A Study of Optical Design of Automotive Lighting System with Laser Source

Chan-Chuan Wen[1], Chao-Hsien Chen[2], Hsiao-Yi Lee[3], Shun-Hsyung Chang[4], Yi Chin Fang[5]

[1] Department of Shipping Technology, National Kaohsiung University of Science and Technology, Taiwan
[2] Department of Mechanical Engineering, National Kaohsiung University of Science and Technology, Taiwan
[3] Department of Electrical Engineering, National Kaohsiung University of Science and Technology, Taiwan
[4] Department of Microelectronics Engineering National Kaohsiung University of Science and Technology, Taiwan
[5] Department of Mechatronics Engineering, National Kaohsiung University of Science and Technology, Taiwan
wencc@nkust.edu.tw, smilechen615@yahoo.com.tw, leehy@nkust.edu.tw, shchang@nkust.edu.tw, yfang@nkust.edu.tw

Abstract

This study proposed a headlight for modern cars that uses lasers as a light source with optical fibers and employed a free-form surface for the optical design. A laser light source has advantages over light-emitting diodes (LEDs), a widely adopted light source on the market, in various aspects such as the emission of polarized light and a high luminous efficiency. However, regarding their application in headlights, lasers have the same weaknesses as do LED lights. They can be overheated when placed too close to engines or when in use for long durations, which causes the components to deteriorate quickly. Furthermore, the complexity of the optical design grew significantly from various problems involving laser light sources. Therefore, this study capitalized on the total internal reflection of optical fibers and located the laser light source to a position to better dissipate heat. An aspherical lens was used to facilitate the uniform distribution of the laser light. Finally, a free-form surface was incorporated into the light distribution design of the headlight. This pioneering optical design was aimed at improving luminous efficiency and reducing the complexity of the optical design. Furthermore, the white-red-green-blue laser light source was made adjustable by users to different color temperatures suitable for the ambient environment, with which the headlight provides various functions, such as changing the color temperature according to different weather conditions and operating as a fog light.

Keywords: Laser-light source, Fiber-optic laser, Non-imaging optical design, Free-form surface

1 Research Motives and Objectives

The development of automotive lighting can be traced back to the use of kerosene as a light source before the electrical lighting system was invented. Power generators for headlights were not developed and widely used in vehicles until the early 20th century, and the halogen headlight was invented in 1960. Halogen headlights remained the most popular headlights until they were replaced by light-emitting diodes (LEDs) after the recent rise of LED technology [1-4]. However, because a single LED provides insufficient brightness, LED lighting uses multiple LEDs, resulting in overheating and bulky LED headlights [5].

Conventional halogen lights are low cost but have a short service life and narrow beam angle. Because halogen lights have a short lifespan and easily overheat, they gradually fell out of use. High-intensity discharge (HID) lights have high brightness and a wide range of color temperature but a short lifespan and frequent light scattering. Although HID lights outperform halogen lights in brightness, they easily result in light scattering and thus cause discomfort for oncoming drivers or even lead to car accidents. LED lights are low cost and consume less electricity but have a limited beam angle. LED lights are the mainstream light source for headlights, have a longer life span than that of the other types of lights, and can be designed in diverse shapes. However, installing LED lights at an incorrect angle increases their potential glare, and such an incorrect angle is often observed even in headlights provided by original equipment manufacturers. By contrast, despite their high cost, laser headlights are small in size and respond quickly to ambient brightness while containing all the strengths possessed by LED lights with an even smaller size, longer lifespan, and higher brightness. Nevertheless, producing laser headlights involves a complex process.

Over the past few years, using lasers as a light source has received increasing popularity and attention, and semiconductor laser technology has gradually matured. Compared to LEDs as a light source, lasers

*Corresponding Author: Yi Chin Fang; E-mail: yfang@nkust.edu.tw
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exhibit various strengths such as higher luminous efficiency and the ability to quickly converge or expand beams. Therefore, companies have begun to research and develop laser-based products, including laser projectors and laser headlights. Accordingly, this study decided to research and develop a laser headlight with qualities missing in current LED headlights on the market. In addition to improving brightness and luminous efficiency, this study reduced the size of the headlight to provide space for other uses in cars. By capitalizing on the phenomenon of total internal reflection in optical fibers, this study moved lasers into a position that facilitates better heat dissipation. An aspherical lens was used for the laser light to be uniformly distributed. Finally, this study designed a headlight with free-form surfaces. This pioneering optical design increased luminous efficiency and reduced the complexity of the optical design. Furthermore, the red–green–blue color setting of the laser light was made adjustable to achieve different color temperatures according to the ambient environment. This headlight was equipped with diverse functions. For example, it could change the color temperature according to varying weather conditions and operate as a fog light.

2 Design Process and Description

The design process comprised two stages:

(1) Optical system layout of a light source and optical fibers:

When a high-intensity laser light is emitted onto a surface, the surface receives high energy per second per unit of the illuminated area, which results in a large amount of heat, a large impact, a high radiation pressure, strong photochemical effects, and a strong electromagnetic field. The nonlinear optical phenomena facilitate the modulation of the pulse width and wavelength (frequency) of light. This contributes to high sensitivity and detectability needed for spectrum detection.

Optical fiber communication is free from interference from electromagnetic waves and long-distance transmission and has a much larger communication capacity than that of an electrical cable line. These strengths make optical fiber communication the mainstream approach for communication, and light sources typically comprise semiconductor lasers.

This study employed the optical design software packages CODE V and LightTool to optimize the design of free-form surfaces, light sources, and optical fiber systems. The optical fibers separate the headlight system with the light source and, through the optical design, facilitate the uniform distribution of laser light.

(2) Free-form surfaces designed in accordance with relevant legal requirements:

A free-form surface is a complex and irregular continuous surface without a rotational axis of symmetry. In other words, it is a surface that can be of any shape. Accordingly, high uncertainty is present in the initial structural calculations, geometric surface, systemic optimization, production, and processing of a free-form surface. However, the development of multiaxial processing machines has enabled the large-scale production of free-form surfaces. Compared to conventional spherical and aspherical lenses, a free-form surface provides a high degree of freedom in design and facilitates flexible spatial arrangement. Therefore, a free-form surface simplifies the structure of an optical system and satisfies market needs for small-sized, miniaturized, and low-cost optical equipment. The optical characteristics of a free-form surface are manifested in its control over the direction of light.

There are various description methods for a free-form surface, all of which have the ability to represent various complex surface forms, good aberration correction performance, and rapid ray tracing and optimization convergence. According to how surface forms are controlled, these methods fall into two categories: global and local control methods. In a global method, each parameter exerts an influence on the global shape of a surface; therefore, even if a change is made in only one parameter, the sagitta and slope across a free-form surface change. Global methods include description by various polynomials. In a local method, each parameter has a limited influence on the shape of a surface; hence, the local shape of a surface can be adjusted through changes in one or some parameters.

In our experiment, free-form surfaces corrected the distribution of the low and high beams, and optical design methods were employed to ensure that the headlight specifications conformed to relevant legal regulations.

3 Specifications of the Laser Light and Optical Fibers

This study adopted a mixture of white, red, green, and blue laser lights, with the following specifications. Please find more information from Table 1.

Table 1. List of experimental equipment for optical system testing

Laser light color	Red Laser	Green Laser	Blue Laser	White Laser
Wavelength (nm)	633 nm	520 nm	450 nm	350~800nm
Optical Output Power (w)	0.08w	0.05w	0.01w	0.12w
Divergence angle $(\theta_{fwhm}\theta_{fwhm}\theta_{fwhm})$	5 × 13	5 × 18	4 × 18	4 × 18

In the light source design, the lasers were arranged in an array. Then, optical fibers were used to facilitate the change of position of the laser light source. The optical fibers (GA.S104, China Electric) were each 1.5 m in length. Table 2 presents the detailed specifications. Please find Figure 1 and Figure 2 for more details.

Table 2. Optical fiber specifications

Product model		Diameter (mm)		Allowable bending radius
End Glow	Solid Core	Solid Core	Teflon Cladding	60mm
GA.S57.E	GA.S57.S	5.7	6	
Refractive index of optical core (Core refractive index)				1.475
Refractive index of optical cladding (Cladding refractive index)				1.34
Numercial aperture (Numerical aperture)				0.62
Acceptance angle (Acceptance angle)				76°
Temperature range (Temperature range)				-20 to 120 °C
Life expectancy (Lifespan)				≥ 10 years
Critical angle (Critical angle)				≤ 50 °C
Attenuation (Attenuation)				≦1.5%m
Transmitting Wavelength (Transmission wavelength)				380~780mm

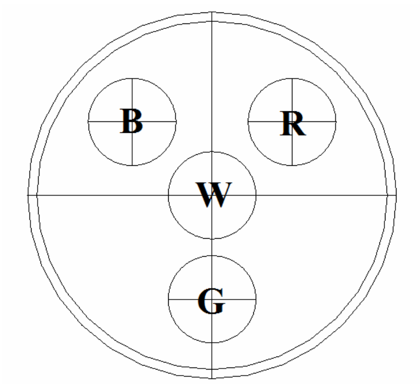

Figure 1. Layout of laser lights. According to the LightTool optimization, the laser output power and layout yielded the optimal result in conjunction with the optical fibers

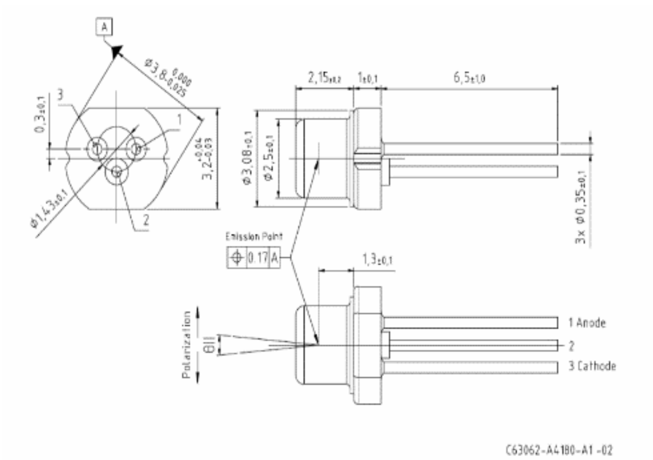

Figure 2. Computer-aided design drawing of the laser lights (presenting data on the laser lights, including their size, caliber, and diameter)

4 Design-Parameters for the Free-form Surface

Figure 3 and Figure 4 and Table 3 to Table 6 present the free-form surface design module and parameters, which were optimized using LightTool and CODE V according to the angles required for low and high beams.

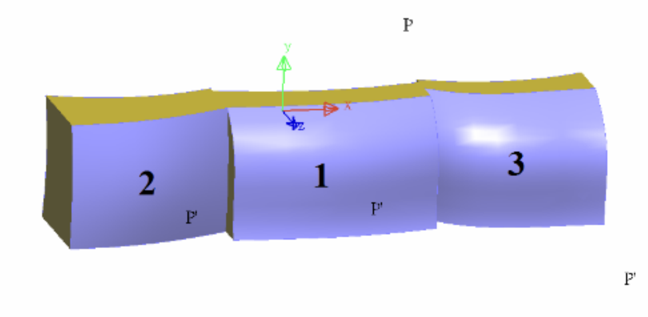

Figure 3. Free-form surfaces design for the low beam module

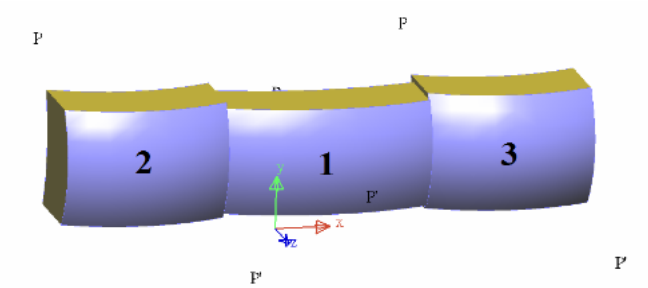

Figure 4. Free-form surfaces design for the high beam module

Table 3. Free-form surface parameters for the low beam module-1

Lenses	1		2		3	
Curvature radius (mm)	Front	200	Front	100	Front	100
	Rear	150	Rear	80	Rear	100

Table 4. Free-form surface parameters for the low beam module-2

Lenses / Coefficient	1	2	3
X	0.03	0.03	0.22
Y	0.037	0.03	0.055
X2	0.0001	0	0
XY	0	0.0015	0
Y2	0.008	0.01	0
X3	1.0e-005	0.0001	0
X2Y	0	0	0
XY2	0	0	0
Y3	0.0003	0.00035	0

Table 5. Free-form surface parameters for the high beam module-1

Lenses	1		2		3	
Curvature radius (mm)	Front	200	Front	100	Front	100
	Rear	150	Rear	100	Rear	100

Table 6. Free-form surface parameters for the high beam module-2

Lenses / Coefficients	1	2	3
X	0	0.02	0.02
Y	0	0	0.055
X2	0	0	0
XY	0	0.	0
Y2	0.007	0.005	0.007

5 Design Results

This design used 1.5-m-long optical fibers to lead the laser light source to a position where high heat dissipation could be attained. Then, an aspherical lens was used to uniformize the laser light distribution. Finally, a free-form surface was used to facilitate light distribution and light intensity distribution conforming to the legal regulations for headlights. The color temperature was set at 4000 K. The headlight cover's dimensions were 26 cm in width, 11.4 cm in length, and 9.5 cm in height. Figure 5 to Figure 10 present the headlight structure, light intensity distribution, and light color.

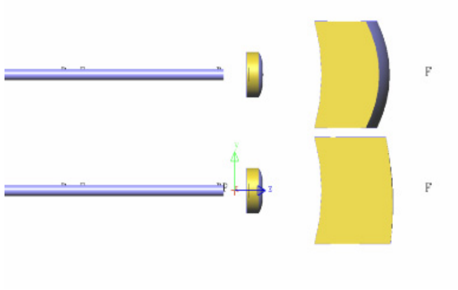

Figure 5. Laser headlight design-1

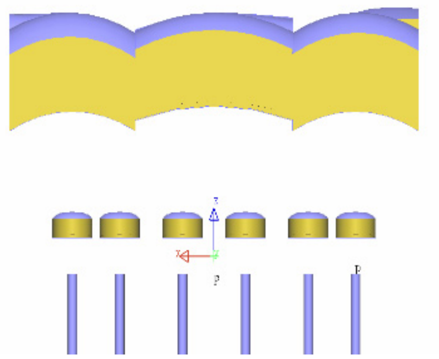

Figure 6. Laser headlight design-2

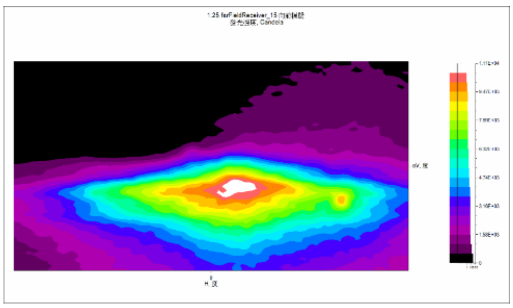

Figure 7. Light distribution simulation result for the low beam (which meets current European legal requirements)

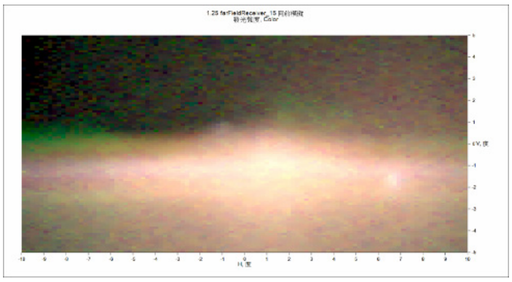

Figure 8. Light color simulation result for the low beam (which meets current European legal requirements)

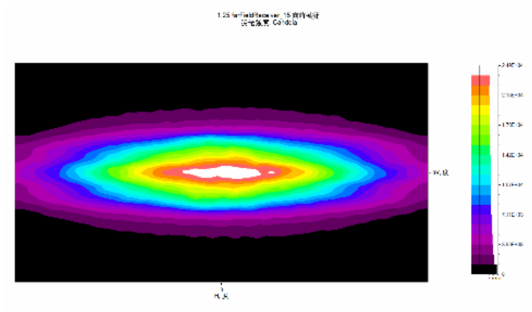

Figure 9. Light distribution simulation result for the high beam (which meets current European legal requirements)

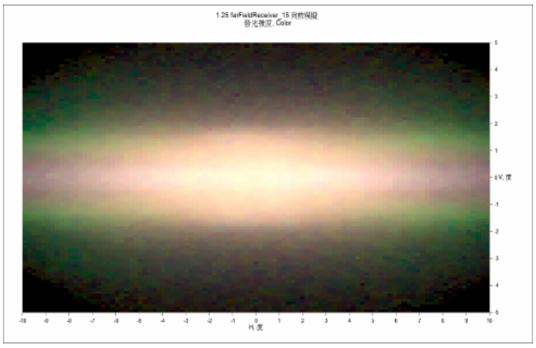

Figure 10. Light color simulation result for the high beam (which meets current European legal requirements)

6 Conclusion

In this design, white, red, green, and blue lasers were used to build the light source, and optical fibers—which exhibited total internal inflection—were used to lead the light source to a position in which better heat dissipation was facilitated. This prevents the overheating in headlights that is often generated after a long duration of use and when the car is running, thereby reducing the attrition of headlight components. Finally, a free-form surface was used to meet European legal requirements for the light distribution and light intensity distribution of high and low beams. This design comprised six light modules, among which only four were running under regular conditions. The other two modules were only activated when the car made turns to compensate for blind spots that could not be illuminated by the four modules that were regularly turned on. The greatest strength of the white–red–green–blue laser light source was its ability to change the color temperature of the headlight by controlling the electrical network.

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Biographies

Chan-Chuan Wen, a deputy professor of Kaohsiung University of Science and Technology, has engaged in both underwater surveying and integrated navigation system design for more than 30 years. At present he is also the chairman of Kaohsiung Marine Engineering Association that is the largest ocean engineering in Taiwan and now has paid a major attribution to the Taiwanese offshore wind farm development.

Chao-Hsien Chen earned his B.S. degree in physics from the Chinese Cultural University, M.S. and Ph.D. in electro-optical engineering from Notional Chiao Tung University. In 1999 he joined the Industrial Technology Research Institute, where he worked on optical design and measurement. In 2005, He joined

the National Kaohsiung University of Science and Technology and is now a professor.

Hsiao-Yi Lee is currently a professor at the Optoelectronic System Design Laboratory of Electrical Engineering Department at National Kaohsiung University of Science and Technology; and also a joint appointment professor at the Graduate Institute of Clinical Medicine, Kaohsiung Medical University. Dr. Lee has published more than 60 peer-reviewed journal papers and held more than 70 patents. His major research interests are: optics design, lighting design and optoelectronic systems for the applications of biomedicine.

Shun-Hsyung Chang had served as the Vice President of National Kaohsiung Marine University, Kaohsiung, Taiwan, from 2003 to 2006, and is currently a professor in the Department of Microelectronics Engineering at the National Kaohsiung University of Science and Technology. He has published over 250 scientific-technical publications, among which are 14 monographs (in particular, 6 books published with Springer and 8 books with Nova Science Publishers). He was co-chair 8 International conferences (PHENMA) in different Asian countries.

Yi Chin Fang is currently a professor at the department of mechatronics at National Kaohsiung University of Science and Technology. He was a lead featured editor of special issue of Applied Optics and Applied Optics; editor of IEEE journal. His academic interests are optical design, infrared physics, remote sensing and opto-mechatronical system design and testing.