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Design of the Optocoupler Applied to Medical Lighting Systems

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Abstract: A new type of optocoupler applied to medical lighting system is proposed, and the principle, Etendue and design process is introduced. With the help of Tracrpro, modeling and simulation of the optocoupler is conducted and the parameters are optimized. Analysis of factors affecting the energy coupling efficiency is done. With a view towards the development of Ultra High Brightness Light Emitting Diodes (UHB-LEDs), which play an important role a new sources of lighting in various biomedical devices, including those used in diagnosis and treatment, a series of simulations are executed and a variety of solutions are achieved. According to simulation results, the design target of coupling efficiency is achieved and the optical uniformity is also significantly improved. According to the result of theoretical analysis, verification experiments are designed and simulation results are verified. The optocoupler, which has simple structure, compact size and low cost, is suitable for applications in the field of low-cost medical domain.

Keywords: UHB-LED, Tapered optocoupler, Tracepro, Energy coupling efficiency.

1 Introduction

High light energy coupling efficiency is important for many technologies including medical lighting, pocket projector, military equipment and some demanding fields. A large number of modern medical equipments[1], such as endoscope, surgical microscope, astral lamp, put forward harsh request to high brightness illumination[2,3]. As a kind of new light source in medical fields, UHB-LEDs(Ultra High Brightness-Light Emitting Diode) play an important role in the field of lighting, diagnosis and treatment.

Here, aiming at the applications of UHB-LEDs in the medical lighting systems,

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the principle, theory analysis and design method of a new type of optocoupler is discussed in this paper. According to the simulations with Tracepro, optical model is constructed and optimized design is obtained.

2 Etendue of Lambertian radiator

If a light source is the Lambertian radiator, it would be reasonable to anticipate that:

$$I_\theta = I_0 \cos\theta \tag{1}$$

Where I_0 is the intensity at vertical direction and I_θ is the intensity at the angle θ.

Etendue describes the integral of the area and the angular extents over which a radiation transfer problem is defined. Etendue is used to determine the trade-off between the required area and angular extents in nonimaging optical designs. One definition of Etendue is

$$etendue = n^2 \iint \cos(\theta) dA d\Omega \tag{2}$$

where n is the index of refraction and θ is the angle between the normal to the differential area dA and the centroid of the differential solid angle $d\Omega$.

Luminance divided by the index of refraction squared is the ratio of the differential flux $d\Phi$ to the differential Etendue:

$$L/n^2 = d\Phi/d\ etendue = d\Phi/[n^2 \cos(\theta) dA d\Omega] \tag{3}$$

The L/n^2 over a small area and a small angular extent is constant for a blackbody source. A consequence of constant L/n^2 is that if optical elements are added to modify the apparent area of the small region, then the angular extent of this small area has to be also changed.

In a system where the Etendue is preserved, these Etendue relationships highlight that increasing either θ or R requires a reduction in the other, as depicted in Fig. 1.

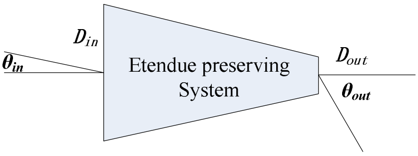

Figure 1: Etendue preservation.

For the UHB-LED discussed in this paper, the shape of the emitting area is rectangle, which follows the pattern of Lambertian radiation and the maximum half-angle is 90^o. So, its Etendue can be described as follows:

$$Etendue = n^2 \cdot A \cdot \pi \cdot \sin^2 90^\circ = n^2 \cdot A \cdot \pi \tag{4}$$

Optical fiber is the most commonly used optical transmission media in medical lighting domain, whose Etendue is decided by *NA* and the radius of aperture *R*:

$$Etendue = \pi \cdot A \cdot (NA)^2 = \pi \cdot (\pi R^2) \cdot (NA)^2 = \pi^2 \cdot R^2 \cdot (NA)^2 \tag{5}$$

The main purpose of lighting system design is maximizing the energy transfer efficiency and meeting the special requirements of illumination and uniformity. For the lighting system based on optical fiber, the Etendue of UHB-LED and optical fiber must be matched to maximize the energy transfer efficiency:

1. E_{LED}>E_{fiber}: Light emitted from UHB-LED cannot be coupled into the fiber efficiently, which will cause large energy loss;
2. $E_{LED} = E_{fiber}$: Light emitted from UHB-LED can be coupled into the fiber efficiently, whose coupling efficiency will realize the theoretical maximum value;
3. E_{LED}<E_{fiber}: Light emitted from UHB-LED can be coupled into the fiber, but restricted by the Etendue of UHB-LED and optical fiber, the light output may not meet the lighting system design requirement.

The acceptable beam angle of widely used optical fiber in medical lighting domain is about 70^o. Take the optical fiber of Φ=5mm and *NA*=0.6 as an example, its Etendue is about 22 sr·mm^2 and the matching emitting area of UHB-LED is 7mm^2. In the practical application, due to the problem of mismatching, the emitting area of UHB-LED is larger compared with the theoretical value.

3 Design of tapered optocoupler

Ignoring the absorption of material, reflection of lens, scattering and other relevant factors, optical characteristics of LED are mainly decided by refractive index of packaging materials, geometrical shape of lens, relative position of chips and lens.

3.1 Working principle of tapered optocoupler

Fig. 2 shows the overall structure of the tapered optocoupler, whose inlet area is smaller than the exit area. The light emitted from the LED is coupled into the tapered optocoupler and escaped from the exit surface after many total reflections. Each reflection forms a virtual light source, as shown in Fig. 3. Multiple virtual light spots forms the two dimensional array. So, the point light source is equivalent to multiple sources after the tapered optocoupler and the energy uniformity can be significantly improved.

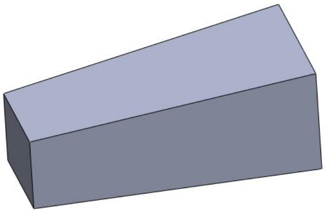

Figure 2: Conical lens

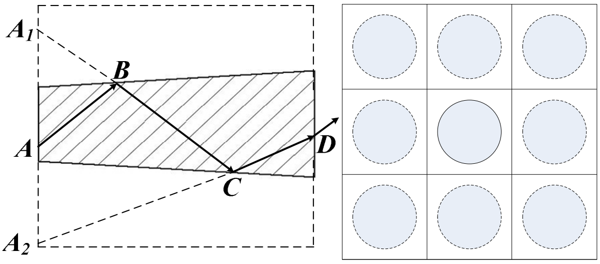

Figure 3: Working principle of conical lens

Sectional structure of the conical lens is demonstrated in Fig. 4, whose materials is transparent optical glass. As shown in the meridian plane, the light shoots out from the LED into the optocoupler and spreads along it. According to the law of reflection of geometrical optics, every total reflection will bring an angle decreases of δ relative to the main axis, where the angle δ is made by the two walls of the optocoupler. Therefore, as the light spreads in the tapered optocoupler, the angle becomes smaller and smaller. After m times of reflections, the angle shown in Fig. 4 between the spreading light and the main optical axis is:

$$\theta_m = \theta_0 - m\delta = \arcsin(\frac{n_0}{n_1}\sin\phi_1) - m\delta \tag{6}$$

The numerical aperture[4] of the light beam could be changed using the tapered optocoupler. If the incidence area of the optocoupler isS_1, exit area is S_2, numerical aperture is NA_{in} and NA_{out} respectively, according to the law of energy conservation, there will be the equation:

$$S_1 \cdot (NA_{in})^2 = S_2 \cdot (NA_{out})^2 \tag{7}$$

$$D_1 \cdot \sin\phi_1 = D_2 \cdot \sin\phi_2 \tag{8}$$

Where D_1 an D_2 are side lengths of incidence surface and emergent surface respectively.

The area ratio of emitting surface to incident surface is proportional to the compression effectiveness and the energy coupling efficiency. Considering these two factors, the optimal energy coupling efficiency could be realized through the reasonable area ratio.

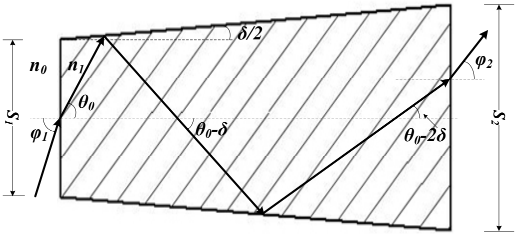

Figure 4: Angle compression of the optocoupler

For the UHB-LED in this paper, whose main energy concentrates in the angle of 120^o, the divergence angle of the emergent light could be compressed to 70.5^o using the area ratio of 1:1.5, which will improve the coupling efficiency immensely.

The Etendue of UHB-LED could be calculated as follows:

$$Etendue = n^2 \cdot A \cdot \pi \cdot \sin^2 90^\circ = n^2 \cdot A \cdot \pi \tag{9}$$

Where A is the light-emitting area and n is the refractive index.

The Etendue of the optical fiber is:

$$\begin{aligned} &Etendue = \pi \cdot A \cdot (NA)^2 \\ &= \pi \cdot (\pi R^2) \cdot (NA)^2 = \pi^2 \cdot R^2 \cdot (NA)^2 \end{aligned} \tag{10}$$

Where NA is the numerical aperture and R is the clear aperture.

3.2 Simulation of tapered optocoupler

Aiming at the UHB-LED and optical fiber in the laboratory and combined with the theory of Etendue, we designed the simulation model of medical the lighting system[5–8], showed in Fig. 5. Incident plane of the conical lens and chips are very close to each other, and through the modeling results of the energy emitted from the chips and fiber, we can infer the total efficiency of the optical system.

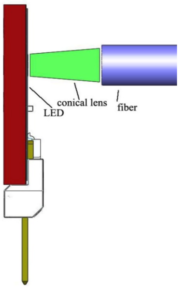

Figure 5: Optical model of lighting system in tracepro

According to the Etendue conservation theory, tapered optocoupler with different area ratio of emitting surface to incident surface is designed and a series of simulation data are obtained through the simulation of energy coupling efficiency[9] in medical lighting system. In each simulation, the energy emitted from the UHB-LED is coupled into the optocoupler and then spreads through an optical fiber with the length of 2m. The simulation result is obtained at the end of the optical fiber. Fig. 6 shows the energy transfer efficiency and angle compression of conical lens with different area ratio.

For the UHB-LED in modulation, when the area ratio of emitting surface to incident surface increases, the angle of the emitting beam decreases and the energy transfer efficiency gradually increases. When the ratio is 1.65, the overall energy transfer efficiency reaches 33.5%, which is the maximum value. It can be concluded that for the same incident area, if the emitting area is different, the beam angle will be different too, which will affect the final energy transfer efficiency of the lighting system.

Fig. 7 is the irradiation map of incident surface(left) and emitting surface(right).High uniformity is achieved through the conical lens, which is critical in medical lighting and much better than the traditional techniques.

4 Experimental results of tapered optocoupler

According to the theory simulation result, the area ratio of emitting surface to incident surface is selected as 1.65 and the test sample of the tapered optocoupler whose material is H-QK3 is made. Through the measurement of the energy emitted from the UHB-LED and the end of the optical fiber, a series of experimental results are obtained and the theory simulation results are verified.

In the experiments, a series of electrical current, such as 3150mA, 6300mA, 9000mA, 13500mA, 18000mA, are selected and the corresponding emitting energy is mea-

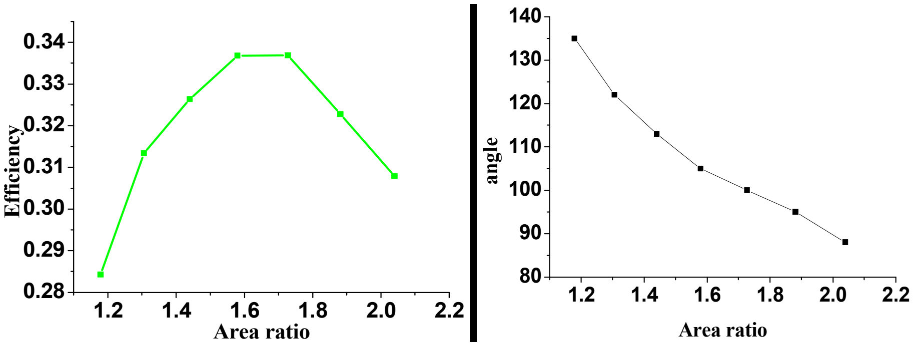

Figure 6: Coupling efficiency of tapered optocoupler

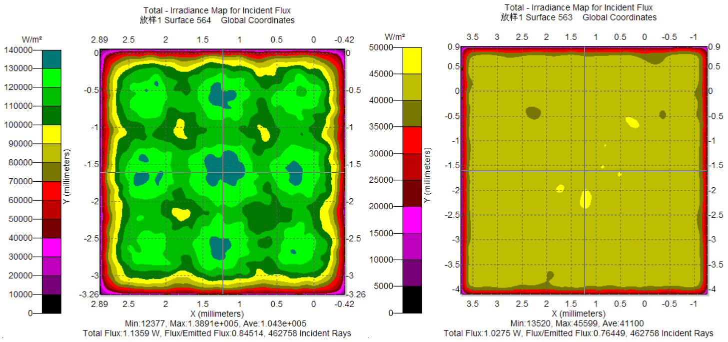

Figure 7: Uniformity of illuminating surface

sured. In the experiment, the length of the optical fiber is 2m and the diameter is ϕ5mm. The final energy efficiency is displayed in Fig. 8 and the maximum value could be reached 29%, which is very close to the simulation result. The difference between the simulation and experimental results mainly comes from the bigger distance between the tapered optocoupler and LED chip. The mechanical tolerance in the system assembly and adjustment process also reduce the efficiency.

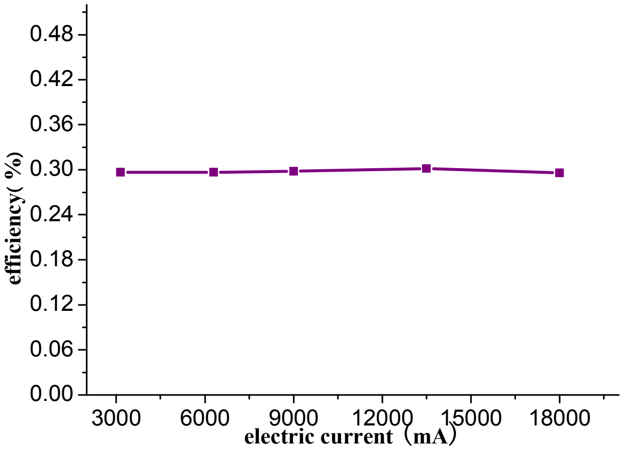

Figure 8: Experimental results

5 Conclusions

A new optical conical lens is proposed in this paper, which can be used in the medical lighting system. The conical lens can increase the coupling efficiency of UHB-LED and improve the uniformity of energy. Through the theoretical modeling and optimization, a conical lens with area ratio is 1.65 is designed to have best coupling efficiency and uniformity. This study can help the miniaturization design in medical lighting system. With low cost and high performance, the lens is expected to be widely used in medical equipments.

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References

1. Hou, J.; Liu, C. (2010): The application and prospect of LED in medicine. *Optical Instruments*, vol. 32, no. 1, pp. 90-94.

2. Liao, Y. B. (2000): *Fiber Optics* Beijing Tsinghua University press.

3. William Cassarly. (2001): *Nonimaging Optics: concentration and illumination.* New York: OSA Handbook of Optics, Vol 3. Chap 2. McGraw-Hill.

4. Winston, R. (1991): *Nonimaging optics.* New York: Sci Am. pp. 26-8.

5. WANG, W. S. (2004): Analysis and design of optical tunnel lighting system for liquid crystal projector. *Optical Instruments*, vol. 26, no. 4, pp. 36-41.

6. Zou, H.; Schleicher, A.; Dean, J. (2005): Design of LED Illumination System in LCOS Micro-Projector. *Society for Information Display(SID), 05 DIGEST*, pp. 1698-1701.

7. Beniamin, A. J.; Robert, D. G. (1996): Beam shape transforming devices in high efficiency projection system. *SPIE*, vol. 2407, no. 8, pp. 48-56.

8. Welford, W. T.; Winston, R. H. (1989): Collection nonimaging optics. *New York: Academic*, pp. 35-39.

9. Brennesholtz, M. S. (1996): Light collection efficiency for light valve projection systems. *SPIE*, vol. 2650, pp. 71-79.