Primary optics for efficient high-brightness LED colour mixing

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ABSTRACT

In SSL general illumination, there is a clear trend to high flux packages with higher efficiency and higher CRI addressed with the use of multiple color chips and phosphors. However, such light sources require the optics provide color mixing, both in the near-field and far-field. This design problem is specially challenging for collimated luminaries, in which diffusers (which dramatically reduce the brightness) cannot be applied without enlarging the exit aperture too much. In this work we present first injection molded prototypes of a novel primary shell-shaped optics that have microlenses on both sides to provide Köhler integration. This shell is design so when it is placed on top of an inhomogeneous multichip Lambertian LED, creates a highly homogeneous virtual source (i.e, spatially and angularly mixed), also Lambertian, which is located in the same position with only small increment of the size (about 10-20%, so the average brightness is similar to the brightness of the source). This shell-mixer device is very versatile and permits now to use a lens or a reflector secondary optics to collimate the light as desired, without color separation effects. Experimental measurements have shown optical efficiency of the shell of 95%, and highly homogeneous angular intensity distribution of collimated beams, in good agreement with the ray-tracing simulations.

Keywords: General illumination, colour mixing, Kohler integration

1. INTRODUCTION

High CRI/Flux LED sources (or light engines) often use LEDs or chip arrays of different color (for instance, red-green-green-blue –RGGB-). When medium or high collimation of such sources is needed, all standard luminaries create unwanted artifacts in the light distributions (see Figure 1), such as:

- color shadows
- multiple shadows (one from each chip/ LED)
- color fringes
- shift of the white color point across the distribution
- intensity artifacts from source

Beside solving these problems, in the framework of European project SSL4EU[1], additional constrains have been imposed in order to make a “universal light engine”, what from the optics standpoint means that:

- The optics is truly a “primary” optics, and along with the chip array, forms an equivalent light source that fits into several types of luminaries and applications. Therefore, the optical solutions should be close enough to the light source.
- The equivalent light source render similar performance benefits (the elimination of unwanted effects shown above plus a high efficacy –lm/Watt- and other features shown below) no matter what kind of luminaire and application is selected).

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The immediate and easier alternative to create a light source with some of the premises aforementioned is adding some diffusers on top of the LED packages. These create a uniform and homogeneous type of light source able to prevent some of the unwanted effects shown above, particularly those dealing with colors. Their main drawbacks are the efficiency (an important part of the light is back-scattered and up to what extent is recycled, greatly dependent on the reflectivity features of the package elements) and an increase on the ètendue of the source (that becomes virtually "larger" and far from the ideal point source light sources most luminaries are meant to perform with) that compromise the options to control the light with the secondary optics afterwards.

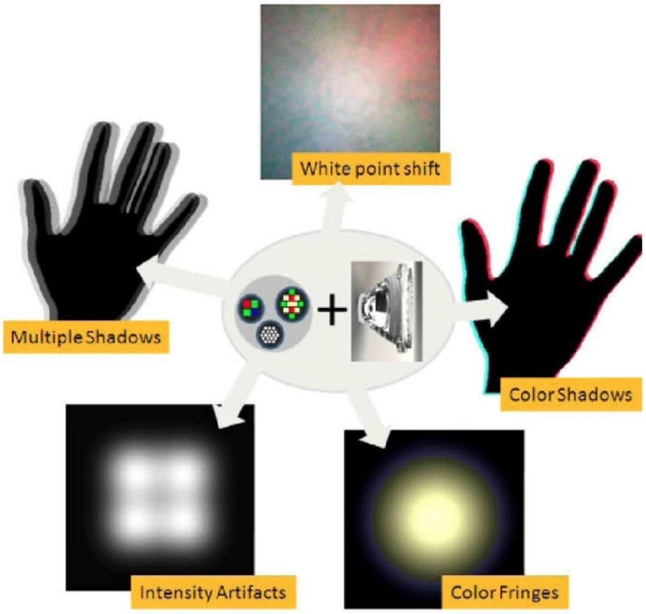


Figure 1 Unwanted effects when using multi-chip (and especially multi-color) packages into typical luminaries.

A refined second option is a LPI-patented solution based on the Köhler concept [2][3][4], an "integration" approach that is compatible with many different optical applications. In Köhler illumination, the optical surfaces comprise a minimum of a pair of shapes that image into each other the ray bundles coming from light source and target, to perform the integration effect: thanks to this, each point of the target is illuminated by the entire source so that irradiance variations across the source do not affect the target illumination. However, if a single pair of optical shapes (mirror, lenses…) is used to collect the flux of the source, intensity variations of the source can limit the achievable uniformity. If a higher number of small refractive or reflective facets are embedded into the optics overall shape instead, each facet receives almost constant irradiance so that arrays of such facets can provide high uniformity and efficiency at the same time.

Figure 2 shows example of two symmetrical lenslet arrays separated by a dielectric material (refractive index $n>1$) by a distance t that is equal to their focal length. If no aberrations are present, all light hitting one lenslet array with an arbitrary intensity distribution within off axis angles limited by $\pm\alpha$ would be transformed into constant intensity between $\pm\alpha$ after the second lenslet, as long as the irradiance of the incoming light is constant over each lenslet. This condition can be met by choosing the lenslets sufficiently small. [5]

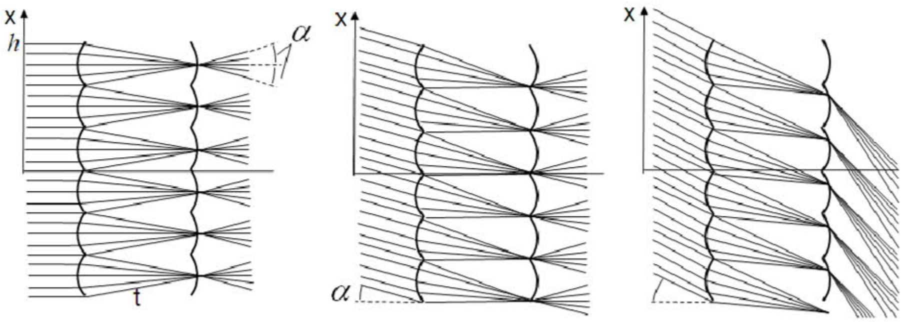
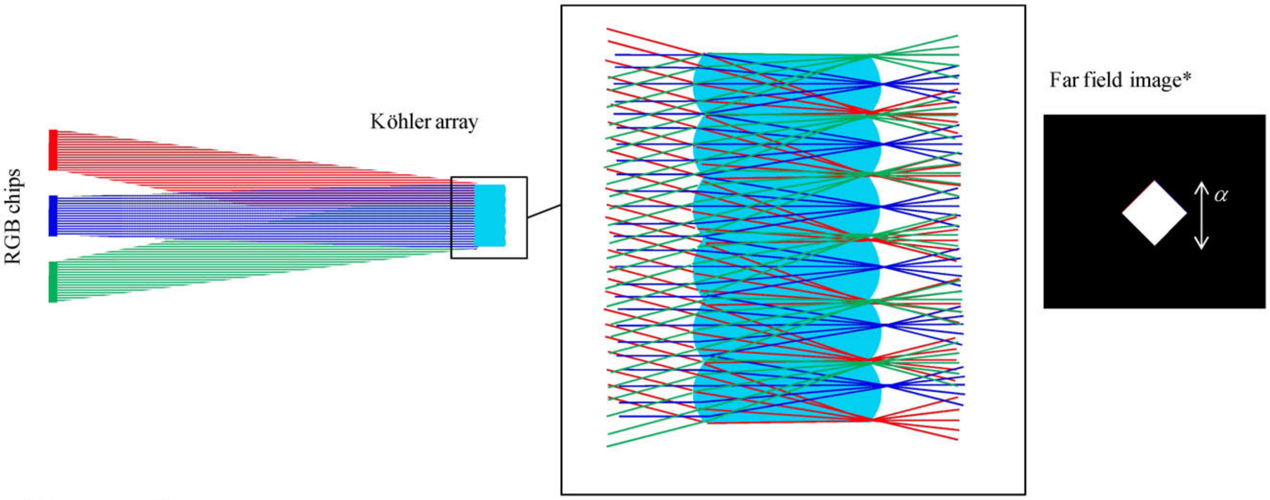


Figure 2 : Operation principles of a basic integrator lens array for perpendicular (left), max angle α incidence (center) and illumination outside the integration zone (right)

Lenticular (faceted) integrators can be applied for light homogenization but also to create special features such as sharp cut-offs or gradients in the output pattern and also for colour mixing. An example of colour mixing application of Kohler integration is shown in Figure 3. If we have three LED chips of different colours (red, blue and green) placed inside of integration zone we'll have at the receiver lenslets images of the same size of all three chips (of all three colours). These images overlap and produce uniform pattern of resulting colour (in this case white). Note that far field image is square, since analyzed microlenses were square.

Köhler integration is not limited only to flat lenslet arrays though it can be embedded onto curved surfaces.



Square microlenses

Figure 3 Operation principles of a basic integrator lens array: colour mixing

2. OPTICAL DESIGN

Shell mixer is an example of cap-type optics that has embedded Köhler optics: the light coming from multi-chips is divided into several channels (pair of lenslets) that virtually create a uniform and mixed light source (Figure 4).

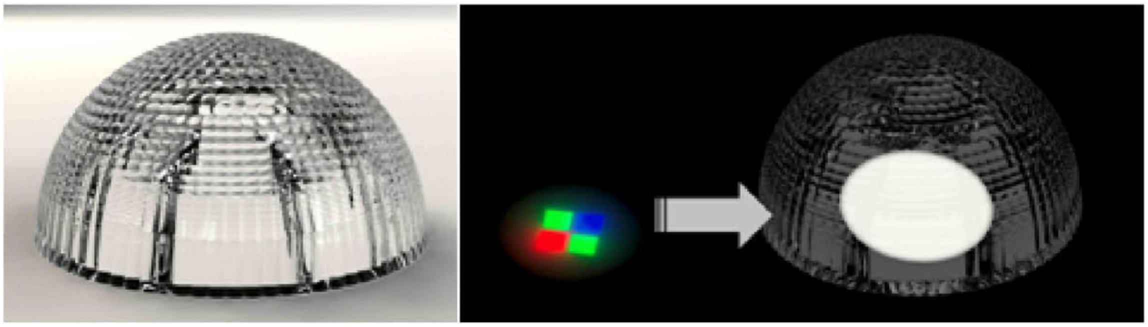


Figure 4 Rendered view of the shell mixer (left) and equivalent virtual light source thanks to the integration effect.

Shell mixer can be placed over the LED package that integrates over the source, so that the equivalent light source still emits into a hemisphere, but now the light can be collimated by luminarie secondary optics, that "sees" a virtually uniform-white source and therefore color or intensity artifacts are less likely to show up.

Figure 5 shows a cross section of shell mixer, and channel distribution along the surfaces. Note that aligned arrays of lenses are placed along inner and outer surface of the cap. They are placed such that for every direction, the observer sees an apparent source with all chips welded.

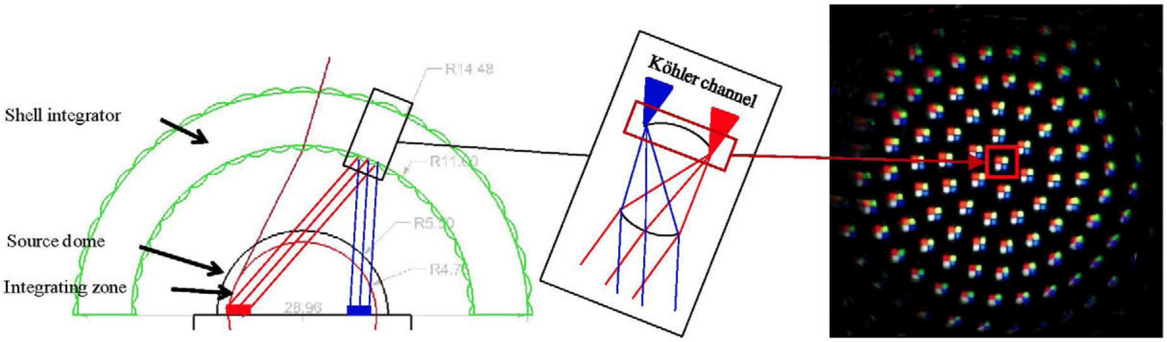


Figure 5 Köhler channels in the shell mixer. Picture on the right shows images chips' images formed on the outer lens of the shell mixer

Main shell mixer design challenges were:

- Small size required (since it has to be a "part" of the light source).
- Angular subtend of the integration zone varies
- Should be compatible with injection molding (draft angle at lower areas is necessary that are compatible with the part removal from the mould)
- 3D tessellation

Through the design process, we have found this primary optics has dimensions approx 3 times the diameter of the apparent LED if we aim at illuminating all kind of unwanted effects when using a perfect imaging lens. When such a lens is placed over an RGGB LED (the worst case LED possible), the source behaves just like a white source, as we show below with two examples.

Among all the options analyzed, we have selected one that accomplish with all goals: it consists of a thin shell (thickness about a 7% of the diameter) with lenses (average size a half of the shell thickness) on the interior and exterior surfaces that can be scaled up or down to fit with any light source. Dimensions of this design (prepared for prototyping) are shown in Figure 6.

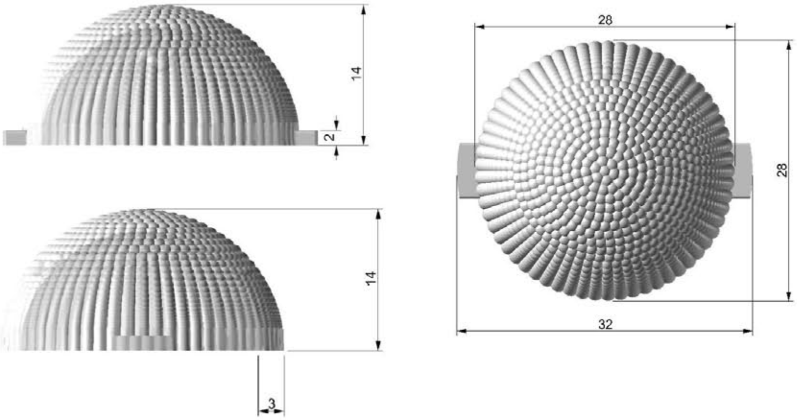


Figure 6 Design prepared for production, the dimensions are in mm

Two main simulations were performed in order to verify the colour mixing: performance with perfect imaging refractive lens and with parabolic reflector.

First analyzed case was ray tracing the performance of a RGGB LED with imaging refractive lens, with and without shell mixer (see Figure 7). The analyzed lens has an ultra-high refractive index (n=5), so we could use a very large diameter (90x the diameter of shell mixer) and collect a very wide shell emission angle (collects light up to 60º off axis). This is definitely the worst case for color mixing optics owing to the imaging capabilities of the lens. Indeed, without the shell mixer the lens perfectly images the four chips onto the lens focal plane. The addition of the shell mixer creates a "virtual" uniform source whose color can be controlled by varying the polarization of each chip (particularly, we can create a perfect white spot).

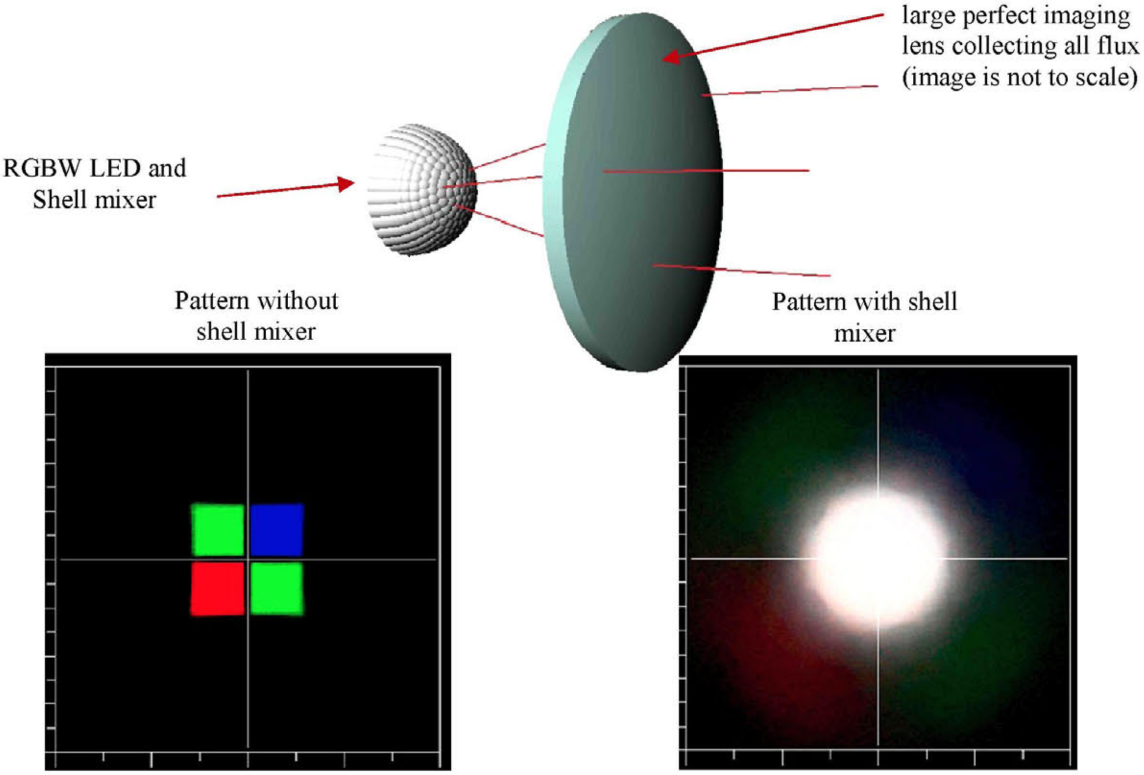


Figure 7 Left: Image of color far field the bare LED source with a lens, which forms an image of the source. Right: Same, but with shell mixer inserted between source and lens

Second analyzed case is more similar to a conventional luminaire approach. We have added the RGBW LED (comertially available similar to Cree XLamp MC-E Colour) a parabolic reflector, with and without shell mixer. In this case sensor is placed 2.5m away from the luminarie (typical location at the ceiling of a domestic room). Again, the mixing skills of the shell mixer are evident (see Figure 8)

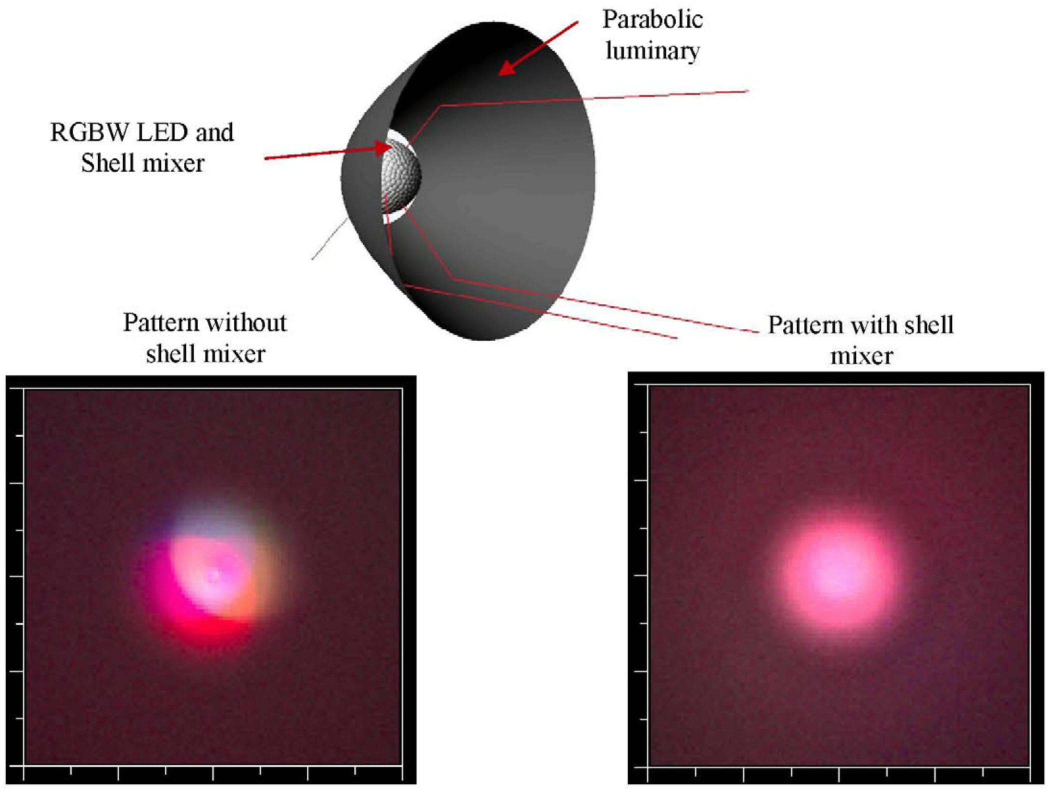


Figure 8 Left: Image of color far field of the bare LED source with parabolic mirror. Right: Same, but with shell mixer added into the mirror. Sensor plane is placed at 2.5m away from luminarie exit plane.

3. PROTOTYPE CHARACTERIZATION

First shell mixer prototype was built of Ultra-clear Polycarbonate Makrolon LED 2245 by injection molding. It was designed for chip diameter of 9mm and its size was adjusted to fit into the housing that meets Zhaga standards [6]

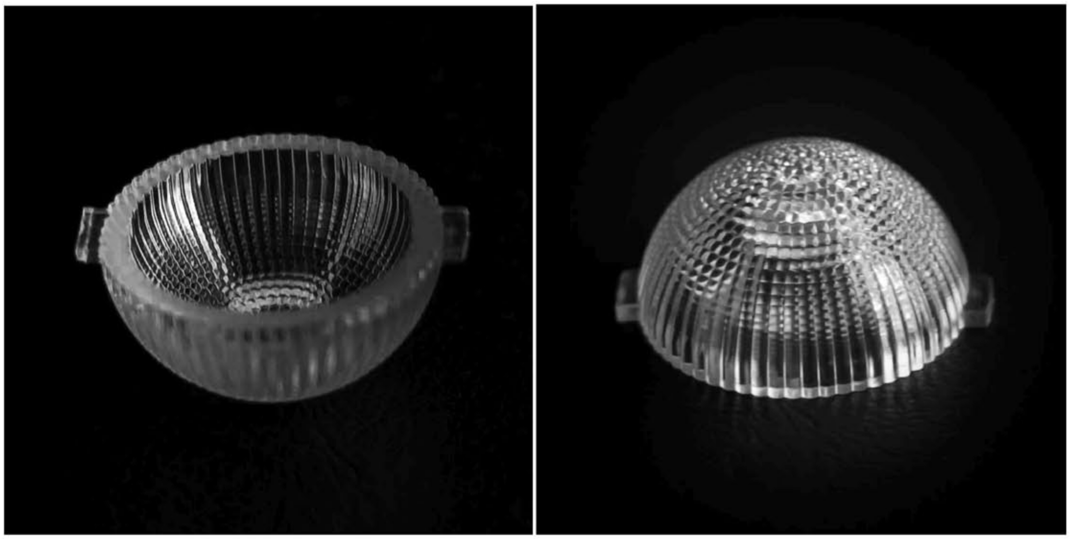


Figure 9 First shell mixer prototype

In Figure 9 shows pictures of whole shell mixer and in Figure 10 can be seen pictures of different parts of shell mixer second prototype taken through microscope, taken for the surface quality control.

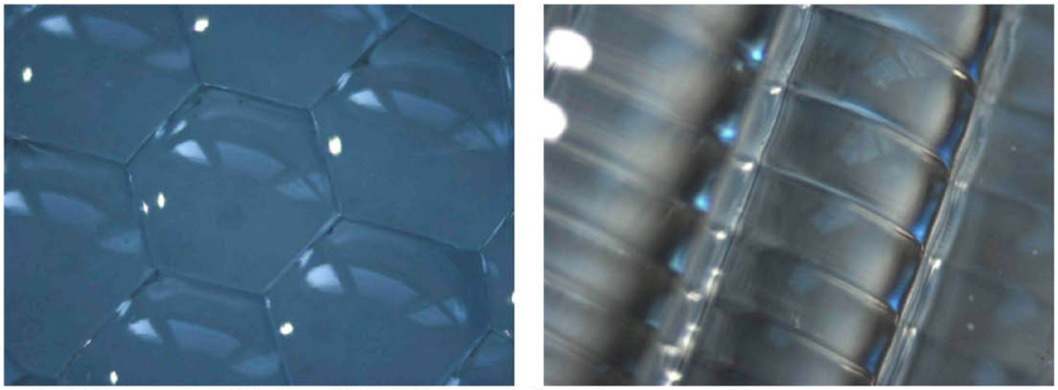


Figure 10 Shell mixer, central (left) and lateral (right) part of outer lenses

3.1 LOR (Light Output Ratio)

The efficiency of the shell mixer can be defined as the light flux exiting the optics that is collectable by a luminaire (within an angular range of ±90deg, for instance) over the light flux available at the exit of the LED package. Ray tracing models show this efficiency or light output ratio (LOR) is very high in the cases analyzed, mostly owing to:

- The high reflectivity of dies and LED packages (which is white "lambertian" in the gaps between chips)
- The fact that the shell mixer is actually a set of surfaces forming "spherical shell" that envelopes the LED, and therefore the Fresnel reflections are bounced back to this high reflectivity light source, with the correspondent probability to be recycled

The measurements of LOR can be done with an integrating sphere and by means of a gonio-meter, and both should compare the bare LED emission and the emission of LED with shell set. The alignment between shell and the chip was not well controlled, due to the lack of housing. The schematic set-up is shown in Figure 11.

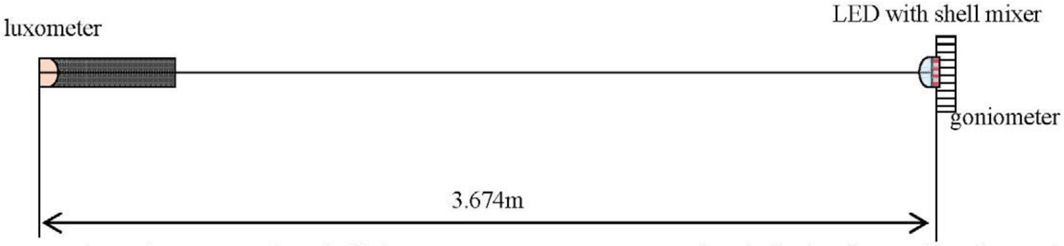


Figure 11 Schematic representation of efficiency measurement set-up. Note that shell mixer is out of housing, and that no back-light is being recollected

Measurements have been done in one section and graphs are shown in Figure 12. The actual 3D performance can be deduced from the cross section, applying rotational symmetry, and the encircled flux available calculated easily. Integrating areas in the graphs the efficiency of 89.2% was measured.

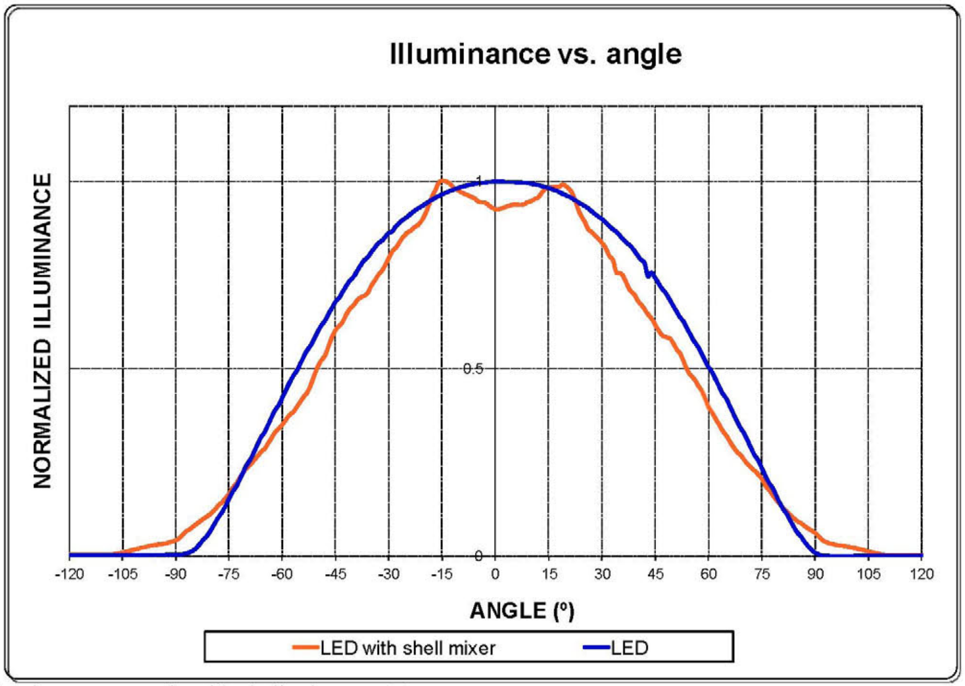


Figure 12 Illuminance vs. angle with shell mixer prototype

The shell performance has also been analyzed with a high efficacy LED provided by Osram whose package has been designed to achieve high reflectivity. The efficiency of the shell with such LED has been measured by Osram in an integrating sphere, resulting 95%, which confirms the potential of the shell to recycle part of Fresnel reflections.

Figure 13 shows shell mixer on top of multicolour LED module (7mm diameter source consists of 10 chips: 4 red, 5 white and 1 blue). Instead of 10 different colours can be seen only a virtual white source. Note that the image doesn't change from any angle (the same virtual white source is visible all along the surface).

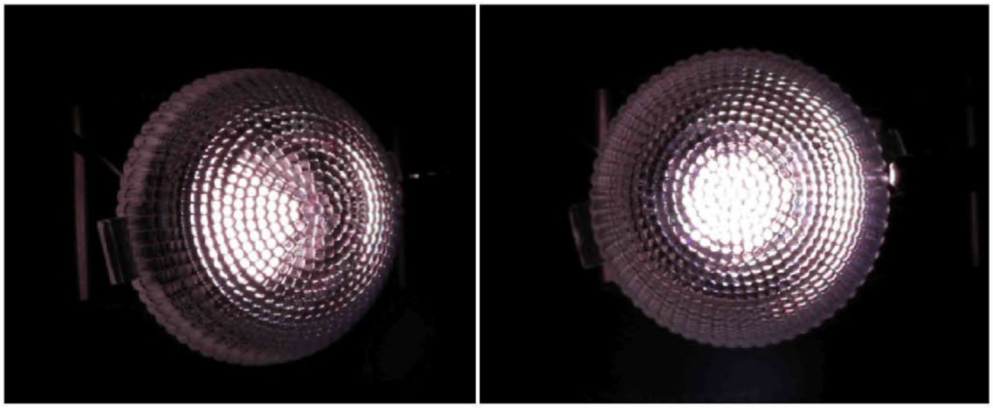


Figure 13 Shell mixer on top of multicolour LED (7mm diameter source consists of 10 chips: 5white, 4 red and 1 blue). Notice that, instead of 10 chips of different colours, only a virtual white source is visible.

3.2 Illumination pattern

In Figure 14 is shown set-up and images on the wall of Cree RGBW chip (Cree XLamp MC-E colour) with and without shell mixer. For this test we have used a low depth of field lens as luminaire and one additional lens to project the far field performance of the shell onto a screen at a finite distance from the set.

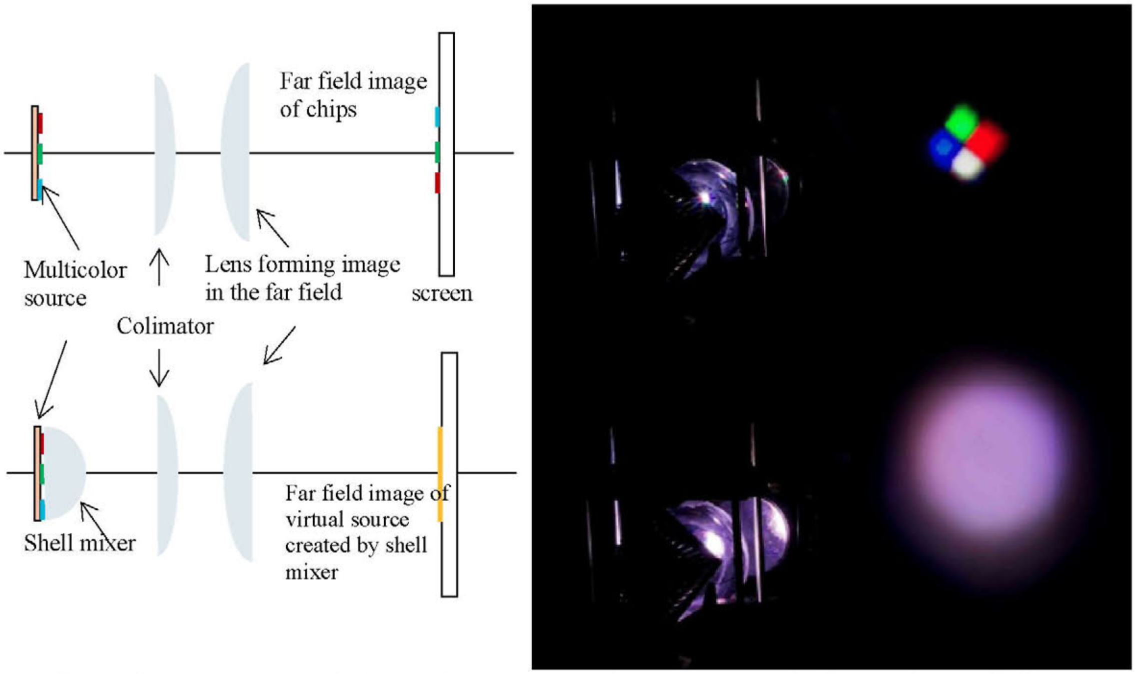


Figure 14 Schematic representation of set-up and picture of a spot on the wall without (up) and with (down) shell mixer

Another test of colour mixing was performed. Figure 15 shows the performance with the standard parabolic luminaire Both tested cases (beam at floor, at 2.5m and wall wash) show the improvement of performance features achieved thanks to the shell. Notice both the color and illuminance uniformity is enhanced.

These tests have been repeated with sources of different diameters to confirm that the ètendue increment was constant (~20%) for chips smaller than designed area of integration zone.

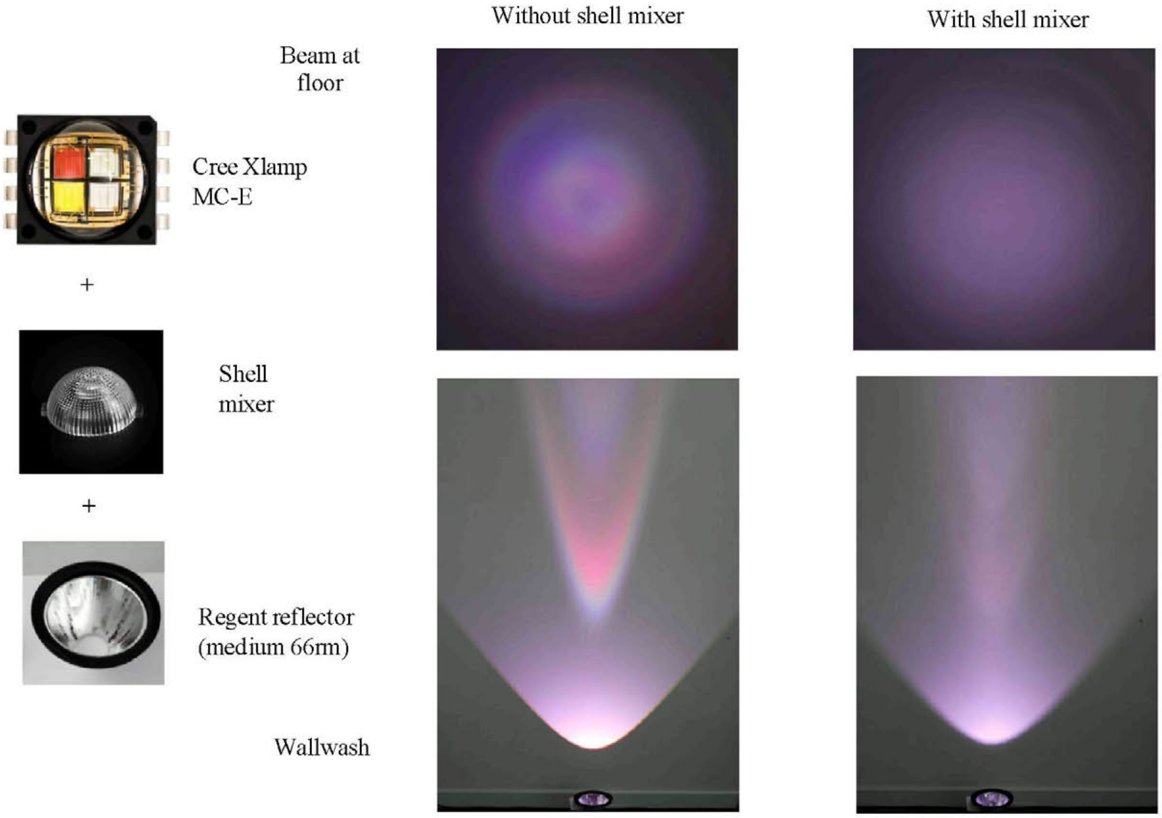


Figure 15 Performance with and without shell mixer for the Regent reflector (medium 66rm). The beam aesthetics substantially improves with the addition of shell mixer.

4. CONCLUSIONS

The shell-mixer eliminates all problems noticed in conventional lamps, like color shadows, multiple shadows, color fringes and shifts, and any other kind of intensity artifacts from source. The source simply behaves like a single uniform emitting disk, no matter what the real source looks like.

The apparent size of the source increases only slightly (typically by 20%), so that the ètendue of the source is not increased by much. This is extremely beneficial for high collimation applications like spot lights.

In contrast, if one wants to achieve similar color mixing and smoothing with diffusers, no matter where in the optical path they are used, the apparent source size and the collimation angle increases by a factor of typically 2-3, while the efficiency is compromised owing to back scattering losses.

First shell mixer prototype was built and tested. It shows results close to simulated.

ACKNOWLEDGMENTS

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