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Paper

LED Flat Panel Capable of Seamless Connection for Use in Lighting

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ABSTRACT

We propose a light-emitting diode (LED) flat lighting panel that is capable of seamless connection by optimizing the shape of the optical elements, as well as the concentration of the scattering particles used in the diffuser material. The LED flat lighting panels that we develop can be connected to other panels while maintaining a uniformity of 90% throughout the entire surface. The results of subjective experiments reveal that the seams between the connected LED flat panels are virtually unnoticeable. We also discuss the optimal lighting designs for using the LED flat lighting panels as bracket lighting and ceiling lighting by measuring their primary optical characteristics. In particular, the unified glare rating of the seamless panel is 19.4, which corresponds to the minimum level of uncomfortable glare. Moreover, the seamless panel exhibits a luminous efficiency as high as 79.6 lm/W, which satisfies Energy Star requirements. These evaluations show that the LED flat panel is capable of providing comfortable space and lighting designs for architecture in an environmentally friendly manner.

KEYWORDS: LED, Seamless connection, Flat lighting panel, highly scattered optical transmission polymer

1. Introduction

In recent years, light-emitting diodes (LEDs) have become increasingly popular for use in general lighting on account of their low power consumption, long life, and low heat generation compared to conventional light sources. An LED is a point light source whose lighting characteristics—such as the light ray distribution angle and light-emitting areas of the optical element—are easy to control.[1)2)] However, LEDs possess high directionality and brightness, which lead to an uncomfortable glare upon the human eyes. To reduce such glare, LED flat lighting panels are becoming more popular in the market these days. An LED flat lighting panel emits light from a larger area in order to provide less intensive luminance while maintaining an equivalent total luminous flux. Because of these advantages, LEDs are often used in various lighting fixtures, such as downlight lenses.

Various sizes and shapes of bracket lighting and ceiling lighting have been proposed by lighting designers. Designing and producing light devices in various sizes and shapes requires optical elements of various sizes and shapes, which in turn require increased costs and manufacturing time. However, if the proposed sizes and shapes can be created by combining multiple square units, differently sized and shaped lighting devices can be obtained relatively easily. In this way, manufacturing square units in large quantities can help to reduce the overall costs incurred. For bracket lighting and ceiling lighting, LED flat lighting panels that use light guide panels (LGPs) have become popular; that is because it is easy to accommodate the thin lighting devices in existing building materials using such panels. Most LED flat lighting panel fixtures utilize backlight technology, which makes use of LGPs. However, because LGPs are assembled with a frame around the edges (and because the frames do not transmit light), the brightness of the frames differs from that of the rest of the LGP. Even some frameless LED flat lighting panels have not been able to achieve a sufficiently consistent brightness over the entire surface, which renders each individual panel and the seams between the panels visible. Accordingly, these conventional LED flat lighting panels do not create seamlessly lit surfaces.

The purpose of this article is to propose a thin seamless lighting device (hereafter referred as a seamless panel) that can be combined with other seamless panels to create a larger lighting surface. Crucially, the connected areas between the seamless panels are virtually unnoticeable in practice. The seamless lighting device consists of an LGP, a diffuser panel, and an LED. The optimal structure of the diffuser panel makes the seams virtually unnoticeable, and furthermore optimizes the concentration of the scattering particles in the diffuser material. We discuss optimal lighting designs that use the seamless panels for bracket lighting and ceiling

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lighting by measuring the primary optical characteristics of the seamless panels.

2. Development of the seamless panel

2.1 Structure of the seamless panel

Figure 1(a) shows a sectional drawing of a conventional LED flat lighting panel that has 9 LED light sources on the sides of the LGP, with 18 sources per unit. The arrows in the figure represent the approximate paths of lights inside the device. The solid lines represent light from the LED on the left side of the device, whereas the broken lines represent light from the LED on the right side. Conventional LED flat lighting panels contain LEDs at ends of the LGP, as well as a diffuser sheet, an LGP, a reflection sheet, and a frame that holds the aforementioned parts. The frame brings light that leaks from the LGP back into the unit to increase the uniformity of luminance. It is important to note that this conventional device does not allow for seamless connections because the frame is made of an opaque material, for example stainless steel. A cross-sectional drawing of the proposed seamless panel is shown in Figure 1(b). The diffuser plate of the seamless panel that holds the parts together diffuses light in order to make the luminance even. This structure allows for light emission from the entire surface of the device.[3)4)] Both the LGP and the diffuser panel contain a highly scattered optical transmission (HSOT) polymer. The lights bending inside the LGP represent the fact that the lights are scattered by the scattering particle inside the HSOT polymer. The HSOT polymer contains optimized heterogeneous structures that produce homogeneously scattered light with forward directivity.[5)]

The seamless panel has dimensions of 150 mm × 150 mm. The Japanese construction industry traditionally uses 1 shaku (approximately 300 mm) and 1.5 shaku (approximately 450 mm) as primary units. Accordingly, the size of the seamless panel is suitable for traditional Japanese construction standards. The seamless panel is 10.3 mm thick, and is as thin as conventional construction board.

Figure 2 shows an enlarged illustration of the primary light rays near an LED light source in the seamless panel. The light rays were traced assuming that the LGP and the diffuser panel are made of transparent material using the refractive index of polymethyl methacrylate (PMMA). The LGP and the diffuser panel that were used in the experiment also used PMMA that contained the scattering particle. The solid lines represent light rays from an LED on the left side of the device, whereas the broken lines represent light rays from an LED on the right side. The light emitted from the left LED enters into the diffuser plate where total reflection occurs on the vertical surface of the diffuser plate; the light then reverses in the opposite direction. The light emitted from the right LED does not totally reflect on the vertical surface or travel to the sides of the panel; instead, it travels through the air and enters the diffuser panel. This structure of the diffuser panel guides some light away from its original direction and to the peripheral parts instead. This figure illustrates that some light is guided to the central area of the diffuser panel and some to the peripheral part, which enables high luminance uniformity over the entire surface of the device (This structure is hereafter called the total-reflection structure).

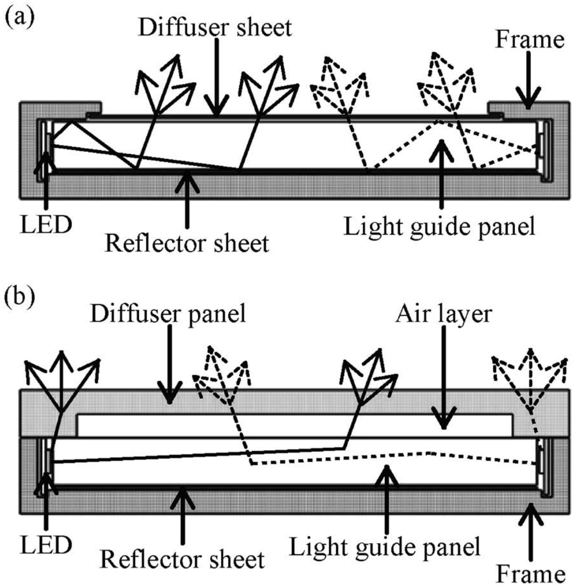

Figure 1 Comparison of the conventional light-emitting diode (LED) flat lighting panel and the seamless panel. (a) Cross-sectional drawing of the conventional LED flat lighting panel. (b) Cross-sectional drawing of the seamless panel.

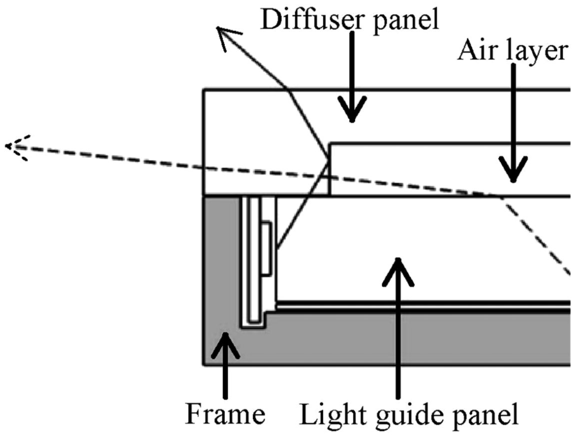

Figure 2 Enlarged illustration of primary light rays near a light-emitting diode (LED) light source in the seamless panel. The solid lines represent light rays from an LED on the left side of the device, whereas the broken lines represent light rays from an LED on the right side.

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2.2 Measurement method of the seamless panel

Figure 3(a) shows the coordinate system used for a single seamless panel, whereas Figure 3(b) shows the coordinate system used for two seamless panels that are connected to each other. In the case of the single panel, the origin of the coordinate system is located at the center of the seamless panel; in the case of the two connected panels, the origin of the coordinate system is located centrally along the shared side of the panels. The luminance of the two connected seamless panels was measured at different angles Figure 3(b) describes the viewing angles θ (from Z to X) and φ (from Z to Y).

The luminance distribution was measured with a 2D luminance meter (Radiant Imaging Prometoric PM-1400F) at a distance of 700 mm using a lens with a focal length of 20 mm (AI AF Nikkor 20 mm f/2.8D) and an f-number of 8.0. The luminance distribution and total flux were measured with a goniophotometer (LMT GO-DS1600) at Gunma Industrial Technology Center. The distance between the light source and the detector via a mirror was 19.25 m in the measurement.

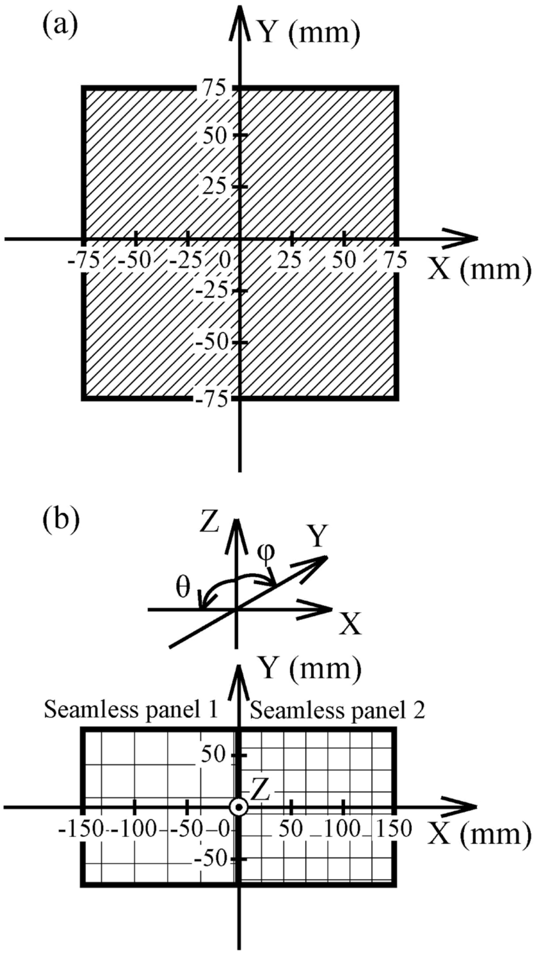

Figure 3 Coordinate systems of the seamless panels used in luminance measurements. (a) Coordinate system of a single panel. (b) Coordinate system of connected panels.

2.3 Effect of the seamless panel structure

Figure 4 shows light rays near the LED light source in a device whose diffuser panel is shaped so as to not cause total reflection (This structure is hereafter called the conventional structure). The solid line represents a light ray from an LED on the left side of the device, whereas the broken line represents a light ray from an LED on the right side. The angles and locations of light emitted from LEDs are the same as those in Figure 2. The light released from the left LED does not undergo total reflection at the diffuser panel and travels out from the middle area of the surface, rather than along the periphery. The structure of the diffuser panel that causes total reflection could lead more light to the periphery, as shown in Figures 2 and 4.

Figure 5 shows the normalized front luminance measured for a single seamless panel along the X-axis for both the total-reflection structure and the conventional

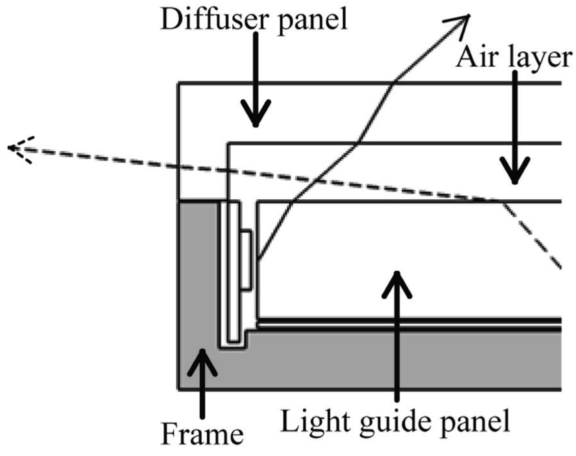

Figure 4 Enlarged illustration of major light rays near the light-emitting diode (LED) light source in a device whose diffuser panel is shaped so as to not cause total reflection. The solid line represents a light ray from an LED on the left side of the device, whereas the broken line represents a light ray from an LED on the right side.

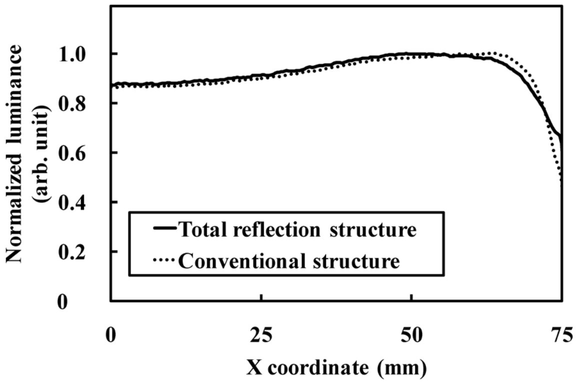

Figure 5 Measured luminance along the X-axis of the seamless panel.

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structure; X=75 mm represents the edge of the seamless panel. The only difference concerns the structure of the diffuser panel that sits on the bottom frame, whereas the concentration of the scattering particle in the HSOT polymer and the thickness of the diffuser panels were all identical. The luminance from the total-reflection diffuser panel was 20% more than that from the conventional diffuser panel at X=75 mm. As shown in the measurement results, the luminance along the periphery could be improved by structuring the diffuser panel properly.

2.4 Optimization of the diffuser panel

Figure 6 shows the luminance of the single seamless panel measured along the X-axis for diffuser panels made with different concentrations of scattering particles in the HSOT polymer. Panel 1 was made with the lowest HSOT polymer concentration, whereas panel 3 was made with the highest concentration. Panel 1 showed non-uniform luminance along the periphery because the concentration of the scattering particles in the HSOT polymer was too low; on the other hand, panel 2 and 3 did not show non-uniform luminance. However, panel 3 showed the overall brightness was low, and the light was not emitted efficiently. For panel 2, which had an optimal scattering particle concentration, the luminance across the entire panel was maintained uniformly, while sufficient luminance was maintained in the center (The details are described in the following sections).

2.5 Luminance measurements along the common boundary

Figure 7 shows the luminance of two connected seamless panels measured along the X-axis. Figure 8 shows pictures of the panels taken during the measurement.

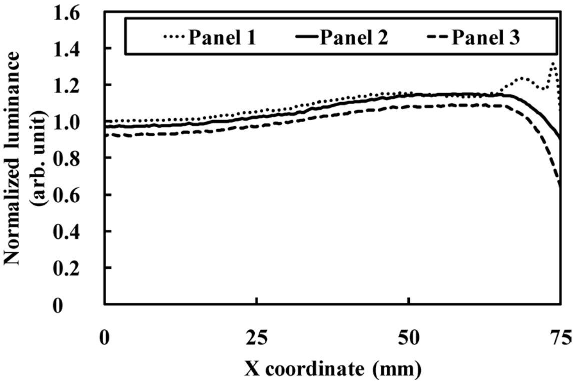
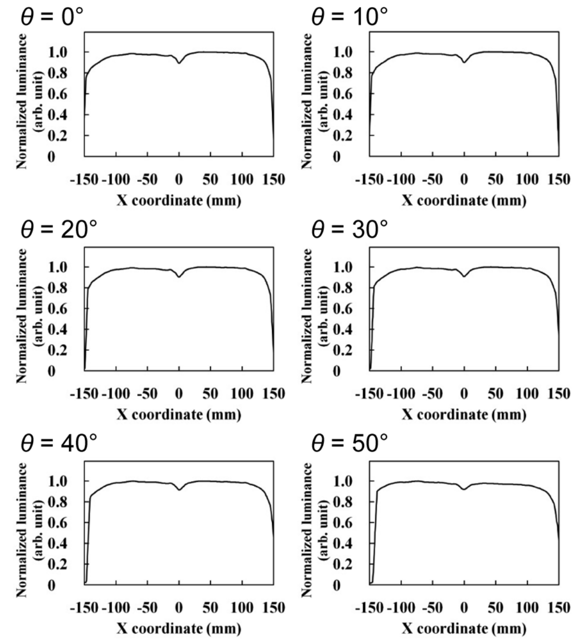


Figure 6 Measured luminance of a single seamless panel along the X-axis for different scattering particle concentrations in the highly scattered optical transmission (HSOT) polymer. Panel 1 was made with the lowest HSOT polymer concentration, whereas panel 3 was made with the highest concentration.

The diffuser panels were made with the optimized HSOT polymer concentration shown in panel 2 of Figure 6. The luminance was measured in both the θ (from Z to X) and φ (from Z to Y) directions at 10° intervals between 0° and 50°; the measured luminance decrease was at most 10%. The luminance of the panel was 4400 cd/m^2 from the frontal direction. For the measurement ND1 filter (10% transparent) was used, in order to achieve the appropriate exposure. These results indi-


Direction of θ

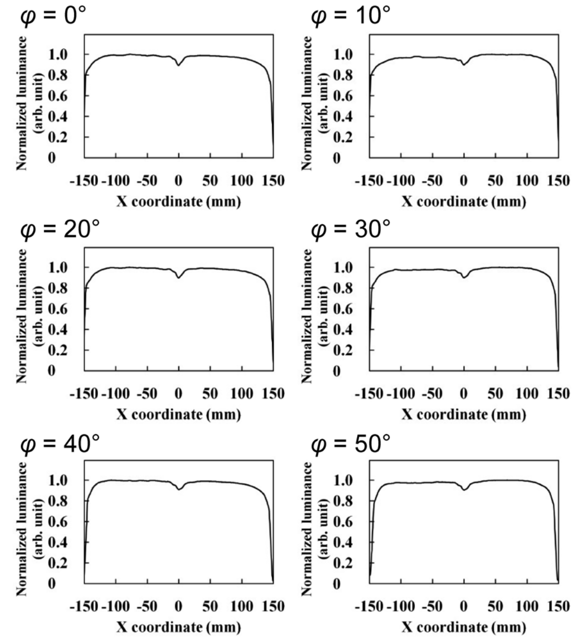

Direction of φ

Figure 7 Luminance of two seamless panels connected to each other measured along the X-axis.

cate that selecting a proper shape for the diffuser panel and choosing an optimal polymer concentration enables the seamless panels to be connected while maintaining the uniformity of 90%.

3. Lighting design with the seamless panel

We performed subjective experiments in order to evaluate the noticeability of the area where the seamless panels are connected. We also evaluated lighting systems designed with seamless panels. Based on these experimental results, we discuss optimal lighting designs created by the seamless panels.

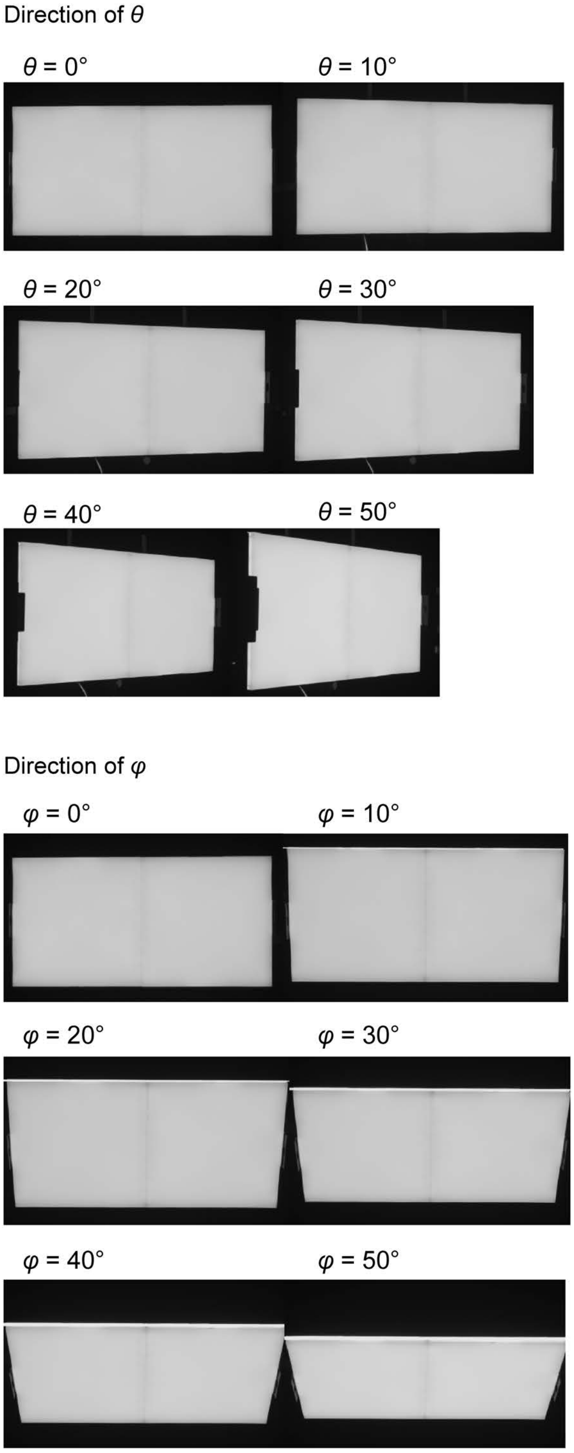


Figure 8 Pictures of the seamless panels taken during the measurement.

3.1 Subjective experiments with the seamless panels

In the subjective experiments, we evaluated white-colored (5200 K) and warm-colored (3200 K) seamless panels to verify possible differences that result from different color temperatures. The brightness values of the seamless panels were 4400 cd/m^2 (white-colored) and 3800 cd/m^2 (warm-colored). The evaluation was carried out from the frontal direction from distances of 0.5 m and 1.0 m. The luminance non-uniformity of the connecting area was rated on four different levels: not noticeable at all, not very noticeable, slightly noticeable, and noticeable.

Table 1 shows the ratings obtained from the subjective experiments, and Figure 9 shows a picture of the warm-colored seamless panels that were used in the experiments. The color variation at the connecting area of the white panels was largely evaluated as noticeable. In particular, when observed from a distance of 1.0 m, the connecting area was evaluated as slightly noticeable. In contrast, the warm-colored panel was deemed to be not noticeable at all from a distance of 0.5 m, and not very noticeable from 1.0 m.

In terms of distance, the evaluations of both the white- and warm-colored panels showed that the connecting area was less noticeable as the observer moved closer to the panels. Assuming that the diameter of the pupils remains the same as the observer moves closer, we can suppose that light enters the pupils from a wider solid angle at a closer distance. For this reason, when the observer moves closer to the panel, the connecting area becomes less noticeable because the angle variation of the light emitted from the seamless panel becomes less noticeable, and because the brightness is

Table 1 Ratings from the subjective experiments.

Distance	White-colored Panel	Warm-colored Panel
0.5 m	Not very noticeable	Not noticeable at all
1.0 m	Slightly noticeable	Not very noticeable

Figure 9 Picture of a warm-colored seamless panel that was used in the subjective experiments.

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Table 2 Basic characteristics of the seamless panel.

Items	Seamless panel		LED	
	White color	Warm color	White color	Warm color
Luminance (cd/m^2)	4400	3800	—	—
Correlated color temperature (K)	5200	3200	5000	3000
Color rendering index	85	85	85	85
Luminous efficacy (lm/W)	79.6	66.5	110	92

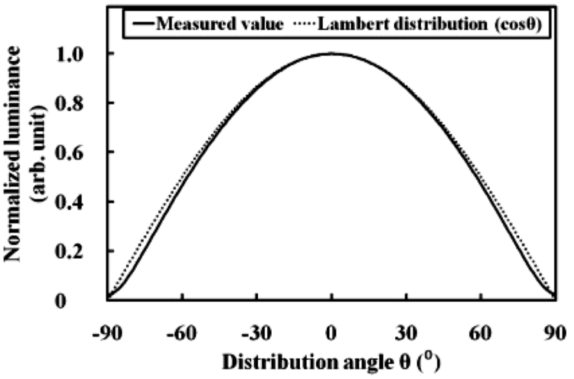

Figure 10 Measured luminance intensity distribution as a function of the distribution angle *θ*.

more easily saturated.

3.2 Evaluation of a lighting system designed with seamless panels

Table 2 shows the basic characteristics of the seamless panel. The luminous efficacy was measured at 79.6 lm/W. The efficiency of the seamless panel was therefore 72%, because the LEDs used in the seamless panel were measured to be 110 lm/W. This demonstrates that the seamless panel satisfies the criteria of Energy Star, which specify that the luminous efficacy of a lighting device must be less than 10 W and more than 10 W to be 50 lm/W and 55 lm/W, respectively. The color rendering index does not affect the characteristics of the LED light source and meets the tolerance requirements of Energy Star, which specifies that the color rendering index of a lighting device must be more than 80.

The measured luminance intensity distribution of the seamless panel is shown in Figure 10. The results were obtained in the form of Illuminating Engineering Society (IES) data. The solid line represents measured values, whereas the broken line represents the ideal Lambertian distribution. From the measured values, which were consistent with the Lambertian distribution, we found that the seamless panel creates uniform luminance at any angle. When the seamless panel is used for bracket lighting, it can achieve equal brightness and direct glare equivalent to that of conventional bracket lighting, because the seamless panel can be made in various sizes and has equal distribution characteristics to a conventional lighting system.

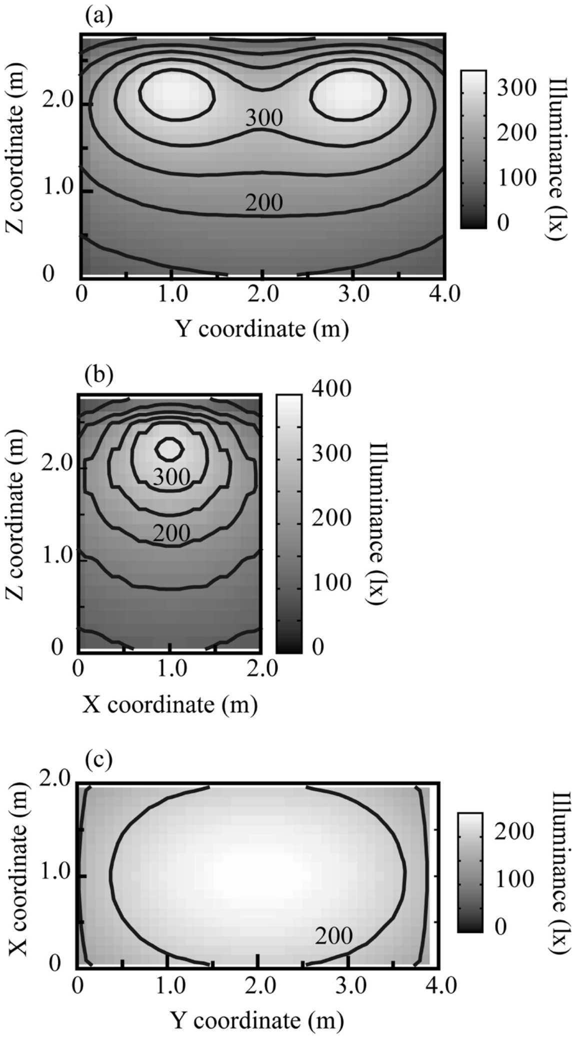

Figure 11 Calculated illuminance distribution in a space that is 2.0 m wide, 4.0 m deep, and 2.8 m high. (a) Simulated illuminance on the wall of the 4.0 m width. (b) Simulated illuminance on the wall of the 2.0 m width. (c) Simulated illuminance on the floor.

The seamless panel was simulated as a ceiling light in an ideal lighting space by using the IES data. Figure 11 shows the illuminance in a space that is 2.0 m wide, 4.0 m deep, and 2.8 m high. The reflection rates on the ceiling, the walls, and the floor are 70%, 50%, and 10%, respectively. Two seamless panels were placed 1.0 m above the floor and 2.0 m apart. Figure 11(a)–(c) show the simulated illuminance on the wall of 4.0 m depth, the wall of 2.0 m width, and the floor, respectively. It can be seen that the seamless panel is able to illuminate the wall better than the floor. Recent research has found that walls, which are vertically positioned in a space, give a more direct impression of the brightness in the space than the floor and ceiling, which are positioned horizontally with reference to people in the space. This is because a high correlation with the human assessment value has

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Table 3 Calculated results of unified glare rating (UGR) in the seamless panel.

Room dimensions	Viewed crosswise	Viewed endwise
X=2H Y= 2H	13.8	13.9
3H	15.7	15.8
4H	16.5	16.6
6H	17.0	17.2
8H	17.2	17.4
12H	17.4	17.5
X=4H Y= 2H	14.5	14.6
3H	16.6	16.7
4H	17.5	17.6
6H	18.2	18.3
8H	18.4	18.6
12H	18.6	18.8
X=8H Y= 4H	17.8	17.9
6H	18.7	18.8
8H	19.0	19.1
12H	19.3	19.4
X=12H Y= 4H	17.9	18.0
6H	18.8	18.9
8H	19.1	19.2

been verified by setting the computation range of the geometrical average brightness, which has a vertical view angle of 85° (35° above and 50° below the view line) and a horizontal view angle of 100°.6)7) Considering this fact, the seamless panel becomes even more suitable for spaces that require the brightness.

The seamless panel was evaluated in terms of uncomfortable glare according to the Unified Glare Rating (UGR) using measured IES data. The UGR can be defined as follows:8)9)

$$\mathrm{UGR}=8\log\left[\frac{0.25}{L_{\mathrm{b}}}\sum\frac{L^2\omega}{p^2}\right], \tag{1}$$

where L_{b} is the background luminance, L is the luminance on the light-emitting surface of a lighting device in the direction of the observer's eye, ω is a solid angle on the light-emitting surface in the direction of the observer's eye, and p is the Guth position index in relation to the distance from each device.

Table 3 shows the calculated UGR values. The calculation assumed reflection ratios of 70%, 50%, and 20% for the ceiling, the walls, and the working plane, respectively. The total luminous flux of the seamless panel was 3100 lm, and the size of the panel was 600 mm×300 mm. H represents the height from the surface where the lighting device is attached to the eye. H is 2.0 m. The room is stated as an integral multiple of H. The height from the floor to the eye is 1.2 m, while the height from the floor to where the lighting device is attached to is 3.2 m. The UGR was calculated assuming that the distance between the lighting devices is 1H and for two different eye directions, one of which is when the eye direction is perpendicular to the axis of the lamp in the lighting device and the other is when the eye direction is parallel to the axis of the lamp in the lighting device. The other conditions, including the size of the room and the placement of lighting equipment, were in accordance with the standard conditions of Commission Internationale de l'Eclairage (CIE). The maximum UGR of the seamless panel was 19.4. Table 4 shows the relationship between the UGR value and degrees of glare discomfort for Japanese people.10) The maximum UGR of the seamless panel falls within the lowest range of uncomfortable glare. On the basis of this calculation, the seamless panel was shown to be suitable for illuminating spaces without an uncomfortable glare.

Table 4 Relationship between unified glare rating (UGR) and degrees of glare discomfort for Japanese people.

UGR	Extent of discomfort from glare
38	Intolerable
35	Just Intolerable
32	Uncomfortable
28	Just Uncomfortable
25	Unacceptable
21	Just Unacceptable
18	Perceptible

4. Conclusions

We have proposed a seamless, connectable panel by optimizing the shape of the optical elements, as well as the concentration of the scattering particles in the diffuser material. The seamless panel can be implemented by combining more than one panel, which maintains the uniformity of 90% throughout the entire surface. From subjective experiments, we found that the panels can be connected with virtually unnoticeable seams. We also evaluated optimal lighting designs that use the seamless panels as bracket lighting and ceiling lighting by measuring the primary optical characteristics. We found that the seamless panel had a Lambertian distribution, and that it can provide a higher illuminance for a vertical surface than for a horizontal surface in the same space. The UGR of the seamless panel was 19.4, which represents the minimum level of uncomfortable glare. In addition to these advantages, the luminous efficiency of the panel was measured to be as high as 79.6 lm/W, which satisfies the requirements of Energy Star. The seamless panel is therefore capable of providing seamless connections between multiple devices, thereby providing much more freedom in efficient and comfortable designs in an environmentally friendly manner.

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