Ultra-thin Direct-lit LED Modules with Beam-shaping Thin-film optics

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Large-area panels based on LED arrays are widely used, for example in offices and shops due to their appropriate illumination characteristics. Direct-lit LED modules offer several advantages over edge-lit both cost and performance-wise. However, large light-mixing air gaps are required to provide aesthetically appealing and glare-free uniform luminance over the entire emitting area of the panel. Consequently these LED modules are significantly bulky. The air gap can be substantially reduced by beam-shaping the typical Lambertian emission pattern of the LEDs into a batwing shape without compromising the luminance uniformity (LU) value. CSEM has envisioned a thin-film solution based on pixelated periodic microstructures which have theoretically demonstrated effective batwing beam-shaping and over 60% panel thickness reduction compared to unshaped lambertian LEDs.

White LEDs have become mainstream in lighting products. Although extremely bright, the small emitting area results in optical output levels insufficient for professional or residential applications. Consequently, LED-based lighting modules very often use LED arrays.

The light emitted by the LEDs in the array needs to be properly handled to prevent undesired effects such as glare, multi-shadows and non-uniformly lit areas, common causes of visual discomfort and eye fatigue.

A common and effective solution is to distribute the emitted light over a large area. In the so-called edge-lit approach, the LED light is edge-coupled into a few millimeters thick light mixing transparent plate whereas in the direct-lit approach, a diffusive plate/foil is directly illuminated by the LED array, located several centimeters below.

The direct-lit design offers interesting benefits over the edge-lit one, including lower weight, higher efficiency and higher luminance uniformity. Unfortunately, the Lambertian emission, typical of LEDs (black curve in Figure 1; top), requires air gaps larger than the LED pitch.

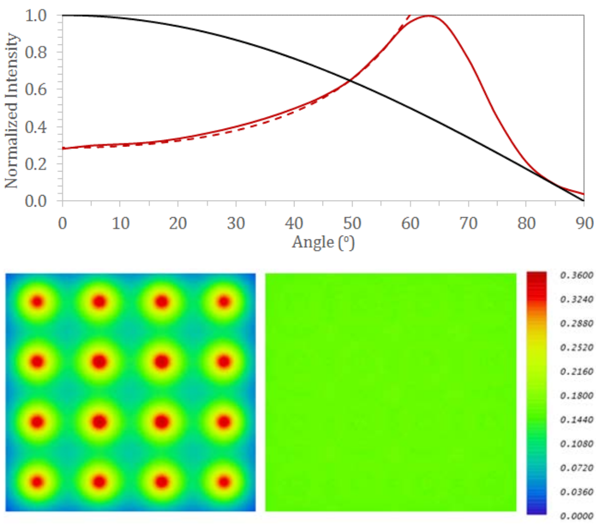

Figure 1: (Top) Lambertian (red), cosine-cubed (dotted red) and optimum batwing (solid red) normalized intensity distributions. (Bottom) Irradiance produced by a 4 × 4 LED array over a plane target situated 15 mm above the array for lambertian (left) and batwing-shaped (right) LEDs.

Beam-shaping offers a way to reduce the air gap thickness. Indeed, the illuminance produced by a Lambert emitter over a planar target decreases as $1/\cos^3\theta$; being θ the incident angle referenced to the target normal. Therefore, the so-called inverse cosine-cubed distribution (dotted red line in Figure 1; top) produces more uniform illumination (see Figure 1; bottom).

Beam-shaping can be achieved attaching lenses to the LEDs. Such "*one lens per LED*" approach, currently exploited by. Samsung, OSRAM, and LG is nonetheless costly.

Alternatively, complex free-form optical microstructures can be used with their profiles at every point specifically tailored to the incident angle of the incoming light at this point. However, the microscopic profiles needed might be rather complex and not compatible with standard fabrication techniques such as diamond milling.

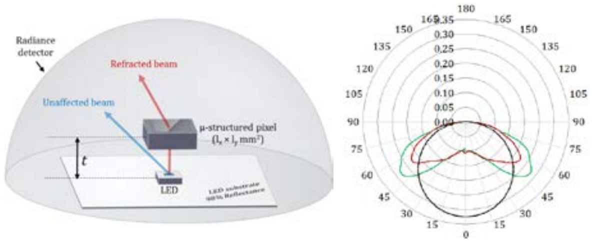

Figure 2: (Left) Conceptual representation of the proposed beam shaping thin-film solution. (Right) Theoretical angular emission pattern of an LED without (black) and with (green: C0-180 and C90-270 planes; red: C45-225 plane) CSEM thin-film solution.

A much simpler solution is provided by periodic microstructures (prismatic, lenticular) replicated in the form of small pixels. The final shape of the beam is then determined by the profile of the microstructures as well as by the pixel aperture, i.e. by the pixel area and its distance to the LEDs as sketched in Figure 2; left.

With the selected microstructures and optimized pixel size (l_x, l_y) and distance (*t*) values a batwing emission pattern is predicted (Figure 2; right). In an array, this translates into a 60% reduction in the number of LEDs (for 80% LU; see Figure 3). Alternatively, for the same number of LEDs, a twofold thickness reduction of the modules can be realized.

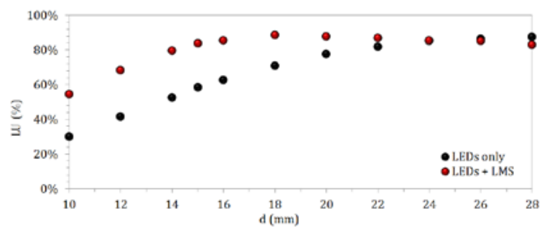

Figure 3: Luminance uniformity of a 15 mm thick 600 × 600 mm^2 area lighting module as a function of the air gap thickness. t: 1 mm, LED pitch: 30 mm.

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