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Hollow Light Guide Module Involving Mini Light-Emitting Diodes for Asymmetric Luminous Planar Illuminators

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Abstract: Light-emitting diodes (LEDs) have numerous advantages. However, LEDs only offer a point light source. Therefore, transforming LEDs into planar light sources is a new objective in general lighting applications. Solid light guides have strong uniformity but are marred by their material absorption characteristics and weight. Hollow light guides constitute a solution to the weight problem but exhibit poor uniformity and necessitate sacrificing efficiency to enhance uniformity. To resolve the uniformity, weight, and efficiency problems simultaneously, we propose a hollow light guide architecture involving mini-LEDs with asymmetric luminous intensity. To develop this guide module, we first optimized the aspect ratio of the cavity and then modulated the light path by using varied angles of the reflection surface on the end wall of the module. We then designed a beveled reflection surface near the mini-LEDs to further enhance uniformity. An archetype of the proposed architecture for planar light source modules had a width and depth of 51.5 and 9.95 mm, respectively. Experimental results revealed a total efficiency of 83.9% and uniformity of 92.3%. The module weight was determined to be 215 g, which was 40% lighter than that of similarly sized solid light guide modules.

Keywords: planar illuminators; diffuse reflection cavity; asymmetric; mini-LED

1. Introduction

After several decades of light-emitting diodes (LEDs), emergent, LED lighting technology has undergone several significant developments and has gradually become the typical light source for backlighting liquid crystal displays and lighting devices. This revolution has marked a milestone breakthrough in LED technology and led to LEDs becoming an irreplaceable light source. Using LEDs rather than fluorescent lamps as light sources offers several advantages due to the higher color performance, energy efficiency, and eco-friendly characteristics of LEDs [1–3]. Studies have been conducted to test designs for extracting light from backlight modules [4–6]. Recently, planar panel light sources, a new lighting product, have been used in lighting applications. Planar illuminators are usually designed using the concept of side-light backlighting. Such illuminators include LEDs, light guide plates (LGPs), brightness enhancement films (BEFs), and reflection films [7]. Direct-type backlighting modules are another category of backlighting systems, and such modules are relatively thick. Therefore, several studies have been conducted on hollow light guides. The primary problem



encountered in hollow light guides is uniformity. Researchers have attempted to resolve this problem by using a second lens to modulate the luminous intensity of LEDs [8], using multicolored LEDs with micro-lens arrays [9–13], using LEDs with the anodic aluminum oxide structure [14], and using multiple LEDs with various angles of emission toward a reflector [15]. Moreover, researchers have attempted to enhance the uniformity of diffusion plates to avoid partial reflection and transmission of light [16–18]. To modulate the light distribution profile of LEDs to enhance uniformity, a study proposed the use of a second lens with a parabolic surface and different focal lengths [19]. The estimated overall efficiency achieved through the aforementioned designs is 80% [20]. In hollow light guides, reducing the thickness is difficult because of the absence of a solid light guide. Uniformity and efficiency can be enhanced by designing a diffuse reflection cavity that provides multiple reflection rates [21]. Accordingly, this study proposes a hollow light guide architecture involving mini-LEDs with an asymmetric luminous intensity distribution, diffuse reflection cavity, and beveled reflection surface to enhance efficiency, enhance uniformity, and reduce weight.

2. Hollow Light Guide Architecture Involving Mini-LEDs with Asymmetric Luminous Intensity

LEDs are point light sources, so the traditional design must be converted to a surface source by using an LGP. Traditional architectures typically include light guides, reflector films, dot patterns, and optical films [22–25]. A light guide plate is mainly made from solid materials such as polycarbonate (PC) and polymethyl methacrylate (PMMA). Using a light guide plate has several disadvantages due to its bulky characteristics in size and weight. Therefore, we propose using varied angles of the reflection surface (VARS) on the end wall in the diffuse reflection cavity. The proposed hollow light guide structure does not have any of these components or optical films. Instead, it uses a brightness enhancement film and diffuser plates. Figure 1 presents a comparison of a solid- and hollow-light guide for a planar light module. The hollow light guide was simulated and optimized to improve the aspect ratio (ASR) of the hollow body and adjust the VARS to a uniform planar surface source.



Figure 1. (**a**) Solid light guide module for backlighting applications and (**b**) proposed hollow light guide module for backlighting applications.

2.1. Simulation and Design of Proposed Hollow Light Guide Involving Mini-LEDs with Asymmetric Luminous Intensity Distribution

A simulation was conducted to demonstrate the effectiveness of the proposed hollow light guide module. Specifically, a ray tracing simulation was performed using TracePro (LAMBDA Corp., Virginia, MA, USA). Figure 2 shows a light source module that contained the proposed hollow light guide and had widths of 51.5 (W_1) and 42.8 mm (W_0), length of 100 mm (L_0), and height of 9.95 mm (H_0). The diffuse reflection cavity was composed of aluminum 6061 and was fabricated through extrusion. The mini-LEDs with asymmetric luminous intensity distribution were packaged in a flip chip package [26]. Table 1 lists the surface and material parameters of all components of the light source module used in the simulation.



Figure 2. Dimensions of light source module.

Table 1. Simulation	parameter settings.
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Components	Specifications		
I	Surface Characteristics	Material	
Diffusion Reflection Cavity	Diffusion white reflection: $R = 94\%$	Aluminum 6061	
Varied Angle of the Reflection Surface	Diffusion white reflection: $R = 94\%$ BRDF: 0.94 BRDF g = 0 BRDF B = 0.1 BRDF A = 0.329132	Aluminum 6061	
Diffusion plate	BRDF: 0.66 BRDF g = 0 BRDF B = 0.1 BRDF A = 0.231 Thickness (mm): 1.5 Transmittance ratio: 0.33 Diffusion type: Lambertian Manufacturer: Entire Technology Company Limited. Model: EML-R35A	polycarbonate (PC)	
Metal Core PCB (printed circuit board)	Diffusion white reflection: $R = 90\%$	Aluminum	
Brightness Enhancement Film	Index = 1.59 Surface: polished Prism Angle (degrees): 90 Prism Pitch (μ m): 50 Caliper (μ m): 152 Thickness (μ m): 155 Model: 3M AEF-155 Manufacturer: 3M TM	polyethylene terephthalate (PET)	

2.2. Simulation and Design of Optical Cavity of Hollow Light Guide

The efficiency and uniformity of a light module depends on the aspect ratio of the optical cavity, which can be expressed as W_0/H_0 , where W_0 represents the optical cavity width and H_0 represents the optical cavity height. Height is the key factor related to uniformity. Accordingly, we set a constant width but varied the height to evaluate the best aspect ratio of the optical cavity in our simulation. Figure 3 illustrates the hollow light guide module for a planar light source containing mini-LEDs with asymmetric luminous intensity distribution, a brightness enhancement film, and a diffusion plate. Table 2 presents the efficiency and uniformity simulated for different aspect ratio values.



Figure 3. Hollow light guide module for planar light source, where BEF is brightness enhancement film.

W ₀	H ₀	Aspect Ratio (W ₀ /H ₀)	Uniformity (%)	Efficiency (%)
42.8	12.5	3.4	87.1	79
42.8	11.5	3.7	88.2	80
42.8	10.5	4.1	89.4	80.2
42.8	9.95	4.3	90	80.9
42.8	9.5	4.5	88.6	81.6
42.8	8.5	5.0	82.8	84.6
42.8	7.5	5.7	75.4	84.8
42.8	6.5	6.6	61.4	85
42.8	5.5	7.8	50.52	85.4
42.8	4.5	9.5	46.7	85.8

Table 2. Efficiency and uniformity of a light module at various aspect ratio values.

In this paper, the hollow cavity was used to replace the traditional conductive medium with solid light guide plate. First, we optimized the values of the primary hollow light guide, H_0 and W_0 , where we defined the aspect ratio value as W_0/H_0 and the evaluation functions were efficiency and uniformity. The uniformity is expressed in Equation (1) [27], where "minimum" and "maximum" denote the degree of illumination (*E*) that can be measured from a detection surface.

Uniformity = 100%
$$\frac{\text{minimum } E(lux)}{\text{maximum } E(lux)}$$
 (1)

Figure 4 shows the relationship between efficiency and uniformity at various aspect ratio values. At an aspect ratio value of 4.3, the observed uniformity was superior to the efficiency. Nevertheless, the efficiency was still reasonably favorable. Figure 5 presents the illumination map observed by the detector at an aspect ratio of 4.3. It can be seen from Table 2 and Figure 5 that the efficiency was 80.9% and the uniformity was 90%. The efficiency was improved when the hollow body was a rectangular cavity, however, the light was still ejected inside causing loss of efficiency. For further efficiency enhancement, the end wall of the light guide was tilted at an angle of Θ_e (Figure 6). In order to further improve the efficiency, a hypotenuse angle Θ_e was designed at the end of the hollow cavity to reduce the loss caused by the internal bounce of light. Figure 7 shows the illumination map observed for the detector at a Θ_e value of 45°. Table 3 presents the simulated uniformity and efficiency at different Θ_{e} values. In the Table 3 and Figure 7, the efficiency and uniformity were about 86% and 84.4%, respectively, when the Θ_e was at 45°. The angle of the bevel at the end of the hollow cavity was a single angle, causing the light to concentrate too much in a certain area, resulting in a decrease in uniformity. Therefore, it was necessary to optimize the curvature of the tail end to change to the multi-section curvature. As indicated in the Table 3, the best efficiency was observed at a Θ_e value of 45°. However, the uniformity decreased to 84.4% at this angle. We could not achieve favorable efficiency and uniformity simultaneously at the same $\Theta_{\mathbf{e}}$ value. Therefore, we proposed the use of VARS on the end wall in the diffuse reflection cavity.



Figure 4. Relationship between efficiency and uniformity at various aspect ratio values for hollow light guide.



Figure 5. Illumination map observed by a detector.



Figure 6. Lateral section of the light guide module that show a tilting end wall at an angle of Θ_e .



Figure 7. Illumination map of a light guide module measured by detector at $\Theta_e = 45^{\circ}$.

Tilting end Wall Angle (Θ_e)	Uniformity (%)	Efficiency (%)
20°	84.6	85.3
30°	84.5	85
45°	84.4	86
60°	82.2	85

Table 3. Simulated efficiency and uniformity at different Θ_e values.

2.3. Optimized VARS

Figure 8 illustrates the VARS implemented on the end wall. It shows the VARS structure design, which was used to adjust the uniformity distribution of the light emitted from the hollow cavity. The main idea of this study was that the light shone out in the middle of the hollow body. Figure 9 presents the ray tracing in VARS that is an explanation for the derivation of the VARS theory.



Figure 8. Varied angles of the reflection surface (VARS) implemented on the end wall.



Figure 9. Geometry structure of ray tracing with VARS.

To optimize efficiency and uniformity, we let the L1, L2, and L3 rays travel toward the center of the diffusion plate through the reflection engendered by the VARS. In Figure 9, W_0 represents the width, and H_0 represents the height of the VARS. Moreover, N_1 – N_3 denote the normal lines perpendicular to the X–Z sections, respectively. The tilt angles Θ_1 , H_1 , and Θ_{r1} are defined in Equations (2)–(4). Θ_{i1} is the incident angle, Θ_{r1} is the reference angle of Θ_1 , and Θ_{o1} is the reflection angle corresponding to N_1 in the X section.

$$\tan \Theta_{r1} = \frac{H_0 - \frac{H_0}{6}}{\frac{W_0}{2}},$$
(2)

$$H_1 = H_0 - \frac{H_0}{6},\tag{3}$$

$$\Theta_1 = 90 - \Theta_{r1} - \Theta_{i1}. \tag{4}$$

The second tilt angle Θ_2 and H_2 are defined in Equations (5) and (6). Θ_{i2} is the incident angle, and Θ_{02} is the reflection angle corresponding to N_2 in the Y section.

$$\Theta_2 \cong 90 - \Theta_1, \tag{5}$$

$$H_2 = H_0 - \frac{3H_0}{6}.$$
 (6)

The third tilt angle Θ_3 and H_3 are defined in Equations (7) and (8). Θ_{i3} is the incident angle, and Θ_{o3} is the reflection angle corresponding to N_3 in the Z section.

$$\Theta_3 \cong 90 - \Theta_I, \tag{7}$$

$$H_3 = H_0 - \frac{5H_0}{6}.$$
 (8)

Through Equations (2)–(8), VARS profiles can be drawn, and VARS can be defined by the following polynomial equation:

$$Y = C_0 + \sum B_i * X^i \ i = 0, \ 1, \ 2 \dots$$
(9)

where C_0 is a constant, and B1–B6 are the coefficients of the polynomial equation listed in Table 4.

Symbol	Value
Intercept (C_0)	-3.49128×10^{-14}
B1	16.708
B2	-48.53044
B3	56.33018
B4	-18.82259
B5	-4.49559
B6	2.73919

Table 4. Coefficients of polynomial equation.

Figure 10 shows the proposed hollow light guide with VARS. It illustrates a 3D schematic diagram of a hollow cavity combined with VARS. Figure 11 illustrates the illumination map observed for the proposed hollow light guide with VARS. The uniformity was determined to be 89%, and the overall efficiency was determined to be 85%. It can be seen from the light trace that the light was concentrated in the middle of the hollow cavity through designing multi-segment VARS. At this time, the uniformity was 89%, and the efficiency of 85% had reached a good result. In order to improve overall uniformity, the design of a beveled reflection surface at the entrance of the hollow cavity could converge the LED light intensity distribution at the module.



Figure 10. Hollow light guide with VARS: (a) side view and (b) isometric view.



Figure 11. Illumination map of a novel hollow light guide with VARS.

2.4. Beveled Reflection Surface Design and Optimization

As indicated in Figure 11, the luminance at the center of the detection surface was higher than the overall luminance because the light was directed to the center through the VARS. We optimized Θ_4 to further enhance uniformity. A beveled reflection surface was designed to reduce the vertical axis beam angle of the mini-LEDs to enhance uniformity. Table 5 lists the efficiency and uniformity measured at various angles of reflection bevel edge Θ_4 .

Table 5. Efficiency and uniformity of calculation results at various bevel angles Θ_4 .

Reflection Bevel Edge (Θ_4)	Uniformity (%)	Efficiency (%)
10°	86.7	80.7
20°	88.2	81.1
30°	90.8	82.5
40°	90.6	81.7
50°	87.1	81.3

Figure 12 illustrates the illumination map measured for the beveled reflection surface. After optimization, it can be seen from Table 5 and Figure 12 that the efficiency can be increased to 82.5% and the uniformity can reach 90.8% when the $\Theta_4 = 30^\circ$. Figure 13 shows the intensity distribution curve for the beveled reflection surface in the detector. Figure 13 is the light distribution curve after the simulation, wherein the blue line is a 0° tangent angle, the green line is a 45° tangent angle, the red line is a 90° tangent angle, and the cyan line is a 135° tangent angle light distribution curve, respectively.



Figure 12. Illumination map for beveled reflection surface.



Figure 13. Intensity distribution curve for the beveled reflection surface.

3. Actual Production and Verification

Figure 14 is the actual finished product which depicts an archetype of the planar mini-LED light source module with VARS and a beveled reflection surface. Figure 15 shows the measured intensity curve obtained using the LEDGON goniometer instrument (Instrument Systems GmbH, Munich, Germany). Approximation and simulation data are presented in Figure 13. Figure 16a presents the illumination map measured when the module was shut down. Figure 16b shows the illumination map when the module was in operation. Nine equidistant points were established to evaluate uniformity, and Figure 17 shows these measurement points obtained using a BM-7 luminance meter (Topcon Corporation, Tokyo, Japan). Uniformity was evaluated by determining (Lmin/Lmax × 100%). Table 6 lists the measurement results. The data presented in Table 6 were measured at point 1 was 92.3%. Table 7 presents the measured optical characteristics of the module. The module efficiency was 83.9%.



Figure 14. Archetype of light source module with VARS and beveled reflection surface.



Figure 15. Intensity distribution of actual light guide module.



Figure 16. Illumination conditions of proposed light source module: (a) shut down and (b) in operation.

	Wo	
1 (0.9Wo, 0.9Lo)	2 (0.5Wo, 0.9Lo)	(0.9 Wo,0.9 Lo) 3
(0.9Wo, 0.5Lo)	5 (0.5Wo, 0.5Lo)	(0.9Wo, 0.5Lo) 6
7 (0.9Wo, 0.9Lo)	8 (0.5Wo, 0.9Lo)	(0.9Wo, 0.9Lo) 9

Figure 17. Measurement points on light source module for uniformity evaluation.

Position	Relation Luminance L (nits)
P ₁	0.925
P ₂	0.923
P_3	0.927
P_4	0.984
P_5	1
P_6	0.986
P_7	0.936
P_8	0.931
P9	0.938

 Table 6. Relative luminance measured at nine points.

 Table 7. Optical characteristics of light source and light source module.

	CIE x	CIE x	Flux (lm)	Efficiency (%)
Light source	0.3792	0.3821	300	100
Light source module	0.3802	0.3734	251	83.9

Item	Simulation	Measurement
Uniformity (%)	90.8	92.3
Efficiency (%)	82.5	83.9
Horizontal axis (degree)	104	106
Vertical axis (degree)	76	74

Table 8. Comparison of simulation and measurement results.

4. Conclusions

This paper presents a novel planar light source module involving mini-LEDs with asymmetric luminous intensity distribution and a novel optical cavity consisting of a diffuse reflection cavity, beveled reflection surface, and VARS to achieve high efficiency and uniformity. The archetype achieved a uniformity of 92.3% and efficiency of 83.9%. We used varied angles of the reflection surface (VARS) on the end wall in the diffuse reflection cavity instead of traditional solid light guide architecture to reduce the thickness and weight of this light source module. This architecture with an asymmetric luminous intensity distribution and diffuse reflection cavity can improve LED lighting performance. The proposed hollow light guide had a width of 51.5 mm, making it more suitable for linear lighting or slender backlighting than for display stand applications.

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References

- Parikka, M.; Kaikuranta, T.; Laakkonen, P.; Lautanen, J.; Tervo, J.; Honkanen, M.; Kuittinen, M.; Turunen, J. Deterministic diffractive diffusers for displays. *Appl. Opt.* 2001, 40, 2239–2246. [CrossRef] [PubMed]
- 2. Son, C.-G.; Yi, J.-H.; Gwag, J.-S.; Kwon, J.-H.; Park, G.-J. Improvement of color and luminance uniformity of the edge-lit backlight using the rgb leds. *J. Opt. Soc. Korea* **2011**, *15*, 272–277. [CrossRef]
- 3. Huang, Y.-S.; Luo, W.-C.; Wang, H.-C.; Feng, S.-W.; Kuo, C.-T.; Lu, C.-M. How smart LEDs lighting benefit color temperature and luminosity transformation. *Energies* **2017**, *10*, 518. [CrossRef]
- 4. Horibe, A.; Baba, M.; Nihei, E.; Koike, Y. High efficiency and high visual quality lcd backlighting system. *SID Symp. Dig. Tech. Pap.* **1998**, *29*, 153–156. [CrossRef]
- 5. Teijido, J.; Herzig, H.; Dandlinger, R. Diffraction properties of volume holographic diffusers. *Proc. SPIE* **1996**, 15, 747–756.
- Teijido, J.M.; Herzig, H.P.; Daendliker, R.; Grupp, J.; Poli, J.-C. Design of a nonconventional illumination system using a scattering light pipe. In *Design and Engineering of Optical Systems*; International Society for Optics and Photonics: Bellingham, WA, USA, 1996; pp. 747–757.
- Teng, T.C.; Kuo, M.-F. Highly precise optical model for simulating light guide plate using led light source. Opt. Express 2010, 18, 22208–22214. [CrossRef] [PubMed]
- 8. Shimizu, T. Planar Light-Emitting Device. U.S. Patent US20120250313 A1, 4 October 2012.
- 9. Wu, P.C. Lateral Planar Light Emitting Module. U.S. Patent 20130163284 A1, 27 June 2013.
- 10. Chen, Y.-S.; Lin, C.-Y.; Yeh, C.-M.; Kuo, C.-T.; Hsu, C.-W.; Wang, H.-C. Anti-glare LED lamps with adjustable illumination light field. *Opt. Express* **2014**, *22*, 5183–5195. [CrossRef] [PubMed]
- Hsiao, Y.-P.; Wang, H.-C.; Chen, S.-H.; Tsai, C.-H.; Yang, J.-H. Identified early stage mycosis fungoides from psoriasis and atopic dermatitis using non-invasive color contrast enhancement by LEDs lighting. *Opt. Quantum Electron.* 2015, 47, 1599–1611. [CrossRef]
- 12. Wang, H.-C.; Chen, Y.-T. Optimal lighting of RGB LEDs for oral cavity detection. *Opt. Express* **2012**, *20*, 10186–10199. [CrossRef] [PubMed]

- 13. Wang, H.-C.; Chiang, Y.-T.; Lin, C.-Y.; Lu, M.-Y.; Lee, M.K.; Feng, S.-W.; Kuo, C.-T. All-reflective RGB LED flashlight design for effective color mixing. *Opt. Express* **2016**, *24*, 4411–4420. [CrossRef] [PubMed]
- Huang, Y.-R.; Chou, Y.-C.; Wu, Z.-L.; Huang, K.-C.; Ting, S.-Y.; Yao, Y.-F.; Chiang, P.-J.; Tseng, S.H.; Wang, H.-C. Light extraction efficiency enhancement of flip-chip blue light-emitting diodes by anodic aluminum oxide. *Beilstein J. Nanotechnol.* 2018, 9, 1602–1612. [CrossRef] [PubMed]
- Nakamura, Y.; Furuya, E. Liquid Crystal Display Device Backlit by Led's Coupled to Printed Circuit Board. U.S. Patent 5,453,855, 26 September 1995.
- 16. Allekotte, H.A.; Sturm, G. Light Box. U.S. Patent US4989122 A, 29 January 1991.
- 17. Sakai, S.; Mori, A.; Yamaguchi, T.; Yoneda, T. Planar light source device and display device using the same device. U.S. Patent US7350951 B2, 1 April 2008.
- Xu, S.; Yang, T.; Miao, H.-H.; Xu, Y.-Z.; Shen, Q.-X.; Guo, T.-L.; Cui, Z.-X.; Chen, E.-G.; Ye, Y. Tilted light coupling structure for the thickness reduction of a liquid crystal display backlight. *Appl. Opt.* 2019, *58*, 2567–2574. [CrossRef] [PubMed]
- Ye, Z.T.; Kuo, H.C.; Chen, C.H. Thin hollow light guide for high-efficiency planar illuminator. *Appl. Opt.* 2015, 54, E23–E29. [CrossRef] [PubMed]
- Chen, C.F.; Wang, H.T.; Chen, C.H. High throughput reflective light guide for planar illuminator. *Appl. Opt.* 2008, 47, 784–791. [CrossRef] [PubMed]
- Ye, Z.T.; Pai, Y.M.; Kuo, H.C.; Chen, C.H. Hollow light guide for light weight and high efficiency planar illuminator. In Proceedings of the 2017 Asia Communications and Photonics Conference, Guangzhou, China, 10–13 November 2017.
- 22. Zhao, H.; Fang, S.; Shang, B. Adaptive neuro-fuzzy inference system for generation of diffuser dot patterns in light guides. *Appl. Opt.* **2010**, *49*, 2694–2702. [CrossRef]
- 23. Xu, P.; Huang, Y.Y.; Su, Z.; Zhang, X.; Luo, T.Z.; Peng, W. Research of micro-prism distribution on the bottom surface of the small-size integrated light guide plate. *Opt. Express* **2015**, *23*, 4887–4896. [CrossRef] [PubMed]
- 24. Yang, J.C.; Huang, C.C. Using UV roll-to-plate imprint lithography to fabricate light guide plates with microdot patterns. *Micro Nano Lett.* **2012**, *7*, 244–247. [CrossRef]
- 25. Xu, P.; Luo, T.-Z.; Zhang, X.-L.; Su, Z.-J.; Huang, Y.-Y.; Li, X.-C.; Zou, Y. Design and optimization of a partial integrated backlight module. *Opt. Commun.* **2018**, *427*, 589–595. [CrossRef]
- 26. Ye, Z.-T.; Pai, Y.-M.; Chen, C.-H.; Kuo, H.-C.; Chen, L.-C. A Light Guide Plate that Uses Asymmetric Intensity Distribution of Mini-LEDs for the Planar Illuminator. *Crystals* **2019**, *9*, 141. [CrossRef]
- 27. NSAI. Light and Lighting—Lighting of Work Places—Part 1: Indoor Work Places; Beuth Verlag, EN 12464-1; NSAI: Dublin, Ireland, 2011.



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