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Optical Transform Limitations in Headlamp Photometric Performance

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ABSTRACT

Automotive lamps are essentially the optical transform devices. A light intensity angular distribution from a given light source (filament, HID arc, LED, etc.) is transformed to a desired new light intensity angular distribution namely beam pattern by means of an optical system such as a reflector or lens optics, or a projector module system. There are fundamentally five types of optical transformations occurring in a headlamp optical design: A). Light intensity angular distribution transforms from a light source to a beam pattern that is another fashion of angular distribution via a reflector-optics device. This transform device, sometimes, is referred to as the free-form reflector design; B). Light intensity angular distribution from a light source is transformed to a spatial distribution on a focal plane of an ellipsoidal (or similar) reflector; C). Light intensity spatial distribution on the focal plane of the ellipsoidal reflector is transformed to a beam pattern (angular distribution) using a projection lens. The combination of these transforms, B and C, is referred to a projector module system; D) Light intensity angular distribution is transformed to a quasi-parallel beam (uniform angle) via a parabolic reflector; E) The quasi-parallel beam is transformed to a beam pattern (angular distribution) using a traditional lens array. The combination of the transforms of D and E is referred to the lens optical design.

In an optical system, both luminous flux and etendue is conserved. These conservations dominate optical design limits for a headlamp photometric performance. This paper discusses these limitations: luminous intensity and size for a headlamp using studies of the above mentioned optical transformations. Furthermore, the paper will show that these limitations are related to the light source and the uniqueness of LEDs. This is the continuation of the studies published in the last year's SAE paper written by the same authors.

INTRODUCTION

The very first electrical automotive headlamp was developed in early 1900s. Since then, various of light sources have been developed and used in the headlamp systems: tungsten filament in 1915, tungsten halogen

bulbs in 1960s, high intensity discharge source in 1990s and in a perceived near future, the LED sources. Several automotive headlamp optical systems have also been developed such as sealed beam, lenses optics, reflector optics, projector optics and combination of any of the above types of optics. The principle for designing optics for all those lamps is the same, which is the transform of an angle light distribution from a light sources to a beam pattern that is a new or desired light distribution. In different development stages of headlamps, often one type of optics was predominantly used largely based on vehicle styling needs and technological status. Currently, the main types of optics used in headlamp design are reflector optics and projector optics. Assuming these two types of optics are used for the future LED sources, one can categorize the optical transforms with the corresponding etendue limitations as the following:

- A. Light intensity angular distribution transforms from a light source to a beam pattern. The etendue limitations were discussed in the articles listed in Reference [1] and [2].
- B. Light intensity angular distribution from a light source is transformed to a spatial distribution on a focal plane of an ellipsoidal (or similar) reflector.
- C. Light intensity spatial distribution on the focal plane of the ellipsoidal reflector is transformed to a beam pattern (new angular distribution).
- D. Light intensity angular distribution from a light source is transformed to a quasi-parallel (or quasi-collimated) beam.
- E. The quasi-parallel beam is transformed to a beam pattern (new angular distribution).

In an optical system, luminous flux and etendue are both conserved. These conservations are the fundamental limits for optical design of an illumination system such as a headlamp. The limitations include photometric performance and the configurations (dimensions and shapes) for the headlamp, which will be discussed in this paper. The discussion will be based on the optical

transforms of the headlamp systems, particularly, when the LED light sources are used.

TRANSFORM A – ANGULAR DISTRIBUTION TO ANGULAR DISTRIBUTION

Reflector optics used in the headlamp design is a typical example of the optical transform of angular distributions, from a light source to a desired beam pattern. The optical elements on the reflector surface named facets, in general, are formed in the complicated shapes that are not easily described with analytical mathematical equations. The distribution of luminous intensity and light transform efficiency are commonly used to evaluate the performance of a lamp. The characteristics of the optical transform of the reflector may be described as a “transform function” which depends on light source size and shape, luminous flux, and reflector size, shape and its optical properties (e.g., reflectivity etc.). Optical engineer who designs the lamps typically uses ray-trace approach to simulate and analyze the angular candela distribution against the required test points. In addition, a feasibility study for the lamp design, in the early stage of the lamp development is commonly done by the optical engineer with estimation of the luminous flux values using physics principles.^{[1],[2]}

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 optical unit may have a different etendue value, or it provides a different luminous intensity distribution. The total lumen flux from the 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 LED emitter size; Ω_s is the solid angle of the emitting light 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} and L_s are the luminance of the headlamp and the luminance of the LED respectively. The total lumen output from the headlamp is always less than the total lumens emitted from N pieces LEDs. Because the etendue value of the headlamp cannot be reduced, e.g.,

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

thus the actual optical system causes the luminance reduction as:

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

If further assuming that portion of the headlamp aperture A_1 and N_1 pieces of LEDs are contributing to the

luminous intensity at the hotspot of the beam pattern, then,

$$I_{hotspot} = \frac{I}{\Omega_{hotspot}} \eta N_1 L_s A_s \Omega_s = A_1 \eta N_1 L_s. \quad (4)$$

$\Omega_{hotspot}$ is the spread angle for the hotspot. To increase the luminous intensity of the hotspot, for given system efficiency, larger lamp aperture, greater number of LEDs, or higher luminance is desired. However, because both lamp aperture and number of LEDs that can be physically packaged into the lamp aperture are limited by vehicle level design restriction, the hotspot luminous intensity level is highly depending on the LED's luminance, rather than its total lumen output. Actually, this analogy is also applicable to form other part of the beam pattern. Based on available white LED parameters and those equations, one can calculate headlamp aperture needed for low beam and high beam, and luminous intensity of hotspots. 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 devise from light intensity angular distribution of 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.

TRANSFORM B – ANGULAR DISTRIBUTION TO SPATIAL DISTRIBUTION

An ellipsoid reflector collects an angular light distribution from a non-point source located at its first focal point, and transforms to a spatial light distribution at its second focal plane (perpendicular to the optical axis) shown in Fig. 1. LED is a non-point source. The light spatial distribution on the second focal plane is related to the dimensions and light angular distribution of the LED emitter, as well as the characteristics of the ellipsoid reflector. For the ellipsoid reflector, light from the center point of the LED emitter will be formed an image point at the second focal plane (perpendicular to the optical axis). Light from other points away from the center of the LED emitter will form a spread area, or off-centered disc on the same plane. The optimization needed for the ellipsoid system is to reduce the spread caused by aberrations.

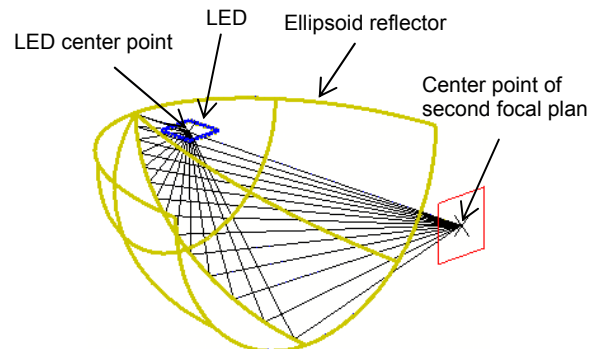


Fig. 1 Ellipsoid reflector with LED light source
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By choosing the characteristics of the ellipsoid reflector in such that if not all but majority of the light from the LED emitter is collected, one can obtain a high collecting efficiency.

One assumes that the light angular distribution from the LED emitter is a Lambertian distribution and total flux is $\Phi_s(lm)$. If further assuming that LED emitter has a planar surface, the total solid angle for emission is 90° , then the total effective solid angle could be calculated using following formula.

$$\Omega_{se} = \int_0^{\frac{\pi}{2}} \int_0^{2\pi} \cos \theta \sin \theta d\theta d\varphi = \pi \quad (5)$$

For a planar LED emitter, one can further assume that light emitted within 90° to 50° solid angle is collected by the ellipsoid reflector, thus,

$$\begin{aligned} \Omega_{ref,e} &= \left[\pi - \frac{1}{2} \left(\pi - \int_0^{50^\circ} \int_0^{2\pi} \cos \theta \sin \theta d\theta d\varphi \right) \right] \\ &= \left[1 - \frac{1}{2} (1 - \sin^2 50^\circ) \right] \pi = 0.80 \pi \end{aligned} \quad (6)$$

The collecting efficiency of the reflector can be as high as $\eta_{ce} = \Omega_{ref,e} / \Omega_{se} = 80\%$ for the planar LED emitter. If the LED emitter is integrated with an optical lens named “dome”, the totally collecting efficiency could be higher than 80%.

Again, the image size on the second focal plane depends on the properties of the reflector. Because of the aberrations, for the light emitted from an off-center and paraxial point of the LED emitter, a vertical image is formed on the second focal plane of the reflector shown in Fig. 2a. For the light emitted from an off-center and off-axis point of the LED emitter, a horizontal image is formed on the second focal plane shown in Fig. 2b. For the light emitted from other points of the LED emitter, the image formed will have a compound angle.

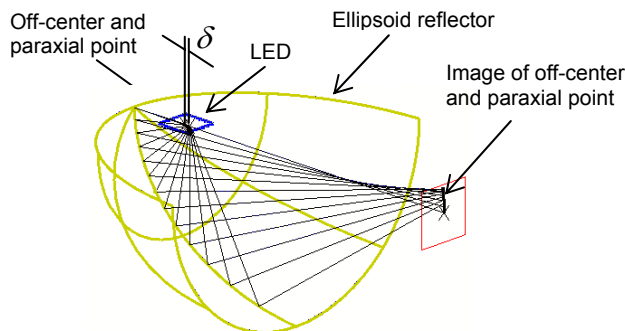


Fig.2a Off-center and paraxial point of LED forms a vertical Imaging spot

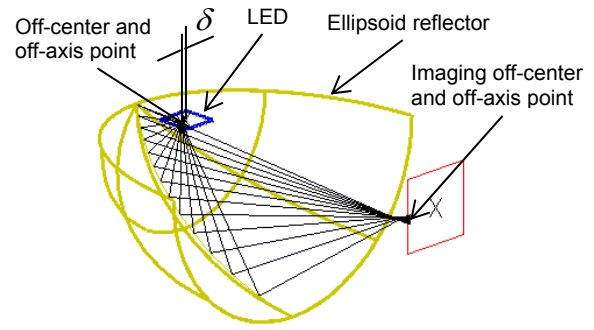


Fig.2b Off-center and off-axis point of LED forms a horizontal Imaging spot

When considering the surface reflection loss of the reflector, the output flux from a lamp is

$$\Phi_{lamp} = \eta \eta_c \Phi_s \quad (7)$$

Where the reflectivity, $\eta = 0.9$ is commonly assumed and $\eta_{ce} = 0.8$ is the reflector collection efficiency. According to equations (1) and (2), the output solid angle of the lamp, Ω_{lamp} needs to be much smaller than light source light emission solid angle Ω_s . Therefore, because of the etendue conservation, the imaging size A_{lamp} has to be much larger than the LED emitter size A_s shown in Fig. 3. In general, the goal is to minimize the reflector aberration effects to obtain smaller image of the light source, which is critical to design an automotive lamp optical system.

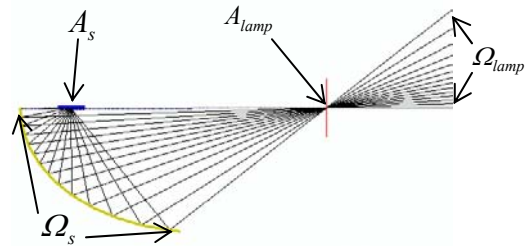


Fig.3 Etendue of ellipsoid reflector

The effective solid angle of entire LED emission with Lambertian distribution is shown as equation 5. The solid angle collected by the reflector is shown as equation 6. When using an aspherical projection lens to collect the light coming from the reflector, the collection angle is depending on the size and focal length of the lens. Assuming the collection angle is 35° , then, the lamp solid angle is:

$$\Omega_{lamp} = \frac{1}{2} \int_0^{35^\circ} \int_0^{2\pi} \cos\theta \sin\theta d\theta d\varphi \quad (8)$$

$$= \pi \sin^2 35^\circ = 0.17 \times \pi$$

1/2 represents that the light entering in the aspherical lens has been compressed only on the top half space. Then, the smallest size of the lamp aperture (size of the image on the focal point in this case), based on the system etendue conservation equation (2), should be:

$$A_{lamp} = A_s \frac{\Omega_{ref}}{\Omega_{lamp}} = 4.8 A_s \quad (9)$$

This result indicates when using ellipsoid reflector to collect light, although it has high a collecting efficiency, the reflector forms larger image size on the focal plane, therefore, it is difficult to obtain higher luminous intensity in the hotspot.

TRANSFORM C – SPATIAL DISTRIBUTION TO ANGULAR DISTRIBUTION

Fig. 4 indicates a transform from a spatial distribution to an angular distribution via an aspherical projection lens with a focal length f . The object is located at the first focal plane of the lens. Point 1 is at the center of object on the axis, which corresponds to 0 degree angel, or parallel light after the transform. Points 2 and 5 indicate the points on the objects located at h and $-h$, θ and $-\theta$ are the transform angel respectively. Point 3, 4, 6, 7 are at $2h, 3h, -2h, -3h$ of the object and $2\theta, -2\theta, 2\theta, 3\theta, -3\theta$ are the transform angels. From the spatial distribution point of view, the object is transformed to a group of parallel lights, or an angular distribution, which is a Fourier transform. The detailed explanation of the optical spatial Fourier transform can be found in the reference.^[3]

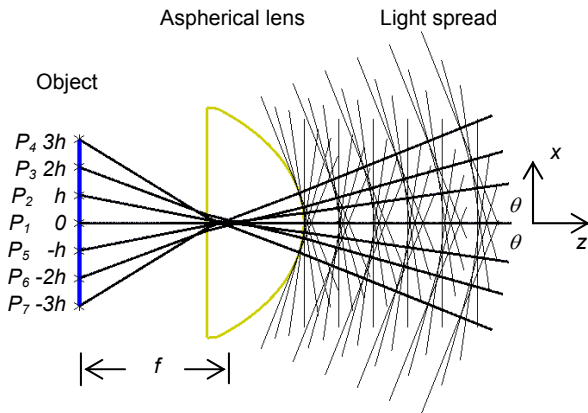


Fig. 4 Spatial distribution transformed to angular distribution by an aspherical lens

One-dimension Fourier transform devices are well-known and widely used in electronic signal processing. The relationship between time and frequency domains

using Fourier transforms are expressed as:

$$F(\nu) = \int_{-\infty}^{\infty} f(t) \exp(-j2\pi\nu t) dt, \quad (10)$$

$$f(t) = \int_{-\infty}^{\infty} F(\nu) \exp(-j2\pi\nu t) d\nu, \quad (11)$$

Where $f(t)$ is a signal; $F(\nu)$ is its spectrum. t (unit: second) and ν (unit: Hz) are variables in the time and the frequency domains.

In an optical processing system such as the projection lens shown in Fig. 4, the spatial distribution is transformed to the angular distribution via the aspherical lens, it is a two-dimension Fourier transform. An object or image $f(x, y)$ has illuminance distribution with position variables x, y , and

$F(k_x, k_y) \exp[-j(k_x x + k_y y)]$ is a series of plane waves with luminous intensity of function $F(k_x, k_y)$.

The tow-dimension Fourier transform can be expressed as:

$$F(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \exp[-j(k_x x + k_y y)] dx dy \quad (12)$$

$$f(x, y) = (1/2\pi)^2 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(k_x, k_y) \exp[-j(k_x x + k_y y)] dk_x dk_y \quad (13)$$

Where $k_x = 2\pi\nu_x, k_y = 2\pi\nu_y$ are directions of light propagation on x, y axes respectively; ν_x, ν_y are spatial frequencies in x, y directions.

Because of the rotational symmetry of the aspherical lens, one can assume that it is a one-dimension Fourier spatial transform devise. For simplification, let light propagate in $y = 0$ plane. Then, the spatial frequency exists only in x direction and

$$k_x^2 + k_z^2 = k^2. \quad (14)$$

Light emitted from point 1 in Fig. 4 transforms to a plane wave with angle θ on z axis. Similar, light emitted from points h and $-h$ transform to plane waves with angle θ and $-\theta$ with respect to z axis, where $\theta = \tan(h/f)$ and f is the focal length of the aspherical lens. Clearly, the aspherical lens transforms the object's light located at its front focal plane to the angular distribution of wave-front. If one controls or

varies the object's light distribution on the front focal plane, the output angular distribution, or consequently the beam pattern will be varied also. In vehicle headlamp design, knowing desired light distribution of the low or high beam, one can calculate the light distribution of the object on the front focal plane of the lens using reverse Fourier transform of equation (13). The light collection device, such as the ellipsoid reflector, should make a light distribution to meet the desired object calculated in the above.

TRANSFORM D – ANGULAR DISTRIBUTION TO QUASI-PARALLEL BEAM

A parabolic reflector that collects an angular distribution of a light source at focal point and transforms to a quasi-parallel light distribution at its output aperture is shown Fig. 5.

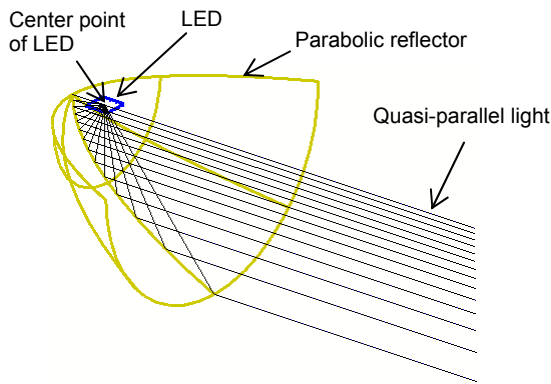


Fig.5 Parabolic reflector with LED light source

The light collection efficiency of the parabolic reflector is similar as the ellipsoidal reflector. The reflector aperture is $A_{lamp} = \pi r^2 / 2$, where r is the radius of the aperture. If assuming that the effective collection efficiency of the parabolic reflector is as high as $\eta_{ref,c} = 80\%$, from the etendue conservation equation, the spread angle of the quasi-parallel beam can be calculated.

$$\Omega_{lamp} = \frac{A_s}{A_{lamp}} \Omega_{ref,e} = 0.0018\pi, \quad (15)$$

where $A_s = 1.5mm \times 1.5mm$, $r = 25mm$, and $\Omega_{ref,e} = 0.80 \times \pi$ are assumed. Then, the beam spread angle θ is calculated using:

$$\Omega_{lamp} = \int_0^{\theta} \int_0^{2\pi} \cos \theta \sin \theta d\theta d\phi = \pi \sin^2 \theta. \quad (16)$$

Hence, $\theta = 2.5^\circ$. The quasi-parallel light distribution has rather small spread angle, 2.5° with respect to the

optical axis. In this system, the off-center and paraxial point on the LED forms a quasi-parallel light distribution with a horizontal shift shown in Fig. 6a. Light from off-center and off-axis point of the LED forms a quasi-parallel light distribution with a vertical shift shown in Fig. 6b. All other points from the LED emitter will form the spread with a compound horizontal and vertical shift.

Overall, the parabolic reflector forms a quasi-parallel, or quasi-collimated beam, its spread angle is very small. Therefore it will be very desirable to form the hotspot.

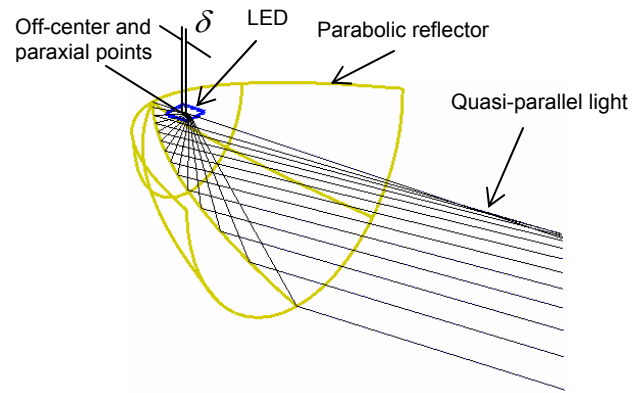


Fig. 6a Off-center and paraxial points of the LED emitter form horizontal shift

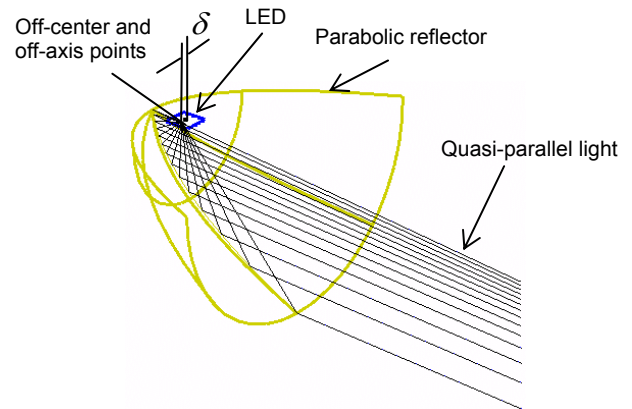


Fig. 6b Off-center and off-axis points of the LED emitter form horizontal shift

TRANSFORM E – QUASI-PARALLEL BEAM TO ANGULAR DISTRIBUTION

The transform from a quasi-parallel light distribution to an angular light distribution has been used most in both automotive headlamps and signal lamps for many years. These old fashion lamps use a parabolic reflector to collect light from a filament to form a quasi-parallel light distribution. It uses a lens or lens array with optics, then, to transform the light to a desire beam pattern shown in Fig. 7.

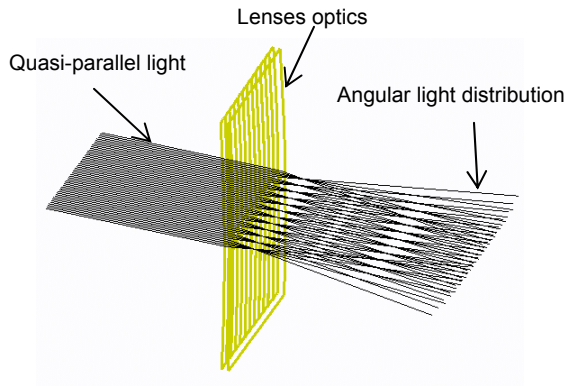


Fig. 7 Transform of a quasi-parallel light distribution to an angle light distribution

The lenses array used in the headlamps, very often, include both lenticular and prismatic structures. Because each lens or prism element can be changed independently, the lamp optical design has more freedom.

The minimum beam spread from this type of lamp is the same as the spread caused by the parabolic reflector discussed in last section.

DISCUSSION – PROJECTOR LAMP SYSTEM

In the previous study^[1] of the reflector optics type of headlamp, one assumed that for the hotspot of a headlamp low beam, the candela value of 25,000 cd is needed. The luminous flux is approximately 50 lm, ($\Phi_{(lamp,1)} \cong 50 \text{ lm}$). The aperture needed to achieve this hotspot performance when using the LED emitters with 100lm output each is $8,000 \text{ mm}^2$. Assuming the hotspot performance and the LEDs used are the same, when using projector system, what should be the aperture size?

First, consider that an LED with a Lambertian distribution is placed at the focal plane of the aspherical projection lens. The area of the LED emitter, $A_{bfp,1} = l_h \times l_v$ is used to form the hotspot. Assuming the hotspot is the zone with 4° horizontal spread and 2° vertical spread, the zonal luminous flux is 50 lm. Amount of light collected by the aspherical lens $\Phi_{lamp,1}$, as well as the corresponding collection efficiency can be calculated with the parameters of aspherical lens (radius r and equivalent focus f) shown in Fig. 8.

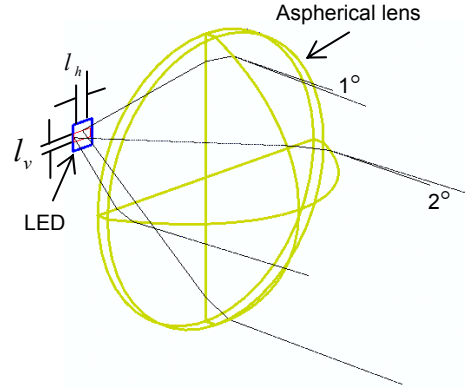


Fig. 8 Aspherical lens with LED light source

If the LED's luminous flux is $\Phi_s (\text{lm})$, the effective LED emitter size is $l_s = 1.5 \text{ mm}$, the aspherical lens radius is $r = 15 \text{ mm}$ and its equivalent focus is $f = 20 \text{ mm}$, then the area of LED emitter used to form hotspot is:

$$A_{bfp,1} = l_h \times l_v = 2f \tan 2^\circ \times 2f \tan 1^\circ \quad (17)$$

If the LED emitter is assumed as the planar emitting surface, and the solid angle collected by the aspherical lens is $\theta_0 = \tan(r/f)$, the luminous flux contributing to the hotspot at the front focal plan is:

$$\begin{aligned} \Phi_{bfp,1} &= L_s A_{bfp,1} \int_0^{\theta_0} \int_0^{2\pi} \cos \theta \sin \theta d\theta d\varphi \\ &= L_s A_{bfp,1} \pi \sin^2 \theta_0 = L_s \Omega_{bfp,1e} A_{bfp,1} \end{aligned} \quad (18)$$

where $\Omega_{bfp,1e} = \pi \sin^2 \theta_0$ is assumed. If the collection efficiency of the aspherical lens is

$$\eta_c = \sin^2 \theta_0 = 0.36,$$

$$\text{i.e. } (r/f) = \arctan(\theta) = 0.75, \theta_0 \cong 36.9^\circ,$$

then the hotspot luminous flux is related to the LED's contribution as:

$$\begin{aligned} \Phi_{(lamp,1)} &= L_{(lamp,1)} \Omega_{(lamp,1)} A_{(lamp,1)} \\ &= \eta n_1 L_s \Omega_{bfp,1e} A_{bfp,1} \\ &= \eta n_1 \frac{\Phi_s}{\pi l_s^2} \times \pi \sin^2 \theta_0 \times l_h \times l_v \end{aligned} \quad (19)$$

where $\eta = 0.8$ is the lenses efficiency counting the surface reflection and transmission lost, n_1 is number of

LEDs used for contributing to the hotspot. If $\Phi_s = 100 \text{ lm}$ is the lumen out of one LED. Then the number of LEDs needed for the low beam hotspot performance is calculated as $n_l = 4$.

The above equation (17) is based on the conservation of etendue of the aspherical lens. Clearly, the luminous flux in the hotspot is limited by the aspherical lens structure, the ratio r/f , or optical power. If the ratio of r/f increases (namely faster optics), the lens will collect more light and the efficiency will increase. However the aberration of lens also increases with the ratio of r/f . Larger aberration causes the light being projected to outside of the hotspot. In the above case, the sub-aperture of a low beam need to form the hotspot is $3,600 \text{ mm}^2$. The total efficiency of this sub-system is 0.288 .

Second, consider the combination of ellipsoidal reflector and projection lens. Assuming an optical filter (shield) is placed at the joint focal plan between the ellipsoidal reflector and aspherical projection lens, then, the total output luminous flux is,

$$\Phi_{(lamp,l)} = L_{(lamp)} \Omega_{(lamp)} A_{(lamp)} = \eta \eta_{ref,c} \eta_{asph,c} \eta_f n_l L_s \Omega_{ref} A_{ref} \quad (20)$$

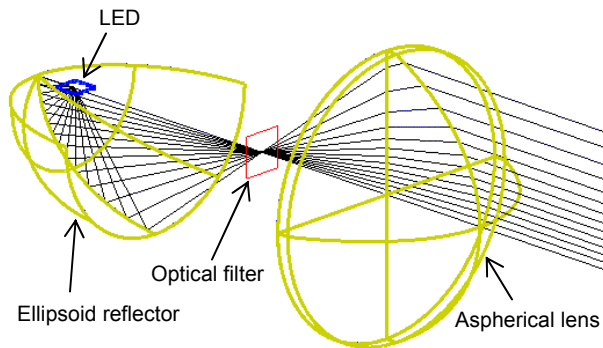


Fig. 9 Ellipsoid reflector and Aspherical lens system

Where $\eta_{ref,c}$ is the collection efficiency of the ellipsoidal reflector, $\eta_{asph,c}$ is the collection efficiency of the aspherical projection lens, η_f is the optical filter efficiency at the joint focal plane, $\eta = 0.7$ is the lamp system efficiency relating to the reflector and the lens reflection and transmission losses. As previously stated in the above, the ellipsoidal reflector collection efficiency $\eta_{ref,c}$ can be as high as 0.8. If one designs to allow all light comes from the ellipsoidal reflector pass through the aspherical lens, then $\eta_{asph,c} = 1$. If the optical filter is assumed be a perfect mirror with no loss, $\eta_f \cong 1$. Thus the total efficiency of the entire lamp system can be $\eta_s = 0.56$.

In the above projector lamp, light is collected by the ellipsoid reflector and focused on the second focal plane that is co-located at the first focal plane of the aspherical lens. The aspherical lens (very often combining with a shield) projects light to form the beam pattern of the headlamp. Because of the etendue conservation, the LED emitter image on the second focal plane of the ellipsoid reflector is larger than the size of the LED emitter, but with a smaller spread angle.

Because the LED emitter image size at the second focal plane of the ellipsoid reflector is 4.8 times of the original LED emitter size (shown in equation 9), for the square-shaped emitter, the effective dimensions of the image are now $3.3 \times 3.3 \text{ mm}$. The luminance of the image used for the aspherical lens is then reduced. For simplicity, one assumes the luminance of the image is an exponential distribution shown in equation (21):

$$L_{lamp}(x) = L_{lamp,0} \exp\left(-\frac{x}{x_0}\right), \quad (21)$$

where $L_{lamp}(x)$ is luminance at x point, $L_{lamp,0}$ is a maximum luminance at the center point of the image, x_0 is a constant. With the exponential luminance distribution, the luminance at the edge of the image ($x = 3.3 \text{ mm}$) is 0.1 of the maximum luminance, then one can find $x_0 = 1.43 \text{ mm}$. When using the aspherical lens shown in Fig. 8, the portion of the image that contributes to the hotspot is $0.35 \times 2 \text{ mm} \times 0.7 \times 2 \text{ mm}$ at the first focal plane of the lens. The luminance at the vertical edge the (hotspot) portion of the image is calculated as: $L_{lamp}(0.35) = 0.78 L_0$; and the luminance at the horizontal edge is $L_{lamp}(0.70) = 0.61 L_0$. Furthermore, the average of the luminance of the (hotspot) portion of the image can now be calculated. In addition, the surface reflection loss of the ellipsoidal reflector should be considered, then the average luminance of the image is approximately $0.77 L_0$ (with 10% reflector losses). This calculation shows that the luminance of the portion of the image used for constructing the hotspot is reduced to 77% of the original LED emitter's luminance. If one needs to maintain the hotspot luminous intensity, 4 LEDs are no longer sufficient, and the aperture of the each aspherical lens must be increased. Alternatively, one can increase the number of the LEDs used for the hotspot, e.g., 6 LEDs should be able to construct the same hotspot performance, however, the overall lamp aperture (using 6 LEDs instead of 4) is now increased as well.

As discussed in the above, the projector lamps are the devices that have combination of the angular distribution to spatial distribution, and spatial distribution to angle distribution transforms. The projector lamps, in general, have higher collection efficiency than the reflector lamps.^[1] Inversely, the reflector lamps can achieve higher luminous intensity at hotspot. Because all light on the object plane share the same aperture of the projection lens, the aperture of projector lamps are, in general, smaller than the reflector lamps.

CONCLUSION

As a summary, five basic optical transforms used in the automotive lamp optical design have been discussed. For the automotive lamps (or any illumination system in general), these transforms are:

Free-form reflector (or reflector optics) headlamp performs the transform from the source angular light distribution to a new angular light distribution – desired beam pattern.

Projector optics headlamp performs a combination of transforms: first, it transforms the source angular light distribution to a spatial light distribution on second focal plane of the ellipsoidal reflector, which is collocated at the first focal plane of the projection lens. Second it transforms the spatial light distribution on the focal plane to a desired beam pattern, a new angular light distribution.

Lens optics headlamp also performs two transforms. First it transforms the source angular light distribution to a quasi-parallel light distribution with a parabolic reflector. Then it transforms the quasi-parallel light distribution to a beam pattern, another angular light distribution using lens array.

The limitations for these transforms are based on the etendue conservation. These limitations are the intrinsic properties of the optical systems used in the illumination applications including automotive lamps. When designing the automotive headlamps using the LED sources, the overall balance between the total lumen and luminance of the LEDs and the headlamp optical structures (e.g., aperture) is controlled by these limitations discussed in the above. In principle, to achieve high performance for a headlamp, when the system losses caused by manufacturing (reflection and transmission loss and component variations) are not avoidable, sufficient lumen and luminance of the light sources and sufficient optical systems are always necessary and important.

Other types of optical device used for lamp design such as total internal reflection lenses and light guides, the transform property can also be categorized. However, the limitations of these systems are still based on the conservation of the system etendue.

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