# High illuminance light-emitting diode headlight for medical applications

Ui-Hyung Lee[1], Jae-hun Jung[2], Seung Hyun Park[3], Gye Seon Lee[3], Young-Gu Ju[1*]

[1] Department of Physics, Kyungpook National University, 1370 Sankyuk-dong, Buk-gu, Daegu, 702-701, Korea
[*] ygju@knu.ac.kr

[2] Department of Physics Education, Kyungpook National University, 1370 Sankyuk-dong, Buk-gu, Daegu, 702-701, Korea

[3] Korea Photonics Technology Institute, 5 Cheomdan-5gil, Buk-gu, Gwangju, 500-779, Korea

## ABSTRACT

High brightness light emitting diodes have been used to develop high illuminance headlight for medical applications. It provides various advantages such as high illuminance, long life time, reduced infra red light, extended operation time with battery and light weight. A 3 W LED was employed to achieve the high performance medical headlight. The optical design includes two lenses for high energy transmission and high illuminance. The LED headlight shows 42,000 lux with spot diameter of 80 mm at the distance of 300 mm. For comparison purpose, 5 W LED was also used to obtain the high illuminance headlight. However, the large divergence angle and large spot size of the 5 W LED limits the illuminance to 31,000 lux with increased burden on heat dissipation. The thermal images of the heat sinks indicate that the temperature of the headlight using a 3 W LED is below 50 degree C, which is suitable for medical applications.

**Keywords:** medical, LED, headlight

## 1. INTRODUCTION

In general, surgical illumination using halogen or Xenon lamp reaches an illuminance of 20,000 ~ 200,000 lux depending on the application. As for headlight or endoscopy, the light is delivered through a fiber bundle since the volume of the lamp is too large to carry in a portable form. Although the use of fiber provides the small spot size, it also limits the range of activities and gives fatigue to the operator in case of long-time operation. Furthermore, the coupling into fiber drops the optical efficiency considerably since large portion of light is lost in the middle of travelling over the fiber. Besides the existing lamps are sensitive to shock and vibration, which leads to the fluctuation of illumination during operation. In terms of maintenance, the short life time of the existing lamp demands more frequent replacement and thus higher cost. From the viewpoint of illummination, high color rendering index of the existing lamp can give surgeons higher contrast image. However, the large amount of infrared(IR) light of halogen lamp heats up surgeons and patients during operation. The heating by the light can cause increased troubles such as sweating of the doctors and the rising temperature of the tissue as operation time increases.

The advent of high power LED can solve the above mentioned issues since it is a highly energy efficient light source with small size and light weight. The high efficiency means that it can be operated by battery for long time enough for operation. The small size and light weight also makes the LED light suitable for surgical headlight. The battery operable headlight can get rid of the need for the fiber bundle only if its illuminance is as same as the existing light source. The additional advantage of LED lighting lies in its long lifetime equaling 50,000 hours and the absence of IR and ultra-violet(UV) emission. The reduced IR radiation can alleviate the rising temperature of the tissues and reduces the damage on the cells due to the IR and UV radiation.

In this paper, we design a headlight taking full advantage of high power LED and compare the simulation with the fabricated LED headlight. Optical design deals with the choice of high power LED to optimize the energy transfer

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efficiencies and the control of spot size with a double lens system. The results also include the thermal issues which can be a problem in making small size and high illuminance light source.

## 2. OPTICAL DESIGN

The specification for the medical LED headlight was determined by investigating the specification of the existing headlight and considering the result from the survey over the surgeons working in a hospital. The targeting specifications of LED headlight are as following: The spot size at 300 mm from the headlight is less than 100 mm. Maximum illuminance is greater than 30,000 lux, which is also controllable in multi-steps. The color rendering index(CRI) is greater than 70. The housing temperature is less than 60 °C.

A LED headlight usually consists of LED, lens, reflector, and housing. In order to achieve the desired illuminance of 30,000 lux over the circle with the diameter of 80 mm, at least, 150 lm is required. However, the illumination optics suffers from energy loss, the luminous flux of LED should be far greater than 150 lm. For example, if the energy transfer efficiency of the optics is 50 %, the luminous flux of LED must be greater than 300 lm. The power consumption can't be increased indefinitely to meet the final illuminance. It is because the increased power consumption also increases the heat dissipation and the temperature of LED, which usually deteriorates the device performance and lifetime. In this study, 5 W and 3 W LED were selected among the highest power and highest efficiency LEDs available on the market. The 5 W and 3 W LED used in this paper are P7 of Seoul semiconductor and XR-E Q5 of Cree, respectively. The data sheets of those LEDs are seen in Table 1 and Table 2. According to the data sheets, both LEDs have luminous efficacy as high as 75 lm/W.

As for the reflector, it is frequently used in the design of headlight, especially when the light source is a light bulb. The light bulb emits the light in all directions so that the reflector can collects the light effectively. However, LED is a Lambertian light source having cos θ dependence. It means that less light of LED bounces off the reflector compared to that of light bulb. The relatively small portion of light energy at a large angle prevents a reflector from functioning effectively. Moreover, the external reflector is usually bigger than the package size, which leads to the enlargement of source size due to the virtual imaging of the reflector. The increased virtual image makes it difficult to achieve small spot size at the final stage although the reflector reduces the divergence angle of LED. Therefore, the reflector is not included in our optical design. The headlight in the design is comprised of high power LED and two lenses.

Table 1. Data sheet of 5W LED [1]

| Parameters | Value | Unit |
|---|---|---|
| Luminous Flux ($I_F$ = 1,400 mA) | 400 | lm |
| Forward voltage | 3.3 | V |
| Correlated Color Temperature(CCT) | 6300 | K |
| Color Rendering Index(CRI) | 70 | - |
| View Angle | 120 | deg. |
| Thermal resistance | 3 | °C/W |

Table 2. Data sheet of 3W LED [2]

| Parameters | Value | Unit |
|---|---|---|
| Luminous Flux ($I_F$ = 1,000 mA) | 225 | lm |
| Forward voltage | 3.7 | V |
| Correlated Color Temperature(CCT) | 5,000 ~ 10,000 | K |
| Color Rendering Index(CRI) | 75 | - |
| View Angle | 90 | deg. |
| Thermal resistance | 8 | °C/W |

In a double lens system, the first lens reduces the divergence angle rather than makes perfect collimation. In case of a point source, the smaller focal length results in the smaller beam diameter, and thus the smaller spot at the target plane. However, LED is a plane source with a finite size. Therefore, the placement of LED at the focal plane of the first lens still causes divergence angle to be about the size of the source divided by focal length. The increase in focal length may decrease the divergence angle, but requires the enlargement of the first lens in diameter for securing an energy transfer rate. In this way, the first lens should have high numerical aperture, working for reducing divergence angle moderately. Furthermore, the first lens is in contact with the LED in order to increase the acceptance angle at the sacrifice of condensing effect.

The diameter of real LED package is 5 ~ 8 mm. The minimum diameter of lens should be larger than 8 mm. If the size of lens is smaller than that of LED, the brightness must drop because the lens doesn't collect the light of LED around the edges. The simulation shows that plano-convex lens with the flat side facing LED gathers more rays than a double convex lens. In the final design, the selected plano-convex lens has the diameter of 9 mm and the focal length of 9 mm. Although the first lens succeeds in reducing divergence angle, it doesn't collimate the light from the LED completely due to the short distance between the lens and the LED compared to the focal length. For reducing divergence angle further, the second lens should be used. The second lens is chosen to make a small spot and high energy transfer. The diameter and the focal length of the second lens are 25 mm and 30 mm, respectively.

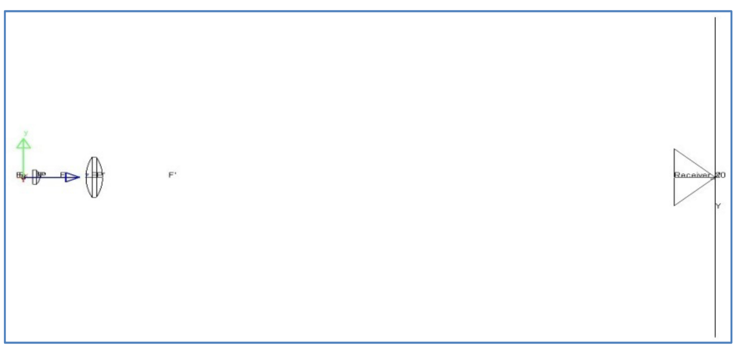

Fig. 1. An arrangement of LED, lens and screen used in the simulation.

After selecting LED and lenses, simulations are performed to find out an optimum arrangement. The simulations are carried out using LightTools 7.0. An arrangement of LED, lens and detector plane used in the simulation is displayed in Fig. 1. For the accuracy of simulation, the data with respect to lenses can be called from the library inside the software. The modeling of LED can also be done in a similar manner. The LED companies provide the ray data of each product and the ray tracing software also supports calling this data file into the program. However, the modeling of LED in this way sometimes disagrees with the experimental data. In order to figure out these troubles, more accurate ray data need to be constructed by measurement. An alternative method is to model the LED in the component level.

5 W and 3 W LEDs are taken apart to find out the dimensions of the components used in the LED. The structures of LEDs are reconstructed in the ray-tracing software. As a result, the divergence angle and other optical feature of the LEDs in the simulation agree with those observed in the measurement. In case of 5 W LED, dome lens is so big that the

distance between LED and lens is large and the uniformity of image is poor. Cutting the dome lens by 2.5 mm from the top solves this problem. The distance between LED source and screen is fixed to be 300 mm according to the specification. The distance between the LED and the second lens has to be decided through the simulation. After the simulation, the optical test is carried out to check the positions calculated by the simulation.

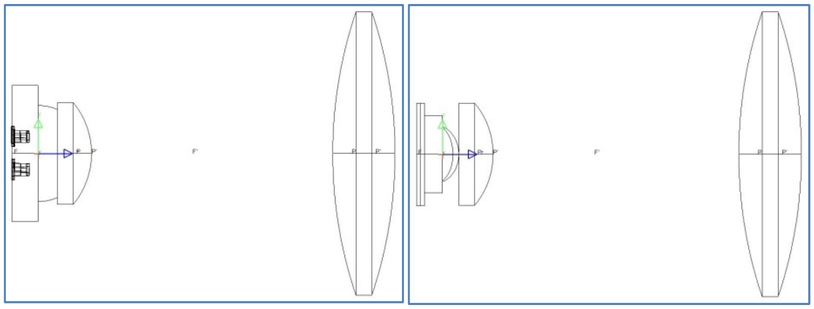

Fig. 2. The configurations of the two types of LED headlights; the left(3W LED) and the right(5W LED).

The simulation and the test shows that, in case of 5 W LED, illuminance was the highest and uniformity was best when the second lens is 31 mm apart from the LED. The measured illuminance is 42,000 lux and the diameter of spot was 80 mm at 300 mm from the LED. As the distance between LED and the second lens changes, the image of LED chip itself appears. Since the chip consists of 2 X 2 smaller chips, the uniformity of the illumination is more degraded. In addition, the size of 5W LED chip is larger than that of 3 W LED. The larger source size means the larger spot size at the imaging plane.

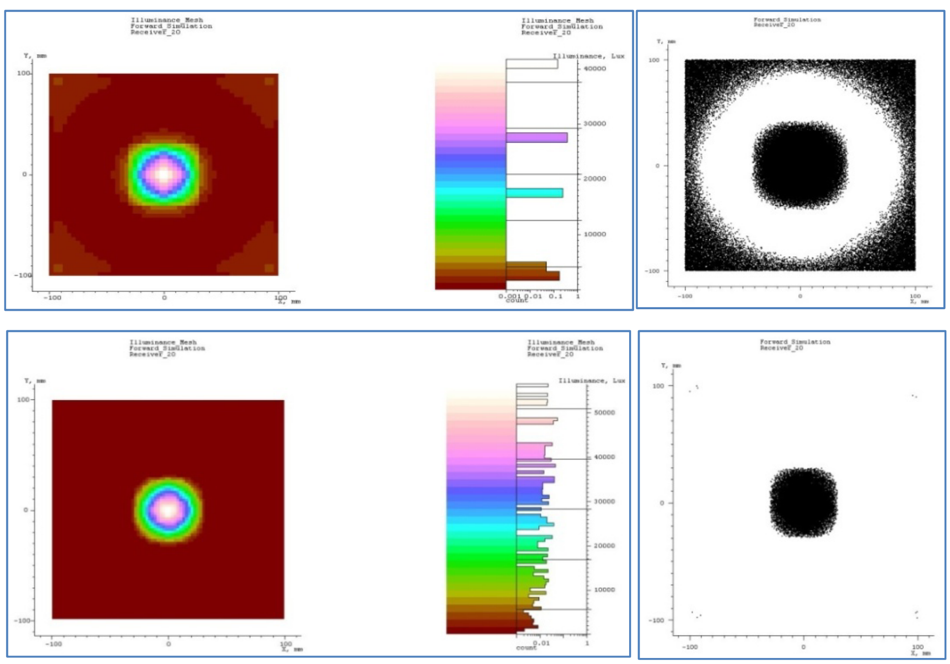

Fig. 3. The calculated illumination distribution; The upper(5W LED) and the lower(3W LED)

In case of 3 W LED, the illuminance becomes 80,000 lux and the diameter of spot is 40 mm at 300 mm apart from LED, when the distance between LED and second lens was 22 mm. From the data sheet as seen in Table 2, divergence angle of 3 W LED is 90 °, which is smaller than that of 5 W LED. The 3 W LED is packaged in a particular way in order to obtain small divergence angle. However, it also deteriorates the uniformity of image at its highest illuminance. The best uniformity is obtained when the distance between LED and the second lens is 29 mm. The illuminance is about 50,000 lux and the diameter of spot was 80 mm. The calculated illumination distributions are presented in Fig. 3 for two types of LEDs.

## 3. RESULT

After iteration of simulation and optical test, a sample of LED headlight is fabricated as shown in Fig. 4. The fabricated sample was sent to Korea Photonics Technology Institute for the accurate characterization of the optical and the thermal performance.

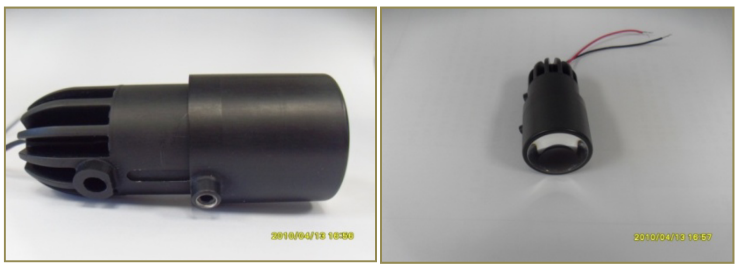

Fig. 4. Photograph of the assembled LED headlight

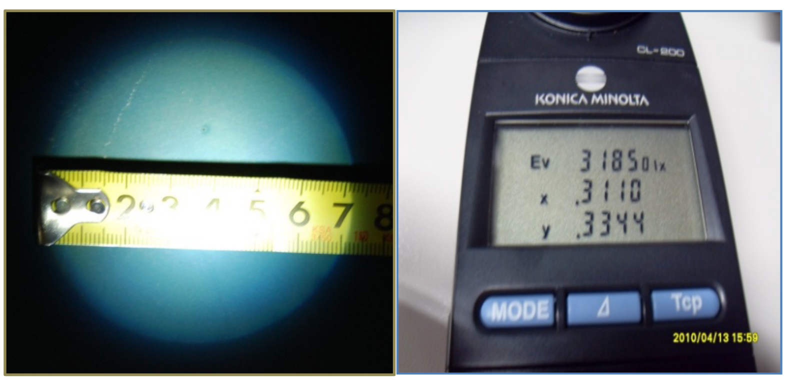


Fig. 5. The spot size and the illuminance of the headlight made of 5 W LED.

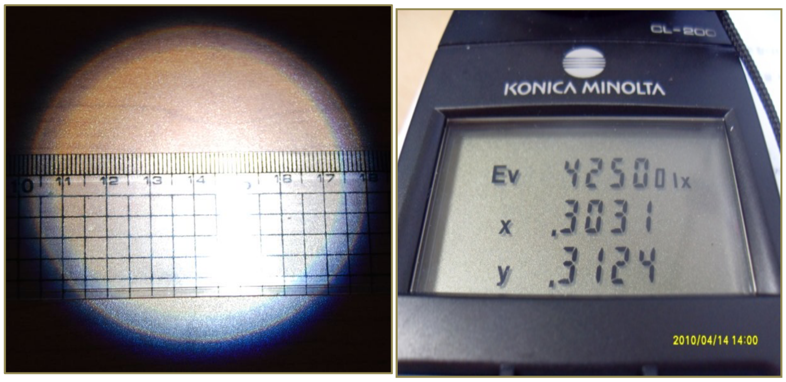


Fig. 6. The spot size and the illuminance of the headlight made of 3 W LED.

In case of the sample using 5 W LED, the diameter of spot is 80 mm and illuminance is 31,850 lux. The CRI is 70.85 and color temperature is 7206 K. In case of 3W LED, the diameter of spot is 80 mm and the illuminance is 42,500 lux. The CRI is 81.39 K and color temperature is 8699 K. Fig. 5 and Fig. 6 shows the spot size and the illuminance of the two types of LED headlights. The measurements show good agreement with those of the simulation except illuminance. It can be ascribed to the increased temperature of the LED and the corresponding degradation of optical performances. Housing temperature is measured every 1 minute for 20 minutes. The temperature of 5 W LED headlight arrives at 53.2 °C and that of 3 W LED goes to 50.1 °C as seen in Fig. 7. The higher housing temperature comes from the higher power consumption of 5W LED as expected. The junction temperature of 5 W LED is also expected to be higher than that of 3 W LED. The high junction temperature usually drops the luminous efficacy significantly so that the efficacy appeared in the data sheet may not be achieved. It can be a reason that the illuminance from the simulation does not agree with that of the measurement. If thermal issues are more carefully managed, the better results are expected.

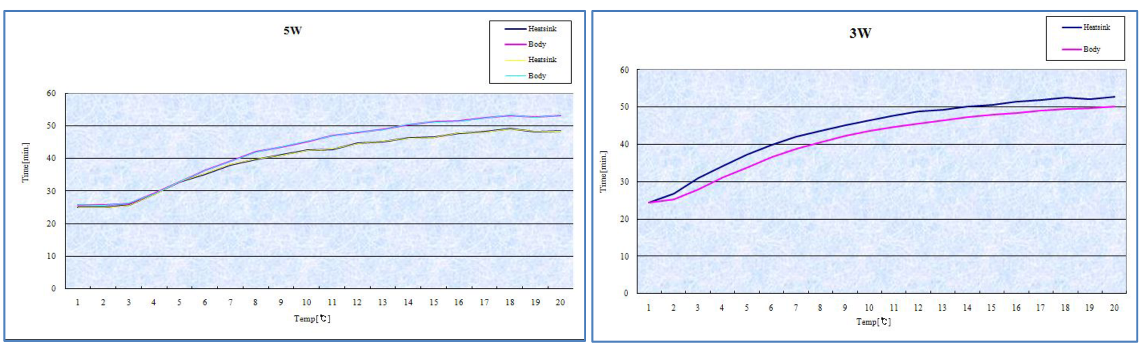


Fig. 7. Housing temperature vs. time

## 4. CONCLUSION

The LED headlight made with 3W LED shows 42,000 lux with spot diameter of 80 mm at the distance of 300 mm. The illuminance of 3 W LED headlight is 80,000 lux and the diameter of spot is 40 mm at 300 mm apart from LED, when the distance between LED and second lens was 22 mm. For comparison purpose, 5 W LED is also used to obtain the high illuminance headlight. However, the large divergence angle and large spot size of the 5 W LED limits the illuminance to 31,000 lux. The divergence angle of the 5 W LED used in the headlight is 120° while the divergence angle of the 3 W

LED is 90 °. Although the luminous flux of the 5 W LED is much higher than that of 3 W LED, the effective optical power of 3 W LED available to the double lens optics is greater than that of 5 W LED due to the small divergence angle. The thermal images of the heat sinks indicate that the temperature of the headlight using a 3 W LED is below 50 °C. The higher power consumption of 5 W LED also gives higher housing temperature, which can leads to the more rapid thermal degradation in terms of optical performance and the life time.

## 5. ACKNOWLEDGEMENTS

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