Design of industrial lamp's optical system based on remote phosphor LED

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Remote phosphor LED light source is widely used because of its special efficient optical characteristics. However, in contrast to the performance of traditional led light source, the available research work on its supporting optical systems is insufficient. Here we report a two-component optical system comprising remote phosphor LED light source and reflective secondary optical element, and the spatial light intensity distribution of remote phosphor LED by a near field photometer was fully taken into account in our design. Compared with the traditional LED industrial lamp, the Unified Glare Rating (UGR) of the industrial lamp is reduced from 19 to 16, and the uniformity of illumination is increased from 0.7 to 0.8.

(Received July 29, 2019, accepted August 18, 2020)

Keywords: Remote Phosphor LED, UGR, Glare

1. Introduction

LED light source with the advantages of small size, high brightness etc. has been widely used in the field of solid-state lighting. With the improvement of LED light source power and light efficiency, the application of LED light source in high-power lamps becomes more and more important [1].

For high-power LED lamps, it is not only necessary to achieve accurate optical design according to the requirements, but also to control glare to obtain the best lighting effect [2-3]. LED light source produces more glare than traditional light source. M. Sivak examined the effects of LED headlamp on discomfort glare for oncoming drivers [4]. Compared with the high-intensity discharge (HID) light sources, the headlamps using the considered range of LEDs are predicted to result in more discomfort glare than HID headlamps. There are different methods to evaluate glare, and each method has different emphasis. D. Sawicki studied the discomfort glare prediction methods for determining unified glare rating [5]. Among the above methods, the International Commission on Illumination recommends using the formula for the Unified Glare Rating (UGR) in predicting glare. UGR is standardized and represents a technical approach to the glare rating scale.

In order to improve the performance of traditional LED light source, remote phosphor technology is used to solve glare and other problems. Wu Z. M *et al.* adopted nanosized phosphor as the material of LED secondary encapsulation structure to enhance the euphoria and reduce the biological hazard [6]. This research studied the blue light radiation of different kinds of light sources including the lamp with phosphorus encapsulation and the blue radiation of low blue bulb lamp is more than 40% lower than that of ordinary bulb lamp. Ming-Te *et al.* introduced ring remote phosphor as an efficient packaging configuration for high-power LED and the results showed the extraction efficiency exceeding 93% [7]. The optical properties of remote phosphor LED light source have been studied and proved to be able to solve the glare problem. However, how to design the secondary optical system based on the remote phosphor light source has not been reported.

In this paper, the remote phosphor LED light source used in high-power LED lamps is studied as a body source. The reflective optical system is designed to reduce UGR and improve illumination uniformity.

2. Light source performance analysis

The remote phosphor LED light source has different light-emitting principle and structure from the conventional LED chips. In order to analyze the optical characteristics of the remote phosphor LED light source, a self-designed remote phosphor LED light source was manufactured as shown in the Fig. 1.

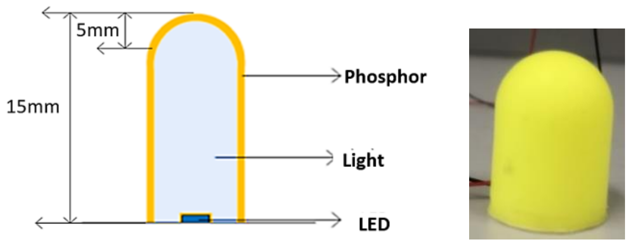

Fig. 1. (a) Diagram of remote phosphor LED light source (b) Remote phosphor gel cap (color online)

In Fig. 1, the remote phosphor LED light source is composed of a gel cap and an internal LED chip, wherein the gel cap is incorporated with a rare earth material as a light conversion material to realize light conversion and finally emit white light. The gel cap is composed of a bottom cylindrical shape and an upper hemispherical shape, and its surface is luminous. The parameters of the remote phosphor LED light source are measured as follows:

Table 1. The parameters of the light source

Performance	Parameters
Single power (W)	15
Light source efficacy (lm/W)	90
Light surface size (mm)	Column height: 15 Spherical height: 5 Spherical radius: 5

The remote phosphor LED light source has different illumination characteristics. It emits light throughout the body, and the light emitting area is the total area of the gel cap. According to the measured size, the calculated area of the single light source is 628.3 mm^2. For the analysis, an SMD LED of the same projected area is assumed, and the area of the SMD LED light emitting surface is 78.5 mm^2. In this case, the area of the remote phosphor LED source is 8 times of the SMD LED source.

The spatial intensity distribution of the light source is also an important indicator of its optical performance [3]. The spatial light intensity distribution function of the traditional SMD LED light source is

$$\mathrm{I} = I_0 \cos\theta \quad (1)$$

where θ is the emitted angle of the light, I_0 is the central light intensity. In order to obtain the optical performance of the remote phosphor LED light source, a spatial photometer is used to test the spatial light intensity distribution. The photometer is shown in Fig. 2, and the experimental parameters are listed in Table 2.

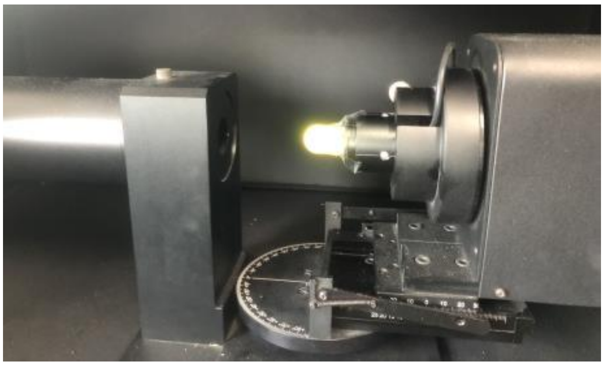

Fig. 2. Source near-field photometric test

Table 2. Experimental parameters

Performance	Parameters
Angular spacing	2°
Test distance	35 mm
C-axial rotation	0°～360°
γ-axial rotation	0°～±90°
Wavelength interval	5 nm
Photometric precision	Level I
Angular precision	0.1°

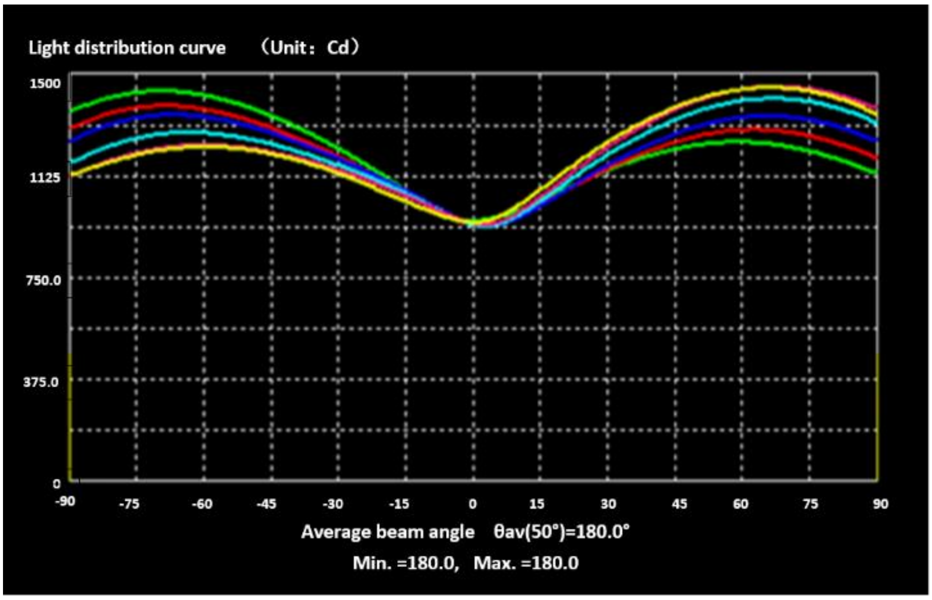

Fig. 3. Photometric distribution of PRLED source (color online)

The spatial light intensity test result is shown in Fig. 3. The different color rays represent the light intensity distribution in different spatial directions. According to Fig. 3, it is found that the spatial light intensity distribution of the remote phosphor LED light source is significantly different from the usual Lambertian distribution.

Assuming that the remote phosphor LED source has an average light intensity of I_{ave} and a spatial solid angle of 2π, the luminous flux of the remote phosphor LED source can be expressed by $\Phi = 2\pi I_{ave}$.

The definition of the brightness is applied according to the brightness of the light source, and the brightness is the luminous flux radiated by the light source per unit area in the unit solid angle. The brightness calculation formula can be obtained according to the spatial brightness of the Lambertian source:

$$L = \frac{I}{\cos\theta \cdot dA} = \frac{I_0}{A} \tag{2}$$

The spatial luminous flux of the Lambertian source is:

$$\Phi = \int_0^{2\pi}\int_0^{\frac{\pi}{2}} I_0 \cos\theta \sin\theta \, d\theta d\phi = \pi I_0 \tag{3}$$

$$L = \frac{\Phi}{\pi \cdot A} \tag{4}$$

where φ is the luminous flux of the light source, I is the light intensity in the direction of the light source, A is the area of the light source surface, and Ω is the solid angle of the outgoing light.

The brightness in each direction of the source is expressed by the equation as follows:

$$L = \frac{\Phi}{A'} \tag{5}$$

where L is brightness of the remote phosphor LED. It is calculated by the luminous flux divided by the area of the gel cap surface. Since the gel cap structure enlarges the light-emitting area relative to the conventional SMD structure, the brightness is lowered. When the outgoing light flux is the same, for the far phosphor LED light source, according to formulas (4) and (5), the surface brightness of the LED remote phosphor light source is approximately reduced 22% of the conventional SMD LED light source.

3. Industrial lamp optical system design

Due to the special structure and performance of the remote phosphor LED light source, this paper analyzes the optical system design of the remote phosphor LED light source with examples. This paper designs an industrial lamp based on remote phosphor LED light source. The technical requirements of the design are shown in Table 3:

Table 3. Performance parameters of the lamp

Performance	Parameters
Single power	15W
Total power	90W
Total luminous flux	＞13500 lm
Installation height	5m
Light angle	＞70°

Since the industrial lamp has a power of 90W, it emits high heat. Therefore, the structure of the whole industrial lamp is composed of a heat sink, an LED heat conducting plate, an LED remote phosphor light source and a compound parabolic reflector. The structure of the industrial lamp is shown in Fig. 4.

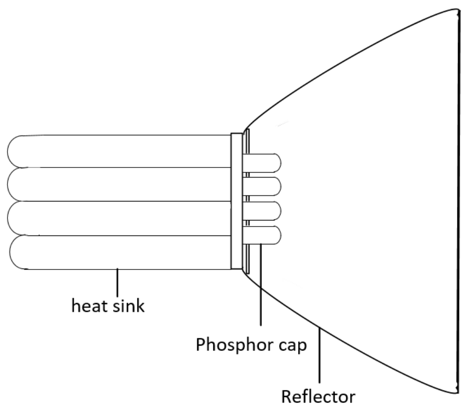

Fig. 4. Schematic drawing of the lamp structure

The reflective optical system structure used in this paper is mainly designed to adjust the illumination range of the emitted light by using reflected light. For the reflector design, the light exit angle of the optical system is first determined. In this design, the installation height of the industrial lamp is 5 meters and the irradiation range is 50 m^2. The light exit angle of the industrial lamp is determined by the equation:

$$\alpha = \arctan\left(\frac{d}{2h}\right) \tag{6}$$

where the installation height of lamps is *h*, the spot diameter is *d*, and the exit angle of the industrial lamp is α.

Since the remote phosphor LED light source has a certain height, the light emitted by the light source can be reflected to the remote phosphor LED light source after passing through the reflector. The light source then blocks the emitted light and cannot be effectively emitted. The traditional SMD LED light source optical system design does not have this problem. The remote phosphor LED source itself has an important relationship to the occlusion of the light and the aspect ratio of the reflector.

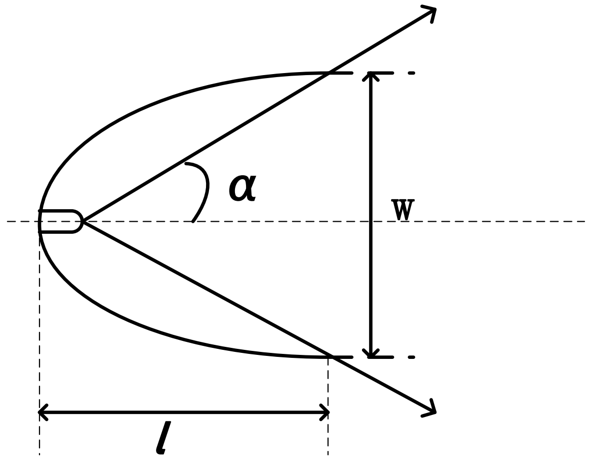

Fig. 5. Reflective optical system structure

The aspect ratio of an LED industrial lamp using a reflective optical system structure is defined as:

$$k = \frac{w}{l} \tag{7}$$

where w is the opening diameter of the reflector, and l is the length of the reflector. The proportion k parameter can be used to represent the proportion of direct light emission. Because of the opening of the reflector, only a part of the light can reach the reflector and be reflected by it. When k is larger, the more light is emitted directly, the less light is reflected. According to the relationship between the exit angle of the industrial lamp and the aspect ratio:

$$\alpha = arctan\frac{k}{2} \tag{8}$$

In this design, the installation height of lamps h is 5m, and the spot diameter d is 8.0 m. The exit angle of the industrial lamp is calculated to reach 68°. The opening diameter of the lamp is 500 mm, and the depth of the lamp is 210 mm.

In order to make the illumination light have a designed illumination range, a micro-reflective structure is used on the inner surface of the reflector to improve the uniformity of light emission and avoid the glare. The inner structure of the reflector is shown in Fig. 6, and the light trace result is shown in Fig. 7.

Fig. 6. Inner structure of the reflector

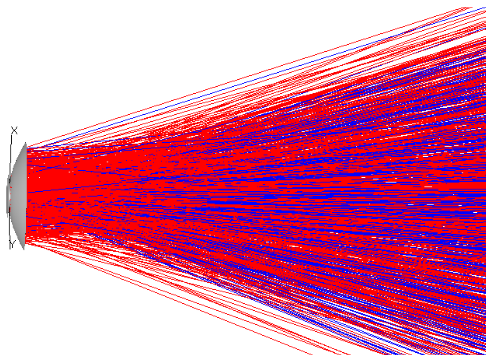

Fig. 7. Monte Carlo rays simulation (color online)

After Monte Carlo ray tracing, the light distribution curve of the reflective optical system with remote phosphor light source can be obtained as shown in Fig. 8, and it shows that the beam angle is 70°.

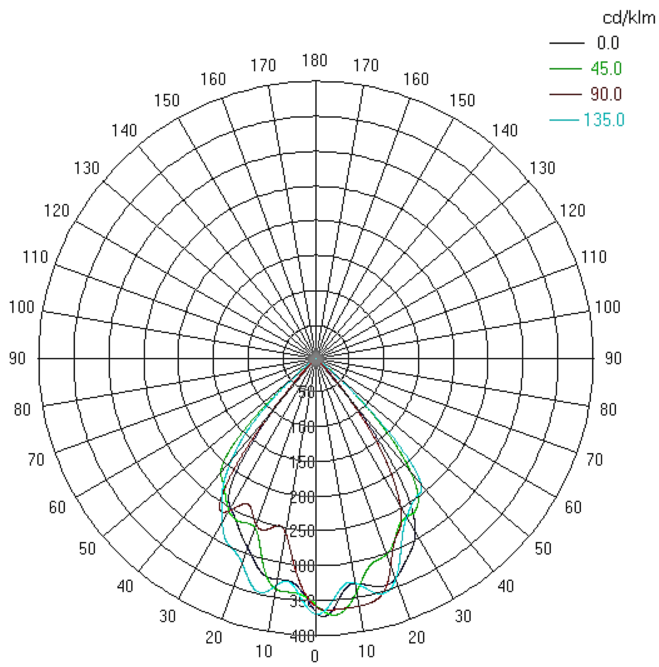

Fig. 8. Light intensity distribution curves (color online)

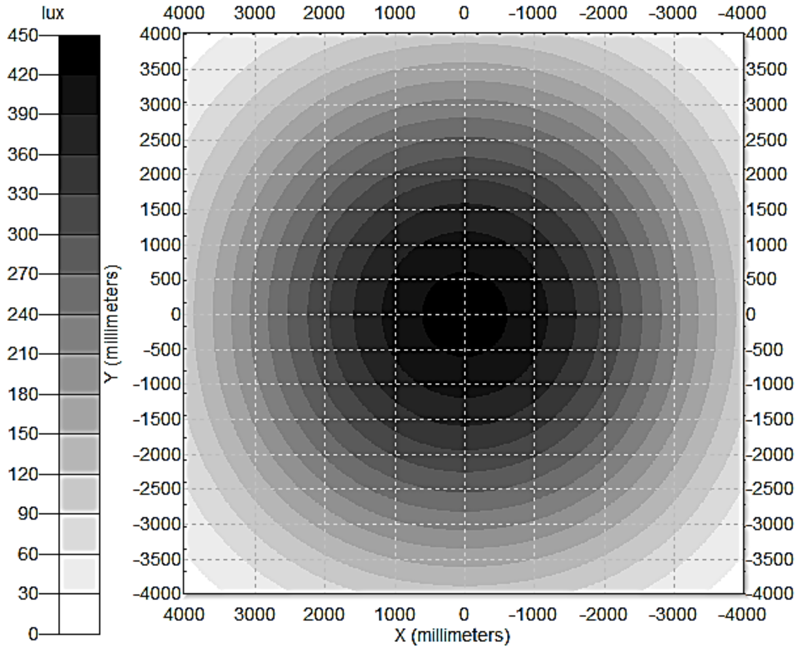

Fig. 9. Illuminance distribution on the receiver

The illumination effect on the work surface is shown in Fig. 9. The average illumination of the illuminated surface at a distance of 5 meters from the lamps is 213 lux, which satisfies the standard requirements for factory lighting.

4. Results analysis

For the above design results, the structure of the lamp is processed, and the structure of the remote phosphor LED lamp is shown in Fig. 10.

Fig. 10. Industrial lamp physical map

The reflector is made of anodized aluminum, and the remote phosphor cap is directly attached to the circuit board. The scaly structure is made on the aluminum reflector to control the glare.

Dialux software is used to simulate the actual lighting scene. The actual scene area of the factory's workshop is 300 square meters and its height is 5m. According to the calculation results based on remote phosphor LEDs, the factory needs to use 6 industrial lamps. The pseudo-color map of the lighting effect obtained in the software is shown in Fig. 11, and the illumination distribution in the factory workshop is shown in Fig. 12.

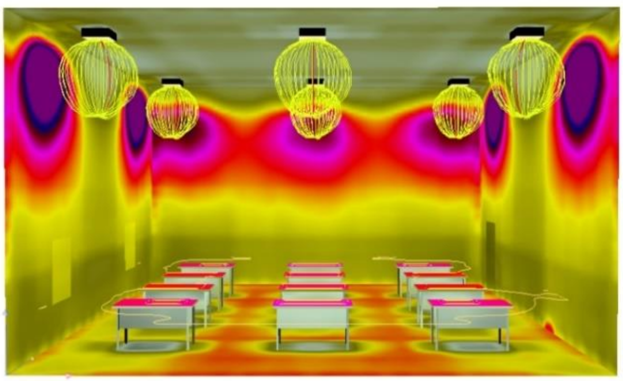

Fig. 11. Lighting pseudo-color map inside the building (color online)

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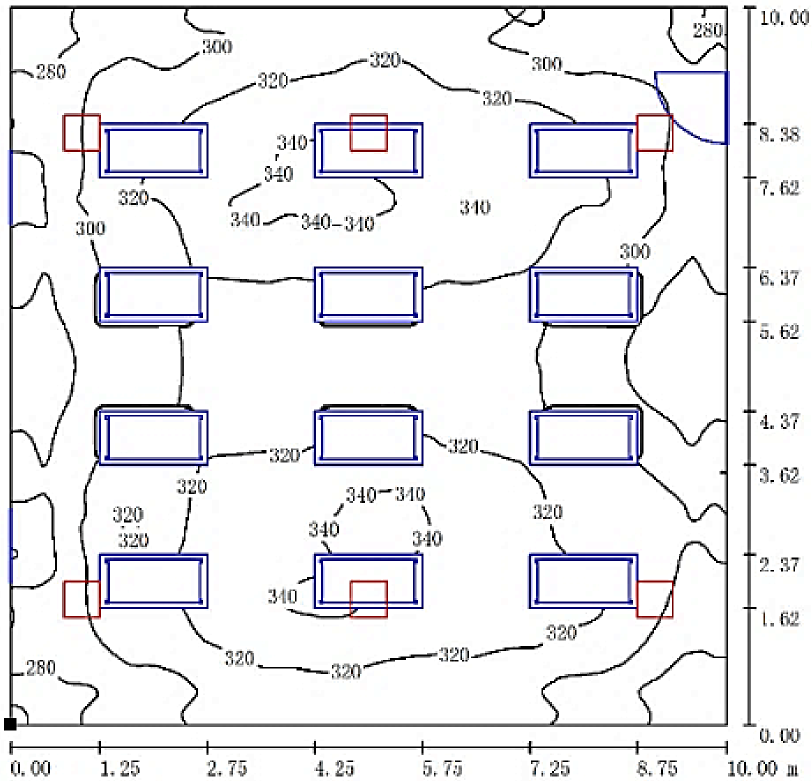

Fig. 12. Illumination distribution map (color online)

According to the National Architectural Lighting Design Standard GB 50034-2013, the average illuminance of the factory space is more than 200 lx, the illumination uniformity is above 0.7, and the glare level is less than 17. Fig. 12 shows that the industrial lamp designed in this paper achieves an average illuminance of 307 lx on the working surface, and the uniformity of illumination is 0.835, which meets the requirements of lighting standards.

Glare is an important problem in the use of high-power lamps. CIE (International Commission on Illumination) recommends the use of UGR as a Unified Glare Evaluation indicator for indoor lighting. UGR is defined as:

$$UGR = 8\,log_{10}\frac{0.25}{L_b}\sum\frac{L_\alpha^2\cdot\omega}{P^2} \quad (9)$$

where L_b is the background brightness, L_a is the brightness of each luminaire in the direction of the observer, ω is the angle formed by the illuminating part of each luminaire to the observer's eyes, and *P* is the position index of the individual luminaire.

In order to analyze the glare of the plant designed in this paper, observation points were set at a height of 1.2 m from the ground, and the angles of the observation points were 90°, 70°, 60°, 45°, 30° and 0°, respectively. The glare test results of the six position observation points are listed as follows:

Table 4. UGR calculation points

Number	Position			Observation direction	UGR value
	X	Y	Z		
1	5.000	0.000	1.200	90°	16
2	5.000	0.000	1.200	70°	16
3	5.000	0.000	1.200	60°	16
4	5.000	0.000	1.200	45°	15
5	5.000	0.000	1.200	30°	15
6	5.000	0.000	1.200	0°	14

The UGR values in the six directions are 16, 16, 16, 15, 15, and 14, respectively, which are better than the glare requirement of the precision processing lighting standard in an industrial factory.

5. Conclusion

In this paper, the remote phosphor LED light source is applied in high-power industrial lamps. Through the near field photometric performance test of the light source, the spatial photometric distribution characteristics of the remote phosphor LED light source are different from the traditional LED light source. It is found that the remote phosphor light source can effectively reduce the glare of the system when applied to the optical system of high-power lamps.

Compared with the traditional LED light source, the remote phosphor light source cannot be used as point source in performance test and optical design. At the same time, due to the large luminous area of the remote phosphor light source, it provides a means for solving the problem of the high brightness of the light source and the glare which is not easy to control due to the small surface area of the traditional LED. Through the contrast analysis of the actual remote phosphor light source and the traditional LED light source, the brightness of the light source is reduced by 22% compared with the conventional SMD LED. In the design example, compared with the similar products of traditional light source the glare level UGR of industrial lamps is reduced from 19 to 16, and the uniformity of illumination is increased from 0.7 to 0.8. It can be seen from the research that the remote phosphor LED light source can provide a solution to reduce glare and improve illumination uniformity in high-power lighting lamps.

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