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Design of LED Lighting System with Improved Color Mixing Uniformity

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We explored the uniformity of light mixing, optical component design, and the directional orientation of the LED projection angles in a new LED lighting system design. To validate the design, we simulated the LED array performance using LightTools software with relevant parameters. The simulation result showed the collimation of light projections of the proposed LED lighting system. At the angles of LED projection from 0 to 30°, better and more uniform RGB three-color light mixing than those of conventional light systems was obtained. Experiments were conducted to confirm the simulation result by constructing a real model that was smaller than the model design for simulation. The results confirmed the collimation. The proposed LED lighting system showed uniform and vivid colors in large areas.

1. Introduction

In lighting design, it is essential to consider the uniformity of illuminance to prevent visual fatigue as well as the usability of the lighting especially in illuminating large areas such as theaters. Sensor technology and lighting systems are important for smart lighting solutions to provide sophisticated control and maintain efficiency and quality of lighting. In a smart lighting system for a large area, sensors are used to detect illumination that may be affected by motion, temperature, and humidity. The system controls the LEDs and adjusts the angles and positions of LED arrays to change the brightness, color, direction, or pattern in accordance with the sensed data. Therefore, it is important to design a lighting system that controls the projected light effectively on the basis of the sensor data.[1,2]

In recent lighting systems, LEDs are used often. An LED is a solid-state light source that operates on different principles and has different photometric characteristics from those of traditional light sources such as incandescent and fluorescent lights. Therefore, it is necessary to select the appropriate light source and design the luminaires and lighting on the basis of the

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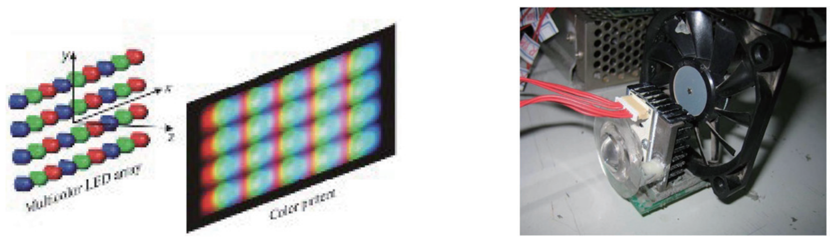
environmental requirements. In LED lighting design, optical component design is often employed to enhance optical efficiency and light uniformity. Color-tunable LED fixtures can be made to show color variation by controlling multiple LEDs of different colors.(3) By employing double total internal reflection (TIR), a combination of lenses with freeform profiles and a Z-shaped structure is used to evenly light a space. In the design of optical components, LEDs are placed in an array(4) using lens design methods,(5) and the performance is evaluated with optical simulations for uniform or enhanced illuminance on the target surface (Fig. 1).

It is necessary to configure LED arrays for maximum illumination uniformity, which depends on the distances between LEDs and from the LED lighting module to the illuminated surface. Uniform lighting distribution is obtained by precisely designing the arrangement of LEDs and considering the maximum illumination uniformity and the aforementioned distances. Then, the effectiveness of lighting design can be improved significantly without trial and error procedures.(6,7) Lee investigated the impact of the RGB LED arrangement on color uniformity and proposed the RG-B-RG arrangement to enhance color uniformity. Because of the shadow effect commonly produced by LED array-based lighting fixtures, a secondary optical component design, such as lens design, is required to adjust the LED's emission angle and its photometric curve. The purpose of this process is to change the LED's emission angle and enhance luminous efficiency.(8)

In lens design, reflection and refraction mechanisms are considered to obtain expected lighting effects such as light concentration, parallel light beams, and uniform diffusion of light (Fig. 2).(9,10) Teupner *et al.* analyzed color uniformity systems in spotlighting.(11,12) They investigated the efffects of human factors on visual perception and standard functions. They



(a) (b)

Fig. 1. (Color online) LED lighting design. (a) LED array and (b) electrical components.

(a) (b)

Fig. 2. (Color online) Lens design. (a) Plano-aspherical lens and (b) ray trace of freeform lens at cross section.

used multiple reflectors with TIR lenses to secure color uniformity in mixed lighting. In the current solid-state lighting (SSL) market, multiple-colored chips and fluorescent powders are sold as mixed light sources. Such mixed light sources require optical components to blend colors effectively in near-field and far-field lighting applications. A spherical shell-mixer optical component was designed (Fig. 3) to enhance color uniformity, brightness, and luminous efficiency in mixed lighting scenarios.(11,12)

Traditional LED light sources have hemispherical packaging surfaces with limited focusing capabilities. Hsieh *et al.* added spotlighting lenses to LED light sources (Fig. 4). These lenses featured 3D structures to enable multiple reflections and refractions within the lens for a spotlighting effect. This approach improved the focusing ability and heat dissipation.(13) In other methods, reflectors were used to improve light beam focusing. Grabovičkić *et al.* used a V-shaped groove reflector (Fig. 5) with traditional lighting sources to save on cost but obtain a focused reflection of light beams.(14) Gadegaard *et al.* used light engines (LEs) in lighting fixtures on the stage. LEDs were used in the LE for rapid color switching and mixing. This method allowed for a longer lifespan of lighting systems and increased energy efficiency compared with traditional lighting technologies.(15)

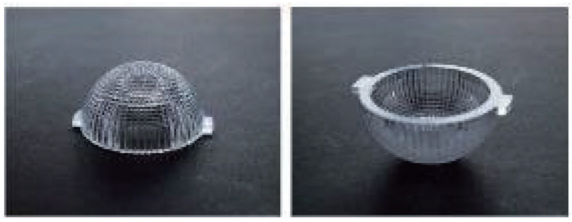


Fig. 3. Spherical shell-mixer.

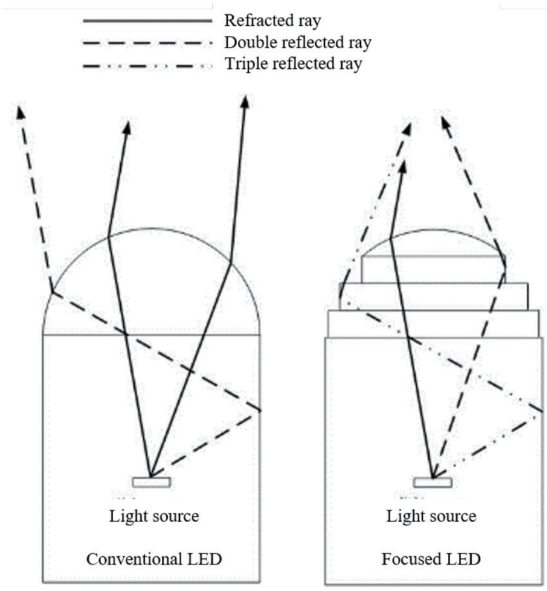


Fig. 4. Ray trace of LED.

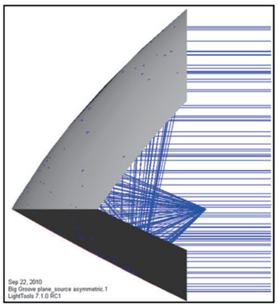


Fig. 5. (Color online) V-groove reflector.

Considering the advantages and disadvantages of previous research results, we improved the lighting efficiency for various performances on the stage by adding a double-reflection mirror and coated reflectors. To evaluate the performance of the developed lighting system, we created a simulation model. The result indicated that the newly proposed lighting system showed coverage of over 90% with uniformly mixed lights and enhanced efficiency in a large area.

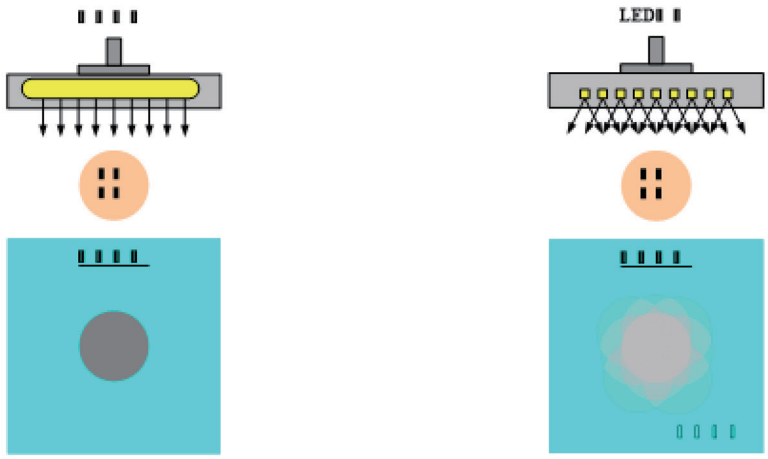
2. Methods

2.1 Spot uniformity

When used for ambient lighting, an LED has a smaller emitting area and a narrower angle than those of traditional light bulbs. Therefore, it is necessary to use multiple LEDs in series to obtain sufficient illumination. However, because of the characteristics of LED emission, ghosting or shadowing effects occur, as shown in Fig. 6. To eliminate such effects, the light sources are precisely positioned and necessary optical components are added. Therefore, a sophisticated optical component design is required. Software such as SolidWorks is used to arrange RGB LEDs effectively, for which a light guide tube is needed. Using such software, we conducted simulations and analyses to ensure the uniform distribution of illumination from the light source onto a projection surface.

LEDs are usually used to light specific spots but, in most cases, large-area illumination is required. Therefore, the arrays of multiple LEDs are required to create a uniform and diffusive lighting to replace traditional light sources; this demands a well-established arrangement of LEDs. We referred to various RGB array configurations from previous research to obtain the best uniformity of light. We used LEDs with different radii and illuminance distributions (E) and arranged them in a circle. In the array, the number of LEDs (N) had to be greater than 4 and an even number. We defined E of the arrays as Eq. (1).

$$E(x,y,z)=z^{m}I_{LED}\sum_{n=1}^{N}\left[\left(x-\rho\cos\left(\frac{2\pi n}{N}\right)\right)^{2}+\left(y-\rho\sin\left(\frac{2\pi n}{N}\right)\right)^{2}+Z^{2}\right]^{-\frac{(m+2)}{2}} \tag{1}$$



(a) (b)

Fig. 6. (Color online) Traditional and LED lighting systems. (a) Traditional lighting system and (b) LED lighting system.

We adjusted the radius of the circle of the array to obtain a uniform illumination at the center of a projected surface, as a circle has perfect symmetry. When calculating the maximum flatness, we considered any two LEDs connected along one axis. For example, along the y-axis at $x = 0$, the maximum separation between each module of a pair was obtained and regarded as the maximum flatness.

By taking the second derivative of E and setting it to 0 at $y = 0$ and $x = 0$, Eq. (2) was derived to calculate the maximum flatness on the z-axis.

$$\rho_{\max} = \sqrt{\frac{2}{m+2} \cdot z} \tag{2}$$

Because of the characteristics of trigonometric functions, Eq. (2) is independent of the number of LEDs. In other words, the scenario for maximum flatness in circular illumination is not dependent on the number of LEDs. This was represented as the transfer function. When the system input is "m" and the system output is "z", the illumination system with a circular LED array achieved a uniform illumination distribution, as shown in Fig. 7. The figure illustrates the illumination distribution of the LED lighting system with a circular array of LEDs (N = 12, m = 1).

2.2 Simulation equation for scattered light amplitude

In the Mie theory, when simulating the scattering of light using spherical particles, the following is assumed.

(1) The incident wave is planar with a unit intensity and is parallel to the x-direction and traveling in the +z-direction in an electric field.

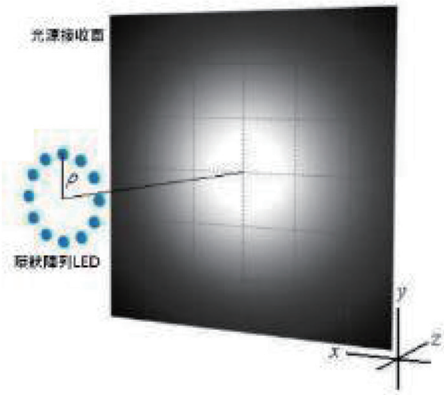


Fig. 7. (Color online) Distribution of illumination with a circular array of LEDs.

(2) Scattering particles are spherical and homogeneous.
(3) The surrounding medium in which the particle is situated is nonabsorbing.
(4) The observation point is located away from the scattering particle so the radius r is longer than the wavelength (λ) of the incident light.

Assuming that a fixed particle of arbitrary shape and composition is illuminated in a plane wave, the origin of the coordinates is chosen at the location of the particle. Then, the incident light is expressed as

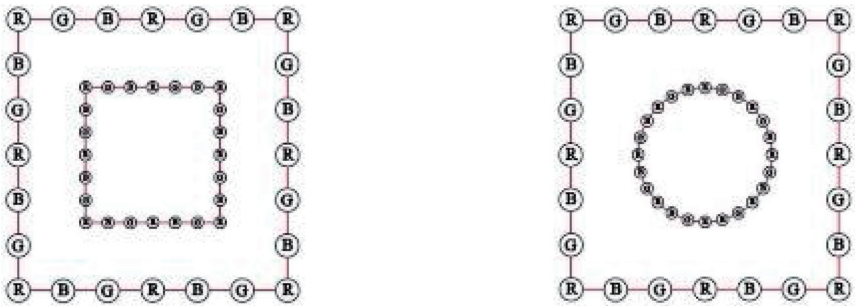
$$u_0 = e^{-(ikz+iwt)}. \tag{3}$$

When scattered light is observed in the far-field region, it is approximated as a spherical wave with an amplitude inversely proportional to the distance r. Therefore, the form of the scattered wave is expressed as

$$u = S(\Theta, \upsilon)\frac{e^{-ikr+iwz}}{ikr}, \tag{4}$$

where Θ and υ represent the scattering and azimuthal angles defining the amplitude function $S(\Theta, \upsilon)$ for the scattering particle. The factor i in the denominator is used for convenience and k is used to ensure that $S(\Theta, \upsilon)$ is a dimensionless pure number.

We used optical software for the simulation of the LED lighting system. Color mixing in the spectrum, using RGB LEDs arranged in two different ways, was assumed to be additive mixing. The light of RGB LEDs was mixed for even distribution. The shape of the emitting surfaces was rectangular or circular. The calculation result confirmed the uniformity of illumination of the array designs shown in Fig. 8. The results of the array design calculation were also used to simulate the performance of the design using LightTools software.



(a) (b)

Fig. 8. RGB array designs. (a) Rotation angle of inner square in circular tube, outer square, and inner square and (b) rotation angle of inner circle in circular tube, outer square, and inner square.

2.3 Simulation

For the simulation, we set the dimensions of the lighting area as 3150 × 3150 × 3150 mm^3 with a recessed groove in the ceiling of 3100 × 3100 × 200 mm^3. The distance to the light-receiving surface was 2500 mm. In the simulation, we used 200000000 rendering rays. The LED arrangement consisted of outer and inner rings. The outer square measured 3000 × 3000 mm^2, and the inner ring measured 1500 × 1500 mm^2. Twenty-four LEDs were placed in each square so 48 LEDs were used. The LEDs in the outer square were oriented vertically downward, while the LEDs in the inner square were angled from 0 to 30° toward the wall. This arrangement was established to uniformly illuminate the surface. Figure 9 illustrates the array used in the simulation.

We estimated the required luminous flux and optical characteristics. The LEDs of the inner square were arranged taking into consideration the direction of light propagation, the path of energy refraction, the angles of light rays, the shape of the luminaire, boundary dimensions, and the position of the light source. Figure 10 shows light projected onto the surface in a focused and uniform manner. The energy gradually transformed from parabolic reflection to multiple reflection to freeform reflection. The desired shape and energy in lighting were obtained with the proposed arrangement.

In the simulation, we employed the "nine-point measurement method" for uniformity measurement [Eq. (5)]. In this method, the optical simulation software calculated illuminance at nine measurement points. The ratio of minimum to maximum illuminance was calculated to present the uniformity of illumination on the surface from the light source. First, we defined the coordinates of the measurement points as shown in Fig. 11. In the figure, H represents the length of the light-projection area in the horizontal direction, V represents that in the vertical direction, and P1 to P9 represent the measurement points.

$$Uniformity = (L_{min}/L_{max}) \times 100\ (\%) \tag{5}$$

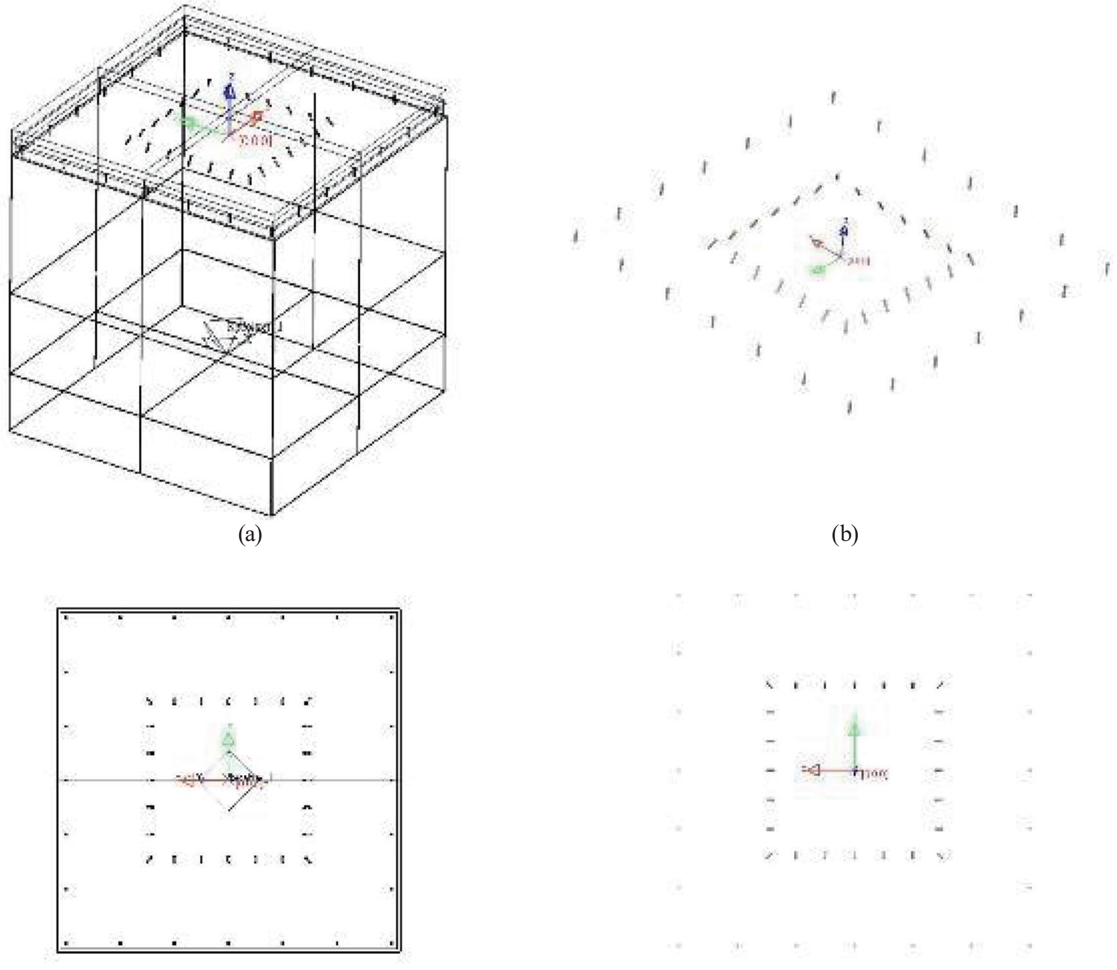


Fig. 9. (Color online) Simulation model of LED lighting system. (a) Overall design for simulation, (b) LED arrays of inner and outer squares, (c) top view of LED array, and (d) LED array in inner square.

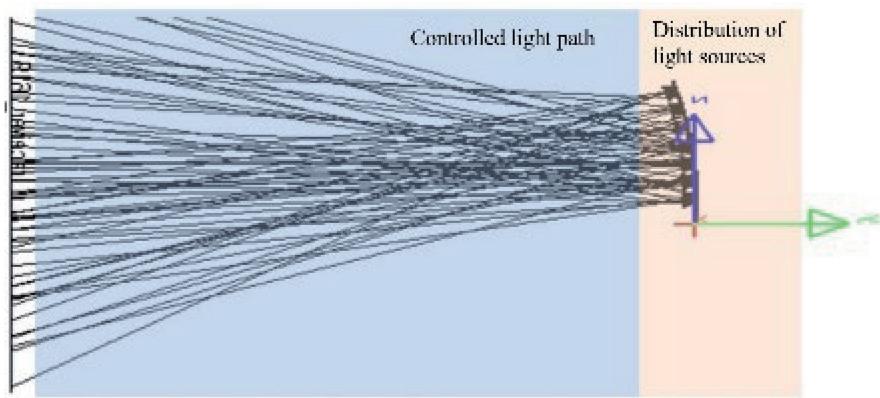


Fig. 10. (Color online) Spatial distribution and optical path of light.

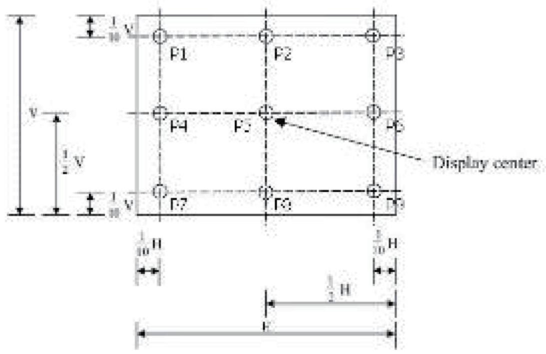


Fig. 11. Coordinates for nine-point measurement of illumination.

3. Results and Discussion

To obtain uniformity in the large-area projection of mixed light, we designed the LED array, optical components, and LED projection angles. The relevant parameters for simulation were determined. The simulation results showed that the arrangement of LEDs projected light in two concentric circles and confirmed collimation. Table 1 shows the simulation results of the proposed LED lighting system including color maps, illuminance maps, and CIE color distribution maps at the angles of 0 to 30° (in 3° increments) of the LEDs in the inner square of the proposed LED lighting system. The color maps demonstrate the uniformity of colors, and the illuminance maps show the range of illuminance in a three-dimensional space. Illuminance is weaker in the four corners. The CIE distribution maps show the color distribution in the projected area. There is little dispersion, highlighting the excellent uniformity of the lighting system.

We created a model to evaluate the uniformity and confirm the dimensions of the projected light. Compared with the large three-dimensional space of the simulation, we scaled down the model dimensions. The physical model was constructed using nontransparent white acrylic sheets with a thickness of 10 mm. The dimensions of the outside of the model were $920 \times 920 \times 920$ mm^3 (length, width, and height). Those of the inside of the model were $900 \times 900 \times 900$ mm^3, and the distance from the light source to the projection surface was 900 mm. The light guide was made of a transparent acrylic cylindrical rod with 110 mm length and 22 mm diameter. A groove of 29 mm depth and 18 mm diameter was machined at the top of the rod to enclose the LED tightly. Figure 12 shows the LED arrays of the inner and outer squares. The angle of LEDs in the inner square was 3°. The length of one side of the outer square with six LEDs was 375 mm. Color mixing in the model was measured to analyze its uniformity. The uniformity of color mixing was above 85% from 0 to 30°, confirming the results of the simulation (Fig. 13).

Table 1
(Color online) Simulation results of proposed LED lighting system with different angles of LEDs in inner square.

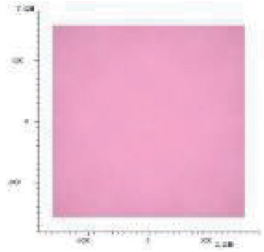
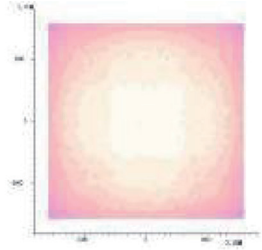
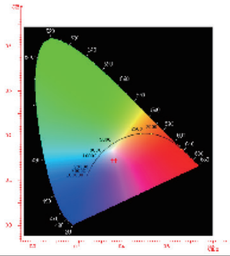
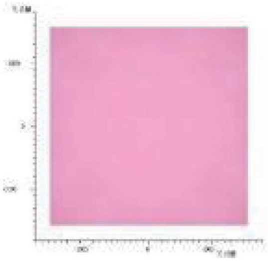
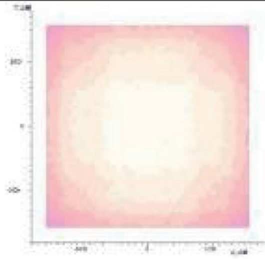
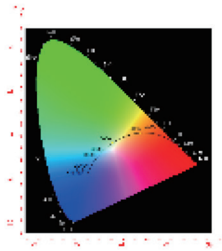
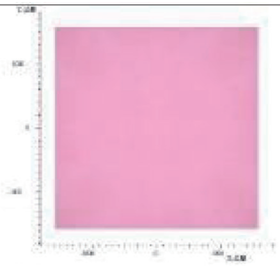
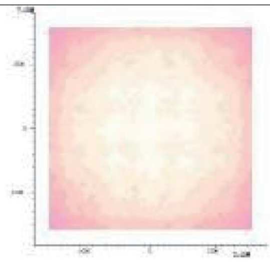
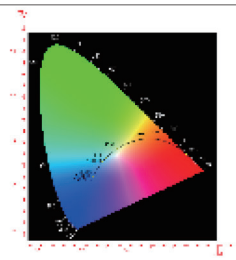
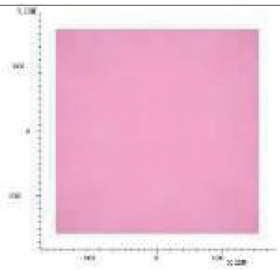
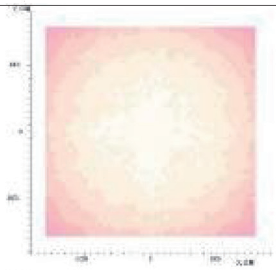
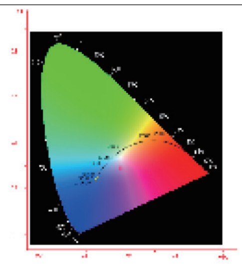
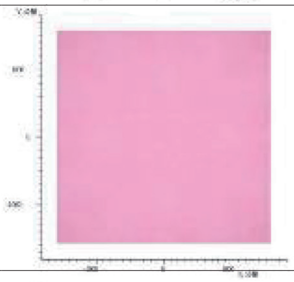
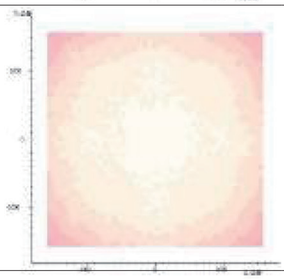
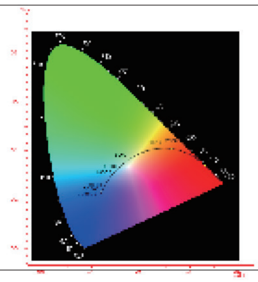
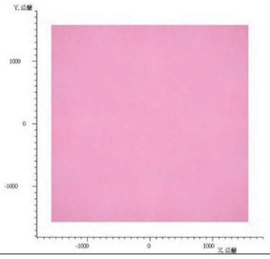
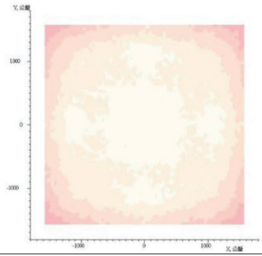
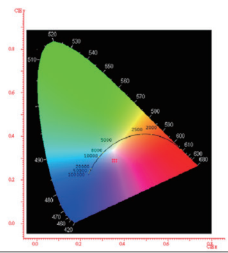
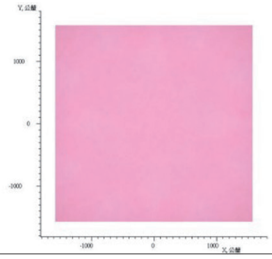
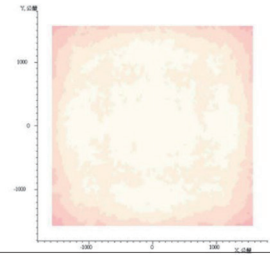
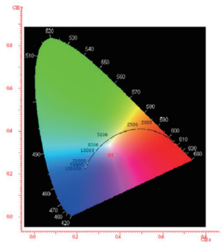
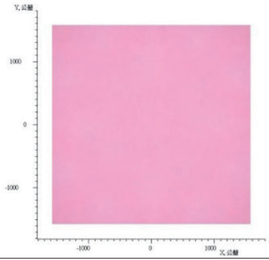
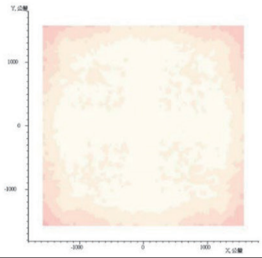
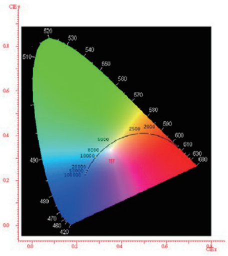
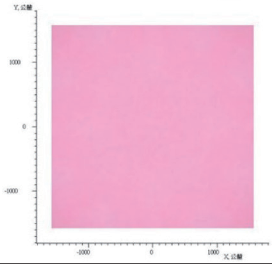
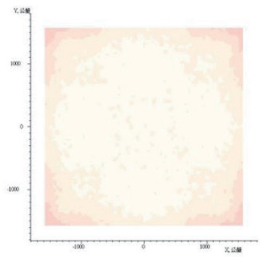
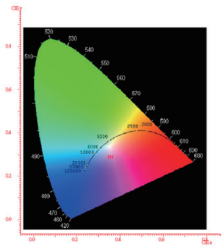
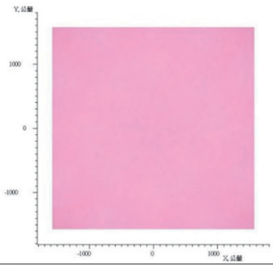
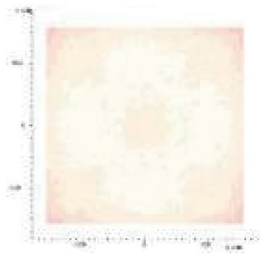
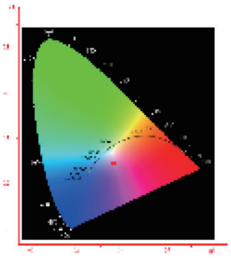
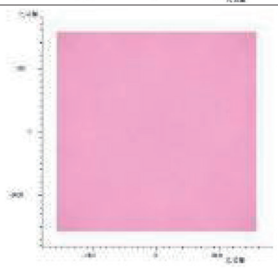
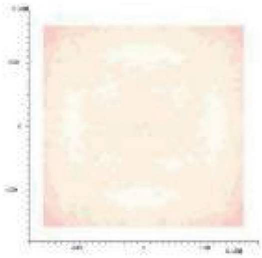
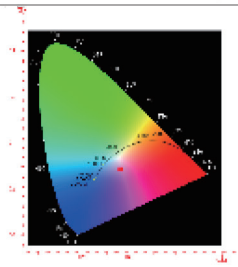
Degree	Simulated Color	Illumination	CIE Distribution
0			
3			
6			
9			
12			
15			

Table 1
(Color online) (Continued) Simulation results of proposed LED lighting system with different angles of LEDs in inner square.

Degree	Simulated Color	Illumination	CIE Distribution
18			
21			
24			
27			
30			

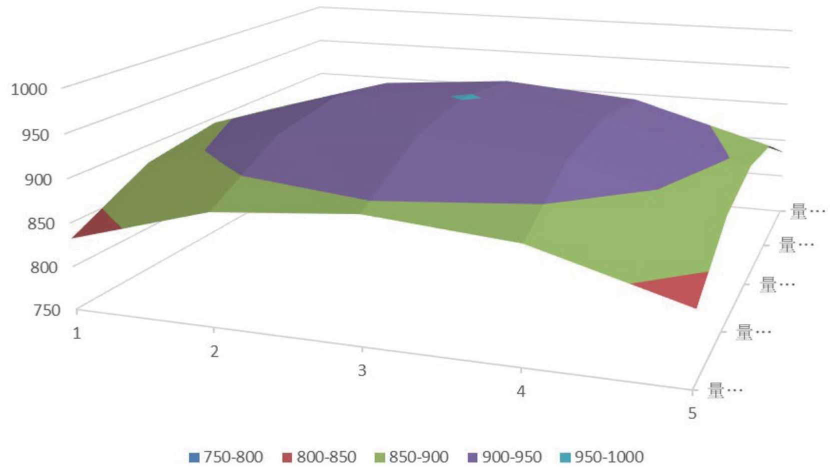


Fig. 12. (Color online) LED arrays in inner and outer squares.

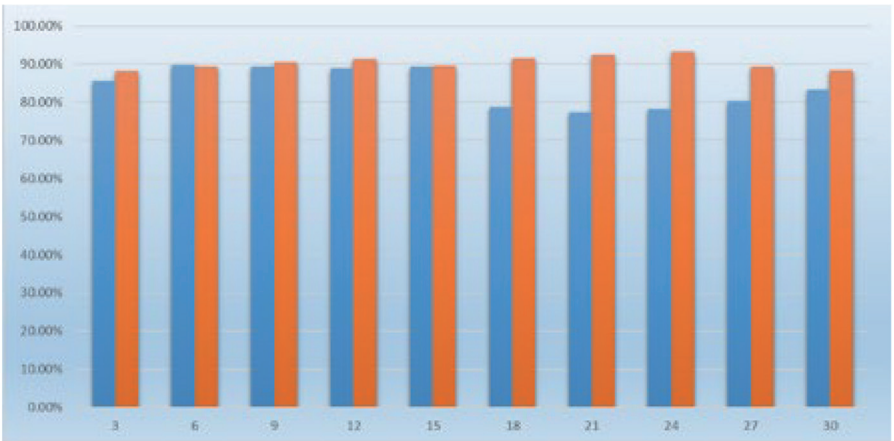


Fig. 13. (Color online) Color mixing uniformity of light projected from LED arrays of inner square at each angle (orange bar: color mixing uniformity of projected light on surface; blue bar: that on path).

4. Conclusions

Color mixing uniformity is required for lighting a large area on a stage for artistic performances. Various lighting systems have been proposed, yet no prominent result has been obtained. Therefore, we designed LED arrays, optical components, and angles of LED projection to maximize uniformity. The design was evaluated in a simulation using several design parameters such as the number of LEDs (a total of 24 in the inner and outer squares), the angle of light projection from LEDs of the inner (0–30°) and outer squares (perpendicular to the surface), and the distance from the LED arrays to the projected surface (2500 mm). The designed simulation dimensions were 3150 × 3150 × 3150 mm ($w \times h \times l$), and the number of rendering rays was 200000000. The lengths of the sides of the inner and outer squares were 1500 and 3000 mm, respectively. The simulation results demonstrated the collimation of the light projection of the designed LED lighting system. Additionally, the light projection of the system showed better and more uniform mixed colors than those of conventional systems. The adjustment of LED projection angles resulted in improved and uniform colors on the light-projected surface. To validate the simulation result, we constructed a model with the dimensions of 920 × 920 × 920 mm. The experiment data for the model confirmed the color mixing uniformity of over 85% from 0 to 30°. The results of this study provide a reference for designing lighting systems to project uniform and light colors on large areas.

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