \times P \times (1 - P)^{2m-n} \times S_1. \qquad (6)$$

After obtaining the E'_n for each element, the uniformity can be calculated. Since we discuss only a 1D direction, the nine-point measuring method [9] is not applicable. In this study we take the E'_n of the 0.1mth and 0.9mth element to calculate the uniformity (U):

$$U = \frac{P \times (1 - P)^{0.9m-1} \times S_1 + R \times P \times (1 - P)^{1.1m} \times S_1}{P \times (1 - P)^{0.1m-1} \times S_1 + R \times P \times (1 - P)^{1.9m} \times S_1}$$

$$= \frac{(1 - P)^{0.9m-1} + R \times (1 - P)^{1.1m}}{(1 - P)^{0.1m-1} + R \times (1 - P)^{1.9m}}. \qquad (7)$$

From Eq. (7), the theoretical value of the uniformity (U) can be derived. Then we use the Lighttools [10] simulation software to obtain the simulated value of U under different reflectivity values ($R = 100\%$, 80%, 60%), and compare the theoretical value with the simulated value.

For these simulation conditions, the thickness of each element (t) was 1.4 mm, and m was 50, the material was PMMA, and the bottom radius of the cylindrical-shaped microstructures was 0.01 mm. The light source we used was a Nichia NESW155T [11]. By simulating, we knew the P_t value was 0.18. We changed the value of P_a by changing the holistic arrangement density of the microstructure density. Finally we took the 5th and 45th element to calculate the uniformity (U). Figure 6 shows the relationship between the probability of light extraction (P), the uniformity (U), and the optical efficiency. Observing Fig. 6, it can be found that the simulated value is very similar to the theoretical value. Within an admissible error range, the theoretical value can be used representatively. According to the figure and the
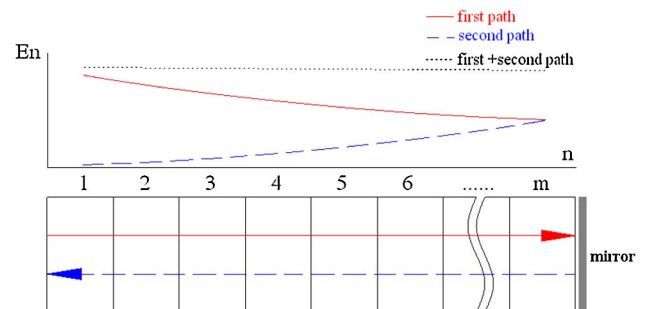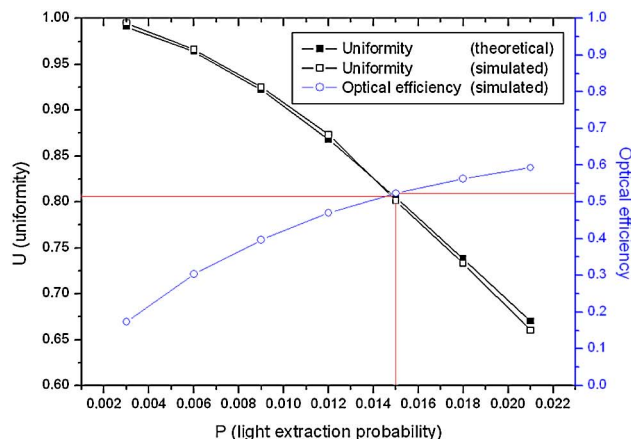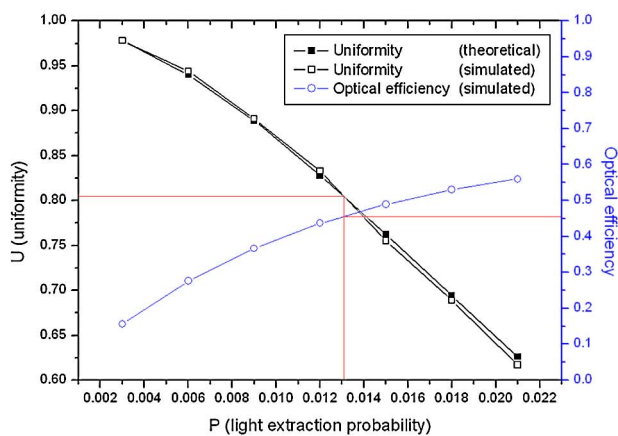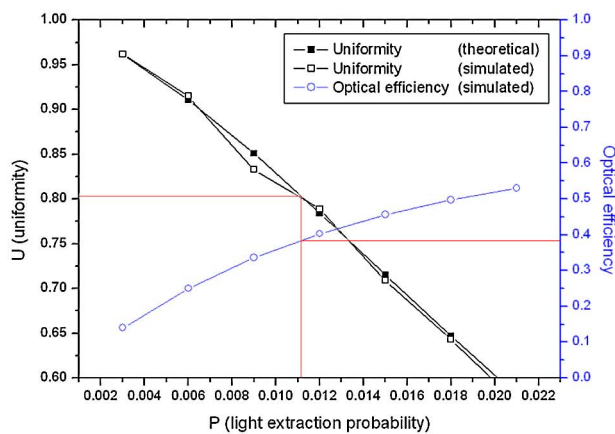

Fig. 5. (Color online) Principle for averaging E'_n in each element.

(a) Reflectivity = 100%

(b) Reflectivity = 80%

(c) Reflectivity = 60%

Fig. 6. (Color online) Relationship between the light extraction probability (P), the uniformity (U), and the optical efficiency under different reflectivity values (R) for the theoretical and the simulated values.

equation, the uniformity (U) is higher when the P and the m values are lower and the reflectivity value (R) is higher. However, the lower P value shows that the optical efficiency will be low. We cannot achieve high uniformity (U) as long as the optical efficiency must be accounted for, however, a uniformity of more than 80% is usually sufficient.

In conclusion, although most studies of an LGP with microstructures used aperiodic or size-varied microstructures to achieve high uniformity, in this study, we propose an LGP with periodic and single-sized microstructures. By controlling the holistic arrangement density of the microstructures, we can still achieve higher uniformity, as the P and m values are lower and the reflectivity value (R) is higher. However, in order to account for the uniformity (U) and optical efficiency, a uniformity of more than 80% is usually sufficient. The periodic and single-sized microstructures have many advantages. The LGP with aperiodic or size-varied microstructures design has to spend a lot of time on the position and size of microstructures, and therefore makes the product produced in time delay. In contrast, the LGP with periodic and single-sized microstructures design and fabrication are simpler and we can use a system where light comes from either side [12].

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