

Research Article

The Development of LED-Based Dental Light Using a Multiplanar Reflector Design

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A multiplanar reflector was designed to enhance the application efficiency of light-emitting diode (LED) light sources that can be employed as LED-based dental lights. This study used a high-power LED developed by Nichia, that is, a single LED capable of providing a total luminous flux of 120 lm, as the primarily light source to design and develop an LED-based dental light. This LED complies with the international standards and regulations stipulated in ISO 9680:2007. The light spots produced by the prototype were rectangular, with a length of 200 mm and a width of 100 mm. These light spots achieved maximum illumination of 12,000 lux. The use of LEDs can reduce energy consumption from 50 W to 3 W, providing an energy saving of more than 90%.

1. Introduction

LED lighting further enhances efficiency by demonstrating directionality, unlike the 180° light-emitting angle of conventional bulbs and tubes [1]. The emission spectrum of LED light sources is pure, and light is concentrated within the visible light range, mitigating problems generated by near ultraviolet and infrared light. Thus, the lighting efficiency of LEDs is excellent. Currently, 120 lm/W LEDs can be mass-produced, and 150 lm/W LED products have been developed. Furthermore, a color rendering index (CRI) of Ra 90 in white LEDs has been achieved, and the theoretical potential of white LEDs is estimated to reach approximately 260 to 300 lm/W in the future. Thus, in contrast to conventional halogen bulbs, which have already reached technological saturation, LED light sources present substantial future application potential [2]. Although ultrawhite LEDs possess superior luminous potential and directivity, these advantages also cause numerous problems for second optics design.

According to the dental light regulations specified in the ISO 9680:2007, illumination generated by these lights must produce distinct light spots on the projected area and exhibit

a visible cutoff point in the direction of the y -axis when ambient light is less than 30 lux. However, this lengthens the light spots in the direction of the x -axis to greater than that in the direction of the y -axis. Thus, the shape of the light spots produced by conventional dental lights is typically oval. The aforementioned regulations also stipulate that the illumination of light spots must show sufficient uniformity, which is easily achieved in halogen light designs. Because the emitting angle of halogen bulbs exceeds 180° and the various illumination velocities are consistent, differences and uniformity between the light spots in the directions of the x -axis and y -axis can be easily achieved through appropriate reflector designs. By contrast, high-power LEDs offer directionality and highly concentrated luminosity. Because of these attributes, the light spots produced by high-power LEDs when using conventional reflector designs become overly concentrated and the length of the light spots in the directions of the x - and y -axes is insufficient.

In this study, LED dental lights were developed using a multiplanar reflector design. Initially, optical simulation software was employed to establish the numerical value of

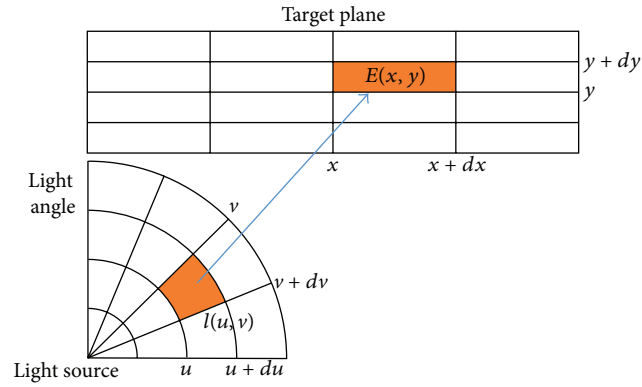


FIGURE 1: The distribution relationship between the various sectors of the light source and the projected light spot.

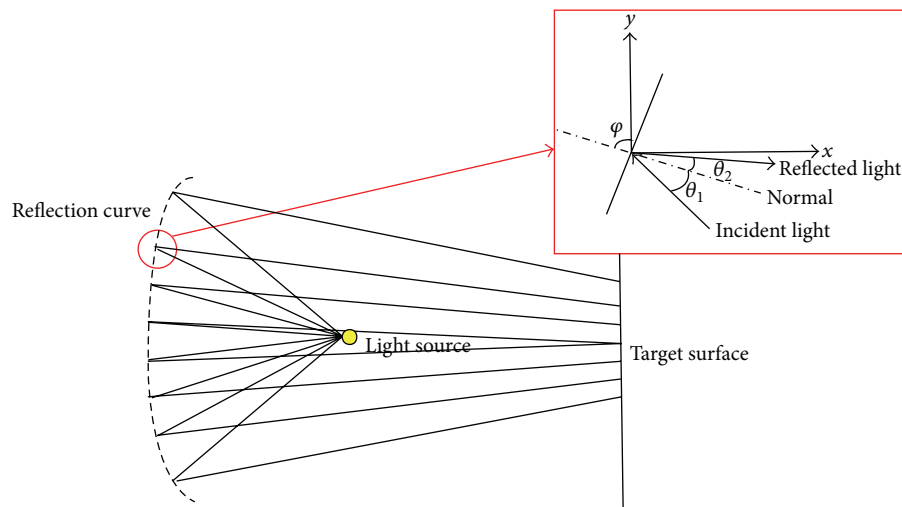


FIGURE 2: Development of a multiplanar second optics component.

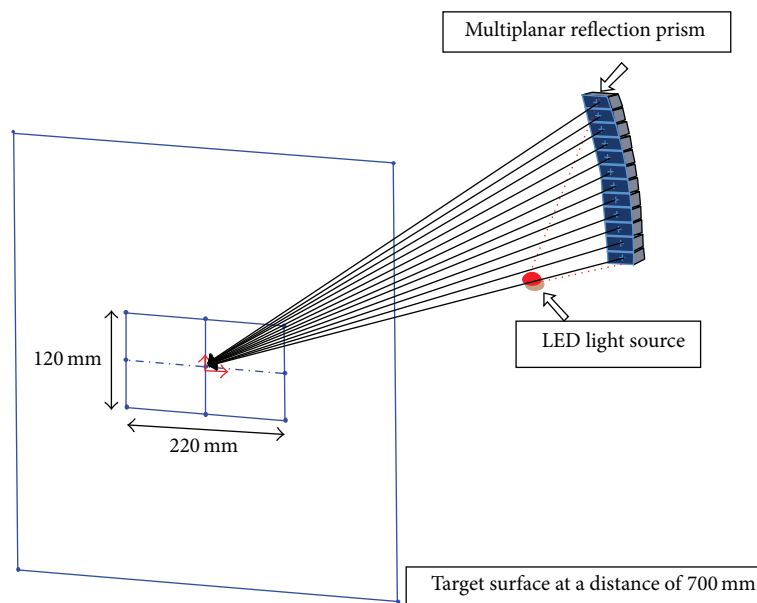


FIGURE 3: Adjusted angles of the various independent surfaces in compliance with the target surface.

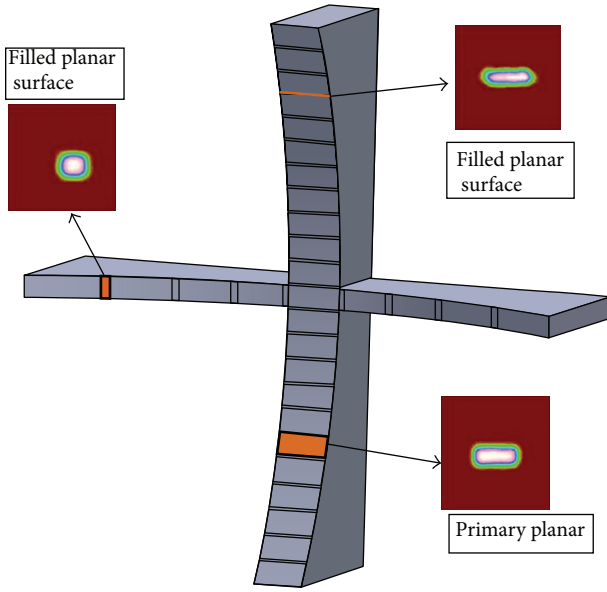


FIGURE 4: Primary rectangular planar mirror and the filled planar mirror.

LED light sources and determine LED light distribution parameters. Then, the target surface was used to set light spot attributes, and a geometric optics method was employed to calculate light paths and inversely estimate the various spatial parameters of the reflecting plane. To perform backward reasoning has been verified in numerous related studies [3–5]. Furthermore, the light spots projected by commercially available dental lights are mostly oval or rectangular, with those in the direction of the x -axis ranging between 180 and 230 mm in length and those in the direction of the y -axis ranging between 70 and 130 mm in length. To satisfy the light spot testing requirements stipulated in ISO 9680:2007, which does not clearly specify light spot size, this study referenced the recommendations of certified and practicing dentists. The length of the rectangular light spots in the direction of the x -axis was set to 200 mm and that in the direction of the y -axis was set to 110 mm in the proposed dental light.

2. Reflector Design Analysis

In this study, a goniophotometer was used to measure the luminous intensity generated at various angles by the high-power LED developed by Nichia (SN: NCSL119A-H1-E). The intensity distribution parameters of the LED light source were established by referencing the vector relationship and energy conservation principles of Snell's Law proposed [6, 7]. See Figure 1, where $I(u, v)$ and $E(x, y)$ represent the intensity distribution of the light source direction, which is presented as (u, v) . The luminous flux of the light source complied with the energy conservation concept and was distributed across the target surface. Subsequently, the sector illumination of the unit area was calculated according to the luminous flux. Equation (1) is defined using Jacobian factors. Consider

$$\iint_{\Omega} I(u, v) |J(u, v)| du dv = \iint_D E(x, y) |J(x, y)| dx dy. \quad (1)$$

Using the Cartesian coordinates (x, y) of the illumination on the target surface, the curvature coverage of the free-form reflector corresponding to the target surface (u, v) can be obtained, as expressed in

$$\begin{aligned} x &= f_1(u), \\ y|_{x=f_1(u)} &= h(v|_u). \end{aligned} \quad (2)$$

Based on (2) and the law of energy conservation, backward reasoning can be used to verify that the light distribution in the various sectors of the target surface and the light source is consistent. This was further expressed using

$$\begin{aligned} u &= f_2(x), \\ v|_{u=f_2(x)} &= g(y|_x). \end{aligned} \quad (3)$$

The energy distribution of a LED light source projected onto various sectors of a target surface can be calculated by dividing the LED light source and the target surface into an identical number of sectors. Then, the sectors of the LED light source are matched to those of the target surface using a variable separation method. These corresponding sectors should contain the same amount of energy.

3. Results and Discussions

3.1. Calculating the Parameters of a Multiplanar Reflection Mirror. Based on the numerical calculation method formulated in the previous sections of this study, the photometric curve parameters of LED energy distribution and the light distribution parameters of the light source were established. The reflective optical component was divided into multiple surfaces, and the spatial coordinates of the component were defined. Next, based on reflection principles, light projected from the light source onto the reflection surface and from the reflection surface to the target surface was defined as the incidence light and reflected light, respectively. In addition, the incidence angle θ_1 and reflected angle θ_2 were obtained by calculating the surface normal N . Spatial concepts were incorporated to determine the configuration of the surface position and angle φ . In conventional design procedures, the known θ_1 and φ are incorporated into reflection principles to obtain θ_2 . However, the inference procedure proposed in this study alternatively incorporates known θ_1 and θ_2 into reflection principles to obtain φ , as shown in Figure 2. With this procedure, the target light spot positions can be used to inversely calculate the positions and angles of the various surfaces to satisfy the light spot shape requirements. Figure 3 shows the adjusted angles of the various independent surfaces and their compliance with the target surface. Because each surface is considered an independent unit during calculations, an interval between these independent surfaces is retained when CAD software is used for model establishment. To achieve a single reflector component design, the intervals between various independent surfaces were filled using a tangent arc method. Subsequently, simulations were conducted to verify whether the filler component influenced the shape of the light spots. The results showed that the reflected light

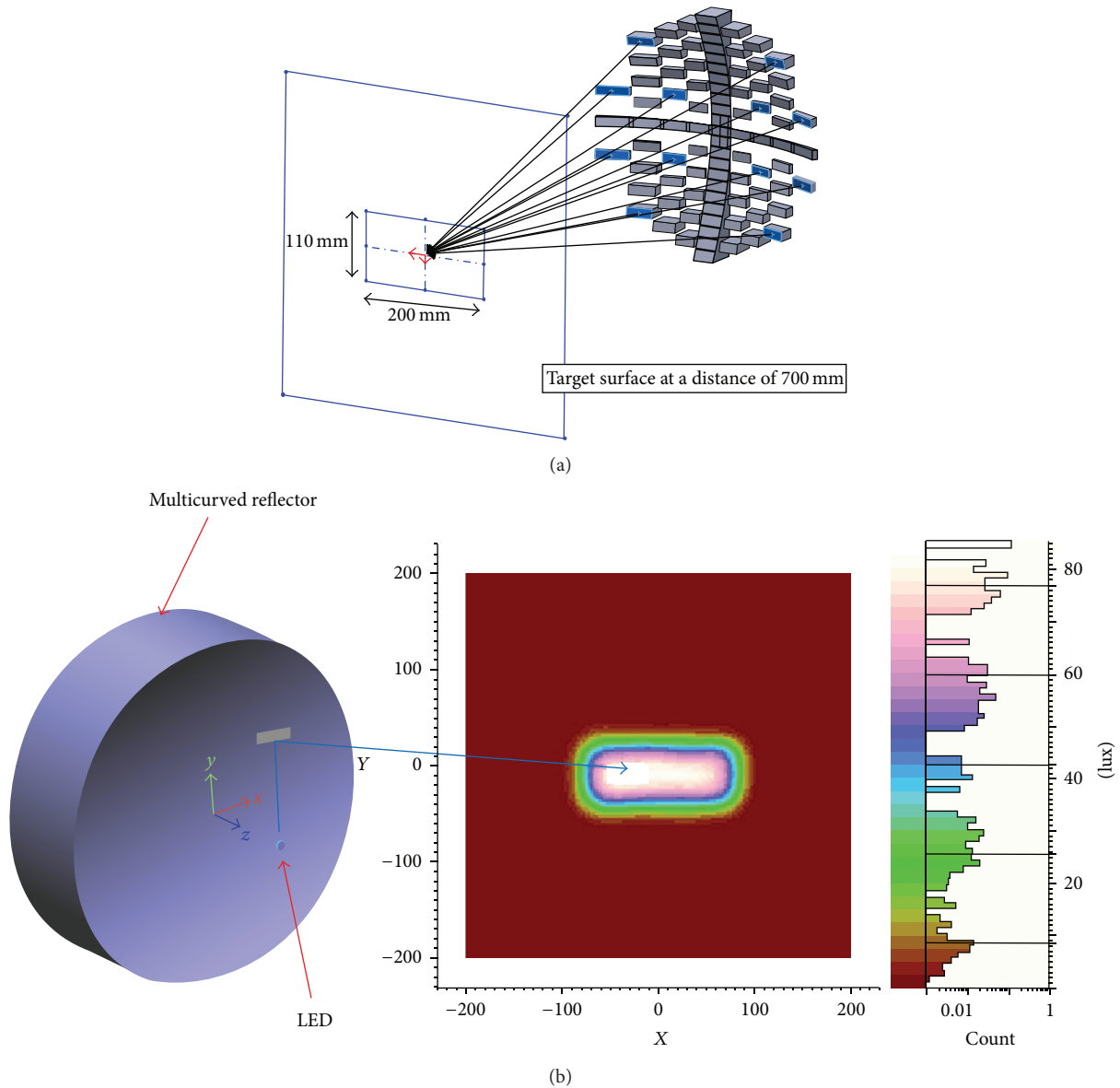


FIGURE 5: The multiplanar reflector dental light prototype and LED simulation. (a) Development of the reflector component and (b) an independent reflector surface and relevant light spot produced after successful projection of the reflected light source.

of the filled planar surfaces measured only 5 to 10 lux and did not significantly influence the reflection of the primary rectangular mirror, which exhibited a reflected light of 65 to 70 lux. Figure 4 shows the light spots and illumination potential of the LEDs projected onto the filled planar surfaces and primary surfaces before reflecting onto the target surface at a distance of 700 mm. To present the entire reflector, the x - and y -axes must first be drawn during component design to establish a cross-shaped framework. Then, optical simulation software must be employed to conduct preliminary simulations. The simulation results should not only confirm that light is reflected onto the target surface by the multiplanar mirror reflector, but also produce rectangular light spots when light is reflected onto the target surface at a distance

of 700 mm, thereby verifying that the reflection angles of the reflector in the directions of the two axes are correct.

3.2. Development of a Complete Reflector Model. By applying the completed cross-shaped reflector framework, the projected light spot contour of the reflector is forming. Thus, the remaining coordinate positions and deflection angles of the surface can be calculated. The reflection angles of the various surfaces are calculated according to the size of the target light spots and their corresponding coordinate positions on the independent surfaces in the various sectors of the reflector. The results are then illustrated using a 3D component, which is incorporated into optical simulation software for verification. As shown in Figure 5, each independent surface can

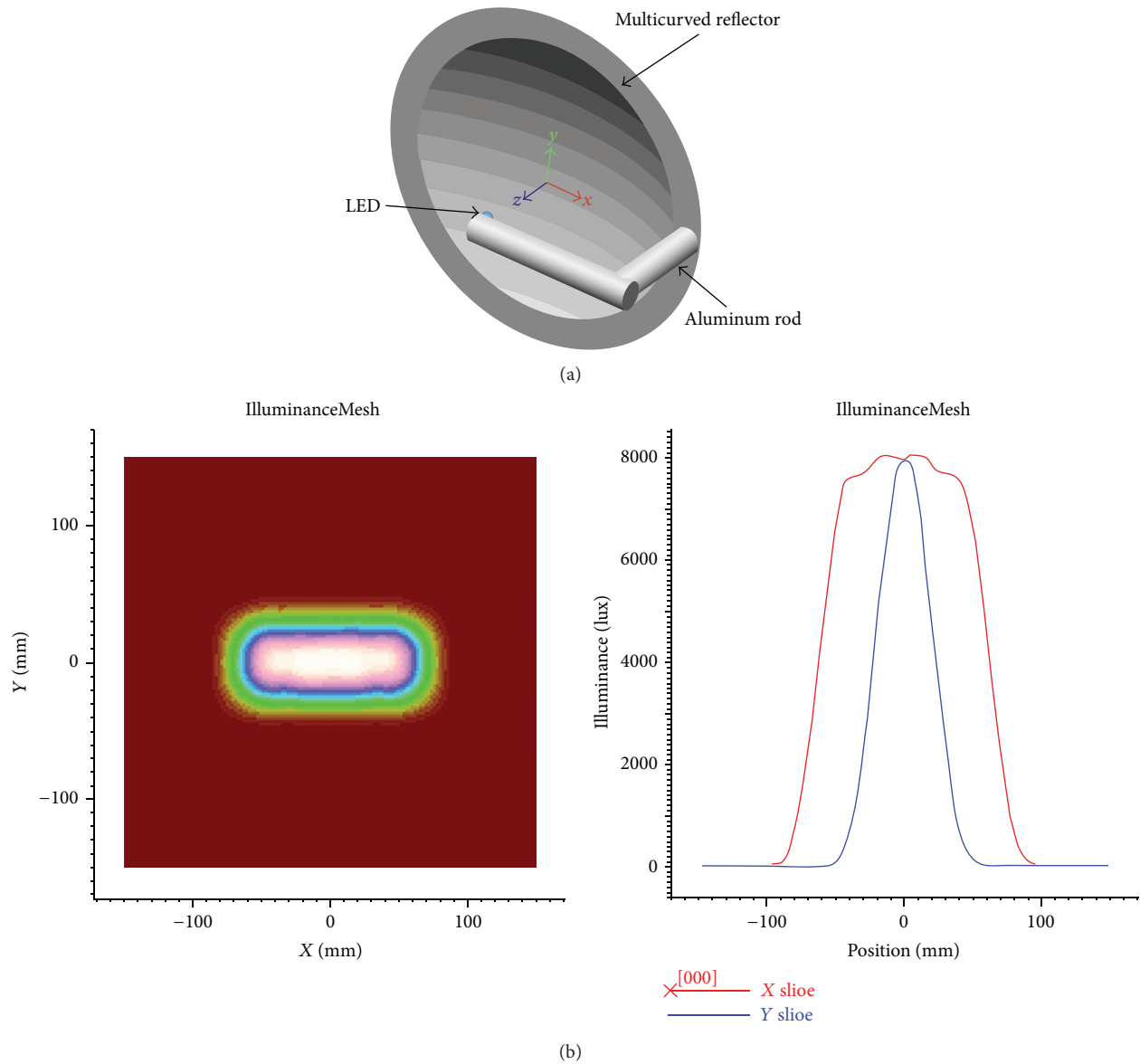


FIGURE 6: Reflector simulation results: (a) the relationship between rods and the reflector and (b) light spot illumination.

be simulated by adjusting the simulation software settings to verify the correctness of the results. Although calculating the independent surface parameters of the reflector is extremely time consuming, the surface structure of the reflector is horizontally and vertically symmetrical, which facilitates rapid calculation of the parameters of the remaining 3 structure quadrants after those in the first quadrant of the mirror are calculated. The filled planar surfaces are then calculated to connect the various independent surfaces into a single structure.

4. Reflector Prototype Trial

Based on the dental lamp regulations stipulated in ISO 9680:2007, at a projection distance of 700 mm, the maximum illumination of the light spots produced by the lamp must

be $\geq 8,000$ lux and $\leq 20,000$ lux, and the CRI must exceed 85 Ra. Figure 6(a) shows the 3D component diagram of the completed reflector model. In this study, the reflector model was formulated using a high-power LED light source developed by Nichia (SN: NCSL119A). The maximum flux for the LED was set as 85 lm. The reflecting material used for the model was aluminum, and the reflection coefficient was set as 90% in consideration of the precision coating on the prototype. Figure 6(b) shows that the results of the optical simulation software achieved target illumination of 8000 lux. In addition, the size of the light spots achieved lengths of 200 mm and widths of 110 mm, which was consistent with the design goals. In the illumination diagram, the red line represents the illumination in the direction of the x-axis and the blue line represents the illumination in the direction of the y-axis. The light spots in the illumination diagram clearly

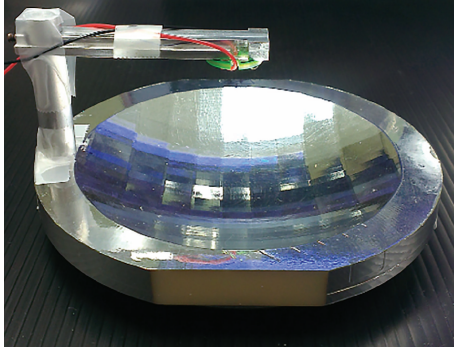


FIGURE 7: Prototype of the LED-based dental light reflector.

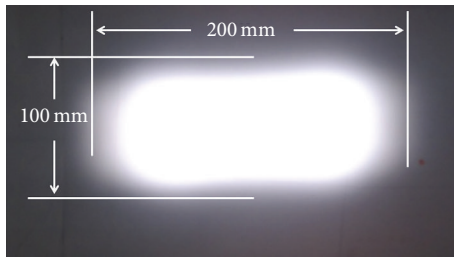


FIGURE 8: The actual light spot projected by the LED-based dental light reflector prototype.

show that significant illumination differences occurred on the edges of the light spots. However, the illumination at the outermost edge of the light spots still achieved 100 lux.

After verifying that the simulation results achieved the design goals, the completed reflector component was manufactured. The finished product is presented in Figure 7, which shows the LED-based dental reflector prototype. The prototype was produced using a high-power LED developed by Nichia (SN: NCSLI19A), with a maximum luminous flux of 120 lm. After the prototype was fitted with the LED, lighting tests were performed. The results of the light spot projections of the prototype are shown in Figure 8, where the light spot size achieved was 200 mm in length and 100 mm in width. The actual illumination was 12,000 lux. The width of the light spots showed a 9% error between the actual prototype and the simulation results. The cause of this error was determined to be the manufacturing process. Because of the limited size of the independent surfaces, the computer numerical control cutting tool lacked sufficient precision to cut the surfaces accurately. In addition, Figure 8 shows that the edges of the light spots exhibited clear cutoff lines. The halation on the outer rim of the light spot was caused by the charge-coupled device of the camera used to capture the image in a dark room. In actuality, the illumination measured less than 30 lux. Under normal room lighting, halation cannot be observed by the naked eye.

5. Conclusion

This study developed a nonarray-type multiplanar reflector that can be used to design LED-based dental lights.

The specific lighting angle of the LED was matched to the multiplanar reflector to enhance the lighting potential of the LED and achieve highly focused, luminous light spots with obvious cutoff lines. The dimensions of the proposed prototype were 120 mm in diameter, with a thickness of 20 mm. The size of the prototype was similar to or even smaller than that of commercially available conventional dental lamp reflectors. In addition, the size of the light spots produced by the reflector measured 200 mm in length and 100 mm in width, with maximum central illumination of 12,000 lux. Furthermore, the proposed prototype complies with the international standards and regulations stipulated in ISO 9680. During dental treatment, light spots in the direction of the x -axis are generally superior for illuminating the entirety of the patient's mouth. However, because the light spots in the direction of the y -axis are shorter, they are not projected into the patient's eyes.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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