Review of SMS Design Methods and Real World Applications

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ABSTRACT

The Simultaneous Multiple Surfaces design method (SMS), proprietary technology of Light Prescription Innovators (LPI), was developed in the early 1990's as a two dimensional method. The first embodiments had either linear or rotational symmetry and found applications in photovoltaic concentrators, illumination optics and optical communications. SMS designed devices perform close to the thermodynamic limit and are compact and simple; features that are especially beneficial in applications with today's high brightness LEDs. The method was extended to 3D "free form" geometries in 1999 that perfectly couple two incoming with two outgoing wavefronts. SMS 3D controls the light emitted by an extended light source much better than single free form surface designs, while reaching very high efficiencies. This has enabled the SMS method to be applied to automotive head lamps, one of the toughest lighting tasks in any application, where high efficiency and small size are required. This article will briefly review the characteristics of both the 2D and 3D methods and will present novel optical solutions that have been developed and manufactured to meet real world problems. These include various ultra compact LED collimators, solar concentrators and highly efficient LED low and high beam headlamp designs.

Keywords: SMS Design, Freeform Optics, Illumination, LED collimator, RXI, Nonimaging Optics, TIR-R, Diamond Turning, SMS Imaging, Condenser

1. INTRODUCION

The SMS design method gives access to solutions of optical problems that can be formulated as the coupling of incoming and outgoing wavefronts. The number of wavefronts that can be controlled on both the input and output side, depends on the number of surfaces to be designed. Other methods create only one profile or surface at a time and therefore only couple one wavefront to another. This can be understood as a generalized Cartesian oval construction. Those solutions may be perfect for point light sources but, in many practical cases, the approximation of an extended light source as a point source results in loss of efficiency and "smearing out" of the output pattern. Iterative design methods try to optimize point source solutions for extend sources. In contrast to this, and without the need of optimization loops, the SMS method inherently uses the extension of the source as an input parameter to create an optical system perfectly adapted to it. Such systems exhibit performances close the thermodynamic limits.

While the SMS 2D method has generated a number of ultra compact and highly efficient devices with rotational or linear symmetry, SMS 3D has matured into a stable design method for a wide range of applications in nonimaging optics that cannot be solved with systems using linear or rotational symmetry. After overcoming complex obstacles in both programming and 3D surface creation, the SMS 3D method now has matured and reached a level of stability that makes it an every day design tool. Some of the results achieved are presented below.

Up to this point, the SMS method has mostly dealt with two pairs of wavefronts to be coupled. The design results are two profiles or surfaces. Many extensions of this method are being developed, some of which we will presented in the last chapter of this article.

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SMS 2D REVIEW

In SMS [1] [2] (simultaneous multiple surface) design procedures, the optical prescription is stated as incoming and outgoing wavefronts. The definition of these wavefronts is sometimes trivial (see example below) but in other cases highly complex: If the design goal is to meet a certain irradiance or intensity distribution, there is no deterministic relation that allows the derivation of exiting wavefronts that create said distribution. However, approximate methods may be applied [3].

In the following section we will review, at a simplified level, the design methods that consist of coupling two pairs of wavefronts that create two generally free form profiles (SMS 2D) or surfaces (SMS 3D) that can be either refractive or reflective. The optical system may consist of any number of surfaces that exist before, after or in between the SMS surfaces. These surfaces are either predefined by the application (e.g. the dome shape of an LED light source or a fixed exit aperture profile) or part of the design, where they are introduced to facilitate the SMS process. The effect of these extra surfaces is taken into account by simply propagating the source and target wavefronts through those surfaces. The resulting wavefronts, now refracted or reflected at the non SMS surfaces, are then used in the SMS calculation. Besides the obvious physical limitations (i.e. etendue conservation [1]), the only condition for a successful SMS design process is the absence of any caustics of the wavefronts to be coupled in the vicinity of the space to be occupied by the SMS surfaces.

In the following example, the edge rays of a 2D light source are to be coupled to two straight exit wavefronts. If the angle between those exit wavefronts is chosen according to the Etendue of the light source and the exit aperture size, this system behaves like a perfect 2D collimator. The input parameters are: Two sources and two target wavefronts, a starting point for one of the SMS surfaces and its normal, the nature of the surface (here refractive) with the index of refraction and two optical path lengths between the conjugated pairs of wavefronts.

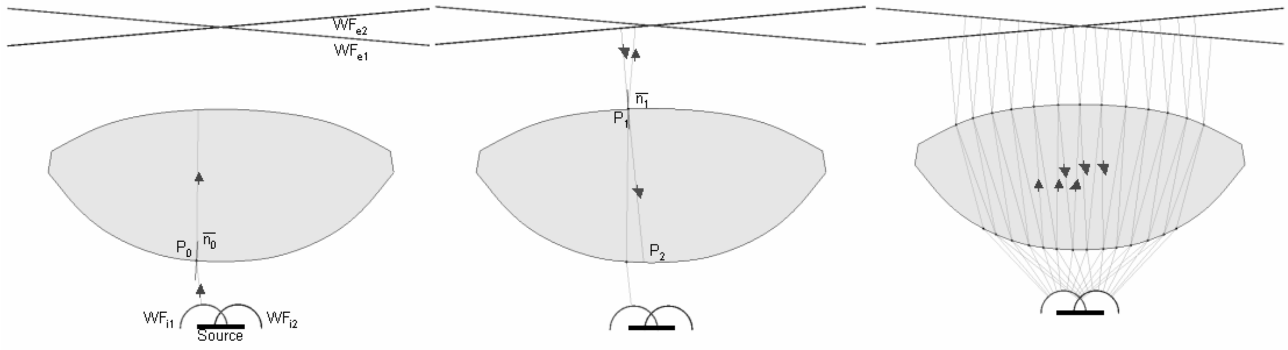

Figure 1: Schematic of design procedure for an RR SMS 2D collimator. The two profiles are calculated starting at a first point P_0 (left). All other points follow from this start point in an alternating algorithm

The profile of the gray lens in Fig. 1 shall be designed. The first point P_0 and its normal n_0 are chosen as input parameters. A ray from the first source wavefront (WF_{i1}) is selected that connects the edge of the source and P_0. This ray is refracted. The first exit surface point P_1 is found by searching a ray that, emitted from the exit wavefront $WF_{e1,}$ has an optical path length L_1. Now a ray from the other exit wavefront WF_{e1} is refracted at this point, and traced. Point P_1 is calculated the same way as before, now utilizing the optical path length L_2. Repeating the same steps produces alternating points on the input and exit surface. On the far right of Fig. 1 it can be seen, that all rays from each edge of the source leave the lens as rays normal to the exit wavefronts. From the edge ray theorem it is known, that all other emitted rays will not be edge rays and therefore have a smaller off axis angle as the design rays.

The final lens profile is obtained as the minimum order interpolation curve through the SMS points. While strictly speaking the method only controls rays from the two design points, the behavior of rays emitted from other points than the edge points as well as all rays hitting the lens profile where the profile is interpolated between the SMS points are not controlled. In most practical cases, however, SMS designs are “well behaved” in the sense that, firstly, the interpolated profile sections are not distinguishable from a “perfect” profile for rays originating from the design points, and secondly, that all rays emitted from source points that are not design points behave as expected.

SMS 3D REVIEW

The SMS 3D design method has, as the 2D design, as input parameters two pairs of wavefronts, now defined as 3D surfaces and two optical path lengths between the two corresponding pairs of wavefronts. But, instead of a single starting point and a normal as free parameters, now a “seed” curve in space can be chosen that will serve as starting points for the SMS point calculations. SMS points generated using the 4 design wavefronts from a point on the seed curve are called chains. The seed curve can be sampled at as many points as desired to create many chains. The full design is eventually defined by all the SMS points that can be interpolated by two 3D surfaces; one of them contains the seed curve.

In the definition of the seed curves lies an important degree of freedom: It can be obtained by a SMS calculation using for example WF_{i1}/WF_{e1} and two new wavefronts WF_{i3}/WF_{e3}. This third wavefront pair can consist of a source wavefront emitted from a third point of the source coupled to a third exit wavefront. The full 3D SMS design maintains the coupling of the third wave front pair in surface regions in the vicinity of the seed curve. In surface regions that are not close to the seed curve, this coupling may be lost. This means that a 3D SMS design can, with two calculated surfaces, control three design points, two of them perfectly, one of them approximately.

Imagine a square light source (e.g. an LED chip, Fig. 2). The SMS device shall be a dielectric solid, with a metallized back surface (the “X” surface) and a refractive front surface, that will at the same time reflect rays by TIR (called “I”) and refract others (called “R”). Those designs are called RXI [9] [10].

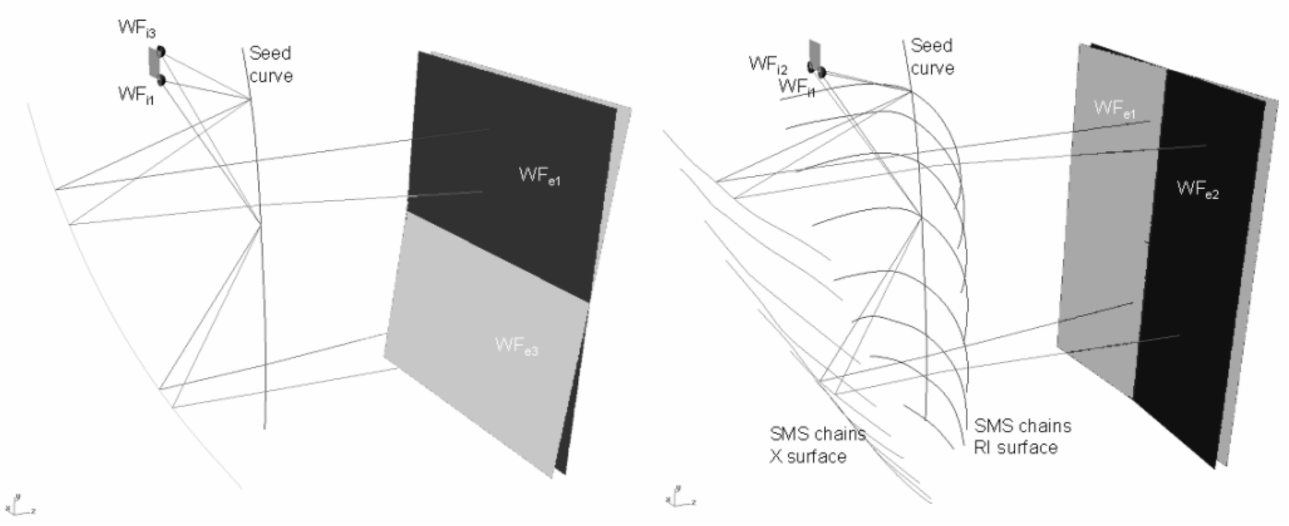

Figure 2: Schematic design procedure for an RXI SMS 3D collimator. Left: “Vertical” wavefronts of source and target are coupled to create two vertical profiles. One profile is the seed curve used to calculate the SMS chains (right).

In total three input wavefronts (e.g. three corners of the chip) and three exit wavefronts are chosen that describe how the light from the chip corners shall be emitted. In the example in Fig. 2 all exit wavefronts are planes rotated 5 deg from the z axis, WF_{e1} and WF_{e2} horizontally and WF_{e3} vertically. This RXI shall produce a far field pattern that is an image of the chip of 5 deg vertical and horizontal size. In a first step (Fig 2, left) two vertical SMS profiles are calculated that couple the two “vertical” pairs of wavefronts with each other. One of those profiles will be used as a seed curve for the calculation of the SMS chains (Fig 2, right): Each pair of chains is calculated by coupling the two pairs of “horizontal” wavefronts with each other. The seed curve can be sampled at as many points as needed in order to calculate as many chains as desired. The two families of chains are then approximated (Fig 3, left) by a smooth CAD surface. The RXI shown now directs all rays from the two lower corners of the chip to 5 deg Left/ Right and, in this example, to 0 deg horizontal. Rays from the third design point (an upper corner of the chip) that hit the SMS surfaces near the seed curve will be directed 5 deg down while all other edge rays from the LED chip top corner theoretically are not controlled. However, in many applications, SMS designs are sufficiently well behaved to maintain the desired characteristics for all non design points (Fig 3, right).

The design shown collects the source light within a half-hemisphere. The other half of the light (the light the chip emits upwards) would be captured by a second design procedure done similarly. The two individual RXIs can collect 100% of the light emitted by a light source into a hemisphere or even up to higher off axis angles.

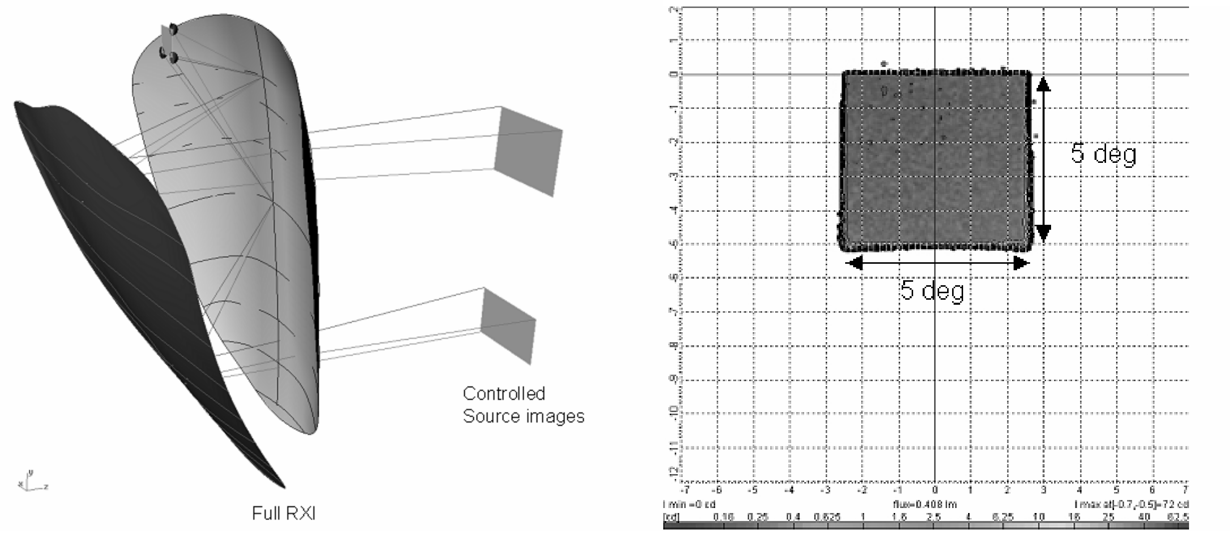

Figure 3: RXI SMS 3D collimator. On the left the two 3D surfaces of the RXI and some source images are shown. On the right: Raytrace of a “well behaved” SMS design with three planar exit wavefronts.

3. COMPARISON OF CONVENTIONAL AND SMS DESIGNS

Conventional design methods design one surface at the time. An example is a freeform mirror used for automotive head lamps. The curvature of every mirror point determines the size and position of the image projected from a small surface element, often called a pin-hole. One design method consists of obtaining a single free-form refractive or reflective surface [4] [5] [6] to solve a prescribed-irradiance problem based on the small-source approximation. This strategy (usually called point-to-point mapping [7]) is well known either for rotational optics, where its solution simply involves the integration of a non-linear ordinary differential equation [8] or for the more general 3D design of a single free-form surface, requiring the solution of a non-linear partial differential equation of the Monge-Ampere type. All of those solutions work well in the small source limit case.

SMS designs control two source points perfectly and a third one partially. The SMS design is fully determined by the choice of the wavefronts and some other simple input values, as described above, with the need of optimization steps.

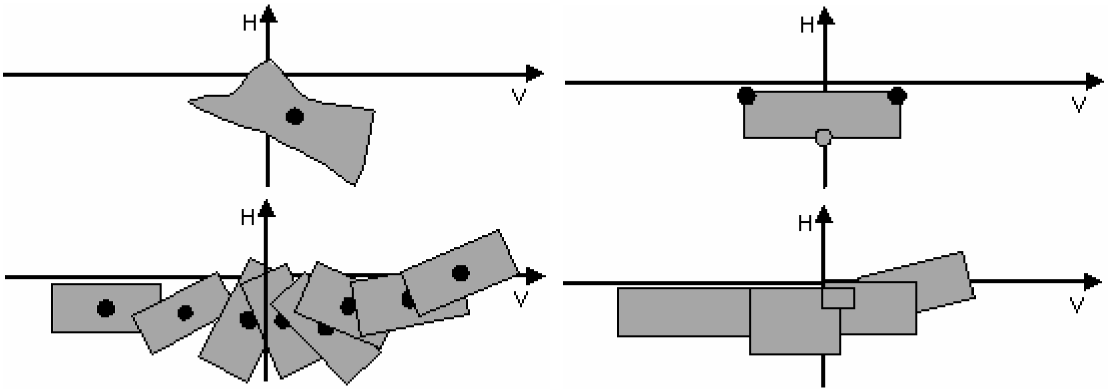

Figure 4: Far field images created by a “pinhole” (upper two graphs) or a set of pinholes (lower two graphs) on the exit surface of a free form optical system illuminated with an extended source. Left: Conventional design: No rotation and distortion control of the images, Right: SMS Design: Size and orientation control of images.

A conventional design only controls one point of the source images. Different sections of e.g. a freeform reflector create far field images of the source of varying size, orientation and distortion (Fig. 4, left). The rotation of the images and their distortion may, if the images are large or if the features to be obtained in the pattern are small, seriously degrade the quality of the output pattern. Not so in an SMS design: The pinhole images of the source are guided by 3 source points in a deterministic manner, so that orientation and size can be controlled.

4. EXAMPLES OF SMS APPLICATIONS

4.1. TIR-R Solar concentrator and LED collimator

The TIR-R system [11] consists of a TIR lens with one flat surface and a secondary lens, both rotationally symmetrical. The secondary lens has a cavity that, filled with an optical coupling gel, holds either a receiver (e.g. a solar cell) or an LED chip as emitter. The two SMS surfaces designed are the reflecting surface of the TIR rings and the surface of the secondary lens. The system has been developed for solar applications to concentrate the solar light onto a small high efficiency solar photovoltaic cell. The theoretical efficiency is 82%. The same optical system, with an adjusted design, can be utilized to collimate LED emitted light with 85% efficiency.

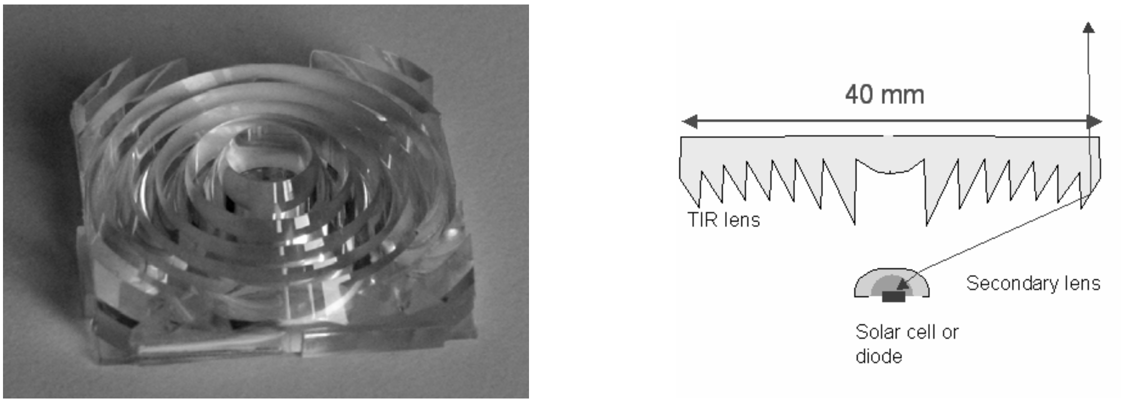

Figure 5: Left: Photo of TIR lens produced by LPI. Right: Working principle of TIR-R combination.

The real-world efficiency of the optical system injection molded with PMMA strongly depends on the surface quality (roughness and deviations from theoretical profile) and the teeth radii of the TIR lens. Since both the convex and the concave vertices are hit by the incident sunlight in the solar application, vertex rounding will reduce the usable surface area and therefore the power transfer to the solar cell.

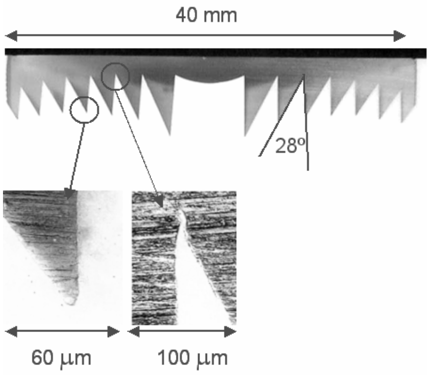

Figure 6: Left: Photo of a TIR lens section and details form its convex and concave tooth vertices.

The TIR shown in Fig 5 and 6, designed for a solar concentrator, has small vertex angles (around 28º) and a diameter of about 40 mm. LPI, who owns the IP for and manufacturers the TIR lens, has demonstrated extremely small tooth radii for lenses molded in a prototype tool. The molding tool has been produced by diamond turning. Injected lenses have been cut to examine their profile under a microscope with digital x-y readout. The convex tooth radii have been measured as 5 µm in average but some radii are below 3 µm, so that they cannot be faithfully resolved under the microscope. The concave teeth yield 14 µm on average and 5 µm minimum. Such small radii suppress the efficiency losses of the system due to rounded teeth edges below 1%.

4.2. RXI LED collimator

The development of the rotational symmetric RXI is a very good example of the SMS 2D design method. Its striking characteristics have been described elsewhere [10]. In fig. 7 an application as an MR bulb replacement is shown: The RXI collects and collimates the light of LumiLeds' Luxeon Lambertian LEDs of any color. The lens is fitted into a housing that includes drive electronics (input voltage 6-24 Vpeak AC/DC) and the LED to make it a full bulb replacement. The RXI lens achieves an extremely tight beam with an opening angle at the physical limit set by the Etendue of the source. The lens diameter is 36 mm and its depth is only 9 mm.

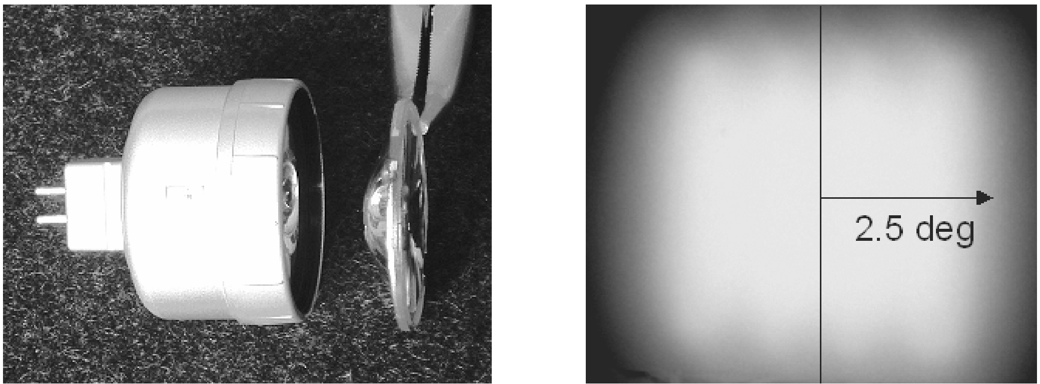

Figure 7: Left: Photo of a “Chip LED bulb replacement”[2]. An identical RXI as mounted in the housing is held in front of the full assembly. Right: Radiation pattern of the RXI with a green Luxeon LED. The vertical bars visible in the pattern are caused by the contacts of the LED chip.

The RXI is designed as a nonimaging device to ensure highly efficient light transfer. This is not incompatible with a good image formation although the names imaging and nonimaging suggest an antagonism [15]. The radiation pattern of the RXI in the far-field therefore shows a clear image of the LED chip.

4.3. RXI LED Headlamp Designs

The RXI’s design principles laid out in the SMS3D review chapter in this paper, have been applied to design several LED headlamps. These are the first Free-form RXI devices ever designed. Such a design will only be efficient, if it collects light from the entire solid angle of the source emission, collimates the light and forms the beam pattern only by reflection or refraction without the help of any blocking devices or shutters. Very high efficiency is important because high performance LEDs are expensive light sources compared to standard light bulbs and the available LED flux still is at least one order of magnitude lower than that of an ordinary bulb. The RXI is highly efficient, as well as compact and optically pleasing, an important “sales tool” in the automotive field where styling is paramount.

Elaborate calculations carried out by proprietary software create the two free from surfaces that transform the source light into the desired pattern without the use of faceting, shutters or any additional optically active surfaces. Extensive raytracing with in-detail modeling of the light source and prescribed optics verify the designs.

The device shown in the following section represents a typical design of an RXI 3D collimator. RXIs for the low beam and high beam application both for the US market (SAE) and the European market (ECE) have been designed using the 3D SMS method. The dimensions of the device are dictated by the etendue calculations (to limit the vertical or horizontal extent of the pattern) and luminance conservation to achieve the needed hotspot intensities. The RXI has a non active center region because the two reflections of the rays displaces them several millimeters up- or downwards from the center of the light source. This will increase the device size, as the lit aperture size is smaller than the physical aperture of the RXI. A possible design that has been investigated is approximately 27 x 60 x 15 (w x h x d) mm^3 in size for the low beam, where the high beam RXI (not shown) is about 40 x 55 x 17 mm^3. The high beam RXI is wider to meet the hot spot requirements and to better collimate the light in the horizontal direction.

By varying the parameter set that our program uses to calculate the RXI surfaces and by choosing outgoing wavefronts, that are adapted to the low and high beam pattern, we were able to obtain “legal” designs for both the low beam and high beam RXIs. In detail raytraces, the designed elements prove their performance. The low beam yields total optical efficiencies (defined as the ratio of flux projected onto the road in +/- 30 deg horizontal and +/-10 deg vertical window divided by the full source flux) of 80%, assuming a reflectivity of 93% for the metallized surface, and anti reflection coatings on the refractive surfaces. Without anti reflex coatings 75% (68% with cover lens) is reached.

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[2] The device is commercially available through Optiled: www.optiled.biz

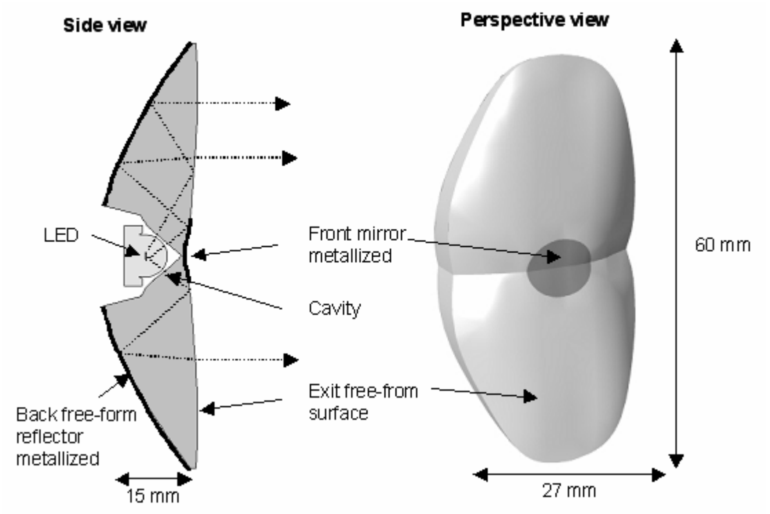

Fig 8: Schematic view of a 3-D RXI (for low beam)

The high beam RXI is even more efficient: Up to 85% with and 80% without anti reflex coating can be achieved. The low beam RXI meets the regulations FMVSS108 Tab. 17 with 8 LEDs (and 8 RXIs) of 80 lm each. It also passes the legal gradient values as defined in FMVSS108 easily. For the high beam, an additional 8 LEDs of 80 lm are used. Both sets of RXIs together meet the high beam specifications. The hotspot of both functions combined is 50000 cd. Prototypes for both low and high beam have been manufactured that perform with almost the theoretical efficiency. Values of 75% efficiency for a diamond turned low beam element without anti reflex coatings and 84% efficiency f an injection molded high beam element with anti reflex coatings have been measured. Raytraces had predicted efficiencies within 2% of the measured values.

The low- and high beam units can be arranged in many different configurations to meet designer’s expectations. The final number of RXI modules is inversely proportional to the available flux of the LED.

By choosing different design parameters and wavefronts, an RXI similar to the shown design in appearance and size, has been designed to meet ECE low beam and high beam specifications. Because of the more demanding gradient specifications of the European regulations and the lower stray light levels (light projected above the horizon), those designs must exhibit even better light control than the SAE versions. The SMS design has therefore been refined to create more precise 3D surfaces that reduce ray angle deviations from the theoretical wavefronts used for the design. Raytraces demonstrate the success of those designs; however, as the gradient is formed by imaging the LED chip edge, placing tolerances on the luminance distribution of the LED chip within its package, the RXI lens must be very tightly controlled.

4.4. Outlook onto future LED lamps designs

A single LED Headlamp will be possible as soon as there will be a chip available that produces more than 500 lm. In the hypothetical case that an LED with chip dimensions similar to today’s LumiLeds Luxeon LED would be available, a full low beam headlamp could be of the size of a single RXI of 25 x 55 x 14 mm^3. Smaller LEDs with the same flux would lead to a linear reduction of aperture size. However from a safety and design standpoint too small aperture sizes may not be desirable.

Besides the inherent advantages of LEDs (their longevity, instant turn on, “whiter” color, and smallness), very bright and small LED chips enables the optical designers to create beam patterns of unsurpassed beam quality, in terms of brightness, uniformity and light control. The SMS method offers the necessary precise light control needed to realize those future designs.

4.5. Incandescent SMS headlamp

Another successful application of the SMS 3D method it the design of a low beam and high beam headlamp that, as conventional headlamp designs, uses a halogen bulb as a light source. The optics, however, doesn’t consist of a typical single free form reflector or a projector system as today’s headlamps, but of a complex lens, that redirects the light from the source by refraction as well as by metallic mirror surface and total internal reflection. As the optical system envelopes the light bulb, the collection efficiency is much higher than of conventional head lamps. Because of the perfect image control of the SMS method, all filament images are kept horizontal all over the exit surface of the optical system. This allows us to reduce the vertical height of the system in comparison to conventional designs. The result is a headlamp that is more compact both in exit aperture size and depth and more efficient in terms on flux projected on to the road than today's best halogen bulb headlamps.

Because of the proximity of some parts of the design to the hot light bulb, glass has been chosen as lens material. In consideration to our customer, we are unable to reveal more detail on this development at this time.

4.6. UFO LED collimators

High power LEDs (e.g. the LumiLeds Luxeon LED) today put out up to 80 lm of white light. Those flux values are made possible by relatively large LED chips that, in the case of the mentioned LED, measures 1 x 1 x 0.1 mm^3. Because of the Etendue conservation, it is not possible to incorporate a collimator into an LED dome (e.g. of 6 mm diameter) that would at the same time be efficient and produce a small collimation angle of the output beam. Therefore, a round dome is placed over the LED chip and the collimation of the now near Lambertian light source is left to external lenses. Purely refractive systems are unable to cover the full solid angle of the emitted light. The collimation of the LED is a classical problem of nonimaging optics- for example the CPC [1] is a well known solution to this problem. However, mass producible metallic surfaces don't reach very high efficiencies and CPCs, for small collimation angles, are very deep. The aforementioned RXI is today‘s most compact collimator, but it also uses metallic reflection. For mass production, besides the fact that no more then 90% reflectivity at each ray interaction is achievable, this metallization means added cost.

TIR reflection is the most efficient reflection process and it doesn't require additional coatings. Today's modern tool making (diamond turning) and injection molding processes enable the reproduction of optical plastic surfaces that achieve the necessary low surface roughness and flatness to ensure full TIR. Several LED collimators using TIR exist on the market, but they often exhibit low efficiency and high depth, so that the associated large plastic volume makes injection slow and expensive. Also, their minimum diameter is relatively large if high collection efficiency is to be maintained.

Here we present a new class of LED collimators, called "UFO", that drastically reduces the plastic volume. The small wall thickness speeds up plastic injection cycle times and lowers cost. At the same time the design is extremely efficient: Raytracing results have demonstrated efficiencies as high as 92%, so that all losses can be attributed to Fresnel reflections at the input and exit surfaces of the device. If anti reflection coatings were applied, efficiencies of almost 100% could be achieved.

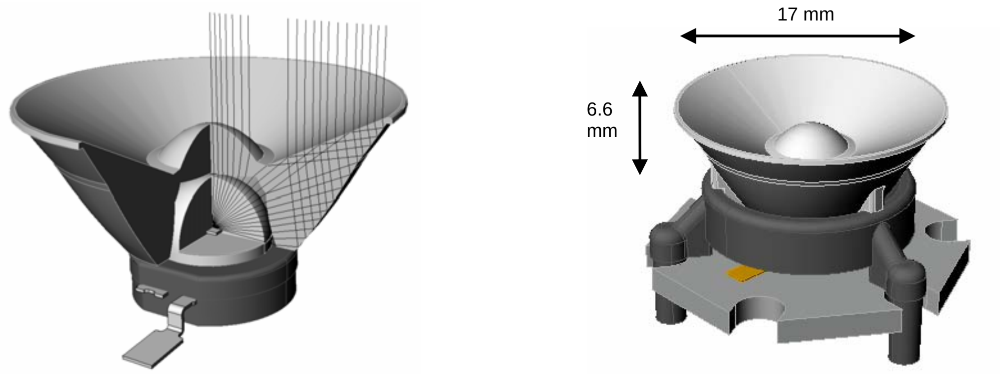

Fig 9: Schematic views of a UFO LED collimator, on the left with a Luxeon emitter and ray trajectories, on the right with a plastic holder to place the LED over the standard Luxeon Star LED.

The UFO design utilizes several sections of different ray trajectories. All surfaces have tailored profiles. The central section captures the LED light emitted close the optical axis and collimates it by two refractions. The second section, of greater off axis angles, is an "RIIR" section: The light is first refracted, then reflected (TIR) at the exit surface, another time reflected (TIR) at the back surface and then refracted at the outer section of the exit surface. Both reflections are TIR. The third section works as "RIR" (Refraction, TIR, and Refraction) and collects the light emitted to large angles.

A variety of designs have been derived with diameters as large as 36 mm to achieve very narrow collimation and as small as 14 mm, much smaller than it would be possible for conventional collimators without compromising efficiency. As a standard product, to be marketed soon by LPI, a diameter of 17 mm has been chosen, as a compromise between collimation angle and compactness. (For comparison: the Luxeon Star LEDs are provided attached to a hexagonal PCB of 18 mm width). The lens itself is only 6.6 mm tall, making very compact assemblies possible. Comparable LED collimators available on the market have slightly larger optical apertures (approximately 18 mm). They are approximately 10 mm tall (see Figure 10), almost 50% taller than the UFO. Their plastic volume is almost three times higher than the UFO.

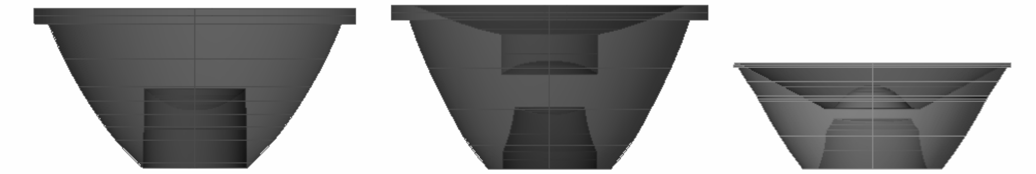

Fig 10: Schematic views of two commonly available Luxeon collimators (left and center) and the LPI UFO (right). All three designs have similar exit apertures and collimation angles. The two designs on the left have plastic volumes of approximately 1500 and 1300 mm^3 respectively, while the LPI UFO (right) has a volume of about 500 mm^3

While the collimation angle of the UFO for the different Luxeon LED colors varies between 8 and 10º FWHM, the efficiency is 90% for all Lambertian Luxeon LEDs. In order to place the UFO lens over the LED and onto the PCB, various holders have been designed that fit over the Luxeon star 1W and 3 W, and can also fit directly onto a PCB if the naked Luxeon emitter is used.

Different UFO models for wider collimation angles but with the same footprint, size and exit surface are being developed by LPI. Those designs exhibit flat intensity patterns and well defined cutoff angles.

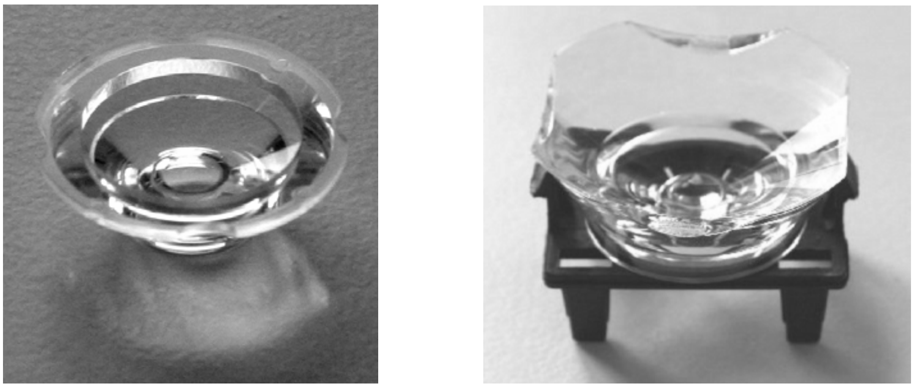

Fig 11: Photo of other UFO LED collimators, designed for specific applications. The lens on the left has a diameter of 18 mm, the right one 30 mm lateral dimension.

4.7. Single piece zoom optics UFO LED collimator

For various illumination applications zoom lenses are employed. Classically this is solved by moving the incandescent bulb along the optical axis out of the focus of a parabolic reflector. However, in most cases neither the focused position forms a bright, well defined and homogenous hotspot, nor is the wide beam free of radial intensity variations noticeable as dark or bright concentrical artifacts. Moreover, if a source is moved out of the focus of a parabola, in many cases a dark center spot occurs.

In order to create a LED collimator with a zoom function, a secondary lens, after or before the collimator, can be employed, that can either rotate or move laterally or longitudinally to open the narrow beam to form a homogenous wide beam. We have employed a different concept: We use the UFO itself to perform this function without the need of extra elements.

A particular design example has a diameter of 35 mm. The UFO is designed in a way to work as a collimator in one position, and, when moved 2 mm away from the Luxeon LED, opens up the beam in a very homogenous way with almost perfectly flat intensity in the far field up to 40 ° off axis angle. The design uses tailored surface sections that are illuminated differently in the two positions of the lens by the three ray bundles of the UFO. The efficiency of the device varies between 80% and 90% at wide and narrow beam positions, respectively. Even between the two different design positions, the device doesn't show excessive intensity variations in the form of concentric artifacts. The central part of the distribution shows a continuous drop in intensify towards the wide beam position without any dark center formation.

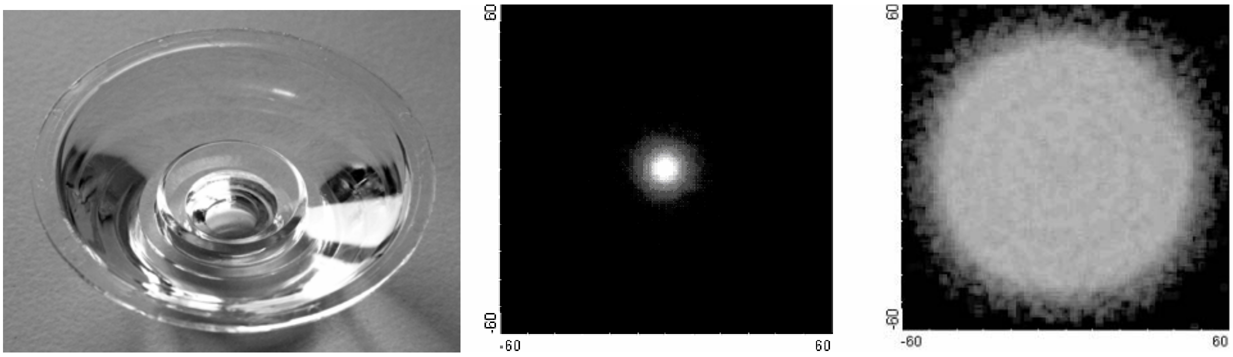

Fig 12 Left: Photo of UFO Zoom lens. Center: Raytraced simulation of the narrow beam with 6º FWHM. Right: Wide beam simulated with flat intensity and 80º FWHM. Raytraces are represented in Munsell “lightness” coding

5. FUTURE SMS APPLICATIONS

5.1. Compact SMS 3D integrators

Integrators have been employed to homogenize the illuminance of projection systems. Such integrators normally consist of two arrays of micro lenses that have the same focal length and are at the same time separated by their focal length. The intensity distribution of the second lens is an image of the illuminance distribution on its focal plane. If the lens pitch is small compared to the distance from the source, the illuminance to be imaged by one micro lens will be almost constant, so that the outgoing intensity pattern will also be uniform. The integration zone can be designed to include the entire emitting zone of the source and the output will be independent of any luminance variations in this zone. If the integrating zone is chosen larger than the source size, the output will stay unchanged, even it the source moves within this zone, so that the design can be made tolerant to source positioning errors.

As SMS designs work close to the light source, they may be more dependent on positional tolerances and the illuminance distribution of the source than conventional designs that use larger optics farther away from the source. In order to combine the compactness of an SMS design with the robustness of a conventional design, we have designed free form micro lenses that can be combined with SMS designs without the need of extra integrating elements. These designs can integrate in one or two spatial directions. A typical application where the integration in one direction is desirable is the automotive headlamp, where a well defined vertical cut-off has to be achieved. In the case of the ECE specification, the intensity may have to drop from 30,000 cd to almost 0 in little more than 1 deg vertical variation, but the horizontal pattern is very wide and has a smooth roll off. An SMS integrator design can produce a vertical cutoff that is independent of the source illuminance distribution and, depending on the design parameters, also tolerant to vertical source positioning.

A different application, where integration in two spatial directions is necessary, is the color mixing of light from an RGB light source consisting of three or more sources that are distributed over different positions (e.g.: an RGB LED with 3 chips in one housing). We expect SMS integrator devices to be developed in the near future that collimate light from such an RGB source while maintaining the same intensity ratio amongst the three sources and therefore the color of the combined light at any point in the intensity pattern.

5.2. SMS condensers

In digital projection the most commonly used light source is an arc discharge lamp. The full optical train consists typically of light source, elliptical mirror, glass mixing rod to achieve constant illuminance at the exit surface of the prism, LCD micro display and optics to project an image of the LCD display onto a screen. The achievable brightness depends on all elements but the condenser may be the most critical.

The typical elliptical mirror collects a certain fraction of the fully emitted light and forms arc images on the entry aperture of the light mixing rod. The size of the images varies (in meridian length and sagittal width) from point to point on the condenser exit surface and the images rotate due to the rotational symmetry of the mirror and the arc. Due to the rotation of the arc images, conventional condensers perform worse when the target aperture is not circular but rectangular, especially when the aspect ratio is high as for a 16:9 picture format. A mixing rod of larger diameter would increase the efficiency but this would have to be combined with a larger display, at a prohibitive cost.

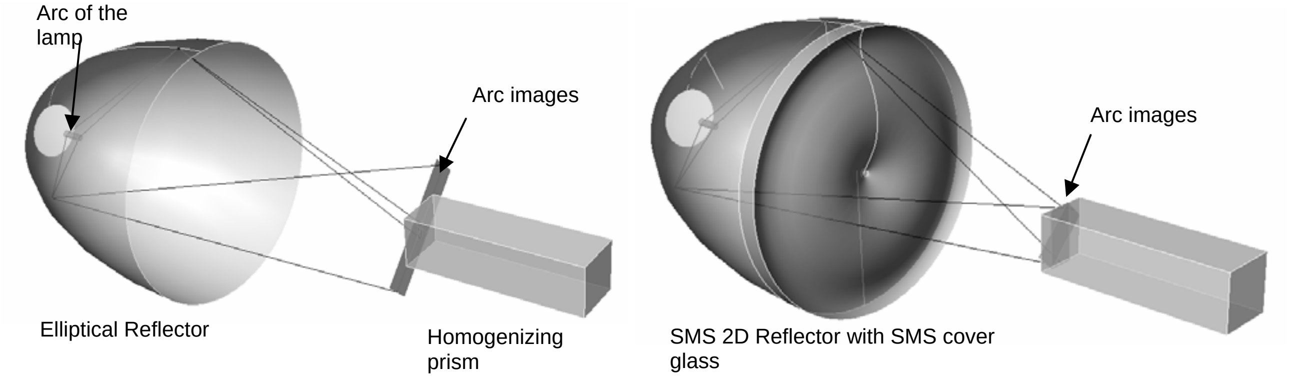

Fig 13 Digital projector condenser, left: Conventional design with arc imagines of varying size, on the right an improved design with constant arc image sized using a tailored reflector and glass cover profile.

As en ellipse perfectly transforms rays emitted form on of its focal points onto the second focal point, all other points are not controlled. An SMS 2D design controls two points (the extreme ends of the discharge in this case) that can be mapped onto a circle of the mixing rod entrance aperture to control the meridian image size. This design (Fig. 13) would use the mirror surface and one of the surfaces of the lamp glass cover as SMS surfaces of rotational symmetry with tailored profiles. A similar solution has been described before, although in the limit of a small source [1] [13]. Such a design results in a noticeable increase of in-coupling efficiency. However, from the description of the SMS method above, it should be clear that a full SMS 3D design would be even more beneficial as it also controls the rotation and the sagittal image extension. Such a design would not have rotational symmetry but it can project source images of constant positional and aspect ratios exactly tailored to the mixing rod dimensions.

5.3. SMS Imaging

The SMS method has been developed for nonimaging applications but the method can be applied to imaging solutions: If the input and exit wavefronts are spherical (for object and image points in the near field) or flat, for points at infinity, one pair of points will be perfectly imaged into two image points. The well known Cartesian converts a parallel wavefront into a spherical wavefront. A single surface that converts one general input wavefront into a given exit wavefront can be understood as a generalized Cartesian oval [14]. It is not trivial, however, that two surfaces (e.g.: of a lens, see Fig. 14, center) can convert two inputs into two exit wavefronts, and that n SMS surfaces will image n points into their conjugate points. With many points imaged perfectly, one can hope that all adjacent points, and eventually a complete area inscribed into the design points, may be imaged with very good quality onto the imaging plane. Conventional optics, consisting of spherical surfaces, doesn't image even a single point perfectly because of spherical aberrations. In order to improve a lens design, often some paraxial aspheres are added. Conventional optics, however, fail to work well for non paraxial rays because the optimization methods start off from the paraxial regime and spherical surfaces. In some cases large off axis angles are desired, e.g. the imaging section of projectors in order to minimize the projector-to-screen distance. Conventional lenses are limited to projection angles of about 30-40º.

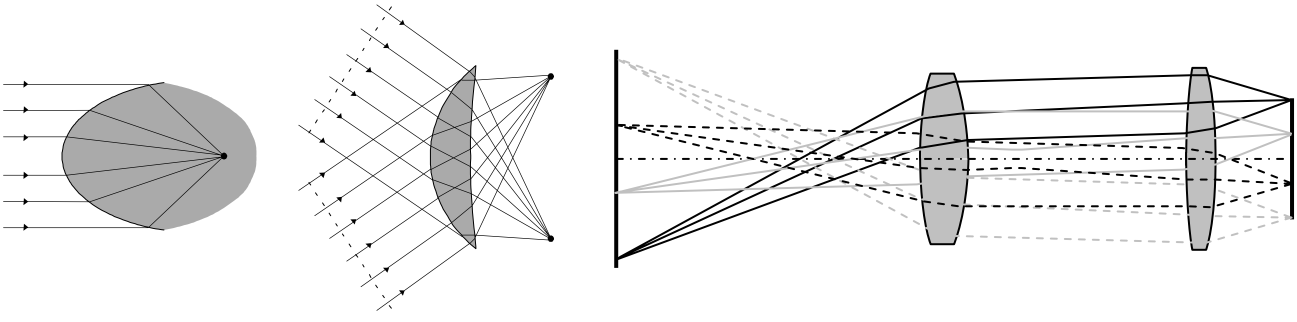

Fig 14: Left: A Cartesian oval focuses a parallel ray bundle into a point. Center: An SMS lens can focus two wavefronts into two different points. Right: Two SMS lenses can focus four objects into four imaged points!

SMS 2D concentrators have been found to work as ultra-high numerical aperture imaging devices [15]. Also, achromatic aplanatic aspheric doublets [16], designed with SMS 2D, have been demonstrated. In general, SMS lenses don't have any paraxial limitation and can therefore be designed to large off-axis ray angles. A projection system with SMS surfaces could therefore be extremely compact as projection angles up to 85 deg can be realized.

The possibilities of SMS 3D in imaging optical systems are still being evaluated but the added wavefront control can make these much more powerful than SMS 2D designs. However, the resulting free form surfaces may be a challenge if applied to glass optical elements but in reflector designs, production technology has reached a level of accuracy that makes free form imaging possible.

6. SUMMARY

The SMS 2D design method has been applied for many practical devices, some of which are presently being mass produced. The much more complex SMS 3D method has reached a maturity and unsurpassed light control capability that makes it the tool of choice for complex illumination tasks and, in the near future, for certain imaging problems. The SMS 3D method, applied in several automotive LED headlamps designs, has proven to produce highly detailed intensity patterns, while at the same time reaching the highest efficiencies and ultra compact dimensions. A future stage in SMS 3D will be the design of three free-form SMS surfaces to perfectly control three wavefronts to enable even a higher level of control of the output beam quality. SMS 3D devices are expected to be mass produced soon and will appear in many different applications ranging from illumination to collimation, condensers and image projection.

All optical devices shown are protected by patents awarded, in allowance or pending. See under patent list.

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Patent list

SMS 2D Design method, RXI 2D (rotational symmetry):
2D SMS patent (issued): "High Efficiency Non-Imaging Optics" Patent # 6,639,733, Issued Oct. 28, 2003. Inventors: Juan C. Minano, Pablo Benitez, Juan C. Gonzalez, Waqidi Falicoff and H. John Caulfield.

RXI 2D (rotational symmetry), UFO, UFO Zoom:
Air-gap RXI and CIP continuance (in allowance): "Compact Folded-Optics Illumination Lens". Inventors: F. Muñoz, Juan C. Minano and Pablo Benitez.

SMS 3D Design method, RXI 3D, Incandesent SMS 3D:
3D SMS: "Three-Dimensional Simultaneous Multiple-Surface Method and Free-Form Illumination-Optics Designed Therefrom" (pending). Inventors: Pablo Benitez and Juan C. Minano.

TIR-R:
J.C. Miñano, P. Benítez, “Device for concentrating or collimating radiant energy”, PCT/ES00/00459