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Design of LED Packaging Module for Automotive Forward-lighting Application

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Abstract

In this study, we firstly analyse the requirements both in optical and thermal fields in theory. With the results of theoretical analysis, we design the application specific light emitting diode (LED) packaging (ASLP) with optimized structure parameters and appropriate packaging materials. According to this design, several samples are made and tested. The test results show that the LED packaging can provide a light flux of 1000lm with a sharp cut-off and the chromaticity of packaging can comply with ECE regulations. Also, the thermal resistance of packaging can be less than 1.3K/W when equivalent heat transfer coefficient of cooling system is about 5000 W/(m^2•K). Secondly, based on the test results, we design a supporting optical system with a novel freeform multi-reflector, an effective cooling system and even a complete LED packaging module for automotive forward-lighting application, including low-beam and high-beam functions. Finally, we test the performances of the LED packaging module, and the test results in simulation can fully comply with ECE and GB regulations.

Introduction

Since LEDs have many advantages over the light sources conventionally used in automotive applications, such as good reliability, energy and space savings, non fragile, environmental friendly and long life, LEDs were used in dashboard lighting, interior lighting and exterior signal lighting in most recent decades [1]. It is natural to apply LEDs in forward-lighting application for automotives and it has been the trend that many car brands have been using LEDs now in their new models. Commonly, halogen bulb or high intensity discharge (HID) is used as the light source of headlamp. These two conventional light sources have same characteristics of high luminance, small etendue, high temperature and a strip shaped emitting area. However in conventional LED packaging, there are many differences both in optical and thermal performances. And these differences cause that LEDs of traditional packaging are not applicable for forward-lighting.

On the other hand, a research has shown that the accident rate at night is about 44% [2]. Therefore, the illumination quality of automotive lighting system is essential for safe and driving comfort. In front-lighting, as low-beam light should give adequate illumination within safe braking distance and cannot make glare to drivers on the opposite lane, there are many restrictions for low-beam light in various regulations, such as ECE regulations in europe, SAE regulations in america and GB regulations in china [3-5]. These regulations specify the range of illuminances on specific points or segment areas and define the minimum gradient of the cut-off line. That is why the optical design of low-beam is the most difficult part in design of whole lamp. In recent years, as the development of non imaging optics, some LED headlamp optical design methods based on non imaging optics are suggested. Oliver Dross *et al.* have invented an excellent approach to designing the optical device of LED headlamp based on SMS method [6]. In their design, the optical efficiencies of both low-beam and high-beam lamp are more than 75%, which are very high values so far. In addition, Fresnel lens and micro lenses array are attempted to be used in low-beam lens design [7, 8]. As the structures of lenses are quite complex, there may be some difficulties in manufacturing process. Further more, some researchers even use optical fiber and digital micro mirror device (DMD) for transmission and control of light in LED headlamp design [9, 10]. All these outstanding design method above can achieve a flexible light distribution. In this paper, we develop optical system with a novel freeform multi-reflector, an effective cooling system and a mechanical structure aiming at the novel application specific LED packaging. It is expected that very low cost LED headlamp can be realized, which will likely challenge HID lighting and even the very cheap halogen bulb based headlamp.

Requirements of LED for Forward-lighting

- ***Small Etendue***

From non imaging optics, we know that the etendue (E) of light cannot be reduced without loss in an optical system [11]. In other words, it means that etendue of light source (E_{Source}) should be not more than the etendue of optic system (E_{System}) to ensure high light transmittance efficiency. This relationship can be described by Eq. 1.

$$E_{Source} \le E_{System} \tag{1}$$

Etendue E is defined to describe the extention of lights both in area and angle, and it is expressed as follow:

$$E = n^2 \iint d\Omega \bullet dA \tag{2}$$

where n is the refraction index of the material the light source embedded in (For traditional packaged LED, this material is silicone), Ω is the solid angle occupied by lights and A is the emitting area.

As most LED modules are lambert emitters, E_{Source} can be expressed as:

$$E = n^2 \bullet \pi \bullet \sin^2 \alpha \bullet A \tag{3}$$

where α is the half angle of the cone the light in (If a LED emits lights in a half space, α is 90°). In forward-lighting of automotive application, the divergence angle of lights in vertical direction is restricted strictly to avoid glare to the drivers on the opposite lane. Additionally, the size of lamp aperture is limited by vehicle design styling. Therefore, the etendue of lamp's optic system is always limited. From eq. 1, we can conclude that LED packaging with a small etendue is needed for high optical efficiency in forward-lighting application.

Eq. 3 shows that the etendue of LED packaging can be decreased by using encapsulating material with a small refraction index *n* and decreasing the emitting area.

- ***High Luminance***

For low-beam light, the light intensity varies in a range of several hundreds to 20000 candelas. At certain derection, the light intensity is very large which is called hotspot, e.g. 75R point, while only about 300 cd in zone III in firgure 1. From reference 11, we can get the light intensity of hotspot as eq. 4.

$$I_{hotspot} = \frac{1}{\Omega_{hotspot}} L_s A_s \Omega_s = A_{lamp} L_s \tag{4}$$

Where $\Omega_{hotspot}$ and Ω_s are the solid angular spreads of hotspot and light source in separately, L_s is luminance of LED, A_s and A_{lamp} is the apertures of LED and lamp in separately. Therefore in order to achieve a large light intensity at hotspot, the aperture of lamp should be large enough. However, the aperture of lamp is always limited by the vehicle styling design. Hereby, the luminance of LED should be increased greatly. For lambertain emitters, L_s can be expressed as follows:

$$L_s = \frac{I_0}{A_s} = \frac{\phi_s}{\pi A_s} \tag{5}$$

In order to increase the luminance, LED packaging should emit more light flux Φ_s and has a small emitting area A_s. For LED packaging, the efficient way to decrease the emitting area is conformal coating technology.

- ***Strip Shape Emitter with Sharp Cut-off***

The method in common use for optical design is overlapping the images of light source on test screen to form a regulation compliant beam pattern. As the beam patterns specified by regulations have a larger spread in horizontal direction than vertical direction, the light source should be strip shaped emiter [12]. Additionally, as low-beam light shoud produce a sharp horizontal cut-off line on the test screen, the emitting area of light source should also provide a sharp cut-off in luminance to form images with sharp cut-off too. In conventional LED packaging, there is a phosphor layer with lager size than LED chip, which increases the emitting area and blurs the cut-off [13]. That is why LED of traditional packaging is not suit for forward-lighting.

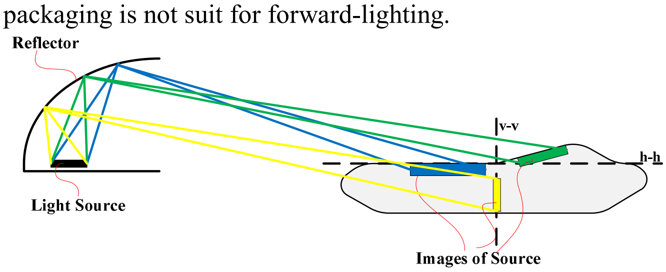

Figure 1. Schematic diagram of overlapping images of light source on test screen.

- ***Small Thermal Resistance of Packaging***

Besides the requirements in optics, there are also many requirements on thermal performance of LED packaging. As headlamp is usually installed in the engine compartment, the ambient temperature of headlamp can reach to 85℃ [14]. The optical performance of LED may degenerate greatly when working at a high ambient temperature. Therefore LED packaging should have a low thermal resistance to keep a low junction temperature of LED chip. In automotive forward-lighting application, as requirements in optics refered above, LED chips array should be arranged densely, which increases the difficulty of thermal management greatly. Therefore some packaging structures with small thermal resistance are prefered in this application specfic LED packaging, such as chip on board technology (COB).

Designing Cases and Experiments

- ***ASLP for Automotive Forward-lighting Application***

In order to comply with the requirement in optics, we design a novel LED packaging with small etendue and high luminance. Additionally, emitting area of this LED packaging is a rectangular area with a very sharp cut-off. Figure 2 shows the structure of this LED packaging.

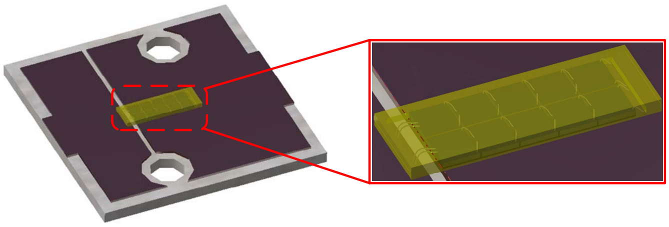

Figure 2. Schematic diagram of LED packaging.

In this packaging, ten conventional high power blue LED chips are arranged in a 2×5 array and covered by a phosphor layer with conformal coating. Wires connect the ten chips into two series circuit (five chips for each branch) and are also packaged in the phosphor layer. As the phosphor layer is exposed in the air directly, the refraction index *n* is 1. Furthermore, the sizes of emitting area for both blue light and yellow light are as small as the size of LED chips array (~2.1mm × 5.3mm), therefore this packaging have a small etendue. Also, this packaging can provide a rectangular emitting area with a sharp cut-off.

The board used in the packaging is direct bond copper (DBC) board and LED chips are bonded on the board derectly. The thicknesses of both the ceramic and copper are optimized to obtain a minimum thermal resistance. We simulate the thermal resistances of LED packaging at different equivalent heat transfer coefficients (EHTC) loaded at bottom surface of the packaging. We get the heat distribution on LED packaging when EHTC is 5000 W/(m^2 • K) and ambient temperature is 85□. From the simulation results, the thermal resistance can be less than 1K/W when EHTC of cooling system is large enough. The simulation result is shown in figure 3.

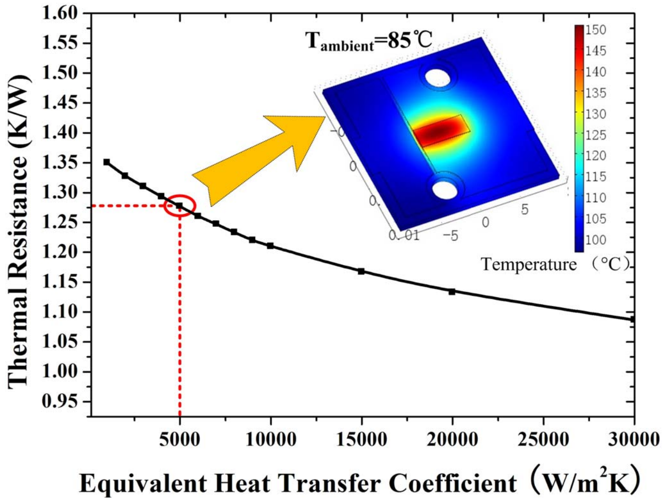

Figure 3. Simulation results on thermal resistance and heat distribution of LED packaging.

We also have made some packaging samples shown in figure 4.

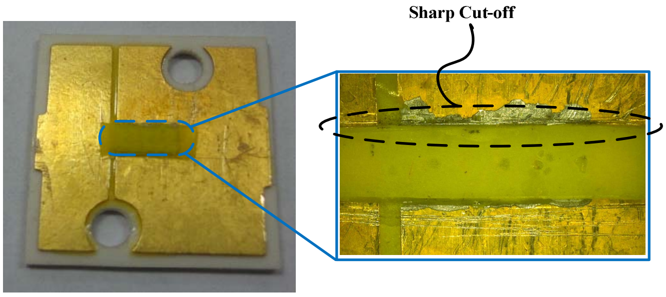

Figure 4. Picture of ASLP sample.

The test results of our samples are listed in table 1.

Table 1. Test results of ASLP samples.

Sample #	*x*	*y*	T_C *(K)*	Φ *(lm)*	*R*
1	0.3389	0.3549	5244	1062	13.4%
2	0.3239	0.3237	5956	1039	13.1%
3	0.3391	0.3532	5238	1003	13.5%

In above table, *x/y* is the chromaticity coortinate, T_C is color temperature, Φ is light flux and *R* is percentage of red light which is required to be greater than 5% according to ECE regulation.

- ***Optical & Thermal Design for Module***

According to the design of ASLP and test results, we build a precise model and design a supporting optical system with a novel freeform multi-reflector, an effective cooling system and even a complete module including low-beam and high-beam functions. Figure 5 shows the module we have designed. Both low-beam and high-beam functions are integrated in this lamp. In optical design, we use two multi-reflectors instead of projection system to achieve low-cost and high optical efficiency. Figure 6 shows the simulated beam pattern of low-beam function on test screen.

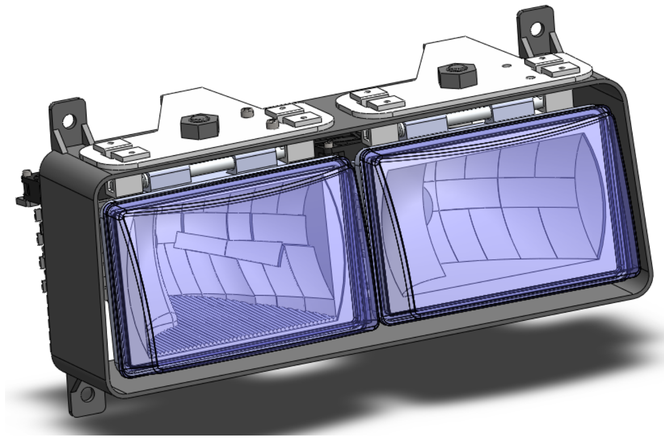

Figure 5. Designed LED lamp with low-beam and high-beam functions.

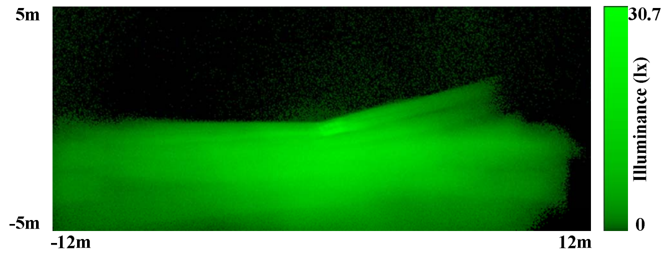

Figure 6. Simulated illuminance distribution on test screen for low-beam function.

The comparison of simulated illumination and required illumination in lux for ECE R112 regulation is shown in Table 2, which indicates the optical performance of the low-beam lens can fully comply with the ECE regulation. Additionally, the optical efficiency of reflector can reach to 65%.

Table 2. Simulated illumination result compared with the corresponding value of ECE R112 (Class B) for low-beam light.

Test Points	**Required illumination by regulation in lux**	**Simulated illumination in lux**
B50L	**⩽0.4**	**0.13**
75R	**⩾12**	**22.1**
75L	**⩽12**	**6.16**
50L	**⩽15**	**8.28**
50R	**⩾12**	**23.94**
50V	**⩾6**	**19.13**
25L	**⩾2**	**9.04**
25R	**⩾2**	**10.25**
Zone III	**⩽0.7**	**√**
Zone IV	**⩾3**	**√**
Zone I	**⩽2E_{50R}**	**√**
Point 1+Point 2+Point 3	**⩾0.3**	**0.36**
Point 4+Point 5+Point 6	**⩾0.6**	**0.67**
Point 7	**0.1-0.7**	**0.19**
Point 8	**0.2-0.7**	**0.32**

The simulated beam pattern of high-beam function is shown in figure 7 and illuminances on test points are listed in table 3.

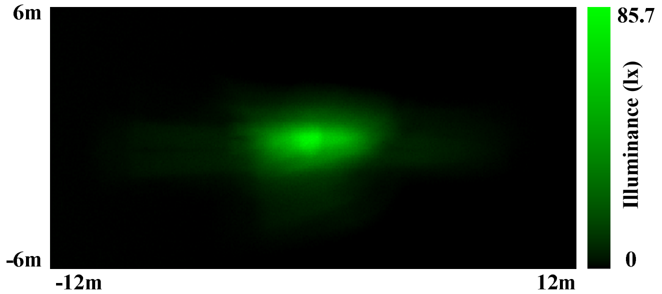

Figure 7. Simulated illuminance distribution on test screen for high-beam function.

Table 3. Simulated illumination result compared with the corresponding value of ECE R112 for high-beam light.

Test Points	Required illumination by regulation in lux	Simulated illumination in lux
E_{max}	⩾48&⩽240	85.7
HV	⩾0.8 E_{max}	83.8
HV to 1125L and R	⩾24	⩾55.2
HV to 2250L and R	⩾6	⩾30.2

The test results shown above show that the LED headlamp with low-beam and high-beam functions can fully comply with ECE regulation and provide a high optical efficiency.

Besides the optical design, we also have done some work on thermal management. In our design, a heat sink with optimized sizes and structures and a fan are used in the cooling system shown in figure 8.

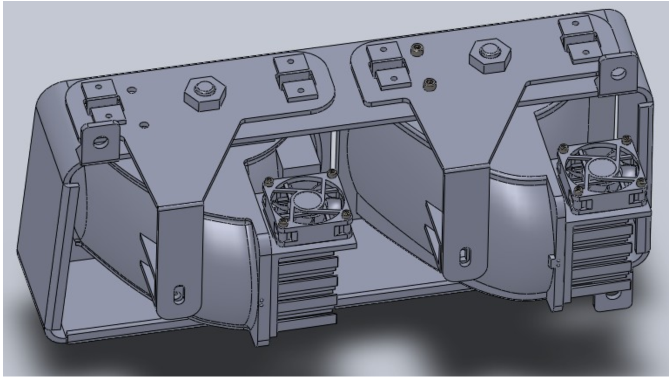

Figure 8. Schematic diagram of cooling system in LED headlamp.

The simulated heat distribution on heatsink is shown in figure 9. The ambient temperature is 85℃ which is close to the temperature near headlamp in engine compartment. The simulation results show that the temperature on the surface ASLP attached on is about 110℃, therefore the junction temperature might be less than 150℃.

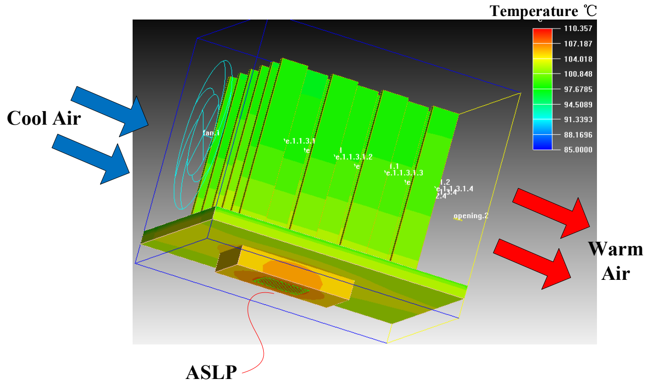

Figure 9. Simulated heat distribution on heatsink when ambient temperature is 85℃.

Conclusions

In this paper, we firstly analyse the requirements both in optical and thermal fields in theory. Secondly, with the results of theoretical analysis, we design the ASLP with optimized structure parameters and appropriate packaging materials. According to this design, several samples are made and tested. The test results show that the LED packaging can provide a light flux of 1000lm with a sharp cut-off and the chromaticity of packaging can comply with ECE regulations. Also, the thermal resistance of packaging can be less than 1.3K/W when equivalent heat transfer coefficient of cooling system is about 5000 W/(m^2•K). Finally, based on the test results, we design a supporting optical system with a novel freeform multi-reflector, an effective cooling system and even a complete LED packaging module for automotive forward-lighting application including low-beam and high-beam functions. The simulation results show that our design of LED packaging module can fully comply with the ECE regulation. It is expected that very low cost and novel LED headlamp can be realized, which will likely challenge HID lighting and even the very cheap halogen bulb based headlamp. However we have not done all the tests by experiment and this work will be done in our further research.

Acknowledgments

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References

1. Liu, S. *et al*, LED Packaging for Lighting Applications, Chemical Industry Press and John Wiley & Sons, 2011 (Beijing 2011).
2. A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System, US Department pf transportation (2001).
3. United Nations Economic Commission for Europe vehicle regulations, Reg. 112-Rev. 2.
4. Society of Automotive Engineers (SAE) for Harmonized Vehicle Headlamp Performance Requirements, J1735.
5. National Standard of the People's Republic of China for Motor Vehicle Headlamps Equipped with Filament Lamps, GB4599-2007.
6. Aleksandra, C. *et al*, "Etendue-preserving Mixing and Projection Optics for High-luminance LEDs, Applied to

Automotive Headlamps," Optics Express, Vol. 14, No. 26 (2006), PP. 113014.
7. Andre, D. *et al*, "New Design Tools for LED Headlamps," Proc. SPIE 7003, 2008.
8. Chen, F. *et al*, "Design Method of High-efficieent LED Headlamp Lens," Optics Express, Vol. 18, No. 20 (2010), PP. 20926-20938.
9. Chen, J. J. *et al*, "Computer Modeling of a Fiber-and-light-emitting-diode-based Vehicle Headlamp," Optical Engineering, Vol. 49, No. 7 (2010), PP. 073002.1-073003.8.
10. A, G. , "Optical Concept for an Active Headlamp With a DMD Array," Proc. SPIE 7003, 2008.
11. Jiao, J. Z. *et al*, "Etendue Concerns for Automotive Headlamps Using White LEDs," Proc. SPIE 5187, 2004.
12. Jiao, J. Z. *et al*, "High Efficiency Reflector Optics for LED Automotive Forward Lighting," Proc. SPIE 6670, 2007.
13. Oliver, D. *et al*, "LED Headlight Architecture That Creats a High Quality Beam Pattern in Dependent of LED Short Comings," Proc. SPIE 5942, 2005.
14. Pohlmann, W. et al, "High Performance LED Lamps for Automobile : Needs and Opportunities," Proc. SPIE 6797, 2007.