

Dot-pattern design of a light guide in an edge-lit backlight using a regional partition approach

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Abstract. This paper employs a regional partition approach to establish the optimal distribution of the diffuser dots in the light guide of an edge-lit backlight. The proposed approach commences by dividing the light guide into a number of partitions and assigning an equal radius to every dot. An iterative optimization procedure is then performed in which the illuminance in each partition is calculated and the dot radius in each partition progressively adjusted until uniform luminance is obtained over the entire light-guide surface. To simplify the geometry construction process and improve the efficiency of the optimization procedure, a simple optical model is proposed for the diffuser dots and the bare surface of the light guide, and an analytical procedure is implemented to take account of the diffuser-film and brightness-enhancement-film effects. The simulation results confirm the ability of the proposed approach to accurately reflect the fine regulation of the dot radius required to obtain uniform luminance for typical light-emitting diode configurations used in practical backlight modules. © 2007 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2721423]

Subject terms: backlight; light guide; diffuser dot; partition approach.

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1 Introduction

Edge-lit backlights are used for many medium- and small-size liquid-crystal displays (LCDs), such as computer monitors, personal digital assistants (PDAs), cell phones, digital cameras, and so on. Figures 1(a) and 1(b) illustrate typical edge-lit backlight units containing one and three light emitting diodes (LEDs), respectively. The light guides in these backlight modules are designed to frustrate total internal reflection (TIR) and to distribute the light emitted from the LED sources uniformly across the light-guide surface.¹⁻³ Of the various fabrication methods available, the diffuser dots are generally reprinted on the light guide using a mold, since this method is capable of producing a near-net shape in one pass.⁴ The function of the diffuser dots is to redirect the light incident on the base of the light guide so that it passes through the upper surface of the light guide. Therefore, controlling the distribution of the diffuser dots across the light-guide surface so that the light emitted from the LED sources extends to the furthest regions of the light guide and achieves a uniform luminance distribution is a crucial task in light guide design.

The diffuser dots of a light guide are generally arranged in one of two basic patterns: a regular dot arrangement⁴ or a random dot arrangement.^{5,6} Random dot arrangements have the advantage that they eliminate the moiré phenomenon,⁵ which arises when the dots have an overly regular arrangement. However, the algorithm required to generate a random dot distribution is very complicated. Ideally, the optimal dot distribution over the surface of a light

guide is obtained from an iterative process in which the results of the optical design phase are fed back to the dot generation algorithm so that the original dot arrangement can be modified to improve the optical characteristics of the light guide.⁶ However, integrating the dot pattern and optical design phases is very difficult when the former phase is based on a random dot distribution algorithm. By contrast, regular dot arrangement algorithms are more easily integrated with the optical design phase, and make it relatively straightforward to implement a two-step dot pattern optimization process. Many software programs^{7,8} are commercially available to support the design of regular dot arrangements and to integrate the results of the dot-pattern design and optical design phases.

However, if the optimization procedure takes the dot radius as the variable to be optimized, then establishing the optimal radii of all the dots within the light guide is very difficult due to the sheer number of dots involved. To reduce the computational task, it is therefore desirable to develop a dot-pattern optimization process in which the number of variables to be optimized is more limited. Lee et al.⁹ developed a fast ray-tracing algorithm to facilitate the design of light guides containing many diffuser dots. The proposed algorithm used a pattern density function based on a regular dot arrangement to determine whether or not the light ray hit a diffuser dot, rather than whether it hit the physical dot surface. The simulation results revealed that the proposed fast ray-tracing algorithm enabled the distribution of a regular dot arrangement to be easily designed and adjusted.

However, the algorithm is not easily integrated with

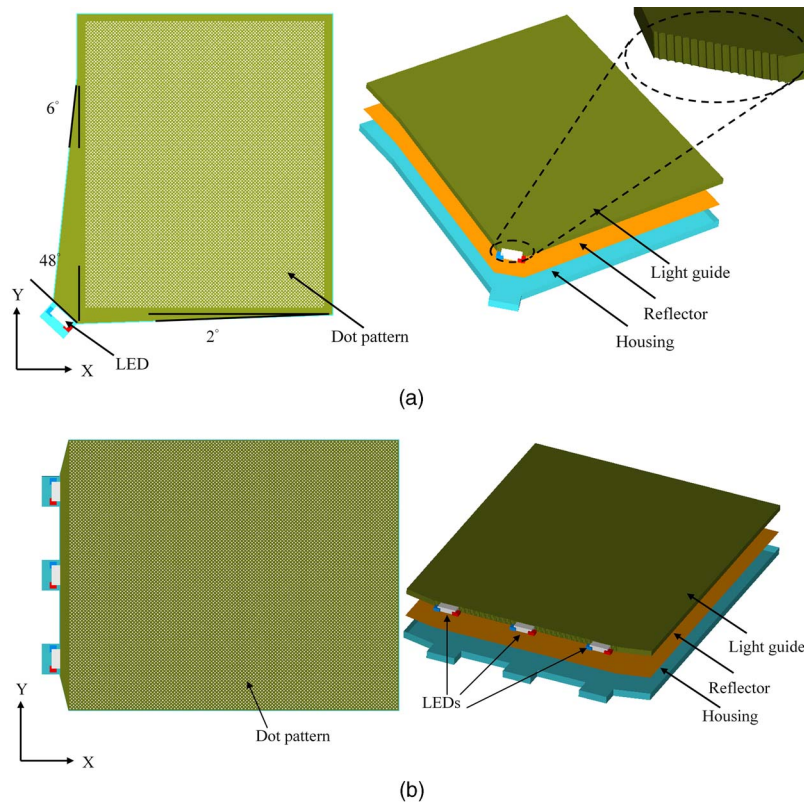


Fig. 1 Configuration of: (a) one-LED backlight, where enlarged schematic shows sawtooth microstructure of light-guide entrance surface in front of LED; and (b) three-LED backlight.

most commercial light-guide design programs, since it is difficult to implement or invoke the ray-tracing engine in external programs. Although some commercial programs provide a similar fast ray-tracing function¹⁰ to support the design of regular diffuser dot arrangements, the inflexibility of the fast ray-tracing function means that only one parameter, viz. the dot radius, can be changed simultaneously for all of the dots in one calculation domain. In other words, it is not possible to obtain an optimal solution for the dot distribution without partitioning the whole domain into a number of subdomains. In addition, most commercial programs do not incorporate optimization rules and functions.

Therefore, this study develops a regional partition approach for designing the optimal diffuser dot arrangement of light guides in edge-lit backlight modules. The proposed approach commences by dividing the light guide into an array of equal-sized rectangular partitions. Initially, all of the dots in the light guide are assigned the same radius, and the illuminance in each partition is determined. In an iterative optimization procedure, the dot density within each partition is then adjusted by varying the dot radius according to the difference between the illuminance output of the partition and the average illuminance across the entire light guide. During the optimization procedure, the radii of the dots in some partitions are reduced from their initial values, while those of dots in other partitions are increased so that uniform luminance is achieved. To simplify the construction of the light-guide geometry, a simple optical model is introduced to assign the optical properties of the diffuser dots and the bare surface of the light-guide panel. More-

over, to improve the efficiency of the optimization process, the optical effects of the diffuser and brightness enhancement film (BEF) components attached to the front of the light guide are modeled by using a simple analytical expression to transform the calculated illuminance result to an equivalent luminance value and then applying an averaging technique to smooth the luminance between neighboring areas of the light guide.

2 Solution Procedure

2.1 Dot-Pattern Construction

In this study, the dot patterns are constructed using the script language provided by ASAPTM, which provides the means of invoking many different basic geometries (i.e., entities) with different shapes with which to construct the required geometry. ASAP has the advantage that it is easily integrated with the optical design phase once the initial dot pattern has been constructed. Hence, using ASAP, an iterative optimization process can be established in which the results of the optical analysis stage are fed back to the original geometry program so that the dot radius can be progressively adjusted until even luminance is obtained.

2.1.1 Dot-region partition and dot position generation

Figure 2(a) shows the dot pattern typically used in a light guide. This study commences by partitioning the light guide into an array of grids of equal size. In the proposed optimization procedure, each dot within one partition has

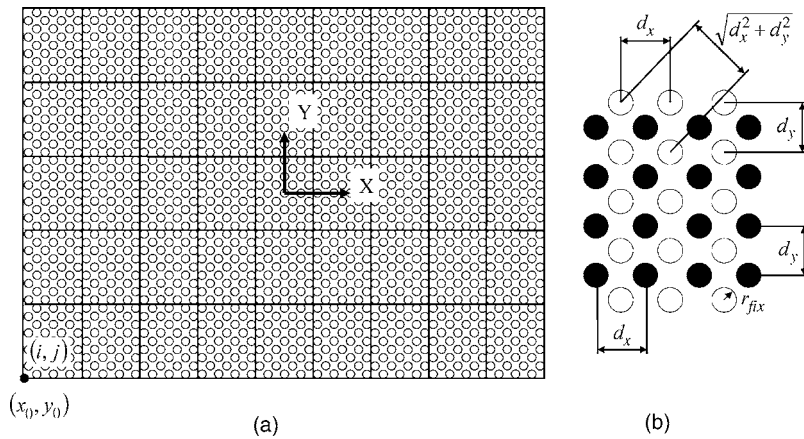


Fig. 2 (a) Regular dot pattern in light guide; (b) typical dot arrangement in single partition, with notation for variables.

the same radius. In other words, the number of variables to be optimized is equal to the total number of partitions in the light guide rather than the total number of dots. As a result, the scale of the optimization task becomes far more manageable. Figure 2(b) provides a detailed view of the dot pattern within a typical partition. As shown, the dot pattern comprises a number of rows of dots (black circles) with a pitch of d_x in the x direction and a number of columns of dots (white circles) with a pitch of d_y in the y direction. Initially, the current design procedure assigns an equal radius of r_{fix} to every dot in the light guide. In the subsequent optimization procedure, the dots retain their original positions in the light guide, but their radius is adjusted to achieve even luminance. To ensure that the dots do not overlap as their radii are increased to r , the dot shift values and the dot radius must satisfy the following condition:

$$(d_x^2 + d_y^2)^{1/2} > 4r. \tag{1}$$

If the original dot distribution is partitioned into k_x by k_y divisions in the x and y directions, respectively, and the total number of dots in the longer row and longer column

of the light guide are given by n_x and n_y , respectively [for example, in Fig. 2(a), $k_x=9$, $k_y=5$, $n_x=32$, and $n_y=23$], then the following expressions must be satisfied:

$$n_x = m_x k_x - \frac{k_x - 1}{2} \quad \text{and} \quad n_y = m_y k_y - \frac{k_y - 1}{2}, \tag{2}$$

where m_x and m_y are the numbers of dots in the longer rows and longer columns, respectively, of each partition [for example, in Fig. 2(b), $m_x=4$ and $m_y=5$]. Note that Eq. (2) is valid only for a dot arrangement that is symmetrical in both the x and the y direction, i.e., the number of dots in the leftmost column must equal the number of dots in the rightmost column, and similarly the number of dots in the topmost row must equal the number of dots in the bottommost row.

2.1.2 Dot-region construction

As shown in Fig. 3(a), the complete dot region of the light guide can be constructed using two dot-pattern templates arranged alternately in the row and column directions. Spe-

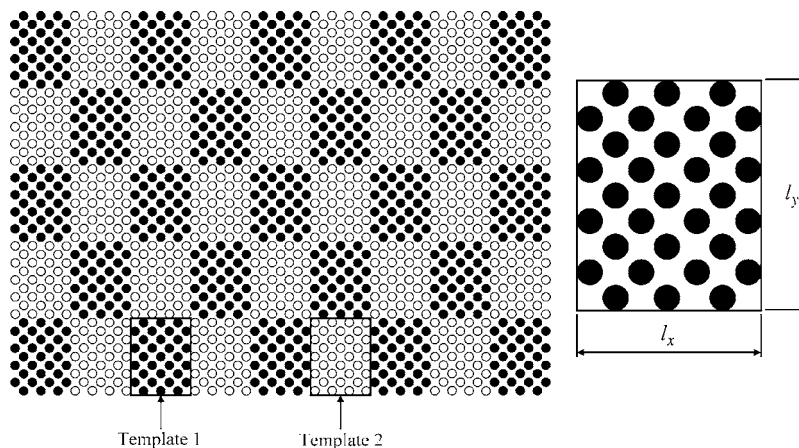


Fig. 3 Dot-pattern construction using two dot templates, with an enlarged view of template 1, in which solid circles have dot radius of r_{fix} and are enclosed by a rectangle of dimensions $l_x \times l_y$.

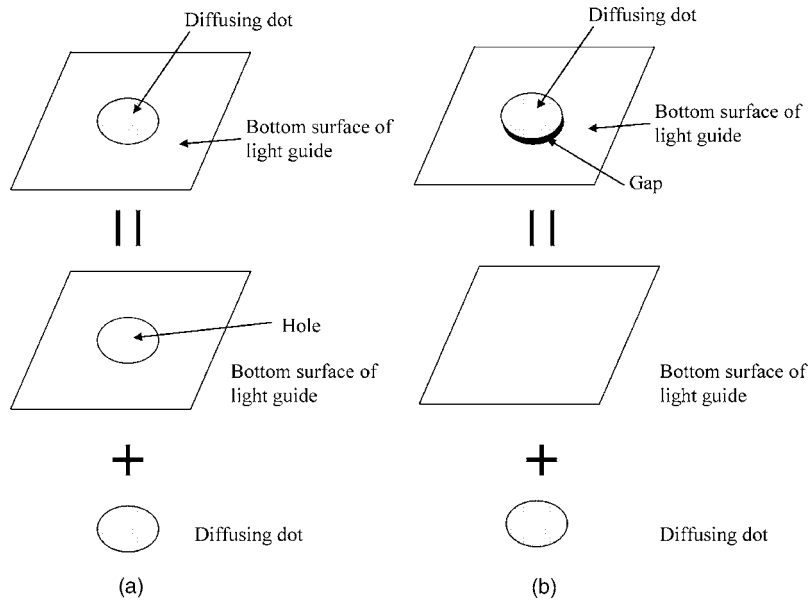


Fig. 4 Optical model of diffuser dots: (a) conventional model; (b) simplified model.

cifically, template 1 is used in a region if the row label i ($=1, \dots, k_x$) and column label j ($=1, \dots, k_y$) of that region are either both odd numbers or both even numbers, e.g., $(i=1, j=1)$ or $(i=2, j=2)$. Similarly, template 2 is used in a region if the row label and the column label of that region are either even and odd or odd and even, respectively, e.g., $(i=2, j=1)$ and $(i=4, j=1)$. Note that the origin of the $(i=1, j=1)$ partition labeling scheme is located in the lower left corner of the light guide, as shown in Fig. 2(a). The detailed procedure for constructing the dot radii in the individual dot template partitions while maintaining the dot positions in their original locations is described in the following.

Firstly, template 1 is generated in the first quadrant using an ASAP array script command, for which the center of the generated template is located at $[(m_x-1)d_x/2, (m_y-1)d_y/2]$. The position of the template is then adjusted so that its center is located at the origin of the coordinate system, $(0,0)$. It can be imagined that each template is enclosed by a rectangular area with a length and height of $l_x=(m_x-1)d_x+d_x/2$ and $l_y=(m_y-1)d_y+d_y/2$, respectively, as shown in Fig. 3. The perimeter of this imaginary area may potentially lie outside or inside the circle enclosing the outermost dots in the template, depending on the relative values of $d_x/2$, $d_y/2$, and $2r_{\text{fix}}$. The position of each template is adjusted depending on the row and column labels of the region to which it is applied, in accordance with the following shift functions:

$$x_{\text{shift}} = x_0 + \frac{l_x}{2} + \left(r_{\text{fix}} - \frac{d_x}{4} \right) + (i-1)l_x,$$

$$y_{\text{shift}} = y_0 + \frac{l_y}{2} + \left(r_{\text{fix}} - \frac{d_y}{4} \right) + (j-1)l_y, \quad (3)$$

where x_0 and y_0 are the coordinates of the lower left corner [see Fig. 2(a)]. The third terms in Eq. (3), $r_{\text{fix}}-d_x/4$ and

$r_{\text{fix}}-d_y/4$, indicate the x and y shift distances, which are designed to ensure that the circle enclosing the outermost dots is tangent to the perimeter of the effective viewing area of the light guide.

It is noted that the proposed dot construction approach enables the dots in different columns or rows to be interlaced to form a close-packed structure with maximum dot density. This characteristic is particularly beneficial in the design of light guides, since regions further from the LED light source receive less light and therefore require a higher dot density to allow more light to pass through the light guide so that even illuminance can be obtained.

2.2 Optical Model

In constructing the optical model of the light guide, without loss of generality, this study uses the simplest Lambertian scattering model to describe the optical properties of the dots, and the Fresnel reflection model to describe the properties of the acrylic light-guide base. This study proposes a modification to the method generally employed to assign the optical properties of the dots and the base surface. Figure 4(a) shows the conventional approach, in which the dot regions are removed from the light guide base surface to leave a rectangular acrylic surface containing an array of circular holes. The circular regions are then assigned a dot optical scattering property, while the surface itself is assigned a bare-surface optical property. However, rebuilding this geometry construction in each iteration of the optimization procedure to reflect the change in the dot radii in the different partitions is a laborious process. Therefore, this study proposes an alternative method for specifying the optical properties of the dots and of the light-guide base surface. As shown in Fig. 4(b), in the proposed approach, the dot surface is separated from the bare surface plane and positioned slightly above it. In this way, the optical property of the bare surface can be specified over the entire rectangular plane surface, while the optical scattering property can be assigned partitionwise to the dots created in the

previous section. The proposed approach simplifies the geometry construction process significantly and obtains very similar results to those of the conventional approach when the gap between the dot surface and the bare surface is sufficiently small. Furthermore, when creating the optical model, the multiple dots in one partition are created in one pass, using the script language provided by the software,¹⁰ rather than on a dot-by-dot basis. Creating the multiple dots in this way can invoke a fast ray-tracing function similar to that used in Ref. 9.

Iteratively determining the optimal dot radius distribution for the light guide is a time-consuming task. Therefore, the efficiency of the optimization procedure is improved by excluding the models of the BEF and diffuser film components from the geometry model. Modeling the BEF and the diffuser is very time-consuming in that the BEF model must take the micro prismatic structure of the BEF into account, while the model for the diffuser must consider the bulk scattering effect. Accordingly, this study proposes a combined analytical and experimental method^{11,12} to take account of the BEF and diffuser film effects in the current simulations.

The basic principle of the proposed approach is to use an analytical method to convert the illuminance (luminous exitance) $E (= \Phi/A)$ emitted from the light guide surface into the equivalent luminance L_0 , which provides a measure of the light leaving the BEF and diffuser. The conversion equation has the form

$$L_0 = -\frac{4}{\sqrt{2}\pi^{3/2}} \cdot \frac{1}{\sigma e^{-2\sigma^2}} \cdot \frac{1}{\left[\operatorname{Erfi}\left(\frac{2\sigma^2 + i\theta}{\sqrt{2}\sigma}\right) - \operatorname{Erfi}\left(\frac{-2\sigma^2 + i\theta}{\sqrt{2}\sigma}\right) \right]_0^{\pi/2}} \cdot \frac{\Phi}{A}, \quad (4)$$

where Erfi is the imaginary error function¹³ and $i = \sqrt{-1}$. Furthermore, A is the viewing area, and Φ is the related output luminous flux. The detailed derivation of Eq. (4) is provided in Ref. 11. In that equation, the luminance distribution of the backlight is assumed to have the form

$$L(\theta) = L_0 \exp\left[-\frac{1}{2}\left(\frac{\theta}{\sigma}\right)^2\right] \quad \text{for } \phi = 0 \text{ to } 2\pi, \quad (5)$$

where L_0 is the luminance at $\theta=0$ (where θ is the zenith angle from the pole and varies from 0 to $\pi/2$) and ϕ is the azimuth angle around the pole. Finally, σ is a parameter used to control the waist of the Gaussian distribution and can be obtained experimentally.¹¹

In the calculations of Eq. (4), the viewing area A can be replaced by an area A_i , i.e., a statistical area for which the illuminance is calculated. The luminous flux in this area is given by Φ_i . Generally, the smaller the value of A_i , the greater the accuracy of the illuminance obtained, provided that sufficient light rays are adopted in the calculation. Having obtained the luminance in each statistical area, a simple averaging technique is then applied to smooth the luminance between neighboring areas so as to represent the smoothing effect of the diffuser film.

Employing Eq. (4) to transfer the illuminance directly to the luminance has many advantages. Since most commercial software programs use statistical methods, the luminance calculation for small cone angles will lose accuracy if a small number of light rays are adopted. Most luminance meters adopt a field (cone) angle of 2 deg to detect the luminance value of the backlight. However, if the same cone angle is specified in the simulations, it is necessary to model a large number of light rays if the simulated luminance value is to attain the same accuracy as that measured experimentally. Clearly, this greatly increases the computational time and complexity. In contrast, Eq. (4) enables the luminance value to be directly obtained from the illuminance result. Furthermore, Eq. (4) provides a simple means of obtaining the luminance variation at different angles.

2.3 Optimization Procedure

In the proposed dot-pattern design methodology, the initial dot-region partitioning step is combined with an optical design phase, in which the dot radius distribution in each partition is iteratively optimized until a uniform luminance condition is achieved. The optimization procedure is based on the dot density rather than the dot radius, since the luminous flux output from the backlight is known to be directly related to the dot density, i.e.,

$$D_{ij} = \frac{A_{\text{dot},ij}}{A_{\text{block},ij}} \propto \frac{\Phi_{ij}}{\Phi_{in}}, \quad (6)$$

where $A_{\text{dot},ij}$ is the total area of the dots in the partitioned area, $A_{\text{block},ij}$ is the total area of the partitioned area, Φ_{ij} is the luminous flux output from the light guide in the partitioned area and Φ_{in} is the luminous flux input to the light guide in the partitioned area. The dot density in the partition is related to the dot radius via the following relationship:

$$r_{ij} = \left[\frac{D_{ij} l_x l_y}{(2m_x m_y - m_x - m_y) \cdot \pi} \right]^{1/2}. \quad (7)$$

By normalizing the luminous flux to the area in Eq. (6), the dot density can also be related to the illuminance. In the dot radius optimization process, the dot density is adjusted according to the difference between the illuminance output, E_{ij} , and the average illuminance, E_{ave} , where E_{ave} is defined as

$$E_{\text{ave}} = \frac{1}{k_x k_y} \sum_{i=1}^{k_x} \sum_{j=1}^{k_y} E_{ij}. \quad (8)$$

Therefore, the dot density D_{ij} is increased if E_{ij} is less than E_{ave} , and decreased if E_{ij} is greater than E_{ave} .

The illuminance of each partition, E_{ij} , is calculated by placing a total number $k_x k_y$ of surfaces just above the light guide with the same arrangement as that of the partitions, to absorb the light rays leaving the light guide.

3 Results and Discussion

Since the current geometry model and the dot arrangement on the base of the light guide are constructed using script language, the geometry can be changed simply by assigning a different dimension as the text input, i.e., there is no

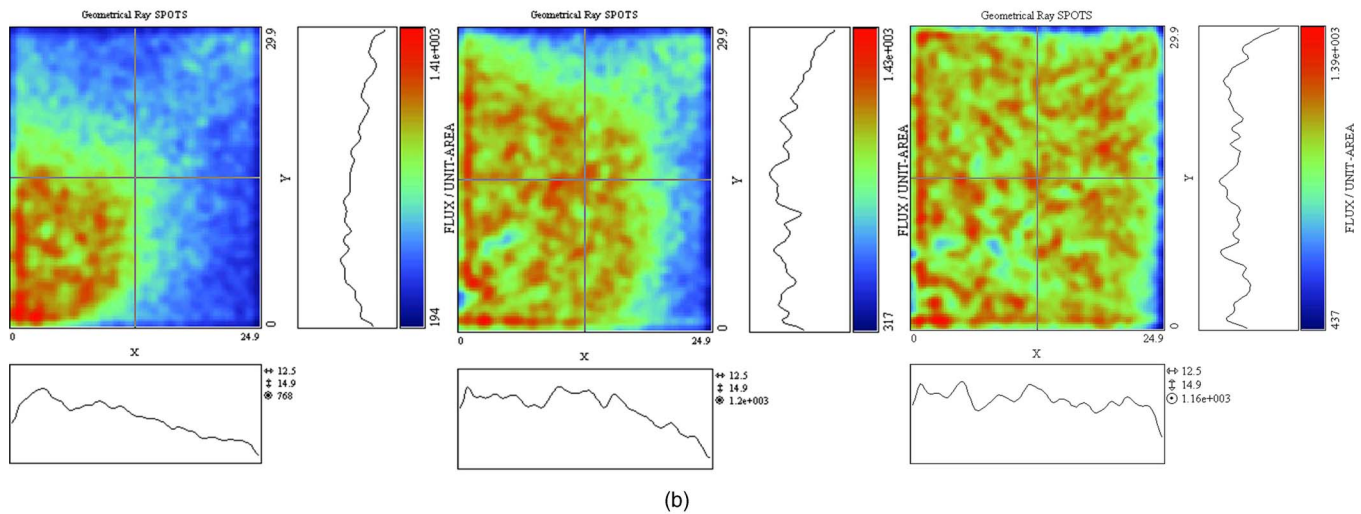
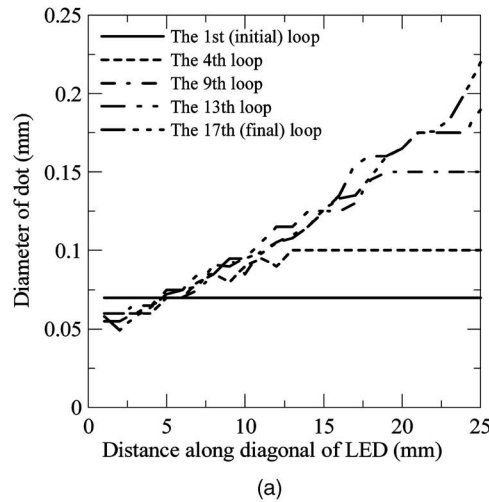


Fig. 5 One-LED configuration: (a) dot diameter variation during iteration along lower-left-to-upper-right diagonal; (b) illuminance variation after 3rd, 7th, and 15th iteration loops.

need to rebuild the model as in a CAD program. The geometry includes the housing that covers the light guide and the LED. The configurations of the one-LED and three-LED backlights used in the following subsections to demonstrate the validity of the proposed regional partition approach are shown in Figs. 1(a) and 1(b), respectively. As shown in the enlarged schematic in Fig. 1(a), the entrance face regions of the light guide immediately in front of the LEDs in the one-LED and three-LED backlights have a sawtooth microstructure, in which the sawtooth angle is 90 deg and the sawtooth pitch is 120 μm .

Based on the LED specification, the present simulations assume that the luminous flux of a single LED is 1.8 lm and that the angle of half intensity is $\theta_{1/2}=55$ deg. Furthermore, the reflector sheet at the base of the light guide is assumed to have a (Lambertian) scattering-type optical property with total integral of reflectance equal to 0.95. The dots are also assumed to have a Lambertian scattering-type optical property, with total integral of reflectance and transmission equal to 0.95. Note that of this 95%, 60% is reflected by the dots, while 40% is transmitted.

3.1 One-LED Backlight

In this example [corresponding to the LED configuration in Fig. 1(a)], it is assumed that the backlight contains a total of 25×30 partitions in the x and y directions, respectively, and has a total of 13,336 dots. Therefore, 750 dot radius variables must be considered in the optimal design phase. Initially, each dot is assigned a radius of 0.035 mm. Figure 5(a) shows the variation of the dot diameter along the diagonal from the LED source (lower left corner) to the opposite (upper right) corner at various stages of the optimization process. Figure 5(b) compares the variation of the illuminance (radiance exitance) of the detector, which is placed a little above the light to collect the light emitting out of the light guide, after the 3rd, 7th, and 15th iteration loops, respectively.

In Fig. 5(a), all of the dots along the diameter have the same initial radius (indicated by the horizontal line at 0.07). However, during successive iterations, the dot radius is gradually adjusted according to the optimization rule just described. It is observed that the radii of the dots closer to

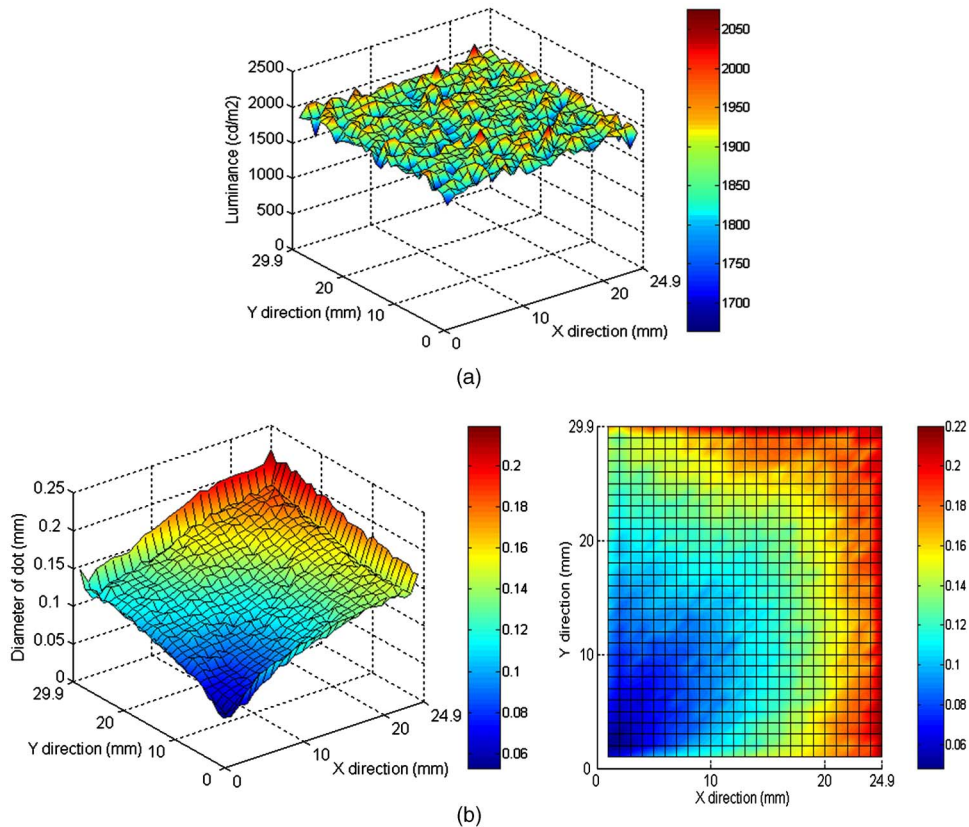


Fig. 6 One-LED configuration: (a) optimal luminance distribution; (b) optimal dot diameter distribution.

the light source become smaller, while those of the dots further from the light source gradually become larger. It can be seen that the radius of the dots increases with increasing distance from the light source. The illuminance variance diagrams presented in Fig. 5(b) indicate that the luminous flux is concentrated in the region of the light source during the initial iteration loops when the dots have the same size, but gradually spreads across the light guide and becomes more uniform as the optimization process continues and the dot density in each partition is adjusted.

Figures 6(a) and 6(b) show the final luminance and dot diameter distribution, respectively. From Fig. 6(a), it can be seen that the average luminance is 1844.6 cd/m^2 . This luminance result is derived from the illumination result using a luminance cone angle of 25° , which is equivalent to a σ value of 0.3706 . By dividing the minimum luminance value by the maximum luminance value, the luminance uniformity over the backlight surface is found to be 84% . Finally, the dot distribution in Fig. 6(b) indicates that the dot radius gradually increases from the corner closest to the light source (lower left corner) to the corner furthest from the light source (upper right corner). It is observed that the dot radius does not increase concentrically about the diagonal, because, as shown in Fig. 1(a), the light source in the lower left corner is oriented at an angle of 48° to the vertical rather than 45° . Therefore, Fig. 6(b) confirms that the proposed iteration scheme obtains an optimal solution that accurately reflects the practical situation.

3.2 Three-LED Backlight

In this example [corresponding to the LED configuration in Fig. 1(b)], the light-guide region is divided into 39×33 partitions and contains a total of $16,088$ dots. Therefore, a total of 1287 dot radius variables must be considered in the optimization process. Initially, the dots are all assigned a radius of 0.05 mm . The iterations are terminated when the dot variation between two successive iterations is smaller than a given tolerance.

Figure 7(a) shows the illuminance results obtained after the 2nd, 3rd, and 36th loops of the iteration process. It can be seen that the illuminance gradually spreads from the left side of the light guide to the right side as the optimization procedure continues. In addition, in the early stages of the optimization procedure, it is observed that the illuminance distribution in the region of the light guide close to the light sources has a two-dimensional sawtooth distribution, in which the maximum illuminance occurs directly in front of the LEDs, while the minimum illuminance occurs in the regions between adjacent LEDs. Figure 7(b) shows the optimal luminance results. The luminance uniformity is calculated to be 87% .

Finally, Fig. 8 shows the optimal dot diameter distribution, where the magnitude of the dot diameter is indicated by the histogram attached to the right side of the figure. A sawtooth shape is again observed in the left-hand region of the light guide near the LED sources, while a flat shape is

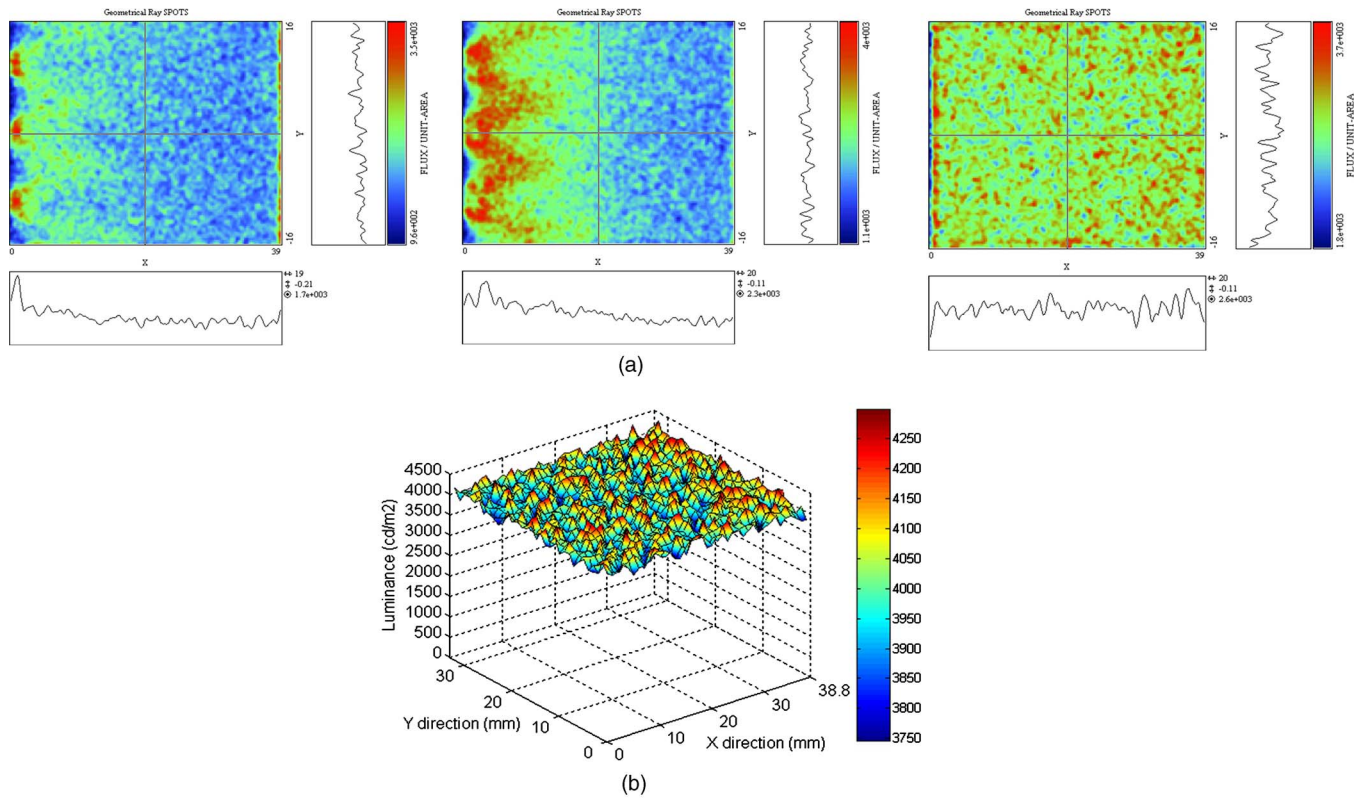


Fig. 7 Three-LED configuration: (a) illuminance variation after 2nd, 3rd, and 36th iteration loops; (b) optimal luminance distribution.

observed in the right-hand region. This result indicates that the dots have a two-dimensional distribution near the LED light sources, viz. the diameter of the dots varies from one partition to the next to ensure that an even luminance is obtained in the regions surrounding (i.e., in front of and between) the LED sources. However, with increasing distance from the LED sources in the x direction, the dot distribution gradually changes to a one-dimensional distribution, in which the dot diameters are uniform from one partition to the next and are larger than those in the region of the LED sources. The two-dimensional distribution near the LED source reflects the point-source characteristics of the LEDs, while the one-dimensional distribution in the

regions further removed from the LEDs is a result of the overlapping of the luminous fluxes of the individual LED sources, which therefore provides a more uniform line source.

4 Conclusion

This paper has proposed a method for optimizing the dot pattern distribution of edge-lit backlights using a regional partition approach. The approach commences by dividing the light guide into a number of partitions and assigning an equal radius to every dot. In an iterative optimization procedure, the illuminance in each partition is calculated and

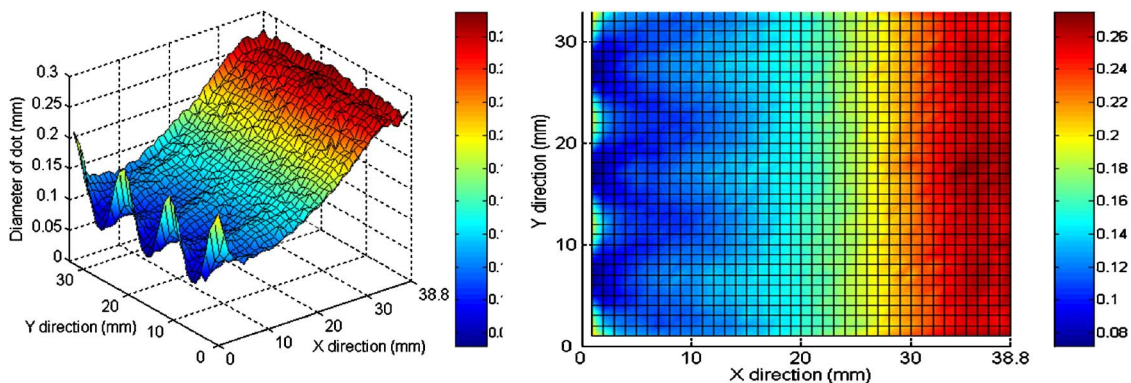


Fig. 8 Optimal dot diameter distribution of three-LED configuration.

the dot radius in each partition progressively adjusted until uniform luminance is obtained over the entire light-guide surface. The geometry construction is simplified through the use of an optical model in which the diffuser dots are separated from the base of the light guide. Furthermore, the efficiency of the optimization process is improved by applying an analytical function and a simple averaging technique to take account of the BEF and diffuser-film effects.

The simulation results have shown that the results of the proposed regional partition approach accurately reflect the fine variation of the dot-pattern distribution required in practical light-guide applications. For example, a nonconcentric variation in the dot radius along the diagonal is found in a one-LED backlight in which the light source is not aligned exactly at 45 deg to the vertical direction. Furthermore, in a three-LED backlight, the results have shown that the dot radius distribution changes progressively from a two-dimensional sawtooth pattern in the region of the light guide near the light sources to a one-dimensional flat distribution in the regions at a greater distance from the LEDs.

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