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Optical design of LED-based automotive headlamps

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ABSTRACT

In order to solve the problem of high cost and low optical efficiency of current LED-based headlamps, we introduced a new optical design approach for LED-based automotive headlamps. In this configuration, 48 pieces of LEDs are used to build a LED array and the measuring screen is divided into multiple blocks to allow each LED to illuminate a block. A kind of secondary optical lens for a single LED is used so that the lights radiated from a single LED can form a rectangular beam region, whose optical efficiency is above 85% in theory. Lighting up different LEDs can illuminate different blocks, so as to realize low-beam and high-beam lighting. Ray tracing simulation results fulfill the low-beam and high-beam optical demands of the regulation. Since low-power LEDs need no additional reflectors, cost lower and obtain higher efficiency than high-power LEDs, this configuration achieves high reliability installation and can partially realize the functions of Adaptive Front-Lighting System (AFS).

1. Introduction

Light-Emitting Diode (LED) is viewed as the most competitive solid light source in the 21st century thanks to their merits such as long life, low energy consumption, fast response, design flexibility and no mercury pollution. The core issue of high-power LED is chip cooling. The luminous efficiency will drop dramatically with the rise of chip temperature. Although the low-power LED has the same problem, it has less heat. We will be able to achieve the purpose of cooling by placing a cooling fin under the MCPCB. Low-power LED also has price and light efficiency advantage meanwhile. Now LEDs are widely used in interior lighting and exterior signal devices [1]. In recent years, with the advance in material and packaging technology of LED, the luminous efficiency of a single LED has reached to 130 lm/W. Therefore, use of LEDs in automotive headlamp is an inevitable tend. However, the luminescence characteristic of LED is greatly different from conventional light sources, thus it becomes particularly important to control LED light distribution [2–8].

Vehicle headlamp is one of the important guarantees for safe driving. The high-power LEDs widely used in the existing LED headlamps can meet the lighting requirements [9,10], but they do not use energy efficiently, cost high and require a complex high-efficient cooling system, which increases the overall cost and reduce the reliability. For example, Cvetkovic et al. have proposed a scheme for the optical device of LED headlamp based on the SMS method [9]. The optical efficiencies of both low-beam and high-beam lamps are just 76% and 77.2%, respectively. It was followed by Chen et al. and they introduced a new method of designing two kinds of lenses. In their study, both of the lenses had optical efficiencies of more than 88%. But the calculation was too complicated, it would take quite a long time to optimize all the parameters [3]. In this work, we designed an optical lens according to reference [11]. The light efficiency of this method was more than 85% and the optical element ensures an increase in light efficiency up to 20–30% compared with the optical elements with single refractive surface. Then a low-cost and low-power LED-based vehicle headlamp was introduced, which did not need the complex cooling system, accordingly was able to reduce cost, increase reliability and save energy. The low-power LED can not only reduce the costs, but also promotes the system efficiency compared to high-power LED.

2. Light distribution demands

The automotive headlamp mainly consists of low-beam lights and high-beam lights, their illumination and distribution are strictly regulated in many countries. Here Chinese National Regulation is employed, which shares similar ideas of the regulations of other countries. Fig. 1 is the 25 m-right-ahead-of-the-headlamp measuring screen, provided by Chinese National Regulation GB 4599-2007 "Motor Vehicle Headlamp Equipped with Filament Lamps" [12], which is similar to the ECE R112 "Uniform provisions concerning the approval of motor vehicle headlamps emitting an asymmetrical passing beam or a driving beam or both

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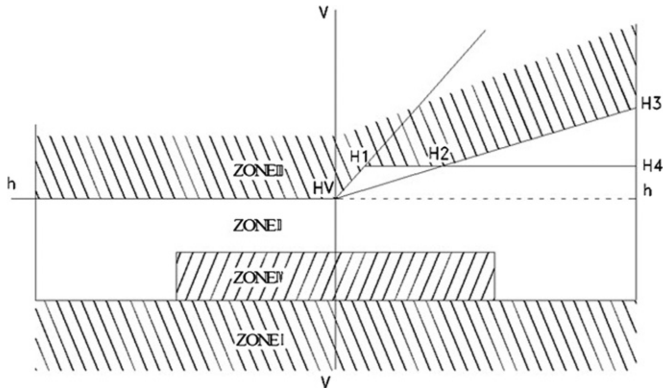

Fig. 1. Measuring Screen.

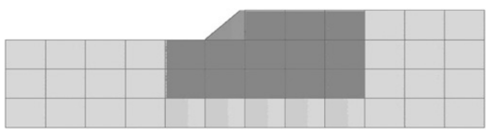

Fig. 2. Measuring screen division of low-beam.

and equipped with filament lamps and/or light-emitting diode (LED) modules" and SAE J1383-1996 "Performance Requirements For Motor Vehicle Headlamps" regulations.

According to the regulations, it is not uniform on the light distribution of the low-beam and the high-beam. Low-beam light distribution is more complex, which demands the light intensity in the middle area of the measuring screen to be higher. Besides, the illumination in zone I and II cannot be more than 20 lx and 0.7 lx, the illumination in zone IV cannot be less than 2 lx. Furthermore, in order to prevent glaring to the driver on the opposite lane, a sharp horizontal and 15° inclined cut-off line or two sharp horizontal and a 45° inclined cut-off line, which is marked as HV–H2–H3 or HV–H1–H2–H4 line as shown in Fig. 1, should be created. In this study, the HV–H1–H2–H4 line is chosen. In contrast, high-beam headlamp light distribution is much simpler, whose light intensity is also higher in the middle area of the measuring screen. Its maximum illumination cannot be less than 32 lx and the illumination at HV point should be more than 28.8 lx.

3. Optical design

In our design, firstly, the measuring screen is divided into multiple blocks so that each LED can illuminate one block. Secondly, LEDs with proper lenses are used so that the lights will generate a rectangular beam region after passing through the lens. Finally, different LEDs are lighted up so that they can realize different lighting functions.

3.1. Measuring screen division

The measuring screen is divided into 48 blocks; the darker color represents high light intensity while the shallow color indicates weak light intensity, as shown in Figs. 2 and 3. In Fig. 2, five rectangular blocks located on the top-left screen are omitted, and a rectangular area is inclined according to the cut-off line.

The two kinds of LEDs, which are used to illuminate the blocks, have the same dimension and luminous angle. Therefore, they can use the same secondary optical lenses to transform the ray to a rectangular beam region. Besides, the 45° inclined cut-off line is realized by lighting up a LED with 45° inclined lens.

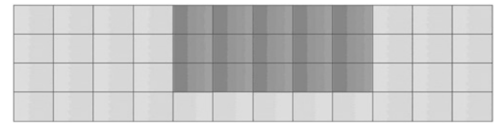

Fig. 3. Measuring screen division of high-beam.

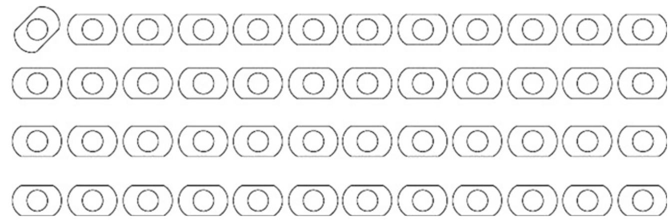

Fig. 4. The schematic diagram of the LED array.

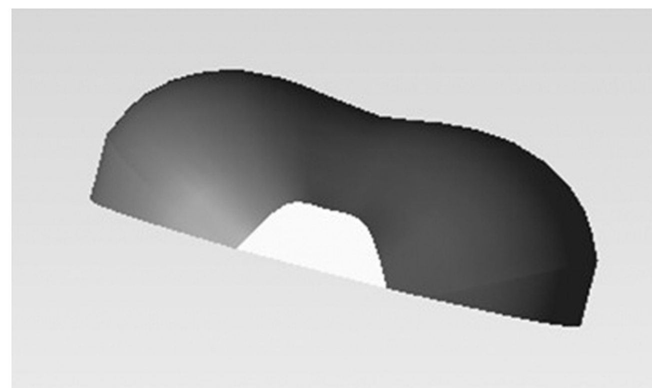

Fig. 5. Design of optical lens.

3.2. Arrangement of the LEDs

According to the measuring screen division and light distribution demands, a LED array is designed as displayed in Fig. 4. Each circle represents a LED with a secondary optical lens on it. The LEDs are on the MCPCB. The LEDs are CREE® XLamp® ML-E and ML-B® LEDs. A total of 48 pieces of low-price LEDs are used and their actual operating power can also be continuously adjusted, some LEDs do not work at the a maximum power. The length and width of the LED array are set at 23 cm and 10 cm, respectively, based on light distribution demands and heat dissipation treatment. These LEDs are distributed in a large area, so it does not require special cooling devices for this headlamp. We can achieve the point by placing a cooling fin under the MCPCB.

3.3. Rectangular beam region

The lenses designed in this study are supported by another research group according to reference [11]. As shown in Fig. 5, they are 17 mm in length and 15 mm in width. The lens material is air–PMMA with a refractive index of 1.491. Ray tracing simulation results demonstrate that the light radiated from a single LED can form a 600 mm × 500 mm rectangular region after passing through the lens, and its maximum illumination is more than 70 lx for a ML-E LED, as shown in Fig. 6. The rectangular beam region is 25 m ahead. Simulation result shows that the optical efficiency of this lens is above 85%. The light intensity in the rectangular edge is weak, so the edges of the illuminated rectangular regions are overlapped.