Design of an efficient projector for LED flat lamp without light guide plate*

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An efficient LED projector is designed for the LED flat lamp without light guide plate (LGP), in order to get high-efficiency lighting capablility and low cost of LED flat lamp. By employing refraction and total reflection, uniform intensity distribution of the emergent light and high-efficiency lighting capablility are achieved. The simulation results show that the output efficiency and intensity distribution on LED flat lamp panel depend on the distance between projector and output panel, the rotation angle of the projector and the gap between projector and LED. It performs well in both lighting efficiency and uniformity, while a distance of 5 mm, a rotation angle of 2° and a gap of 1.2 mm are used with the panel size of 240 mm×360 mm in the LED flat lamp without LGP. And 96.6% of optical uniformity is achieved.
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The LED flat lamp is widely applied in our daily life, such as road lighting, interior and exterior lighting, backlighting for liquid crystal display (LCD) and headlamps of automotives[1,2]. Light guide plate (LGP) is usually used for LED flat lamp to realize great quality of lighting. However, there are several problems, such as low efficiency of coupling between LGP and LED, large loss for reflection and absorption and low light efficiency of a lamp. Besides that, the fabrication of the LGP is complicated. So it is significant to develop an efficient projector which can replace the LGP and make the Lambertian light illuminance uniform.

Direct-lighting structure for the near-field uniform lighting of the LED array has been developed, such as the compact LED projectors designed for the off-axis illumination and headlamps of automotives. Designing the projector by the analysis of SMS[3] can offer some control over the shape of the light source, but stable algorithms for more than two surfaces are few, leading to the model limited in 3D. R. Wu et al[4] proposed a freeform lens array for the off-axis illumination in an optical lithography system, realizing a maximum irradiance uniformity of 92.45% but spending more time. K. Wang et al[5] and Z. X. Feng et al[6] provided a freeform lens for the road lighting with smaller size, higher system luminance efficiency and higher luminance/illuminance ratio. However, these projectors cannot be applied to the LED flat lamp which needs to guarantee the uniform illumination in a large scale. Compared with the direct-lighting structure, this paper presents an efficient projector for LED flat lamp without light guide plate. The design of the projector with high uniformity, high brightness, thin thickness and low cost is meaningful. On the other hand, the projector made of the polymethyl methacrylate (PMMA) is also easy for manufacture, and can realize the large scale lighting easily.

The profile of the efficient projector is shown in Fig.1. There are two major surfaces in the projector as shown in Fig.1, which are the refractive surface (curve 1) and the total reflection surface (curve 2). According to the intensity distribution, it is shown that when the light irradiates curve 1, the light nearly parallel to the output panel is produced to illuminate the area far away from the projector, and the emergent light from curve 2 distributes uniformly near the output panel. Those both guarantee the brightness of the output panel to be uniform in a certain distance. The curve 1 and curve 2 are designed based on Snell's law and conservation of energy, respectively. A projector is obtained by calculating a series of points on the curve 1 and 2 as it is rotational symmetry, and then the points are imported into SolidWorks to obtain the curves, which are shown below in detail.

According to the edge-ray principle, the energy of any point on the output panel is determined by the edge-ray[7-11]. The coordinates are established as shown in Fig.2 according to the location of the light source. ***In***, ***Out*** and ***N*** stand for the vector of incident light, the vector of the output light and the normal vector of refraction point on curve 1, respectively. n is the refractive index of the material of projector. Suppose that the central axis of the

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projector is x axis, and the radial axis is y axis. The LED is put on the origin. The aperture radius of curve 1 is r, and A_{max} is the boundary angle. Dividing A_{max} into N equal parts, a series of angle A_i can be obtained as

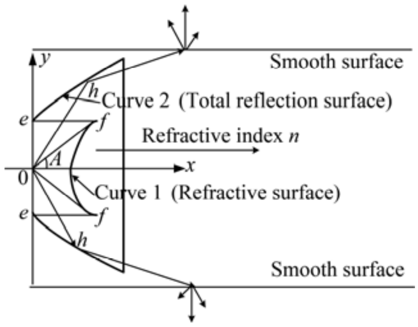

Fig.1 The profile and principle of the efficient projector

$$A_i = A_{max} - \frac{iA_{max}}{N}, \qquad i = 0,1,2\cdots N . \tag{1}$$

With the coordinate of point $P_0(r\cot A_{max}, r)$ and the unit vector of output light on P_0 of $\boldsymbol{Out}_0(r\cot A_{max}, r)$, the normal vector $\boldsymbol{N}_0(Nx_0, Ny_0)$ of P_0 is obtained by Snell's law as

$$\sqrt{1+n^2 - 2\cdot n\cdot(\boldsymbol{Out}\cdot\boldsymbol{In})}\cdot\boldsymbol{N} = n\cdot\boldsymbol{Out} - \boldsymbol{In} . \tag{2}$$

The point $P_1(x_1, y_1)$ is the point of intersection by the light with incidence angle of A_1 and the tangent plane where point P_0 stands. The coordinates of the point P_1 can be obtained by

$$Nx_0(x_1 - x_0)+Ny_0(y_1 - y_0)=0 , \tag{3}$$

$$y_1/x_1 = \tan(A_1) . \tag{4}$$

The subsequent coordinates of point $P_{i+1}(x_{i+1}, y_{i+1})$ on the curve 1 can be calculated by the same method, and the final equations are

$$Nx_i(x_{i+1} - x_i)+Ny_i(y_{i+1} - y_i)=0 , \tag{5}$$

$$y_i/x_i = \cot(A_{i+1}) . \tag{6}$$

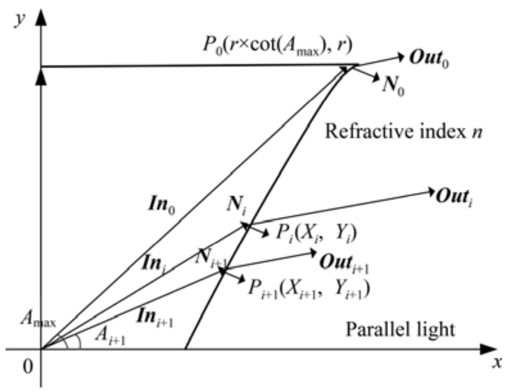

Fig.2 The design principle for the refractive surface of the projector

The design principle of the total reflection surface of the projector is shown in Fig.3. In order to form a uniform illumination ideally, the projector is designed for conveying all of radiation flux received in the range of incident angle A to the elliptical output panel whose long axis is a_{max}. In addition, the illuminance of every point is a constant as E [12,13]. Furthermore, in order to achieve a uniform illumination area on the output panel while the distance l is changing, surface MF is divided into two parts of surfaces R_0M and R_0F. When the light irradiates the surface R_0M, it forms a uniform illumination with length of r_2 on the output panel under the influence of the projector, and when the light irradiates the surface R_0F, it forms a uniform illumination with length of r_1. So the intensity illumination of the light which irradiates the surface R_0M or R_0F and reflects to the output panel is expressed as

$$E_2 = \frac{\phi_{a_{max}}}{S} = \frac{LA[\sin^2(\theta_2) - \sin^2(\theta_1)]}{r_1^2 + r_2^2} , \tag{7}$$

where L is the brightness of light source, A is the area of the light source, θ_1 is the aperture angle of the emergent light corresponding to point B, θ_2 is the biggest intersecting angle between light source center and the optical axis, and the distance between the output panel T and the highest point of the projector is l.

The light irradiates point K at the output panel under the effect of the projector when the light irradiates point R on curve MF with the aperture angle of emergent light of θ. Then the abscissa x_t of point K can be obtained according to the conservation of energy. The ordinate of point K is $l+H_1$, where H_1 is the radius of the projector. When the point R stands on the curve of R_0F, the point K is on the line T_1T_2, and the coordinate of the point K is

$$x_t = \sqrt{\frac{LA[\sin^2(\theta_2) - \sin^2(\theta)]}{E_2}} , \tag{8}$$

where θ is the aperture angle of the emergent light corresponding to point D.

When the point R and the point K are on the curve R_0M and the line T_2T_3, respectively, the abscissa of the point K is

$$x_t = \sqrt{\frac{LA[\sin^2(\theta_3) - \sin^2(\theta)]}{E_2}} , \tag{9}$$

where θ_3 is the aperture angle of the emergent light corresponding to the point R on the curve R_0M.

The satisfactory angle w can be obtained through the abscissa of the point K as

$$x_t = \frac{\ln\sin(w)}{\sqrt{1 - n^2\sin^2(w)}} . \tag{10}$$

The derivative of curve MF at point R is expressed as

$$\frac{\mathrm{d}x}{\mathrm{d}y} = \frac{\sin(w) - \sin(\phi)}{\cos(\phi) - \cos(w)} . \tag{11}$$

As $\frac{dx}{dy}=\frac{dx}{d\theta}\cdot\frac{d\theta}{dy}$ and $x=\frac{y-H}{\tan(\phi)}+\frac{H}{\tan(\theta)}$ while R is on the curve R_0M, the differential equation of y and θ is obtained by derivating to θ and combining with Eq.(11) as

$$\frac{dy}{d\theta}=\frac{\dfrac{H\sqrt{n^2-\cos^2(\theta)}}{\sin^2(\theta)\cos(\theta)}}{\dfrac{\cos(\theta)-n\cos(w)}{n\sin(w)-\sqrt{n^2-\cos^2(\theta)}}-\dfrac{\sqrt{n^2-\cos^2(\theta)}}{\cos(\theta)}}+\frac{[(y-H)+\dfrac{H}{\tan(\theta)}]\dfrac{n^2\sin(\theta)}{\cos^2(\theta)\sqrt{n^2-\cos^2(\theta)}}}{\dfrac{\cos(\theta)-n\cos(w)}{n\sin(w)-\sqrt{n^2-\cos^2(\theta)}}-\dfrac{\sqrt{n^2-\cos^2(\theta)}}{\cos(\theta)}}, \quad (12)$$

where H is the coordinate of point B, and w is the solution of Eq.(8). The initial conditions of the ordinary differential equation are $\theta=\theta_3$ and $y=y_0$, where y_0 is the coordinate of R_0, and the abscissa of the point R_0 is H_0.

A series of points on the curve 2 are obtained by using the Runge-Kutta method[14,15] to solve the ordinary differential equation.

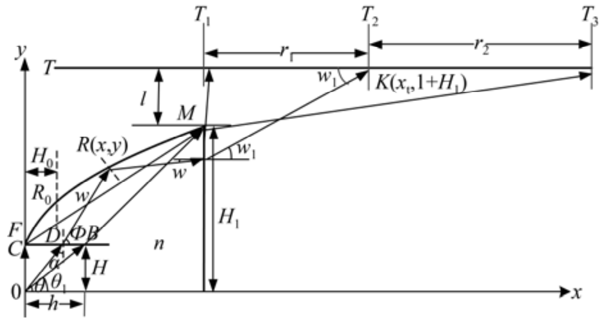

Fig.3 The design principle of the total reflection surface of the projector

The projector is designed for achieving the LED flat lamp with panel size of 240 mm×360 mm to realize the uniform intensity distribution of the emergent light and high-efficiency lighting capability. The simulation model of the flat lamp is shown in Fig.4. 38 LED chips with size of 1 mm×1 mm are used and separated equally on two sides of the LED flat lamp to be the light source. The distance between every two adjacent LEDs, the length of the LED bar and the distance between two LED bars are 20 mm, 380 mm and 240 mm, respectively. The total luminous flux of the LEDs is 380 lm. The projector is made of PMMA which is easy for injection molding, and the refractive index is n=1.49 (λ=0.5461 μm). The structure of the projector is shown in Fig.5. The diameter of the outlet aperture is 20 mm, and the length of the projector is 6 mm. The points of curves 1 and 2 are calculated in Matlab and then imported into SolidWorks to fit the curves 1 and 2 and the 3D model. The designed projectors are placed one by one before each LED, and the light on the output panel of the flat lamp is traced in TracePro.

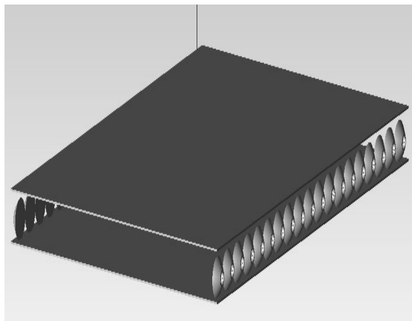

Fig.4 The simulation model of the LED flat lamp

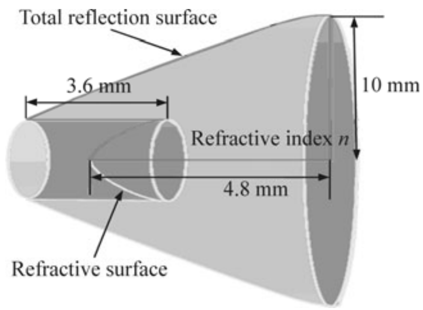

Fig.5 The structure of the projector

Actually we usually use the scratchable latex to measure and calculate the illuminance of the output panel, as shown in Fig.6. The entire output panel is divided averagely into nine areas, and then the illuminance values on the geometric centers of the nine areas are all taken out. The uniformity is the ratio of the minimum value to the average of nine values[16,17].

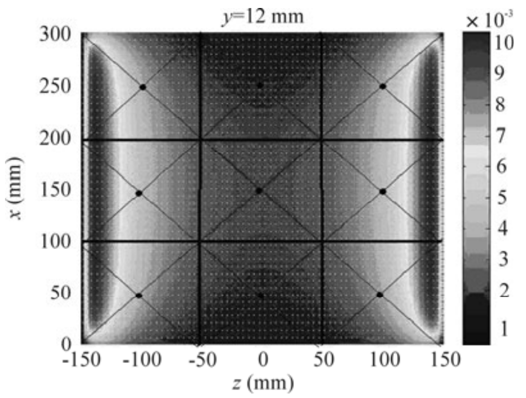

Fig.6 The measurement of illuminance and uniformity by using scratchable latex

The simulation result of the designed projector is shown in Fig.7. The light from LED under the effect of projector distributes symmetrically on both sides. The irradiation angles of the light are mostly in the range from 10° to 20°, and the light on the middle part of the plane is weak.

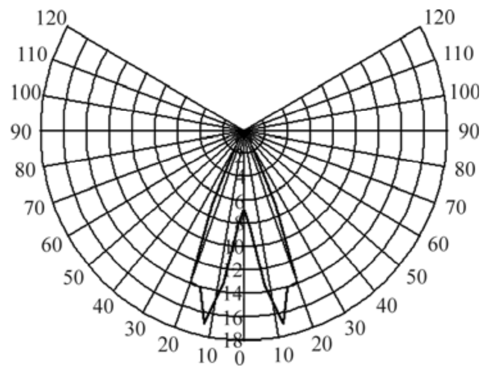

Fig.7 The intensity distribution of the LED with a projector

Next, by adjusting the distances among LED, the output panel and the projector, the uniform illumination of the flat light is achieved.

In the simulations below, the LED is placed at the origin.

If the distance between the output panel and the projector is different, the simulation results of the uniformity of the LED flat lamp are shown in Tab.1. With the increase of the distance between the output panel and the projector, the maximum illumination of the LED flat lamp will be smaller. However, the uniformity of the whole lamp is above 91%. Considering the real situations, the thickness of the LED flat lamp is small when the distance between the output panel and the projector is smaller, so the best distance is 5 mm.

Tab.1 The uniformity on the output panel of the LED flat lamp with different distances between output panel and projector

Distance between output panel and projector (mm)	Uniformity (%)	Minimum illuminance (lx)	Maximum illuminance (lx)
3	92.95	2821	3190
5	96.60	2941	3173
7	91.22	2723	3152
9	95.00	2696	2935
10	92.73	2610	2981

The uniformity and the maximum illuminance of the LED flat lamp with the changing rotation angle are shown in Fig.8. The maximum illuminance of the LED flat lamp increases gradually with the rotation angle of the projector from negative to positive value. Especially when the rotation angle is –6°, the maximum illuminace reaches 3237 lx. In addition, all of the maximum illuminances are greater than 3000 lx. When the projector unilaterally rotates 2° or under 2°, the uniformity of the light is over 90%. While the rotation angle is more than 2°, the uniformity is around 88%–90%. Therefore, the high uniformity of illumination of the LED flat lamp is achieved, which meets the demand of the flat lamp practically.

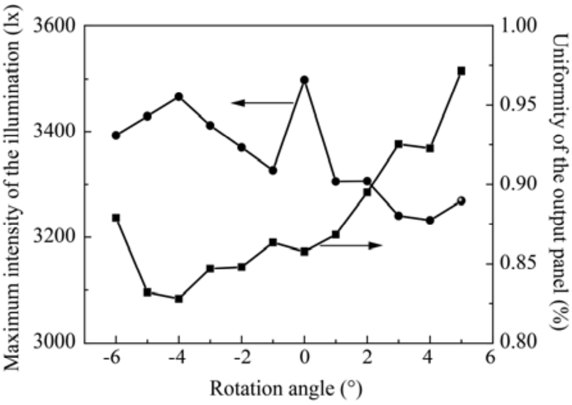

Fig.8 The uniformity and the maximum intensity of illumination of the LED flat lamp with changing rotation angle

The uniformity, maximum illumination, and the average illumination of the LED flat lamp with different distances between LED and projector are shown in Tab.2. The maximum illumination of the LED flat lamp first declines and then keeps around 3100 lx with the increase of the distance between the LED and projector. The best uniformity of the LED flat lamp is 96.6% when the projector is 1.2 mm away from LED, which is the best distance between the LED and the projector.

Tab.2 The uniformity on the output panel of the LED flat lamp with different distances between LED and projector

Distance of LED and projector (mm)	Uniformity (%)	Average illuminance (lx)	Maximum illuminance (lx)
0.9	81.73	3091	3776
1.0	84.27	3026	3488
1.1	88.99	2961	3340
1.2	96.61	3044	3173
1.3	92.21	2844	3041
1.4	91.30	2790	3129
1.5	89.23	2763	3147
1.6	88.53	2707	3136
1.7	80.63	2659	3117

The projector is applied to the LED flat lamp, in which the distance between the output panel and the projector is set to be 5 mm, the LED is 1.2 mm away from the projector, and the rotation angle of the projector is set to be 2°. The uniformity of the LED flat lamp with size of 240 mm×360 mm can reach 96.6%, and the minimum illuminance exceeds 2700 lx, which conforms the need of lighting. The lighting quality is great, i.e., the uniformity is above 90%, when the distance of the output panel and the projector is adjusted.

In this paper, an efficient LED projector is designed for the LED flat lamp without LGP, which not only improves the lighting efficiency but also lowers the cost of manufacturing of the LED flat lamp. By employing the refraction to collect the divergent light, the middle light beam through the refraction then illuminates the remote output panel effectively. The total reflection guarantees the two edges of the divergent light, and makes the emergent light illuminate the closer output panel. With the effect of the projector, uniform intensity distribution of the emergent light and high-efficiency lighting capability are achieved. The results show that when a distance of 5 mm, a rotation angle of 2° and a gap of 1.2 mm are used with the panel size of 240 mm×360 mm in the LED flat lamp without LGP, the projector performs well in both lighting efficiency and uniformity, and the optical uniformity of 96.6% is achieved. Moreover, the LED flat lamp has smaller size. The projector is designed simply with easier injection molding. It is suggested that the designed projector is ideal for general road lighting, especially for the LED flat lamp.

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