Review Article

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Free-form illumination optics

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Abstract: In many illumination problems, the beam pattern needed and/or some geometrical constraints lead to very asymmetric design conditions. These asymmetries have been solved in the past by means of arrangements of rotationally symmetric or linear lamps aimed in different directions whose patterns overlap to provide the asymmetric prescriptions or by splitting one single lamp into several sections, each one providing a part of the pattern. The development of new design methods yielding smooth continuous free-form optical surfaces to solve these challenging design problems, combined with the proper CAD modeling tools plus the development of multiple axes diamond turn machines, give birth to a new generation of optics. These are able to offer the performance and other advanced features, such as efficiency, compactness, or aesthetical advantages, and can be manufactured at low cost by injection molding. This paper presents two examples of devices with free-form optical surfaces, a camera flash, and a car headlamp.

Keywords: cell phone flash lens; free-form; LED lamp; low beam; nonimaging optics; wavefronts.

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1 Introduction

Traditionally, optical design has made extensive use of spherical surfaces. These are the easiest to manufacture accurately with good surface finish. Also, the design and analysis of optical systems is simplified when using spherical surfaces combined with the paraxial approximation. This consists in considering light propagating along the optical axis at small angles, which allows the use of linear approximations of the optical equations. These simplifications were especially important when computers were not available.

Rene Descartes (1596–1650) was the first to publish the now familiar formulation of the law of refraction in terms of sines. He then developed the foundations of the optics of aspheric surfaces. Today, these are known as Cartesian ovals and are aspheric surfaces that, in general, match an input wavefront to an output wavefront. In 1905, Schwarzschild considered a class of telescope objectives consisting of two aspheric mirrors and showed that such systems can be made aplanatic.

In 1992, Miñano extended these methods by simultaneously designing two aspheric surfaces that couple two input and two output wavefronts [1]. When the two input wavefronts collapse into one (and accordingly the output wavefronts), these optics converge to aplanatic configurations. Also, if one of the two surfaces is prescribed, only one input and one output wavefronts can be coupled using the other surface, resulting in a Cartesian oval surface. In 1997, Benitez further extended these procedures to 3D geometry in such a way that now two 3D input wavefronts can be coupled with two 3D output wavefronts [2]. The resulting optic is not only aspheric, but it also breaks the rotational (or linear) symmetry, becoming free-form.

Other important developments in free-form optics include methods for designing optical surfaces that take the light from a point source and produce a prescribed intensity or irradiance pattern on a given target [3–5].

These and other developments have applications in nonimaging optics used in illumination. In nonimaging configurations, image formation is not a requisite and, quite often, it is undesirable. This relaxation in the stringent conditions of image formation allows, for instance and in some cases, for optics, which are more tolerant to errors, which in turn may be fabricated using more relaxed manufacturing methods. However, in other problems, nonimaging design goals can be as hard to achieve as those of imaging applications. In some cases, nonimaging optics has made extensive use of highly aspheric optical surfaces and, in more recent times, also of free-form

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configurations. This paper presents two examples of how these developments may be used to design optics that perform under tight geometrical constraints and aggressive performance goals. These have to do with the stringent volumetric constraints (small volume available for the optic) and shape of the light emission pattern.

2 Cell phone camera LED flash lens

Smartphones had an impressive growth in the last few years. These are powerful and flexible computers that give the user the ability to perform multiple complex tasks. They are also fitted with multiple sensors that extend their capability, such as GPS, compass, or luminosity sensors. Among these, the most used sensor is the camera. People use it to take pictures in all light conditions and of all kinds of objects. One of the drives in smartphone development is to make them as thin as possible. This severely restricts the volume available for the camera, which in turn implies the use of very small lenses and sensors. In broad daylight, with good lighting conditions, these cameras will generally perform well. However, taking good photos in dim light is challenging for these small cameras.

Cameras have always been used in combination with flashlights. These have different uses, such as to illuminate the subject at night or to reduce shadows during the day. In general, smartphones also incorporate a camera flash. Owing to the very small volume available for the flash, LEDs are used as the light source. These, however, are also small LEDs that emit a limited amount of light. Also, they typically emit light in all directions, while the camera will only capture an image within a restricted angular aperture. It is, therefore, desirable to match the flash light emission cone with the camera image-capturing cone. That way, the subject illumination is maximized as all the light emitted by the LED is used to illuminate the subject and not the scene around it. This is achieved by combining the LED with a collimating optic.

Typically, the optic should take the light emission from a square LED and produce a rectangular emission cone matching the cone imaged by the camera. However, due to the compactness of smartphones, the volume available for the LED and corresponding optic is quite small, which makes the optical design quite challenging. If there was plenty of room available for the optic, different design methods could be used. In particular, if the optic was very large, one could consider the LED to be a point source (much smaller than the optic), and one single optical surface would be sufficient to generate any desired output illumination pattern [3, 6]. An alternative approach, which results in more compact optic is to simultaneously design two smooth optical surfaces, as these now have some ability to control the light emission of an extended source (a large LED when compared to the optic size). These optics consisting of smooth optical surfaces may, however, still be quite large for the very stringent volume conditions needed. Folded optics (such as the RXI [7]) in which the light bounces back and forth inside the optic before being emitted have a smaller depth. These, however, may be complex to design and manufacture at such small scales.

For the reasons mentioned above, the typical approach used in camera flash design is to use facetted optics. These may include refractive Fresnel facets, Total Internal Reflection (TIR) facets or a combination of both. These optics, however, have the inconvenient that often the different facets will interfere with each other. These may result in some facets blocking the light coming from other facets. Also, the exit aperture may not fully flashed due to the spacing of the facets, resulting in exit area apertures larger than otherwise needed for the same cone of output light.

The most common optic use nowadays is a Fresnel lens placed above the LED. These lenses, however, have some important limitations. In order to work properly, they must be placed at some distance from the LED and that conflicts with the compactness requirements of a smartphone flash. Placing them closer to the LED (shorter distance than the focal length) will result in more compact devices, but this approach compromises the collimating ability of the lens. In those conditions, Fresnel lenses tend to produce a wider angle (better matching the viewing angle cone of the camera), but also a round illumination pattern on a distant target, which does not match the rectangular shape of the camera viewing cone. Also, the illuminance at the center of a distant target tends to be much higher than that at the edges or corners.

In order to overcome some of the limitations of traditional rotational Fresnel lenses, new configurations may be devised. Figure 1 shows an example of a flash optic designed for a square 1×1-mm flat top LED. On the right, this same figure compares the optic to a 1 euro coin. It is designed to illuminate a rectangular target of 81×106 cm at a distance of 1 m, corresponding to an emission angular aperture of 44°×56°.

The optic is composed of different sections, each one designed with different criteria, as shown in Figure 2, where the black line defines the LED top-emitting surface. At the center of the optic, the LED light is collimated by a rotational refractive surface shown in magenta. Moving

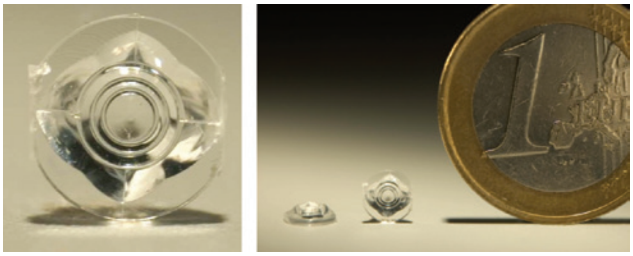

Figure 1: LED flash lens (left) compared to a 1 EUR coin (right).

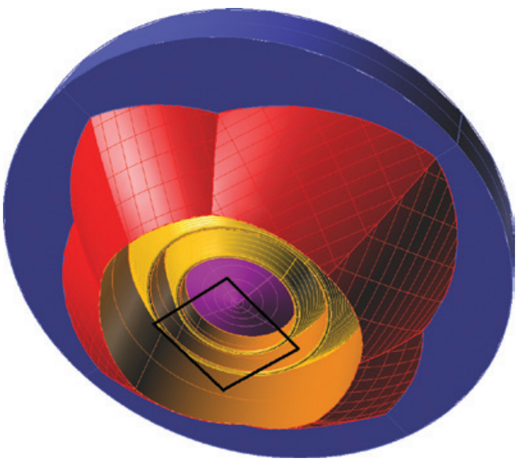

Figure 2: Perspective view of a LED flash lens. The LED has a square emitting area as indicated by the black line.

outward from the center, light is collimated by a rotational TIR lens, as shown by the yellow surfaces. This is not a simple collimator, but it spreads the light over the desired emission angle. These rotational optical surfaces will generate a round illuminance pattern on the target. This, however, does not match well the desired rectangular illuminance.

For that reason, on the outside of the lens there are a series of 'petals', shown in red.

A similar approach is also used in other applications, such as in the design of Fresnel-Kohler solar concentrators where the concentrator must form a square uniform illumination pattern on the solar cell [8].

The whole optic is quite small, as can be seen from the dimensions in Figure 3 on a top view (left) and a side view (right). In particular, its height is only 1.6 mm. The black line represents the perimeter of the LED-emitting area.

The resulting illuminance pattern on the target is as shown in Figure 4 left, clearly showing a shape approximating that of a rectangle. Note that the LED source, optic, and target all have quadrant symmetry and so does the illuminance pattern. Figure 4 right shows the vertical and horizontal pattern cross sections.

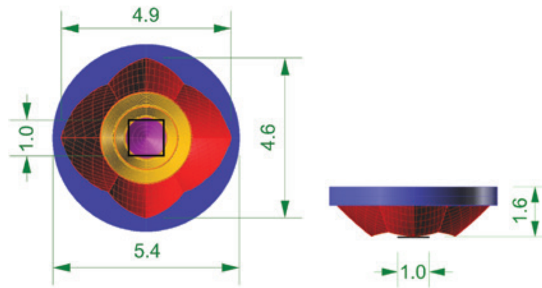

Figure 3: Top (left) and side (right) view of a LED flash lens with dimensions. The LED has a square emitting area as indicated by the black line. Dimensions in millimeters.

In this example, the efficiency of the optic, measured as the percentage of light that reaches the target divided by the amount of light emitted by the LED is 65%.

When compared with a Fresnel lens, this new configuration shows several advantages. By collecting a wider cone of the LED emission (and therefore collecting more LED light), they are able to put more luxes on the target for the same LED lumens. The tailored shape of the optic results in a more uniform illumination of the target, especially at its center. The action of the outside petals of the new optic results in a rectangular pattern that matches the camera viewing cone.

3 Automotive LED low-beam lamp

The automotive field is always open to applying new technologies, and illumination is a good example of continuous change, in the last 25 years, particularly. Old fashioned halogen low-beam solutions (discontinued progressively in the 1990s) were based on a mirror collimator in front of a Fresnel lens split in sectors. The Fresnel lens directed the light collimated by the mirror into a set of directions to tailor the very special light intensity patterns needed in this application. The mirror/lens combination was replaced later with more fancy solutions based in multi-facet mirrors only, where the facets performed similar to the sectors of the Fresnel lens.

Later, the high-intensity discharge (HID) xenon lamps entered the high-end market. These lamps perform much better than conventional halogen solutions, providing more lumens on the road and a better distribution of light for a safer night drive. The typical HID lamp consists of a mirror that collects the light source emission and directs it toward a projector lens. Between the mirror and lens, there is a mask with the shape of the cutoff line, which is imaged by the said lens onto the far field,

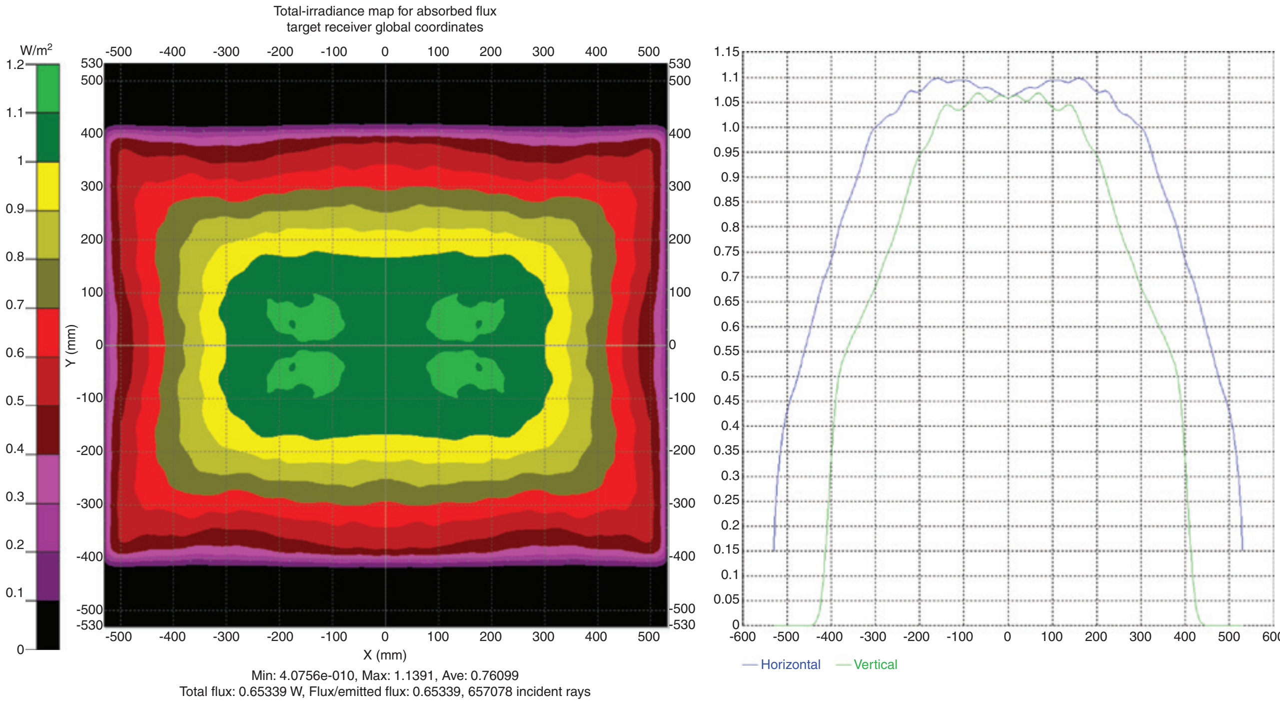

Figure 4: Illuminance on a screen of 81×106 cm size at 1-m distance (corresponding to an angular aperture of 44°×56°).

creating the pattern. This solution is not efficient, as the mask blocks almost half of the original light, but the flux of the xenon arc and its luminance is so high that the loss is affordable. Today's average halogen lamps project about 400–600 lm onto the road, while HID headlamps reach more than 900 lm. Conventional incandescent and HID headlamps use reflectors for the primary collection of the emitted light. Because they usually cannot cover the full solid angle into which the light is emitted, their efficiency remains low. Further losses occur if shutters (projector lamps) are needed to shape the low-beam pattern, like in the case of HID lamps. The optical system efficiency (defined, for example, as the ratio of the flux emitted into the -10/10 deg vertical -50/50 deg horizontal far field angle window vs. the total emitted flux of the light source) of a conventional system ranges from 30% to 50%. Both incandescent and HID sources produce an abundance of light flux that allow low-efficiency optical designs.

LEDs have been successfully applied in numerous CHMSL's, Tail-, Stop-, and Turn-lights, starting by the end of the 20th century. The headlight functions (low beam LB, high beam HB, and daytime running light DRL) started a little bit later, though, as the first white LEDs had relatively low luminance (to be used in the LB and HB functions) and were expensive. The low luminance meant that large sources were needed to get the lumen output needed. These large sources needed to be coupled with large optics, which were not practical. The rise of efficiency of the InGaN blue chip and phosphor conversion has created white LEDs with the required luminance lately, and medium-size chip high flux LEDs now can be utilized in those white functions. Typically, several LEDs per function will be needed. Because of the high price of both the LEDs and the optics in front of them, it is desirable to use the most efficient optics both in terms of collection efficiency and aperture/depth requirements that will collect the LED light and form a legal beam pattern.

Because of the smaller solid angle into which a LED emits its light (±90 deg), highly efficient systems are possible. An average system may reach 50%, where specialized systems have reached up to 78% efficiency (as will be shown below).

Among the three functions mentioned above, the LB represents one of the most challenging optical design problems in illumination. The LB function requires an asymmetrical illumination pattern (see Figure 5) with the following features (explained for right-hand-side driving and considering in the intensity plot the horizontal axis is H, and goes from Left L to Right R, while the vertical axis, V, goes from Down D to Up U):

– It needs a very sharp vertical cutoff separating an almost completely dark from a very bright area. The reasons are, on the one hand, the LB should not blind oncoming traffic, while at the same time, it should

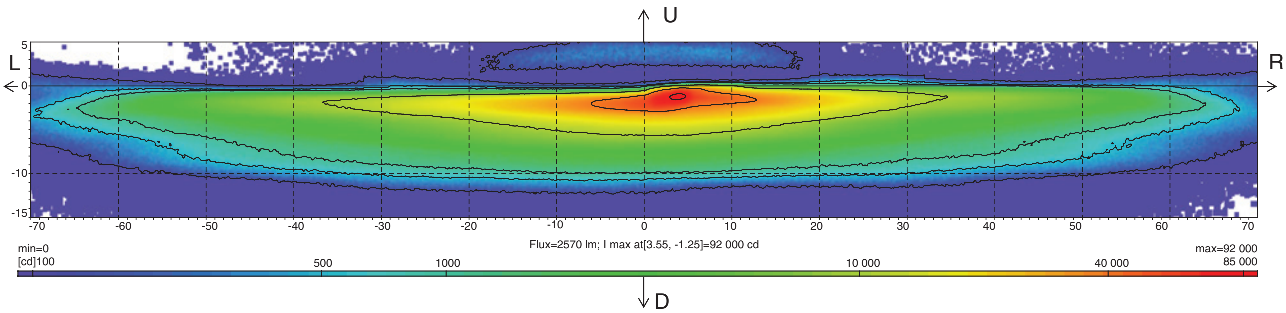

Figure 5: Example of a high-performance low-beam pattern, attained with a LED lamp based on multiple optics. This pattern is the combination of the laft and drive lamps. It features a very intense hot spot (92000 cd), ultra-wide horizontal spread (1000 cd isoline reaches ±65°) and a very sharp vertical cut-off line. A car equipped with this design would put more than 2500 lm on the road.

illuminate as far as possible on the road to enable a safe drive

- The highest intensity (hot spot) should be located slightly to the right of the optical axis (driving direction) to be able to put more light on the lane in front of the car. The hot spot should be located as close to the horizon line (V=0), without surpassing it, to get the most comfortable driving
- The cutoff line is aligned with the horizon (V=0) on the right side of the pattern H>0, while it is slightly below the horizon (V=0.57D) on the left, to prevent blinding oncoming traffic
- The pattern should be quite wide in horizontal, to provide light both to the left and right and have a clear visibility of side lanes, sidewalks, etc.
- In vertical, the intensity should gradually decrease downward from the hot spot to about 10D, to provide the perception of illuminance uniformity toward the front of the car

Regulations that apply in different countries specify minimum and maximum intensities required in the HV plot. The regulation points define a very asymmetric intensity pattern. Car manufacturers specify performance requirements clearly beyond the regulations (wider beams for a better illumination of the areas to the left and right of the car, higher intensities, and punch – the distance at which the road in front of the drawing still looks illuminated – illuminance uniformity on the road to avoid cumbersome artifacts), with the aim of providing the drivers with the safest and more comfortable driving experience.

The simultaneous multiple surface design method (SMS) started in 1992 [9] and led to the invention of the so-called RXI [3] (Figure 6), by then, a rotational device named after the type of deflections the light went through when passing through it (refraction R, Reflection X, and total Internal Reflection I). Originally, this shallow device proved to have very good performance features both acting as a LED light collimator (spot light applications) and as a photovoltaic concentrator. More recently, it was designed in 3D as a free-form device to show its potential in different automotive applications.

In the different free-form RXIs developed in this field, the LED beam typically enters the RXI body through a refractive cavity. The rays are then reflected by TIR at the front RXI surface, toward a metallic mirror at the back. The light bounces at the mirror toward the front surface again, where they are refracted toward the road. Notice that in the RXI, the front surface works both as a lens and as a mirror: this duplicity allows for the excellent RXI compactness. The free-form RXI surfaces are designed to direct the rays coming from the LED outer boundary (defined by a set of so-called ‘edge rays’, typically coming from two LED corners and one additional point at the opposite LED edge) toward a set of preferred directions on the road: the sum of projected LED images eventually sum up to smoothly provide the desired pattern.

The free-form RXI front surface and back mirror (and sometimes, even the RXI cavity) are actually non uniform

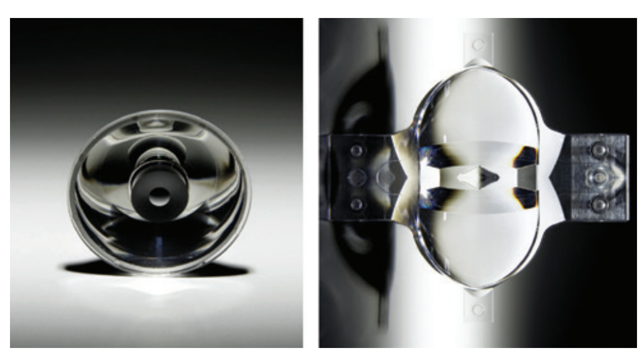

Figure 6: Two examples of actual RXIs. On the left, rotationally symmetric RXI for collimated light. On the right, free-form RXI for DRL applications. Photos courtesy of LPI.

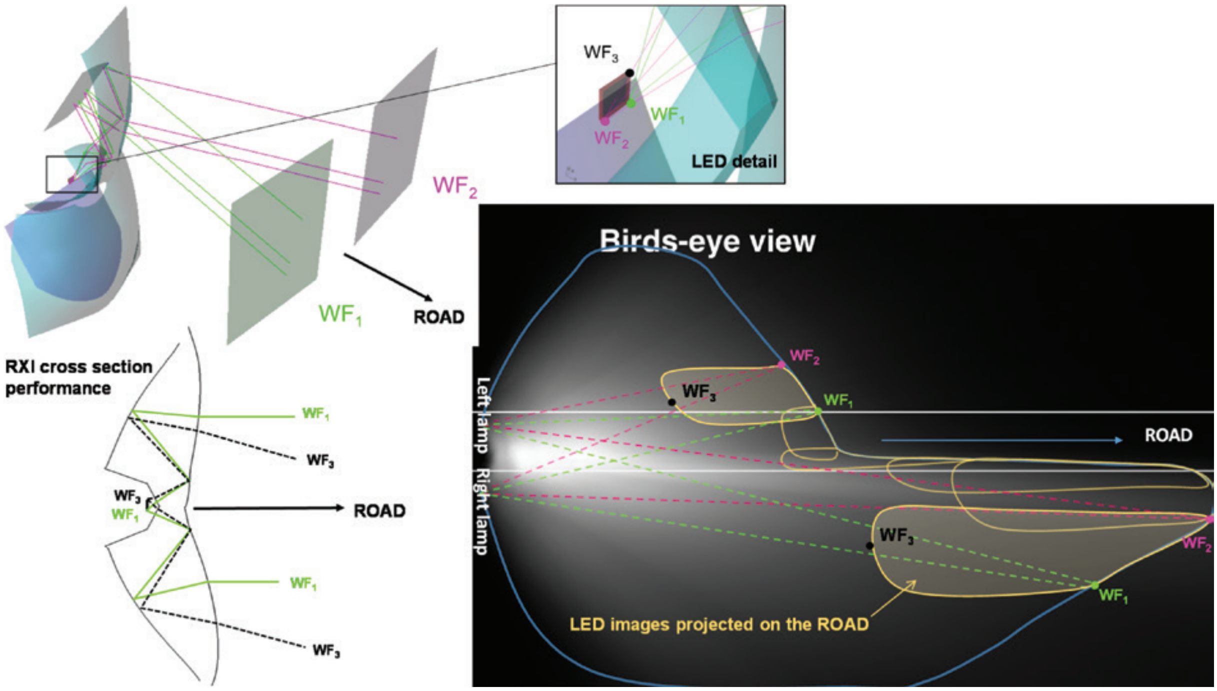

Figure 7: Design wavefronts in a free-form RXI device for automotive applications. In this device, the rays coming from the LED are refracted in a cavity, and afterward, they are reflected by TIR, in the front surface, and at the back mirror, before being refracted toward the road (see the cross-section performance, bottom left). Both the mirror and front surface are free-form and are designed using the SMS method. The output free-form design wavefronts WF_1 and WF_2 are such that the LED images projected onto the road form a high-quality illuminance pattern. A third design wavefront WF_3 is used to control the LED images elongation along the road (vertical spread).

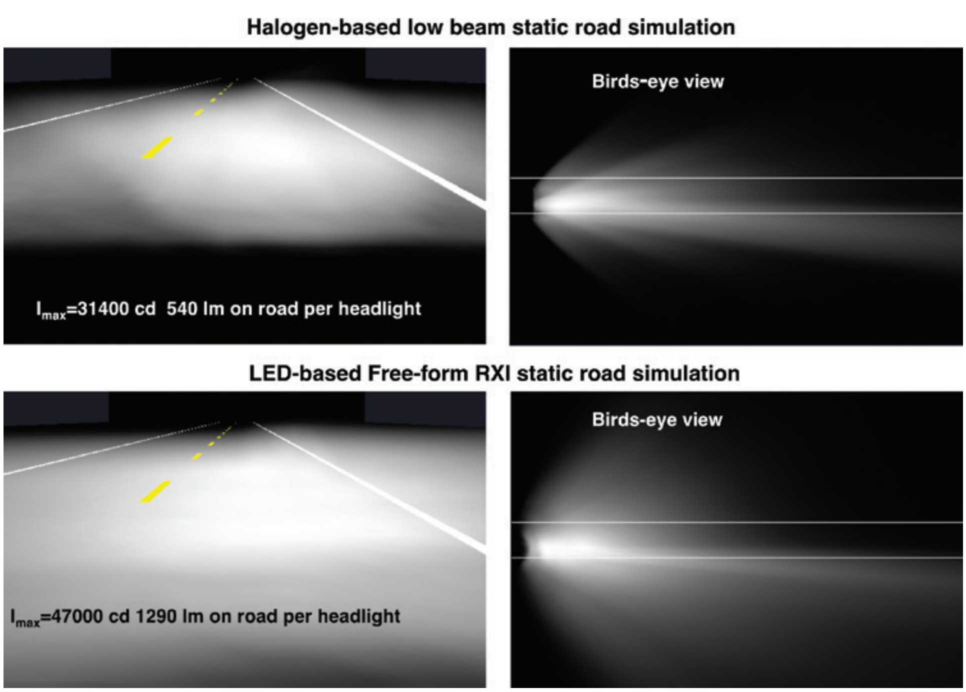

Figure 8: Comparison of a state-of-the-art mirror-based halogen lamp low beam with an advanced LED-based free-form RXI low beam. This high-flux high-intensity headlight distributes the light more uniformly on the road and provides more light frontward and laterally, enabling a safer driving.

rational B-splines (NURBS) comprising a cloud of points calculated through the SMS method in its 3D version [10].

The output wavefronts of a nonimaging optic may be related to the intensity pattern it produces [8]. The 3D SMS surfaces connect two input wavefronts (WF_1 and WF_2, point sources at the two LED corners, for instance, as mentioned above) with two output wavefronts (defining the aim of the light coming from such LED corners and, therefore, controlling the shape LED pinhole-projected images in the far field/road illuminance patterns). The output wavefronts are free-form surfaces especially modeled to produce the kind of pattern required in this application (see Figure 7). The final illuminance on the road is a result of the overlapping of all LED images (of variable size and location thanks to the output free-form design wavefronts, aiming at the edges of the projected LED images) projected by the RXI optics, as the drawing below shows. In order to control the vertical spread of LED images projected onto the road, the RXI central cross-section is designed with a third pair of wavefronts, WF_3, coming from a LED point located at the edge opposite to WF_1 and WF_2.

Thanks to the advanced features of this device, a LED lamp based on a combination of free-form RXIs can reach the performance of a good HID lamp. Figure 8 shows road simulations comparing a 4-RXI lamp with a 'conventional' halogen lamp: notice that the RXI headlight clearly over performs the halogen solution. With good mirrors, light output ratio (LOR) can be as high as 70%, including losses in a protective cover lens. The RXI LED headlamp puts more lumens on the road (1290 per headlight, to be compared with 540 of the halogen solution). The beam pattern is also much wider, both in horizontal and vertical, being able to illuminate both the sides of the road and the road close to the car front end. Finally, it shows a longer 'punch' (maximum reach of the 500 lx iso-line) and is also more uniform in the illuminance distribution.

This patented technology has been successfully applied in the high-end automotive market: the Acura RLX platform equips headlights based on the RXI since 2013 [11].

4 Conclusions

Nonimaging design methods in which the optics couple the light coming from the edges of the light source onto preferred directions defining a desired intensity pattern lead to compact devices and efficient devices. These methods combined with free-form optical surfaces further increase their potential for dealing with complex illumination patterns.

This paper presents two examples of applications. The first example is a flash optic. Owing to the extreme volume restrictions of these devices, the optic atop the LED is quite small when compared to the volume available for the optic, or what is the same, the LED is large relative to the optic. In these situations, the large size of the LED cannot be ignored, and the optic design must consider it. Controlling the light emitted from the edges of the LED is, therefore, of uppermost importance. This design has a rotational central region, which generates a rotational pattern, but it is then complemented with several petals on the periphery that help control the light emitted from the different corners of the LED. This results in a high efficiency device producing a desired rectangular-shape pattern.

The second example shows a compact nonimaging low-beam optic using what is designed to project LED images on the road with controlled aim, size, and rotation. This allows the creation of an illuminance pattern on the road with advanced features, above the minimum regulation legal requirements, for a safer night driving.

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