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Design of LED Bicycle Headlamp with a Horizontally Wide Viewing Angle

Hyun Jung Park[1], Dong Kyu Lee[1], Jae Min Lee[1], Kwang-Woo Park[2], Jae Young Joo[2]*, and Joon Seop Kwak[1]**

[1]*Department of Printed Electronics Engineering, Sunchon National University, Sunchon 57922, Korea*
[2]*Korea Photonics Technology Institute (KOPTI), Gwangju 61007, Korea*

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This paper proposes a LED bicycle headlamp with a wide viewing angle to help bicyclists see the front effectively and because of its high visibility to reduce the risks of accidents around intersections or blind spots. The wide viewing angle was determined to be 28° because it can illuminate a 5 m wide area 10 m away. Therefore, the road conditions of the intersection can be observed with the bicycle handlebar tilted slightly to the left or right. The headlamp has a compact reflector with a width of 30 mm, height of 27 mm, and length of 17 mm. Owing to its size, a change in the position of a light source leads to severe changes in light distribution. Therefore, the tolerance of the source position was analyzed by a simulation. The tolerance was ±0.5 mm at the X, Y and Z axes within a less centered aiming range of ±1°. Finally, the prototype of the bicycle headlamp was made and the light distribution was measured by an automotive headlamp light measurement system. The experimental results indicate that the headlamp illuminates a 5 m wide area with an edge light of 3.2 lx as well as meeting the K-mark regulation.

Keywords : Bicycle headlamp, Reflector design, LED, Tolerance of source position
OCIS codes : (080.2740) Geometric optical design; (220.2945) Illumination design; (220.4610) Optical fabrication

I. INTRODUCTION

Recently, the bicycle market has grown. The advantages of riding a bicycle are transportation savings, easy exercise, energy savings, and contribution to environmental conservation and human health [1, 2]. The main ages of bicyclists range from 10 to more than 70 years old because of the advantages mentioned before, and bicycling has emerged as a popular leisure sport. As the number of bicyclists has increased to suit these trends, the incidence of traffic accidents related to bicycles has increased. For safe bicycle riding, it is necessary for bicyclists to retain a sufficient visual field and be careful around intersections or blind spots [3-6]. Bicyclists can see in the forward direction easily during daytime because there is sufficient light, whereas the headlamp of a bicycle is essential at night to ensure the visual field of bicyclists. On the other hand, the use of a general flashlight as a bicycle headlamp can cause glare to opposite road users, such as oncoming bicyclists, drivers, or pedestrians. To solve these glare phenomena, in Germany, there is the Road Traffic Licensing Regulation (StVZO) 22A No.23 (K-mark regulation), which prevents glare to the opposing road users, which also enables the safe and comfortable riding of bicycles [7].

This paper proposes a light emitting diode (LED) bicycle headlamp which has viewing angle of 28° as well as meeting the K-mark regulation. The 28° means that the headlamp can illuminate an area 5 m wide from 10 m away. If the headlamp widely illuminates a 5 m wide area with an edge light of 3.2 lx, bicyclists can secure the visual field quickly when the direction changes around an intersection area. This also helps the bicyclists be seen by road users around blind spots, which can prevent more traffic accidents.

We designed a bicycle headlamp with a compact reflector using a LED. LEDs have many advantages, such as a small

Corresponding author: *jyjoo@kopti.re.kr, **jskwak@sunchon.ac.kr
Color versions of one or more of the figures in this paper are available online.

size, high efficiency, long lifespan, fast response speed, no mercury, and low energy consumption [8]. On the other hand, the LEDs are susceptible to heat. The junction temperature of the LEDs is approximately 150°C. A heat sink was designed to resolve the excessive heat generation of LEDs. This could improve the durability and performance of the headlamp [9]. The light distribution changes sensitively by the position of the light source because the reflector size is too small. Therefore, the tolerance was analyzed according to the source position. Finally, a prototype of the headlamp was made using a computer numerical control (CNC) machine. The light distribution of the simulation was compared with the experimental result.

II. DESIGN

2.1. K-mark Regulation

Figure 1 and Table 1(a) show the K-mark regulation of a bicycle headlamp. The K-mark regulation requires that the illuminances be measured on a test screen 10 m away from the headlamp. In addition, the light distribution is symmetrical around the vertical line. This regulates the illuminances from 8°L to 8°R and from 5°U to 3.4°O. Based on the horizontal-vertical (HV) point, L means left, R means right, U means under, and O means over. The HV is a point facing the front of the headlamp and is where linear light reaches from the headlamp. For example, 8°L means the point located on the left by 8° from the line that the headlamp and HV point make. Zone 1 means an area above 3.4°O and is an area that can cause glare to the road users on the opposite side. Therefore, the illuminances in zone 1 are permitted only less than 2 lx. The HV point should have an illuminance of at least 20 lx. The E_{max} point is the maximum illuminance that is located on the side of the HV point and its illuminance must not exceed 1.2 times that of the HV point.

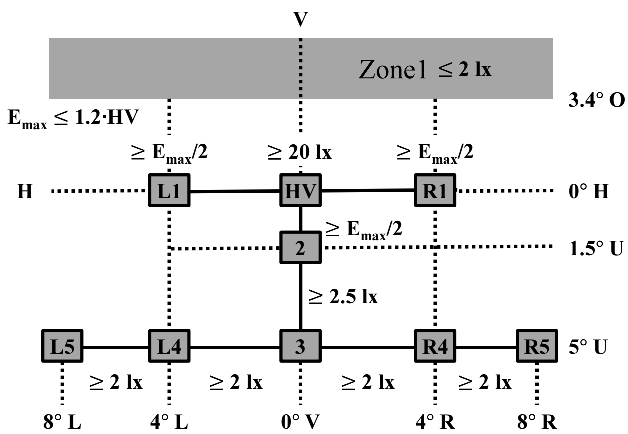


FIG. 1. Light distribution required by the K-mark regulation.

2.2. Design of Freeform Reflective Facets

The design of freeform reflective facets to control the optical path in the desired direction can be formed through the following steps. Step 1) The unit vector of the incident ray ($\overrightarrow{In}$) toward the reflective facets from the source and the unit vector of reflected ray ($\overrightarrow{Out}$) toward the test screen from the reflective facets are determined. The normal vector ($\overrightarrow{N}$) is calculated by Snell's law (Eq. (1)) and the tangent plane on the first point is calculated using $\overrightarrow{N}$. The $\overrightarrow{In}$ and $\overrightarrow{Out}$ of the second ray were determined on the second point which intersected with the first tangent plane, and then the tangent plane on the second point was calculated using $\overrightarrow{N}$ on the second point.

$$\left[2-2\cdot\left(\overrightarrow{Out}\cdot\overrightarrow{In}\right)\right]^{1/2}\cdot\overrightarrow{N}=\overrightarrow{Out}-\overrightarrow{In} \tag{1}$$

Step 2) An initial line is formed by repeating step 1, i.e., it connects the previous tangent plane with the next point continuously. Step 3) To form a facet with the initial line, each point on the initial line is determined as a starting point. Finally, the freeform reflective facets are formed by repeating steps 1 and 2. This process is indicated in Fig. 2 [10-14].

Based on the principles mentioned above, the facets were designed through SYNOPSYS LightTools program. The reflective surface of the headlamp is composed of three facets. The central facet illuminates the central part of the test screen intensively. The left and right facets illuminate

TABLE 1. Comparison between the illuminances results at test points (unit: lux)

Test point	(a) Regulation	(b) Simulation 1	(c) Simulation 2	(d) Experiment	(e) Simulation 3
HV	≥ 20	29.2	31.0	28.7	27.9
E_{max}	≤ 1.2 × HV	33.0	32.8	28.8	29.6
L1, R1	≥ E_{max}/2	25.2, 24.6	21.8, 22.1	21.0, 20.4	19.7, 19.5
2	≥ E_{max}/2	29.3	25.4	28.2	26.8
3	≥ 2.5	8.2	12.0	15.1	14.3
L5, R5	≥ 2.0	2.8, 3.4	6.9, 6.6	5.1, 4.7	7.3, 7.8
Zone1	≤ 2.0	1.3	0.3	0.8	0.5
L14, R14	-	-	4.4, 5.2	3.2, 3.0	4.0, 4.6

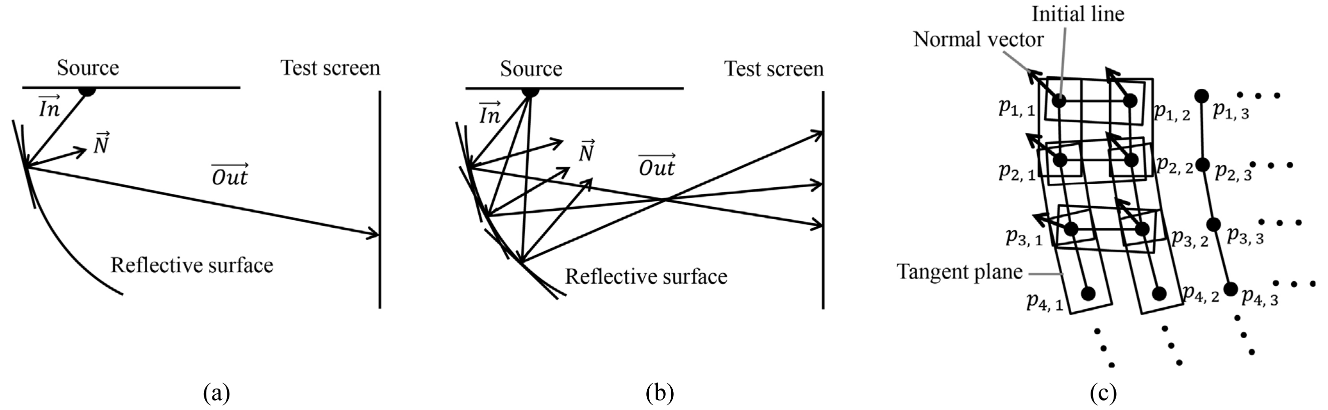


FIG. 2. Schematic diagrams of (a) the step 1, (b) step 2, and (c) step 3 processes.

both edges to the intersected direction to meet at the viewing angle of 28°. The upper part of the facet is designed to illuminate the bottom of the test screen and the lower part of the facet is designed to illuminate less than 2 lx in zone 1. Therefore, the headlamp has a wide viewing angle and effectively meets the light distribution of the K-mark regulation.

2.3. Simulation Process

Figure 3 shows the simulation process of the bicycle headlamp. First, it is designed to the minimum size reflector which meets the K-mark regulation. Second, the size of the reflector is extended to illuminate a 5 m wide area with an edge light of 2 lx and more than 10 m away from the headlamp. Third, it is adjusted to an angle between the reflector and source to emit as much light as possible towards the reflector. Fourth, it is confirmed to the tolerance of the source position at the X, Y and Z axes. If the illuminances do not meet the values of the K-mark regulation when the source is shifted in relation to the X, Y or Z axes by ±0.5 mm each, the reflector design is rebuilt repeatedly until it meets the K-mark regulation. Afterward, the mechanical and heat dissipation designs begin.

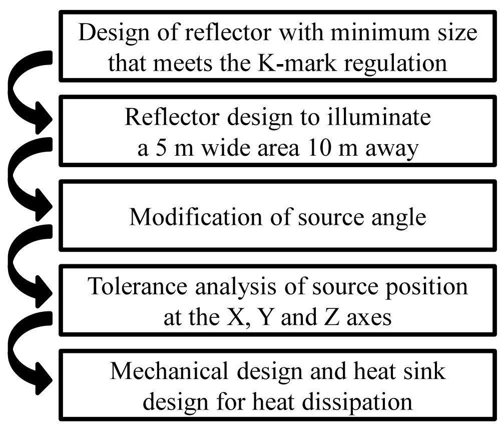


FIG. 3. Design process of the reflector.

2.4. Optical Simulation of the Headlamp

Figure 4 presents a schematic diagram of the reflector, source, and source angle for the headlamp. The CREE XP-E2 LED is used as the source. For the simulation, 200 lm luminous flux was applied. The luminous flux corresponds to 2.17 W (3.1 V, 0.7 A). The reflectance of the reflector was applied to 80%. First of all, the reflector is designed with a minimum size that meets the K-mark regulation. The initial model had a width of 16 mm, height of 18 mm, and length of 12 mm when the source positions were X: 0 mm, Y: -0.5 mm, and Z: 6 mm. At that time, the source angle was 90°. Figure 5(a) shows the result of the log scale light distribution. Table 1(b) lists illuminances on the test points. The initial model has a 55.8% reflector efficiency, which is the amount of light directed to the reflector from the source. In addition, it has a 41.0% detector efficiency, which is the amount of light detected

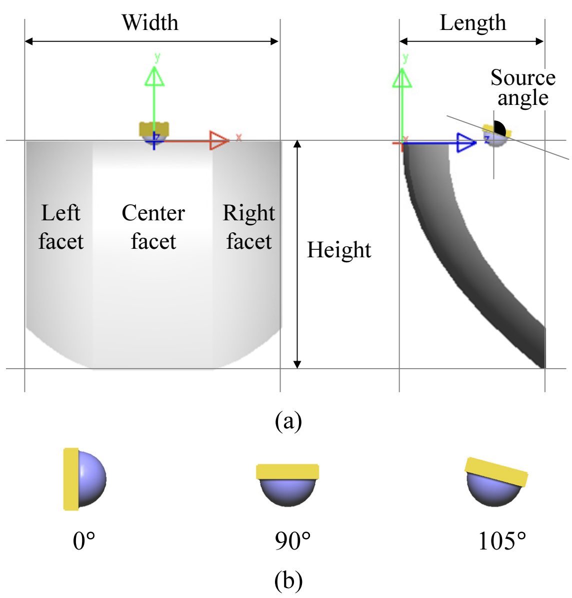


FIG. 4. (a) Schematic diagram of the reflector and source. (b) Indication standard of the source angle.

to the test screen 10 m away. Even if the amount of light loss is large because of the compact reflector, it meets the K-mark regulation.

The initial model was modified to illuminate a 5 m wide area with an edge light of 2 lx and over. The edge of the 5 m wide area corresponds to a viewing angle of 28° 10 m away. The source angle, source position, and reflector size were changed. The reflective surface was composed of three facets. When the reflector has three facets, gaps are formed, unlike the complete freeform reflector. Therefore, the reflector was designed with minimal gaps because the light path can be changed by the gaps, as shown in Fig. 6.

The reflector and detector efficiency were compared as a function of the source angle from 90° to 120°. The efficiencies were found to depend on the source angle. On the other hand, the headlamp size grows with increasing source angle because the source is connected to the printed circuit board (PCB) for the power supply. Therefore, the source angle was selected as 105° considering the headlamp size. To obtain high light efficiency with a compact size, the headlamp should have a small distance between the reflector and source. However, when the distance is small, the light distribution is changed severely for even minute changes in the source position. Therefore, a distance approximately 7 times the source size, was fixed. The tolerance was secured as ±0.5 mm when the source position was moved to the X, Y or Z axes. Although an error is generated when the reflector and source are assembled, the K-mark regulation can be met. The final model had a width of 30 mm, height of 27 mm, and length of 17 mm when the source positions were X: 0 mm, Y: 1 mm, and Z: 11 mm. Figure 7 shows that the reflector and detector efficiencies were 65.5% and 48.4% when considering the light loss by the reflectance of the reflector and PMMA cover.

Figure 5(b) shows an image of the light distribution. Table 1(c) lists the illuminances on the test points required by the K-mark regulation. It was confirmed to be 4.4 lx on 14°L and 5.2 lx on 14°R through a simulation. Therefore, the visual field of the bicyclist can be secured in a 5 m wide area from 10 m away. The illuminances on the test points all passed the K-mark regulation. Figure 8 shows the illuminance distributions when the source position was moved with ±0.5 mm to the X, Y or Z axes, which meets the K-mark regulation within a less center aiming of ±1°. The design of heat dissipation was begun after simulating the tolerance.

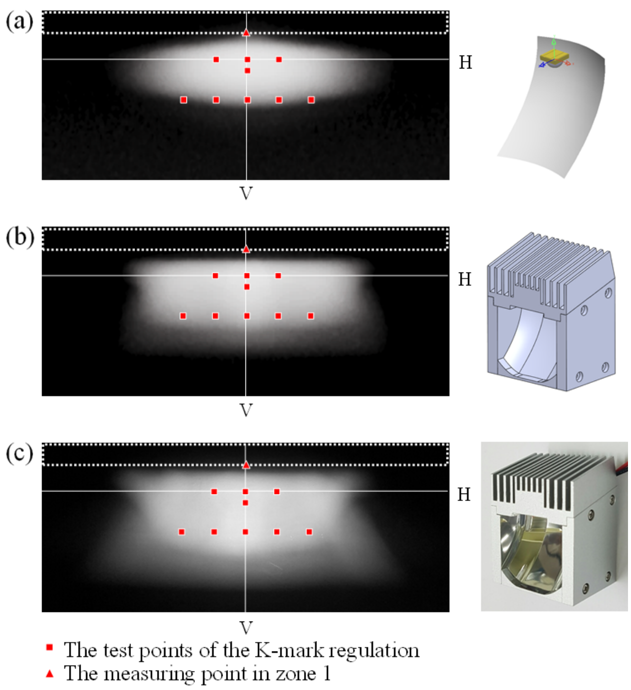


FIG. 5. Light distribution image of (a) initial model, (b) final model, and (c) prototype for bicycle headlamp 10 m away.

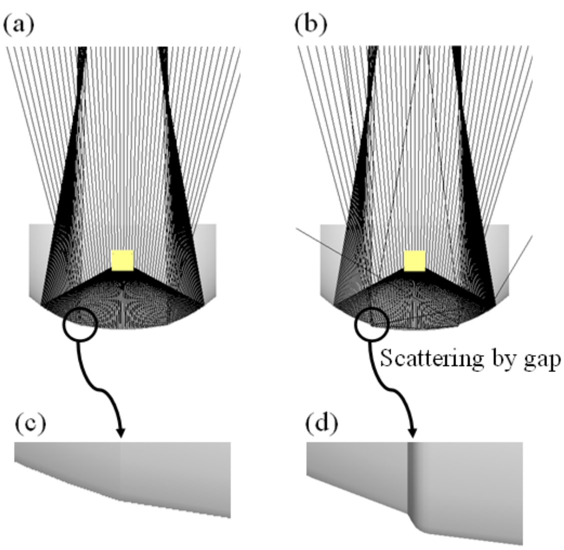


FIG. 6. Change in the light path by gap. (a) Model without gap, (b) the model with gap, (c) expanded image about model without gap, and (d) expanded image about model with gap.

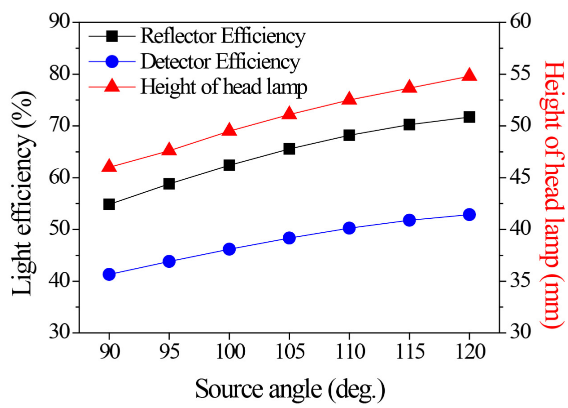


FIG. 7. Reflector and detector efficiency (left Y axis) and height of headlamp (right Y axis) by the source angle.

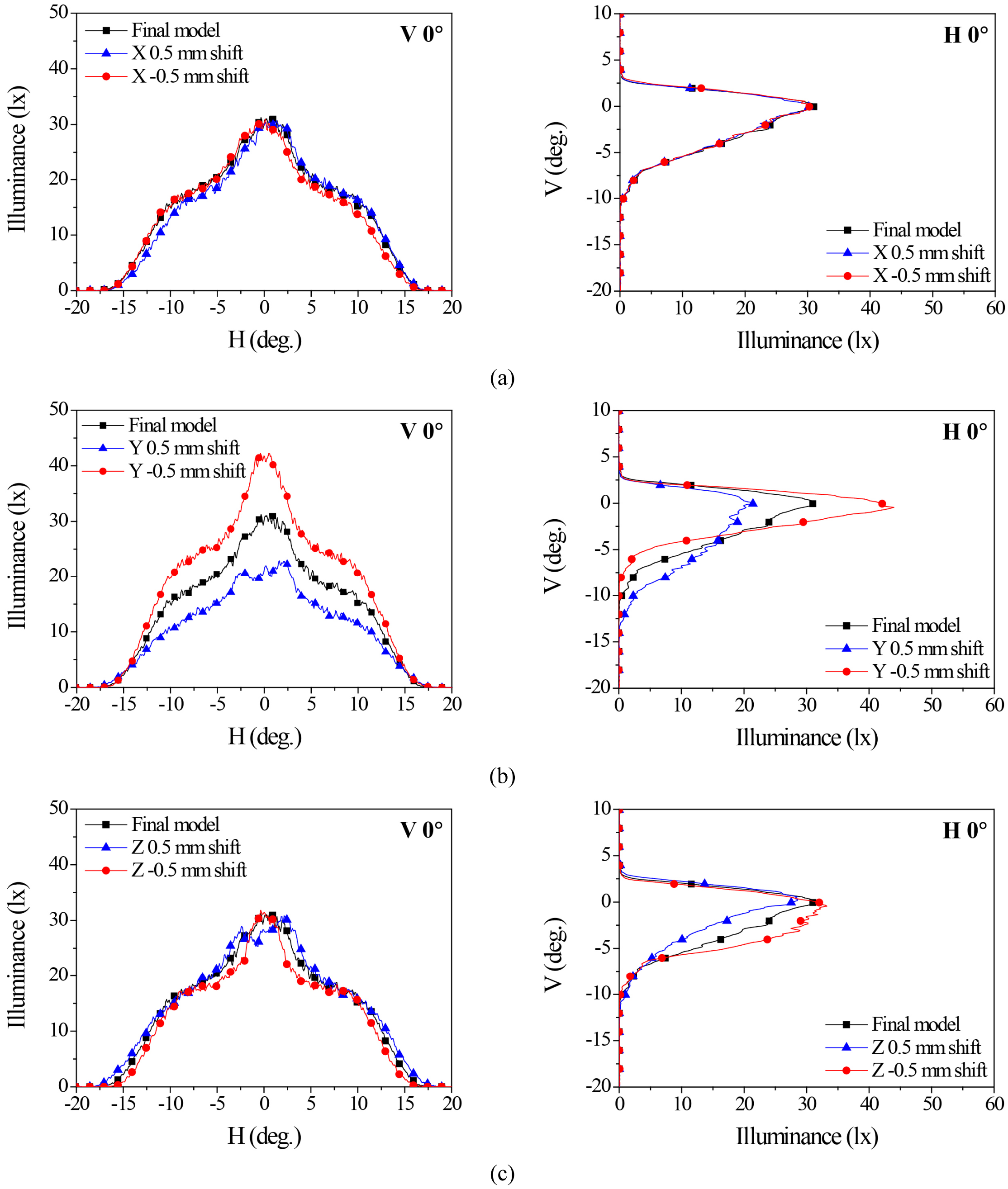


FIG. 8. Tolerance of source position of (a) X: ±0.5 mm, (b) Y: ±0.5 mm, and (c) Z: ±0.5 mm.

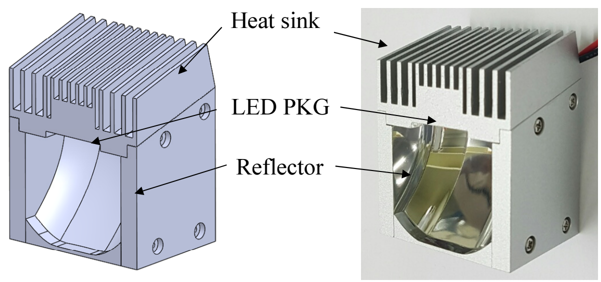
III. RESULTS

3.1. Evaluation of the Bicycle Headlamp

The LED device is susceptible to heat. If heat dissipation is not good, the LED device has problems, such as shortening the device lifespan and degrading the performance [9]. Therefore, heat dissipation is essential for LEDs. The radiation fins of the heat sink were designed using ANSYS mechanical program. The length and the number of fins were 10 mm and 14 for the workability of the prototype headlamp.

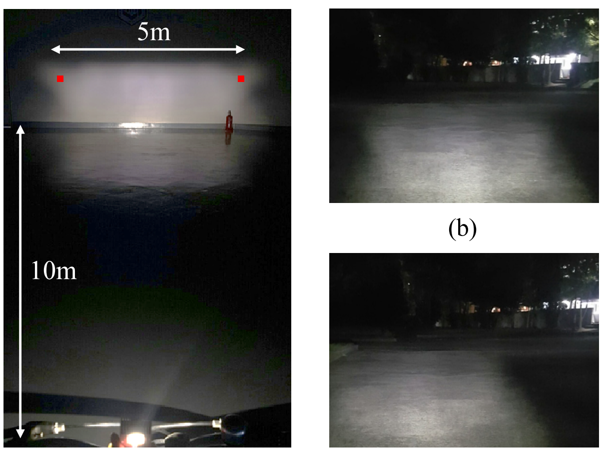
The prototype of the headlamp was made using a CNC machine, which is a numerical control (NC) machine with the additional feature of an on-board computer. A NC is a method of automatically operating a manufacturing machine based on a code of letters, numbers, and special characters [15, 16]. The manufacturing processes for the prototype are as follows. The shapes of the reflector and the heat sink were worked using a thick 7000 series aluminum panel according to the design drawing by 3D machining. The reflector was completed after polishing the reflective surface. Figure 9 shows the final model of the bicycle headlamp.

Figure 10(a) shows the illuminated image on a wall from a 10 m distance when the headlamp was mounted on a bicycle. An object could be identified in the edge, 5 m wide. Figure 10(b) shows the light distribution when the headlamp directly illuminates the front. Figure 10(c) shows the light distribution when the headlamp is tilted to the left by 10°. Therefore, the road conditions of the intersection can be observed with the bicycle handlebar tilted slightly to the left or right.



(a) (b)

FIG. 9. (a) Final model and (b) the prototype applied with the heat sink.



(b)

(a) (c)

FIG. 10. Image that is illuminated (a) to the wall from a 10 m distance, (b) on the street, and (c) on the street with the lamp tilted to the left by 10°, when the bicycle headlamp was mounted on a bicycle.

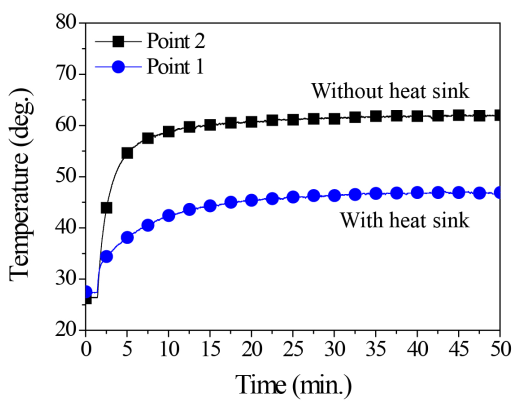


FIG. 11. Experimental results of temperature measurement.

Figure 11 shows the experimental results of the temperature measurement according to time with and without a heat sink by the thermocouple. The temperature was measured on two points. Point 1 was near the PKG of the model with the heat sink, and point 2 was near the PKG of the model without the heat sink. The saturated temperatures on point 1 and 2 were 62°C, and 47°C, respectively. The difference in the saturated temperatures between points 1 and 2 was 15°C. At the initial trend of temperature measurement within approximately five minutes, a gradient of temperature increase on point 2 was higher than on point 1 because the performance of heat dissipation on point 1 was better on point 2 by the heat sink. Therefore, the heat sink should be applied to the bicycle headlamp for good heat dissipation.

3.2. Comparison of the Simulation and Experiment Result

Reflectance of the prototype was measured to be 80% (reference: silver). Figure 5(c) shows the light distribution of the prototype, in which a picture toward the wall was taken in darkness. Table 1(d) lists the results of illuminances through the experiment on the test points with the injected power of approximately 2.17 W. The experimental results met the K-mark regulation. The experiment and simulation have similar light distribution shapes. The illuminances were measured 0.8 lx in zone 1, 3.2 lx on 14°L, and 3.0 lx on 14°R. The contrast between HV and zone 1 was 103.3 in the simulation and 35.9 in the experiment, showing a slight difference between the simulation and experiment. The difference was on test points 2 and 3 of the K-mark regulation. This is compared in Tables 1(c) and 1(d). We found out the reason why the results were different using a simulation. The source position was changed according to the guidelines of the tolerance. In addition, the Gaussian scattering angle was applied. Table 1(e) lists the illuminances on the test points when the source position was X: 0 mm, Y: 1 mm, and Z: 10.9 mm and the Gaussian scattering angle was 0.5°. This indicates similar results between the simulation and the experiment. Although the results of the simulation and the experiment were slightly different due to various and complex reasons, the results still met the K-mark regulation and illuminated a 5 m wide area with an edge light of 2 lx and over 10 m away through tolerance analysis of the source position.

IV. CONCLUSION

This paper proposed a LED bicycle headlamp with a wide viewing angle, which has a tolerance of ±0.5 mm of the source position. The tolerance of the source position needs to be considered in the design. Otherwise, it could cause an asymmetric light distribution, unexpected illuminance, or glare to the other side. By securing the tolerance in advance, even if a slight error could occur during the process, the desired purpose could be achieved. The prototype of the headlamp could illuminate a 5 m wide area with an edge light of more 3.0 lx as well as meet the K-mark regulation basically. This means that bicyclists can see the conditions of an intersection when the handlebar of the bicycle is tilted slightly to the left or right.

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