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Etendue Concerns for Automotive Headlamps Using White LEDs

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ABSTRACT

Based on the recent development of white LEDs, it becomes feasible to design automotive headlamps using LED light sources. While these LEDs are reaching high lumen output, the uniqueness of headlamp applications has not yet been sufficiently addressed. This paper discusses the optical features of an automotive headlamp, its optical design principles, light intensity distribution and concentration requirements, and safety and customer pleasing needs. Comparing LEDs to traditional tungsten halogen bulb filament, LED light sources for headlamp applications are being analyzed. The paper identifies that etendue concerns for automotive headlamps when using white LED light sources. It provides a guideline for considerations of LED development when implementing into automotive headlamp applications.

Keyword: Etendue, LED, Automotive Headlamp

1. INTRODUCTION

In recent years, LED technologies have been greatly improved. With continually increased lumen output of single colored LEDs, the automotive lighting applications have been largely extended, from center high mounted stop lamp, CHMSL, to other signal lamps. In addition, with InGaN and phosphor technologies, white LEDs have been developed to the level of 30 lumens per watt or higher light output per LED. This capacity made white LEDs a very promising technology for automotive forward lighting applications.

For automotive forward lighting devices, namely headlamps or fog lamps, incandescent light sources, or tungsten halogen bulbs, have been predominately used for the last two decades, although the high intensity discharge (HID) sources now have been implemented into some products. In both tungsten halogen and HID cases, the light emitting area is contained in small dimensions, and the light intensity distributions are in general, Lambertian. The light intensity distribution or beam pattern from a forward lighting device is regulated by federal, state and international laws for safety. The optical system design to provide such beam patterns has been largely associated with the characteristics of the tungsten halogen or HID sources. White LEDs, on the other hand, have different optical characteristics, which in turn have impacted the headlamp optical system design. In addition, the lumen output per LED is still much less than that the exiting tungsten halogen or HID sources provide, multiple LED sources must be used for one head lamp. In order to understand the limitations a light source used for optical design for a headlamp, it is necessary to review some of the headlamp system optical properties.

For any system design, it is known that some design limitations always exist. For example, in a communication system, data transfer depends on the system's frequency bandwidth. The bandwidth of the data being transferred through a system must be within, or less than, the bandwidth of the system. Similarly, in an optical imaging system, the data that can be stored in the system depends on the system's spatial frequency bandwidth. The image data being stored in the system must be within or less than the special frequency bandwidth of the system. In this paper, we will discuss, using the same analogy, the limitations of optical energy transfer in the non-image systems and the system etendue. It is beneficial for the automotive lamp optical engineers to identify the system etendue when conducting the headlamp optical design.

2. ETENDUE IN AN ATOMOTIVE HEADLAMP

The current white LED emitter proposed for automotive headlamp application is an extended planar light source. If the Lambertian light intensity distribution from the LED is assumed, the luminous intensity at a given direction is:

$$I(\theta) = I_0 \cos(\theta), \quad (1)$$

where I_0 is luminous intensity normal to the plan of LED emitter; θ is the angle observed at the direction with respect to normal. The light flux $\Phi(\alpha)$ within a cone with a solid angle α , (shown in Figure1) can be expressed as:

$$\Phi(\alpha) = \int_0^\alpha \int_0^{2\pi} I(\theta) d\varphi \sin\theta d\theta = I_0 \pi \sin^2 \alpha. \quad (2)$$

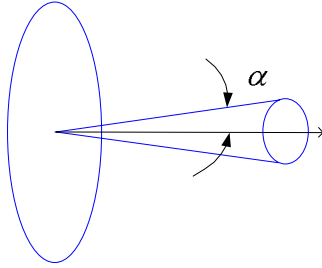


Fig. 1 Observation cone α

If an LED emits the light in a half space, $\alpha = 90^\circ$, the total flux from an LED can be expressed as:

$$\Phi(90^\circ) = I_0 \pi = \Phi_s. \quad (3)$$

Because the LED emitter is a Lambertian light source, its luminance, L_s , is then a constant shown as Equation (4),

$$L(\theta) = \frac{I(\theta)}{A_s \cos(\theta)} = \frac{I_0}{A_s} = L_s. \quad (4)$$

Therefore,

$$I_0 = A_s L_s. \quad (5)$$

For a lamp system, its aperture can be divided into several sub-apertures shown in Figure 2.

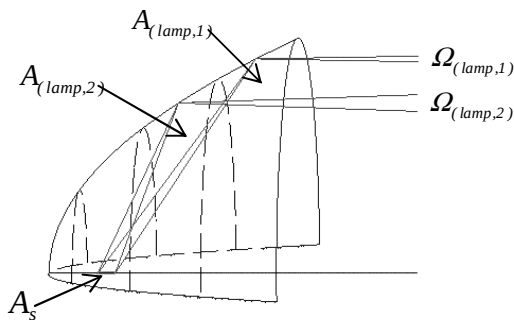


Fig. 2 Light from the source with size A_s is reflected by the sub-apertures $A_{(lamp,i)}$ of the lamp each with a spread angle $\Omega_{(lamp,i)}$

The total lumen of the lamp then is:

$$\Phi_{lamp} = \sum_i L_{(lamp,i)} A_{(lamp,i)} \Omega_{(lamp,i)} . \quad (6)$$

If further assuming that there are no losses for the optical system, the luminance L should be a constant, i.e.

$$L_{(lamp,i)} = L_{lamp} = L_s . \quad (7)$$

Then the Equation (6) will be:

$$\Phi_{lamp} = L_{lamp} \sum_i A_{(lamp,i)} \Omega_{(lamp,i)} . \quad (8)$$

For any passive optical system such as a headlamp, the system has no amplification to the input light, input and output power is conserved; the total lumen output of the headlamp is always less than the total lumen input, or the total lumen output from a light source.

$$\Phi_{lamp} \leq \Phi_s , \quad (9a)$$

or

$$\Phi_{lamp} = \eta \Phi_s . \quad (9b)$$

where the coefficient $\eta \leq 1$. For an LED with the emitter size A_s , emitting light in a solid angle Ω_s that is accepted by a headlamp with aperture A_{lamp} , the above expression can be written as:

$$\Phi_{lamp} = L_{lamp} \sum_i A_{(lamp,i)} \Omega_{(lamp,i)} = \eta L_s A_s \Omega_s . \quad (10)$$

$A_{(lamp,i)}$ is the lamp i th sub-aperture, $\Omega_{(lamp,i)}$ is the solid angle of the sub-aperture. If we assume that the etendue value of the headlamp system is unchanged, i.e.,

$$\sum_i A_{(lamp,i)} \Omega_{(lamp,i)} = A_s \Omega_s , \quad (11)$$

the system loss only causes luminance reduction, then

$$L_{lamp} = \eta L_s , \quad (12a)$$

or

$$L_{lamp} \leq L_s . \quad (12b)$$

This is commonly known as the Brightness Conservation Rule. An optical system loss, as the result, causes the luminance loss. When multiple LED emitters are used for a headlamp, the Equation (11) can be rewritten as

$$\sum_i A_{(lamp,i)} \Omega_{(lamp,i)} = N A_s \Omega_s , \quad (13)$$

where N is the number of LEDs. Again, the etendue value of the headlamp remains unchanged. The equation (10) can be rewritten as:

$$\Phi_{lamp} = L_{lamp} \sum_i A_{(lamp,i)} \Omega_{(lamp,i)} = \eta N L_s A_s \Omega_s. \quad (14)$$

This expression shows that when the headlamp is constructed with multiple optical compartments, each optical compartment may have a different etendue value, or provide different luminous intensity and different spread solid angle, and total lumens output from the headlamp is always less than the total lumens emitted from N pieces LEDs. Realize that the number of the LEDs used need not to be the same number of the sub-apertures in which the headlamp is constructed.

3. FORM AN AUTOMOTIVE HEADLAMP BEAM PATTERN WITH LEDs

Any automotive headlamp beam pattern, either high-beam or low-beam, is a light luminous intensity (candela) angular distribution. The candela values are specified at different vertical and horizontal angles by using test points, lines, and zones. The specifications are governed by federal laws or industry recommendations. For a low-beam headlamp, for example, the beam pattern requirement is based on several factors: A) sufficient road illumination for driver visibility and safety; B) glare light control for the oncoming vehicle drivers; C) lamp aim-ability; and D) spread and foreground light for driver's comfort. Because of these requirements, the headlamp beam pattern must be a highly non-isotropic light distribution; and its light intensity varies in a range from a few hundreds to 20,000 or more candela. In certain angular area where high illumination is needed, the luminous intensity is very high and light is highly concentrated or collimated. This high light intensity area is called hotspot. At the top edge of the hotspot, light intensity is rapidly reduced to form a luminous intensity gradient or cutoff line, which serves two purposes: to control the glare light and to aim the lamp visually. Contrast to hotspot, the light that spreads to left and right or foreground has much less intensity and a large diverge or spread angle instead. Figure 3 provides an illustration of light intensity zones in a headlamp low-beam beam pattern. Zone 1 is a much collimated area that is used to form hotspot. Zone 2 has a medium spread while Zone 3 has a large spread, and they are used to form other parts of the beam pattern.

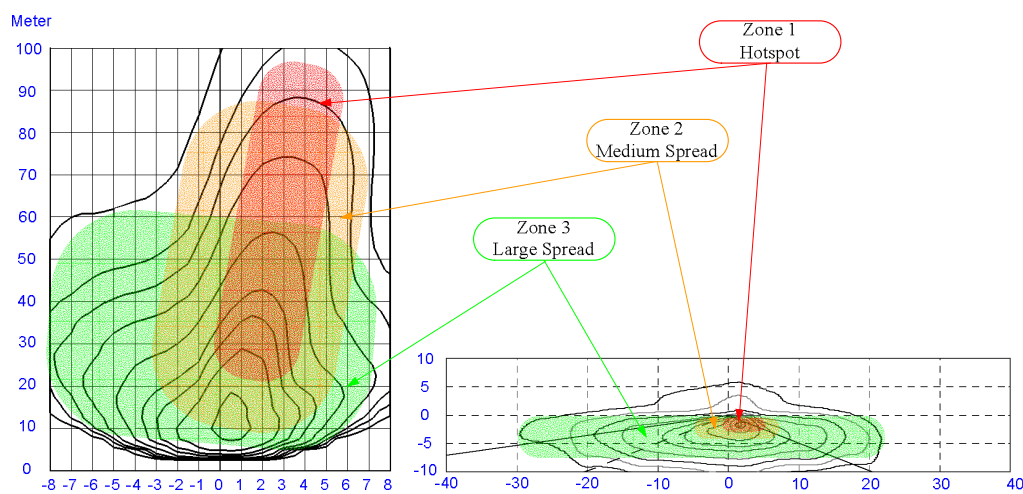


Fig. 3 Low-beam beam pattern intensity zones. The left diagram is the isolux plot projected to a road surface with projection distance in meters. The right diagram is the isocandela plot projected on a test screen. The coordinates are in degrees.

One major difficulty for forming a headlamp beam pattern is to obtain sufficient candela values in the hotspot while the lamp total aperture is limited. For high-beam design, it is more difficult to form the hotspot as its candela value

requirement can be as high as 40,000. Per design specification, if the I_{hotspot} is the required candela value, and the angular spread of the hotspot is Ω_{hotspot} , the amount of lumen flux in the hotspot is:

$$\Phi_{\text{hotspot}} = I_{\text{hotspot}} \Omega_{\text{hotspot}}. \quad (15)$$

If N_l is the number of LEDs used to form the hotspot, each LED has the same L_s , and A_s , then for a given headlamp aperture A_{lamp} , using Equation (14), the hotspot candela value contributed by the LEDs can be obtained as:

$$I_{\text{hotspot}} = \frac{1}{\Omega_{\text{hotspot}}} \eta N_l L_s A_s \Omega_s = A_{\text{lamp}} \eta N_l L_s. \quad (16)$$

Equations (16) provides a baseline for projecting required or desired candela values in the hotspot. There are three main factors that affect the hotspot candela values:

Factor 1, Lamp styling design limitation. Size of the lamp aperture A_{lamp} is in general limited by vehicle design styling, although some negotiations could help the engineering community to convince the vehicle styling studio staff to slightly enlarge the aperture. Clearly, the larger lamp aperture is a great benefit to increase hotspot candela value, but unfortunately this luxury request has not been met in most of the product designs.

Factor 2, Lamp configuration limitation. Obviously all lamp optical system must have losses (e.g., $\eta < 1$), reflection loss, absorption loss, light collection loss and others. For a given headlamp system, although adding more LEDs, N_l may increase hotspot candela value, the maximum number of LEDs is often limited by the physical lamp structure.

Factor 3, Luminance L_s of the LEDs. With the above basic limitations, the Equation (16) indicates that the headlamp hotspot candela value is proportional to L_s , the luminance of LEDs. The larger lamp A_{lamp} , or the higher luminance of LEDs L_s , or more LEDs (if practically achievable) leads to a higher candela value in the hotspot.

Besides the aperture, another limitation to form an adequate headlamp beam pattern is the overall size of the optical system and depth. Because of vehicle styling and packaging needs, the depth of a headlamp is also often restricted. As a consequence, the amount of lumen being collected and projected into the beam pattern through the optical system may not be sufficient to meet all the desires.

4. HEADLAMP DESIGN STRATEGY

Equation (16) show the hotspot light intensity result based on the scenario of the ideal conditions of entire lamp aperture A_{lamp} is used to form the hotspot. However in reality, the entire lamp aperture A_{lamp} cannot be used to form the hotspot. For simplicity, we assume that the headlamp is an aberration-free optical system. Light from a point source is well collimated by the aberrations free optical system (e.g., a reflector or lens) to form the required parallel beam. When using a real light source such as LED with extended light emitting area A_s , light from the extended light source are diverged (or spread) by the optical system. The degree of the collimation depends on both the light source dimensions and the optical system characteristics such as focal length and aperture. If a light source size A_s with spread angle Ω_s is chosen, for a given lamp aperture A_{lamp} , smaller focal length leads to higher light collection efficiency, but less collimation (a dilemma we always have to face). In addition, in a reflector system, the degree of light collimation varies at different parts of the reflector aperture, while a lens system has consistent light collimation throughout the entire aperture. As shown in Figure 4A, if the given light source area is A_s , smaller spread angle is reflected at the farther distance from the light source or near the edge of the reflector aperture. This property of the reflector system may be used for forming the hotspot. Figures 4A and 4B and Figures 5A and 5B show the comparisons of the focal length changes virus light loss and spread angles for a reflector and lens system respectively.

Using the property of the reflector system, the aperture of the system may be divided into several segments, or sub-aperture, while each sub-aperture may be used for forming a different beam pattern such as hotspot and spread. This

approach very often is referred to as the headlamp optical design strategy. An example of the design strategy is discussed in the following section.

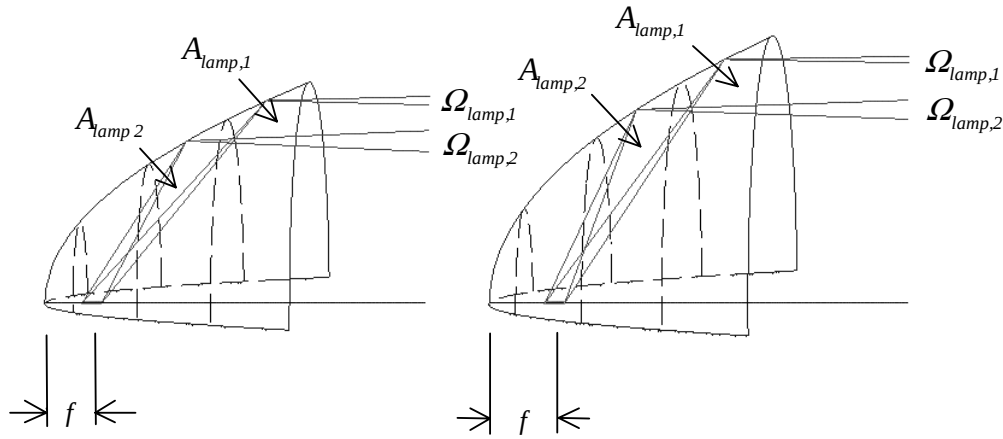


Fig. 4A Reflector with smaller focal length

Fig. 4B Reflector with larger focal length

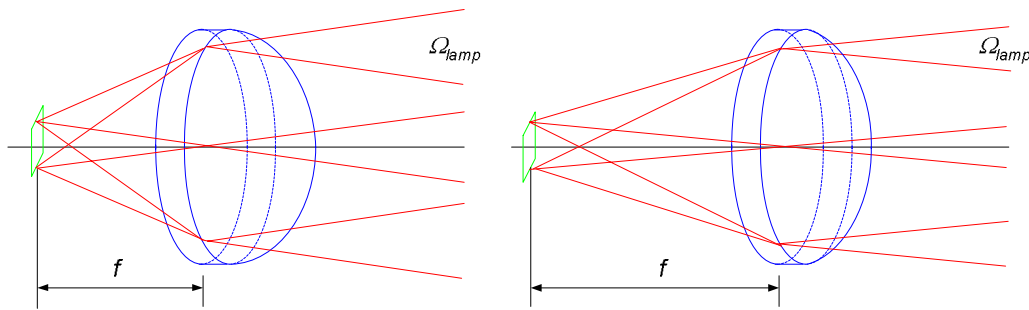


Fig. 5A Lens with smaller focal length

Fig. 5B Lens with larger focal length

5. LED LIMITATIONS IN HEADLAMP OPTICAL DESIGN

For designing an adequate (SAE) automotive headlamp low-beam, several design performance values are desired: A) total lumen within the required beam pattern is around 420 lm; B) hotspot candela value is around 25,000 cd; C) large spread angle, 1,000 cd reaches to 35° left and right. If the total lumen within the beam pattern is divided into three desired angular zonal areas, it can be expressed as:

Zone 1 – hotspot with a 2° horizontal and 1° vertical solid angle, or 4° horizontal spread and 2° vertical spread and 25,000 cd intensity,

$$\Phi_{(lamp,1)} \cong 50 \text{ lm} . \quad (17)$$

Zone 2 – medium spread for foreground with 20° horizontal spread (for light projected from 10° left to 10° right horizontally) and 4° vertical spread and 10,000 cd intensity,

$$\Phi_{(lamp,2)} \cong 200 \text{ lm} . \quad (18)$$

Zone 3 – large spread for light projected from 35° left to 35° right horizontally and 10° vertically and 1,000 cd intensity,

$$\Phi_{(lamp,3)} \cong 170 \text{ lm} . \quad (19)$$

$$\Phi_{lamp} = \Phi_{(lamp,1)} + \Phi_{(lamp,2)} + \Phi_{(lamp,3)} \cong 420 \text{ lm} . \quad (20)$$

When using a typical tungsten halogen light source for the design of a low beam, the lumen output of the light source (e.g, 9006 bulb) is 1,000 lm. If further assuming that the light collection efficiency is 60% and the total system loss (e.g., reflector surface loss, lens surface and transmission loss, etc.) is 30%, to achieve the desired performance described in Equations (17) to (19), the optical system effective aperture required is approximately 12,000 mm².

Using the desired performance scenario, one can make comparison for the system effective aperture when using LEDs versus tungsten halogen bulb. If the effective emitter size of the LEDs is $A_s = 1.5\text{mm} \times 1.5\text{mm}$ (larger than the LED chip size because of the dome effect), the total lumen output is $\Phi_s = 100 \text{ lm}$ per LED, and LED light output is a Lambertian distribution $\Omega_s = \pi$, then the light source luminance is $L_s = 14.15 \text{ cd/mm}^2$. In order to form the hotspot, we first need to balance the trade off and conflict between the aperture and focal length as discussed in the last section. Because of the limitations of lamp aperture, the optical system focal length, and the dimensions of the LED emitter, the total system efficiency is assumed $\eta = 0.42$, which includes reflection loss, transmitting loss, refracting loss and collecting loss (equivalent to the above tungsten halogen case). The total lumen contributed to the hotspot should be:

$$\Phi_{(lamp,1)} = L_{(lamp,1)} \Omega_{(lamp,1)} A_{(lamp,1)} = \eta L_s \Omega_{(lamp,1)} A_{(lamp,1)} . \quad (21)$$

In this expression, the optical system is assumed as an etendue conserved system. The light collected by the optical system is not diverged or spread by the system. Realize that the required lumen amount for the hotspot is $\Phi_{(lamp,1)} = 50 \text{ lm}$ in Zone 1, using the LEDs with the brightness of $L_s = 14.15 \text{ cd/mm}^2$, the required aperture for the hotspot is calculated:

$$A_{(lamp,1)} = \frac{\Phi_{(lamp,1)}}{\eta L_s \Omega_{(lamp,1)}} \cong 8,000 \text{ mm}^2 . \quad (22)$$

Similarly, the required apertures for medium and large spreads are:

$$A_{(lamp,2)} = \frac{\Phi_{(lamp,2)}}{\eta L_s \Omega_{(lamp,2)}} \cong 8,200 \text{ mm}^2 , \quad (23)$$

$$A_{(lamp,3)} = \frac{\Phi_{(lamp,3)}}{\eta L_s \Omega_{(lamp,3)}} \cong 1,200 \text{ mm}^2 . \quad (24)$$

Thus,

$$A_{lamp} = A_{(lamp,1)} + A_{(lamp,2)} + A_{(lamp,3)} \cong 18,000 \text{ mm}^2 . \quad (25)$$

The result in Equation (25) shows that in order to achieve the low-beam performance (420 lm inside the beam pattern, and 25,000 cd in the hotspot), it takes 50% larger effective aperture when using LEDs that have equivalent total lumen output as a tungsten halogen bulb. Although there are several typical optical systems to form a headlamp beam pattern such as reflector system, lens system, projector system, and others, the size of the effective aperture is essential for ensure the desired photometry performance. There may be several approaches to used LEDs to obtain the tungsten halogen equivalent performance with the same size of aperture. The cases are listed below.

Case 1. Because the light source dimensions between tungsten halogen (filament diameter) and LED emitter (chip size) are similar and the LED has half space emission, one simple solution to obtain the tungsten halogen low-beam performance level is to increase the lumen output of the LEDs to 500 lm per emitter without changing the emitter size. Then 2 LEDs each use a half of the original lamp aperture. This will easily lead to a feasible solution of designing a headlamp low-beam: same amount of lumen within beam pattern (420 lm), and same aperture size (12,000 mm²), but LED emitters must have 5 times brightness increase.

Case 2. Increase the lumen output to 150 lm for each LED. This will allow the total of 10 LEDs to use the same size of the effective aperture as for tungsten halogen bulb. However, the total lumen used for the lamp now is 1,500 lm which lead to further reduction of the system efficiency.

Case 3, To overcome the aperture limitation, one approach is to use a shared aperture with multiple LEDs if the higher brightness LEDs are not available. If we assume that N_l of LEDs is used to form the hotspot with the same sub-aperture, then,

$$\Phi_{(lamp,1)} = \eta N_l L_s A_{(lamp,1)} \sum_i \Omega_{(lamp,LEDi)} \cdot \quad (26)$$

Because of the limitation of the physical structure for both reflector or lens system, the combined solid angle from multiple number of LEDs is always larger then the original required angle $\Omega_{(lamp,1)}$ (see Figure 6), therefore additional loss is introduced when the light is diverged to outside of the desired angle.

$$\sum_i \Omega_{(lamp,LEDi)} > \Omega_{(lamp,1)} \cdot \quad (27)$$

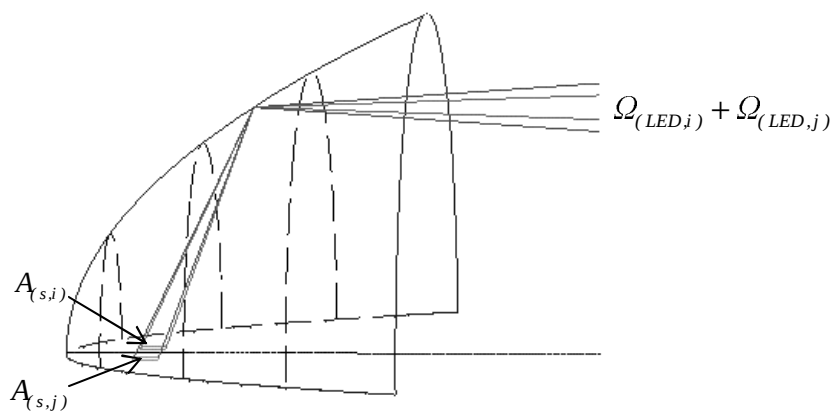


Fig. 6 Multiple LEDs sharing the same aperture

This analysis shows that additional loss will be introduced when sharing aperture. However without significant increasing LEDs' luminance or changing the LED emitter configuration, sharing aperture is the only approach that can make it potentially feasible to implement the current LEDs into headlamp design. Typically there are two ways of sharing aperture: A) using several LEDs for one large aperture; or B) letting some LEDs use portion of the aperture dedicated to another LED. Option A) is limited by the physical package of each LED. Option B) in general has more flexibility for rearranging the usage of each portion of the aperture.

As we mentioned earlier (see Figure 2), the light divergence varies at the different portion of the reflector. For the headlamp design, the portion of the reflector with smaller divergence is commonly used to form the hotspot, where light collecting efficiency has less priority for these reflector areas. For the rest portion of the reflector, the divergence

angle is too large to form the hotspot, the light reflected from those areas is used to form the rest part of the beam pattern, e.g., spread, foreground light, etc. Light collection efficiency in these areas is much more important. When sharing the aperture, the LEDs can be distributed so that some LEDs are predominantly used to form the hotspot by using the smaller divergence portion of the reflector, and the rest of the LEDs are designed with the optics that is more emphasis on the high collection efficiency.

Although the LED current application for headlamp design is limited, because of the flexibility of how to share aperture, it opens a great opportunity and challenge to optical engineers to develop the design concepts that are more efficient. Overall, our experiences have shown that with additional losses introduced by sharing aperture, more LEDs must be added to meet the headlamp beam pattern and total aperture needs. For instance, a headlamp package with approximately 15 LEDs each has 100 lm output (again, total of 1,500 lm input) may be able to meet both performance and aperture requirements discussed in the above. However the total system efficiency is lower than tungsten halogen system.

6. CONCLUSION

The limitations of using an LED light source to design headlamp low-beam beam pattern addressed here are based on two principles of non-imaging optical system: A) The system cannot change (increase) the luminance of the light source used. B) Etendue value of the output from the system is always equal or larger than the input value. Because of these principles, for the photometry requirements of the headlamp beam pattern and the design restriction for the system aperture, the luminance of LEDs must be comparable to or higher than the existing tungsten halogen light sources. As result of the comparisons, in order to achieve a headlamp low-beam design equivalent to a tungsten halogen performance and aperture size, there will be three solutions: A) LEDs need to provide 500 lm per emitter with effective area of 1.5 mm x 1.5 mm, where only 2 LEDs are needed per low-beam design; B) LEDs' lumen flux increases to 150 lm per LED with total of 10 LEDs or 1,500 lm needed; C) without increasing LED luminance, addition more LEDs to the lamp aperture with again approximately 1,500 lm input needed. Solution B) and C) will have lower system efficiency than the tungsten halogen system with the same aperture.

Comparing to filament-like light sources, some disadvantages exist when using multiple discrete (non-elongated as a filament) light sources such as LEDs to design automotive headlamps. As mentioned earlier, the headlamp beam patterns are highly non-isotropic. Although the vertical spread angle is very narrow, the horizontal spread angle is rather large. The etendue values are not the same in these two directions. Because of this asymmetric property, even thought the total system spread (combining vertical and horizontal) may be balanced between vertical and horizontal directions, the total etendue, however cannot be compressed. That is why an elongate light source can be more efficiently used. Further discussion will be carried in our future publications to address the aspect ratio of the LED emitter for its advantages in designing automotive headlamps.

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