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High Efficiency Reflector Optics for LED Automotive Forward Lighting

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ABSTRACT

Although white LED lumen output and luminance have both substantially been increased in the last few years, multiple LEDs are still needed, at present time, to meet automotive forward lighting such as low beam headlamp photometric specifications. Use of multiple LEDs in combination with optics is often constrained by the lamp size. With the goal of minimizing the number of LEDs used in an automotive forward lighting design, further studies have been conducted to optimize reflector optics for the fog lamp and headlamp low beam applications. The studies included different types of LEDs by means of lumen output and effective emitting area. In addition, the system étendue ^{[1]-[3]} and its optical transformations have been taken into considerations in the studies.

Keyword: Étendue, LED, Automotive forward lighting

1. INTRODUCTION

The goal of an optical design for an automotive forward lighting device is to achieve desired photometry performance for public road safety. Very often, the lamp package size, especially the aperture, is controlled or restricted by the vehicle styling preference. Therefore, it is necessary to design the optical system in which the light collection efficiency is optimized. On the other hand, current available single LED device (may contain multiple chips) produces less luminous flux output comparing to the exiting forward lighting light sources such as tungsten halogen bulbs or high intensity discharge (HID) burners. Therefore, multiple LED devices may need to be used. It is important, when LED sources are proposed for the forward lighting applications, the optical system light collection efficiency is optimized so that minimum numbers of LEDs may be used.

In one of the previous studies ^[1], five basic types of optical transformations used in a forward lighting optical design were discussed. These optical transformations are conducted via optical systems of A) a reflector-optics device; B) an ellipsoidal (or similar) reflector; C) a projection lens (The combination of these transforms, B and C, is referred to a projector module system); D) a parabolic reflector; E) a lens array (The combination of the transforms of D and E is referred to the lens optical design). For simplicity, the optical systems can be classified as: Reflector Optics, Projector Module, and Lens Optics. For some LED applications, projection lens can be used alone without constructing the projector module.

Based on the needs of optimization of light collection efficiency when LEDs are proposed to be used for forward lighting application, it is necessary to further study the light collection efficiency for each of five types of optical transformation. In the following section, the conclusion can be drawn that one type of optical system may provide the highest light collection efficiency. If proper LED source devices are selected in the optical design while the light collection efficiency has been optimized, new design proposal can be established so that a compact size of forward lighting system with high photometry performance can be achieved.

In following sections, the efficiency of lamp system with inétendue consideration will be discussed in section 2; and light collection efficiency comparison for different types of forward lighting systems will be listed in section 3. In section 4, LED sources for forward lighting system applications will be expressed. The method of optimized reflector optics system for LED forward lighting lamps then will be introduced in section 5. Hardware test results are shown in section 6 “Design and test results of LED fog lamp” and in section 7 “Design and test results of LED head lamp low beam”.

* Majority of the work was conducted while the author was with North American Lighting, Inc.

2. EFFICIENCY OF LAMP SYSTEM

A typical automotive headlamp is required to provide a specific light distribution output – a beam pattern. When the headlamp is constructed with multiple optical units or compartments and N pieces of the LED light sources, each associated with the optical unit may have a different étendue value, and it may provide a different luminous intensity distribution. The total lumen flux from the forward lighting device (e.g., a headlamp) with multiple optical units and N LED sources can be expressed as:

$$\Phi_{lamp} = L_{lamp} \sum_i A_{(lamp,i)} \Omega_{(lamp,i)} = \eta N L_s A_s \Omega_s \quad (1)$$

where η indicates the system efficiency; A_s is the light source, or the LED emitter size; Ω_s is the solid angle of the light emitting from the LED; $A_{(lamp,i)}$ is the lamp i th sub-(projected) aperture; $\Omega_{(lamp,i)}$ is the solid angle of the sub-aperture. L_{lamp} is the luminance of the lamp, and L_s is the luminance of the sub-component of the lamp, or the luminance of the LED. (If any system or one facet on a reflector, has no any loss, then $L_{lamp} = L_s$). The total lumen output from the lamp is always less than the total lumens emitted from N pieces LEDs, because the étendue value of the lamp cannot be reduced, e.g.,

$$\sum_i A_{(lamp,i)} \Omega_{(lamp,i)} \geq N A_s \Omega_s \quad (2)$$

In reality, the luminance of the sub-component of the lamp, for example the hotspot area of the lamp, is always less than that of the LED source due to the system loss. Thus the actual optical system luminance should be:

$$L_{lamp} \leq \eta L_s, (\eta < 1). \quad (3)$$

If further assuming that a portion of the headlamp aperture A_l and N_l pieces of LEDs are contributing to the luminous intensity at the hotspot of the beam pattern, then,

$$I_{hotspot} = \frac{1}{\Omega_{hotspot}} \eta N_l L_s A_s \Omega_s \leq A_l \eta N_l L_s = \eta_c A_l \eta N_l L \quad (4)$$

$\Omega_{hotspot}$ is the spread angle for the hotspot, A_l is the area of the lamp aperture used for hotspots, N_l is the number of LEDs used for hotspots. To increase the luminous intensity of the hotspot, for a given system efficiency, larger lamp aperture, greater number of LEDs, or higher luminance of LED is desired. η_c is the lamp collection efficiency or étendue loss. However, because both lamp aperture and number of LEDs that can be physically packaged into the lamp aperture are limited by vehicle level design restrictions, the hotspot luminous intensity level and total luminous flux of the lamp beam pattern are highly depending on system efficiency and the LED's luminance. Actually, this analogy is also applicable to forming other part of the beam pattern. Based on the characteristics of the available white LEDs and those above equations, one can calculate lamp aperture needed for a low beam, high beam and fog lamp, and the luminous intensity of hotspots for these lamps. The analysis used in this discussion is used for free-form reflector lamp design; also principally it can be used for any type of lamp design. Free-form reflector is a transform device that transforms light intensity angular distribution from the LED light source to the intensity angular distribution of the lamp beam pattern. For other types of lamp structures, different types of light transforms will take place.

The lamp system efficiency includes lamp light collecting efficiency η_c , reflector reflecting efficiency η_r , lens transmitting efficiency η_t and useful light efficiency η_u

$$\eta_l = \eta_c * \eta = \eta_c * \eta_r * \eta_t * \eta_u \quad (5)$$

The useful light efficiency η_u means the light is actually used in a required beam pattern of lamp. A beam pattern also

has maximum intensity limit. For the headlamp low beam, it is the test point 4D per FMVSS, and for the fog lamp, it is the test point 6D per SAE Standard J583'04 Tab2. In general for forward lighting lamps, one may use useful light in beam pattern between 3U – 7D area. In addition to the light collection efficiency, it is also important to understand the light being collected is efficiently used for the beam pattern, or rather being projected to outside of the beam pattern.

3. LIGHT COLLECTION EFFICIENCY COMPARISON FOR DIFFERENT TYPES OF FORWARD LIGHTING SYSTEMS

In the following discussion, the forward lighting systems are classified with one or combination of two types of transforms, as explained in previous publication^[1].

Reflector Optics system with the transform type A; Projector Module as combination of the transform types B and C; Projection Lens with the transform type C; Lens Optics system as combination the transform types D and E. Normally, for a given aperture and a focal length, an ellipsoidal reflector may have higher light collecting efficiency than that a parabolic reflector, though the depth of the reflectors are different. For sake of simplicity, one can assume that the same size (aperture) parabolic reflector has 60% collection efficiency η_c , and an ellipsoidal reflector has 80% light collect efficiency η_c . In the Reflector Optics system in Fig.1, where normally a parabolic based free-form reflector is used, thus, its light collection efficiency is assumed as 60%. Adding a 15% reflecting loss of the reflecting surface and a 12% transmission loss of the (outer) lens, then the total lamp system efficiency is 45%, it has not included useful light efficiency η_u . In general, lamp size is bigger, the light collection efficiency η_c and useful light efficiency η_u can be higher, and it is difficult to get higher system efficiency with small aperture lamp.

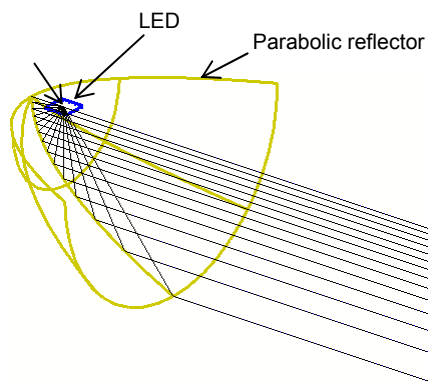


Fig. 1 (Parabolic based) Reflector Optics system, clear (outer) lens is not shown

In the Projector Module system in Fig.2, there are two optical transforms performed by two optical devices, the ellipsoidal reflector and the projection lens. Again, the ellipsoidal reflector's collecting efficiency is 80% with 15% reflecting loss from the reflector surface. The projection lens has 12% transmission loss, and in most of cases, the optical filter (shield) used on the second focal plane is possibly adding an additional 20% loss. Very often, the Projector Module is installed behind a clear outer lens, which may add another 12% transmission loss. The total lamp efficiency is about 48% without outer lens or 42% with outer lens. For this case, it is difficult to get higher useful light efficiency η_u , because the ellipsoidal reflector collects light to the second focal plane and forms a relative larger image, the light passes through an aspherical lens and forms a bigger distribution beam pattern, especially in the vertical direction, bigger than the desired spread size.

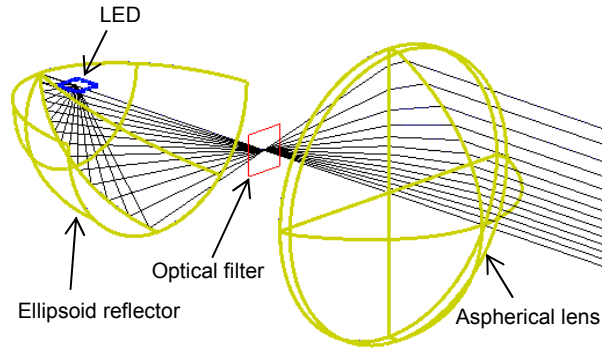


Fig. 2 Projector Module system with an ellipsoidal reflector and an aspherical lens

In the case only the aspherical projection lens in Fig.3 is used in the LED forward lighting applications, the light collection efficiency and the light intensity in the high intensity zone (hotspot) are limited by the aspherical lens numerical aperture,

$$NA = D/f . \quad (6)$$

Where D is the diameter and f is the focal length of the lens. For a larger numerical aperture, the lens light collection efficiency increases, however the aberration of lens also increases. Larger aberration will cause less useful light collimation, or less intensity in the hotspot. As an example, if the aspherical lens radius is 15mm, and its equivalent focus is 20mm. The total efficiency of this lens is estimated approximately 30% for the LEDs with lambertian distribution. Such low efficiency is not a proper choice for the LED forward lighting applications. However, in this system, useful light efficiency η_u is almost 100%, because all the light being collected is projected in the useful beam pattern area, within $3U - 7D$ in vertical direction.

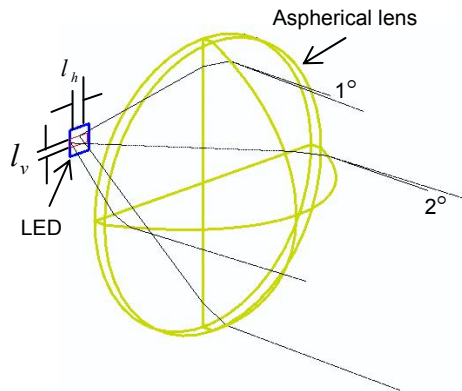


Fig. 3 Aspherical lens for an LED light source

In the Lens Optics system in Fig.4, the parabolic reflector has 60% light collection efficiency. With reflection surface reflection loss and lens transmission loss, the system may have 40% of efficiency.

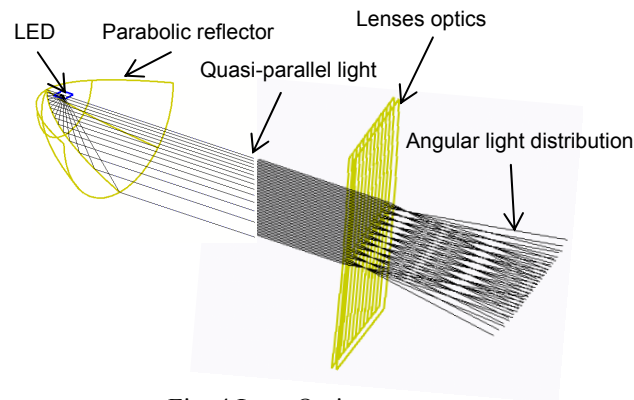


Fig. 4 Lens Optics system

In the above comparison, if the same optical aperture applies, the reflector optics system appears to have higher light collection efficiency.

In the LED lamp system, even reflector optical system has total lamp efficiency 45% (it not includes useful light efficiency η_u), it still may not have enough light to meet headlamp requirement with one LED source, multiple LED lamp units may be needed to meet the requirement. Again, the practical lamp size may limit number of the LED lamp units can be used. New concepts of the reflector optical lamp system are needed to decrease lamp size and increase lamp system efficiency at same time.

4. LED SOURCES FOR FORWARD LIGHTING SYSTEMS

For the LED light sources used in the automotive forward lighting systems, currently, there are two types of LED packages. One is the LED device that has a primary optics or “dorm” mounted above the top of the emitter or chip. Another type is no primary optics or “dorm-less”. Assuming that the LED chips for both LED packages are the same dimensions, e.g., 1mm x 1mm in size, and further assuming that both packages emit same amount of luminous flux, then, one can realize that the optics or the “dorm” magnifies the chip imaging in a lamp optical systems, from 1mm x 1mm to 1.5mm x 1.5mm. As the result, such LED package’s luminance is reduced by approximately 2.25 times. Higher luminance light source is always preferred for forward lighting applications. For the dome-less LED packages, several multiple chip arrangements are used, i.e. 2 of 1mm x 1mm chips, 4 and more 1mm x 1mm chips. Fig.5 shows one 1mm x 1mm LED chip emitter images formed by a free-form reflector, where a mapping strategy is used to form a hotspot with sufficient gradient (cutoff) for visual aiming.

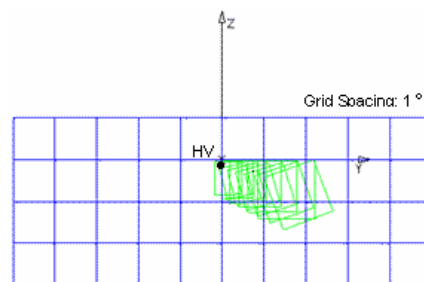


Fig.5 Square-shape LED emitter images

The headlamp low beam hotspot zone is required to have larger horizontal spread angle (e.g., $\pm 2^\circ$ or more) than the vertical spread angle ($\pm 1^\circ$). The square images of the LED emitters formed by the free-form reflector need to be arranged to compensate the hotspot shape required. If an LED emitter is shaped as a rectangle instead of square, the

emitter images can be overlapped in the hotspot zone.

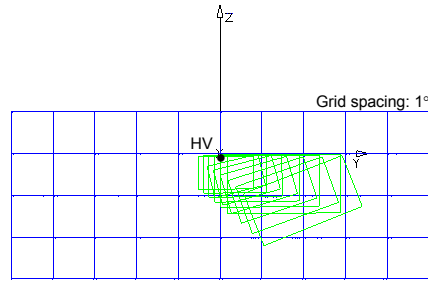


Fig.6 LED emitter images with aspect ratio of 2:1

Fig.6 shows the images of emitter size of 1mm x 2mm (or 2 of 1mm x 1mm chips emitter). A desired low beam hotspot horizontal spread angle, i.e., the preferred cutoff line width for visual aiming is at least 3 degrees wide.

Comparing between Fig.5 LED emitter images with aspect ratio of 1:1 and Fig.6 LED emitter images with aspect ratio of 2:1, the Fig.5 pattern has less horizontal spread angle than Fig.6 pattern. Furthermore, 4 of 1mm x 1mm chips emitter has more horizontal spread, but also introduces more vertical spread as well. For designing a forward lighting lamp, overall considerations of the lamp size, beam pattern luminous flux, hotspot intensity level and other factors are needed. Although the luminous flux per LED package (including multiple chips) is an essential factor to be considered for the feasibility of the lamp design, by increasing the emitter size to achieve higher luminous flux is not preferred, specifically, the emitter dimension that introduces vertical spread in the beam pattern should be avoided.

When multiple chips are arranged linearly, such as 2 or 4 1mm x 1mm chips lined up inside of the LED package, if the current density of the package is assumed the same for the above chip arrangement, higher temperature or high heat is generated for the LED packages with larger chip numbers. In practice, the heat dissipation may not be linearly related to the power of the LED packages, thus, due to the junction temperature dependence, the luminous flux of the LEDs is not linearly related to the chip numbers. If one assumes that one of the 1mm x 1mm chip LED has a Φ_{1x1} luminous flux output, then, 2 of the 1mm x 1mm (for simplicity, namely 1x2) chips LED may produce the luminous flux of:

$$\Phi_{1x2} = (1 + \Delta) * \Phi_{1x1} , \quad (7)$$

and 1 x 4 chip LED may produce the luminous flux of:

$$\Phi_{1x4} = (1 + \Delta) * \Phi_{1x2} = (1 + \Delta)^2 * \Phi_{1x1} , \quad (8)$$

where $\Delta \leq 1$. If an ideal heat sinking system is used, then, $\Delta = 1$.

For a forward lighting device, either a headlamp or a fog lamp, as stated in the above, normally the aperture of the lamp is limited. Therefore less number of LEDs each with higher luminous flux is desired. In addition, in the previous publication [2], it was discussed that based on étendue restriction, when using reflector optics to design forward lighting systems, the elongated light source is preferred. This leads to the preference of using 1 x 2 or 1 x 4 type of chip LED packages for the forward lighting applications.

LED is known with its thermal behavior as such that its luminous flux output depends on the junction temperature, see Fig. 7. The LED's junction temperature is related to the ambient temperature and thermal resistances of the system.

$$T_j = T_A + (P * R\Theta_{j-A}) , \quad (9)$$

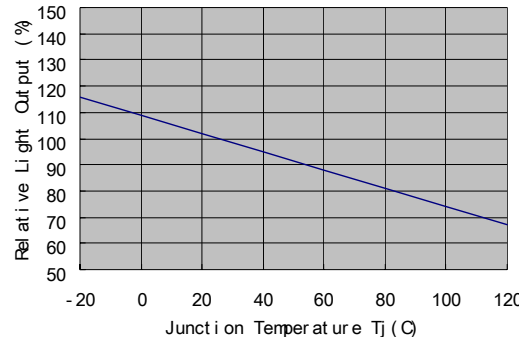


Fig. 7 LED light output vs. junction temperature

where T_J is the LED Junction temperature, T_A is the ambient temperature, P is the power dissipated from the LED, $R\Theta_{J-A}$ is the thermal resistance of the system, from the LED junction to the ambient. The total thermal resistance of a lamp system consisted of third parts:

$$R\Theta_{J-A} = R\Theta_{J-C} + R\Theta_{C-B} + R\Theta_{B-A} \quad (10)$$

$R\Theta_{J-C}$ is the thermal resistance from junction to LED package case, $R\Theta_{C-B}$ is the thermal resistance from the LED base to the circuit board, and $R\Theta_{B-A}$ is the thermal resistance from the board to the ambient.

When large LED chips or multiple chip LED packages such as 1 x 2 or 1 x 4 are used, one can assume that the LED junction to case thermal resistance is linearly related to the size of the LED chip. Therefore, if 1 x 2 LED chip thermal resistance is $R\Theta_{J-C}$, 1 x 4 LED's thermal resistance should be $0.5 \times R\Theta_{J-C}$. If the power of the 1 x 2 LED device is P , and if the current density is the same for both LEDs, then the power of 1 x 4 LED should be $2 \times P$. When applying both LEDs in the same size of heat sink (both LED devices have the same package size), and mounted on the same type of circuit board, and placed in the same ambient, then, T_A , $R\Theta_{C-B}$ and $R\Theta_{B-A}$ are same for both LEDs. Hence, the junction temperature for each type of LED can be calculated as:

$$(T_J)_{1 \times 2} = T_A + P * R\Theta_{J-C} + P * R\Theta_{C-B} + P * R\Theta_{B-A} \quad (11)$$

for 1 x 2 LED, and

$$\begin{aligned} (T_J)_{1 \times 4} &= T_A + [2P * (0.5R\Theta_{J-C} + R\Theta_{C-B} + R\Theta_{B-A})] \\ &= T_A + P * R\Theta_{J-C} + 2P * R\Theta_{C-B} + 2P * R\Theta_{B-A} \end{aligned} \quad (12)$$

for 1 x 4 LED. Therefore, under the conditions stated in the above, junction temperature for 1 x 4 LED device package should be higher than that of 1 x 2 LEDs. Using the relationship of the junction temperature versus the light output in Fig. 7, one can derive the LED light output corresponding to the junction temperatures shown in Equations (11) and (12).

As stated earlier, when designing the forward lighting lamps, light source luminance is important to achieve high light intensity level of the hotspot when the aperture of the lamp is limited, while the relative luminous output per LED device is also critical for overall lamp performance. In the above analysis, it shows that 1 x 2 LED may have higher luminance given the same lamp system conditions, while 1 x 4 LEDs provide higher total luminous flux per LED. The option to use either LED depends on the design priority of the lamp aperture size and lamp application.

5. OPTIMIZED REFLECTOR OPTICS SYSTEM FOR LED FORWARD LIGHTING LAMPS

There have been many design proposals for the LED forward light applications^{[4]-[13]}. In general these proposals may be grouped into two families: conventional optics (e.g., all types listed in the above), and non-conventional optics where total internal reflection (TIR) principles and so on are used.

In the conventional optical systems, the above analysis shows that the reflector optical system can achieve the highest system efficiency, while the ellipsoidal reflection has the highest light collection efficiency. To improve the system efficiency, one can assume that parabolic based reflector optics may be modified in such that faceted reflector surfaces are built on an ellipsoidal base. To apply this strategy, one has to ensure that high intensity zone or hotspot can be achieved in the far field.

For any optical system, based on étendue conservation theory^{[1]-[2]}, the output flux from an optical system is always equal or less than the input flux, or the light source shown by formula (1)-(4) as discussion in section 2. If the light source used in the optical systems is the same, the hotspot intensity will be limited by the aperture (the depth can be a variable). The larger the lamp aperture, the hotspot intensity is higher. However the hotspot intensity cannot exceed the limitation calculated by formula (4).

One of the objectives in designing LED forward lighting system is to improve the total lamp system efficiency, and meantime, to achieve desired hotspot intensity level. As discussed in the above, the ellipsoidal based free-form reflector can have 80% light collection efficiency. To maintain such high efficiency and achieve the hotspot intensity level in the same time, one set of the design strategy is to establish the sub-areas of the reflector as shown in Fig.8.

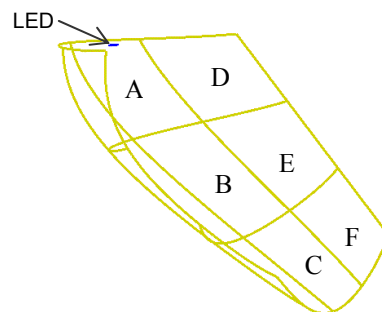


Fig. 8 Ellipsoidal based faceted free-form reflector

The reflector is formed symmetrically with respect a center axis at the focal point where the LED is located. On each side of the center axis, the reflecting surface is divided into six local areas namely A, B, C, D, E and F. The LED device use has the elongated emitter geometry. Naturally, the images of the LED emitter are formed on these reflector sub-areas with different orientations and sizes. From these emitter images, different light intensity in an angular distribution is projected on a vertical screen where the beam pattern is formed. In this study, each facet or sub-area of the reflector is designed in such that the headlamp low beam or the fog lamp beam patterns are formed by superimpose the emitter images. Notice that giving the fact of the vertical diverge angle is very small (about 2 degrees) for both lamp applications, the hotspot intensity level strongly depends on the luminance of the emitter and the size the reflector aperture. When multiple reflection, for example total internal reflection (TIR) lamp, are used, the reflection losses will reduce the luminance, and consequently the hotspot intensity will be reduced. When property design is used the above reflector system, not only the 80% of the reflector collecting efficiency is achieved, total system efficiency is higher than 60%, and high hotspot intensity is also achieved. Thus the beam patterns provide high performance.

6. DESIGN AND TEST RESULTS OF LED FOG LAMP

In applying the above reflector design strategy, one multiple chip LED device (1 x 4) is used to design a fog lamp. The design result meets the SAE J583 2004 Table 2. The aperture of the fog lamp is about 45 mm height x 50 mm wide. In the design, over 80% of light collection efficiency of the reflector has been achieved. The total lamp system efficiency, considering surface reflection loss, lens transmission loss and useful light efficiency η_u , is around 60%. The light intensity level in the hotspot is greater than 5000 cd. The hardware is shown in Fig.9 and the photometry tests results are shown in Fig.10.

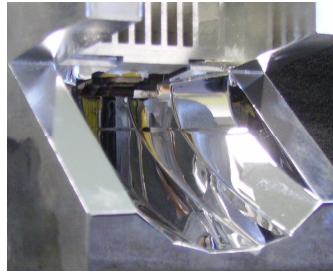


Fig. 9 The mockup of the LED fog lamp

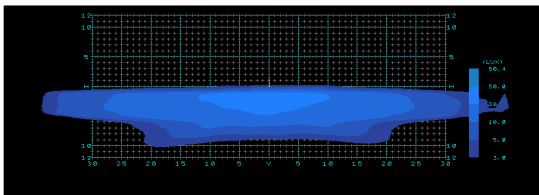


Fig. 10A The ISO diagram of test results of the LED fog lamp Fig. 10B Road render of test results of the LED fog lamp

7. DESIGN AND TEST RESULTS OF LED HEADLAMP LOW BEAM

In applying the above reflector design strategy, multiple chip LED device (1 x 2) is used to design a low beam headlamp. The design result meets the FMVSS Fig.17-2 request. The aperture of the low beam lamp is about 45 mm x 50 mm. In the design, over 80% of light collection efficiency of the reflector has been achieved. The total system efficiency, considering surface reflection loss, lens transmission loss and useful light efficiency η_u , is around 60%. If several LED lamp units (module) are used (number of units is depending on the LED luminous flux), the light intensity level in the hotspot can reach to 35000 cd. In principle, if one LED luminous flux is around 400 lm, 1 x 2 LED package may be preferred, and if one LED luminous flux is around 800 lm, 1 x 4 LED packages may be preferred. The photometry tests results are shown in Fig.11.

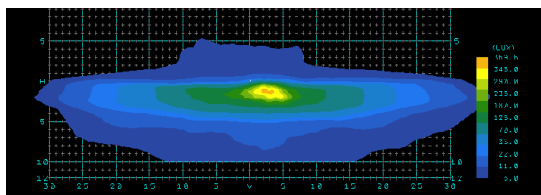


Fig.11A The ISO diagram of test results
the LED low beam head lamp



Fig.11B The road render of test results
of the LED low beam head lamp

8. CONCLUSION

For the conventional optical systems for the automotive forward lighting applications, overall system optical efficiencies are studied and compared. In general, simpler the system is (with less reflections and refractions), the higher the optical efficiency is. Because the ellipsoidal reflector has higher collection efficiency comparing to the parabolic reflector given the same aperture and focal length, the desired system should be the combination of simpler system using ellipsoidal based reflector optics.

Because of the étendue conservation, for the automotive forward lighting applications in which higher luminance are required to form the high intensity zone, larger aperture or higher light source luminance is needed. In practice, larger lamp aperture is often not available in the vehicle body styling design.

LED devices, at current stage, comparing to the existing light sources, either have lower luminous flux or less luminance. Some LED devices provide the luminance equivalent to the tungsten halogen bulbs, but have less total luminous flux per package, thus multiple LEDs may have to be used for a forward lighting application. In the fog lamp application, this study concludes that a higher efficient optical system with one LED device with elongated emitter geometry can achieve the desired photometry performance, around 300 lm inside the beam pattern, and greater than 5000 cd for the high intensity zone, and such lamp can have the aperture as small as 45 mm x 50 mm. For low beam headlamp multiple LED packages are still needed to provide desired photometric performance.

It is worth to notice that for the non-conventional optical approaches in the automotive forward lighting applications, very often, the TIR method is used, by doing so, multiple reflections and refractions are introduced. Even though the system collect efficiency may be increased, the output luminance which is essential to form higher candela values for the hotspot and total lamp efficiency, will be reduced, because the system may have lower reflecting efficiency η_r , (multiple reflection), lower lens transmitting efficiency η_t , (longer optical path) and lower useful light efficiency η_u .

The effective approach to form high performance forward lighting lamps, when the aperture is the major limitation, is to adopt the simplest optical system, to apply proper LED emitter geometry, and to optimize the reflector optics so that the luminous flux, luminance and efficiency (including LED's efficacy) has been balanced.

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