A narrow beam reflector for a two dimensional array of power LEDs

Filip Vandeghinste, Guy Durinck, PhD, Stefaan Forment, PhD, Geert Deconinck, PhD and Peter Hanselaer, PhD

Abstract – A major problem in solid state lighting is the limited flux emitted by a single power LED. This flux is insufficient for most lighting applications. A possible solution is using not one but an array of LEDs as a light source. However, the optical control of the flux emitted by such a spatially extended and inhomogeneous light source is difficult, especially if a narrow beam of light is desired and the optics have to be compact. In this paper we discuss a compact narrow beam reflector that enables a two dimensional array of power LEDs to act as a light source for spot lighting in domestic and retail lighting.

Keywords: array of LEDs, optical design, luminaire, reflector, ray tracing

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1 Introduction

Solid state lighting is often presented as the lighting technology of the future for object lighting and even for general lighting. However, several technological problems have to be solved before LEDs can become an important, energy efficient, general purpose light source. The LED dies themselves have to be further improved until a high efficacy device emitting warm white light becomes available. Elegant solutions to the heat sink problem have to be found because nobody likes luminaires with huge, bulky cooling fins and, when LED arrays are used, new customized optics have to be developed (Pelka and Patel 2003, Protzman and Houser 2006). LED arrays are often necessary because the flux of a single power LED is to low for most lighting applications. Chip on board (COB) technology allows the positioning of many LEDs relatively close together on a single device creating a light source with a flux that is sufficient for many lighting applications. However, the optical engineer is than faced with the challenging problem of designing optics for a spatially extended and non uniform light source.

In this paper we discuss the optical design and behaviour of a reflector to be used in combination with a two dimensional array of power LEDs. This is a crucial step in the design process of an LED spotlight of approximately the same dimensions as a halogen spotlight for domestic and retail lighting, a problem brought to our attention by several lighting companies. Although in optical engineering for LED-sources often a combination of lenses and reflectors is used (Chaves, Falicoff, Sun and Parkyn 2004) we think that for an application such as this it is better to keep the optics as simple as possible. The performance of a class of reflector designs and some interesting peculiarities concerning the combination of several small surface area sources and a parabolic reflector are tested by ray tracing. The ray tracing software package TracePro® from Lambda Research Corporation is used to simulate the candela plot and the illumination on a surface.

Assuming a specular reflector and from geometrical optics it is known that a parabolic reflector creates a parallel beam of light rays from rays originating from a point source located in its focal point, thus creating an ideal spotlight (Murdoch 2003). Other reflector shapes are possible; for instance, by imposing the condition that the light beam exiting the luminaire should illuminate a predetermined surface homogeneously, a reflector shape which is not a conic section is found from classic reflector design theory (Zhao 2005, Zhao 2006).

The assumption of a point source works well as a first approximation if the source is small relative to the dimensions of the reflector. This is usually the case if the light source is the filament of an incandescent lamp or the arc of a HID lamp. If the dimension of the light source is not small relative to the reflector, for example the case of a frosted bulb or a fluorescent lamp, there is far less control over the resulting beam of light. However, in some cases it is possible to take the dimensions of the light source in account while designing a reflector (Elmer 1980, Korobko and Kush 2004). In such design strategies it is assumed that the light source is the surface of a three dimensional object, usually a sphere or a cylinder, that is placed inside a reflector. The surface is assumed to be a Lambertian emitter. A reflector curve is then constructed to optimize the collimation of the light beam. In the case of a two dimensional LED array however the source consists of many, spatially separated, sources which are positioned in a plane at the base of the reflector. The traditional approach is not expected to work well in this situation.

In the present work we set our goal to be the design of a 50W LED array based spotlight emitting a smooth light distribution with a full width at half maximum (FWHM) of approximately 20 degrees. We decided to start with the classic, basic parabolic design which was then altered and optimized to create a narrow, well defined, beam of light. As will be demonstrated, this basic approach works remarkably well.

2 Design and optimization of the reflector

2.1 The LED array

The EdiStar Emitter is a two dimensional LED array produced by the Taiwanese manufacturer Edison Opto. It consist of 49 1W power LEDs without primary optics. The LED dies are arranged in a 20mm by 20mm 7x7 matrix. Each LED has dimensions 1.9mm by 1.9mm and emits a lambertian radiation pattern, the distance between two neighbouring dies is 1.1mm. The total size of the package is 30mm by 30mm by 0.8mm. The device is designed to operate at a DC current of 2.4A and a DC voltage of 23V, thus consuming approximately 55W of power. The total lumen output is claimed to be 1800lm for the ENEW-05-0707-DA version which emits cool white light of unspecified colour temperature (Edison Opto 2006). Thus the efficacy is 33 lumen per watt which is not very impressive although it is superior to the efficacy of a halogen lamp. It is expected that in the near future the efficacy of power LEDs will keep improving so that a LED array of a similar design will become an efficient light source.

2.2 The basic parabolic reflector

As a first step in the design process for the reflector a paraboloid of revolution was constructed with a base that fitted tightly around the LED device (Fig. 1a). The reflector was

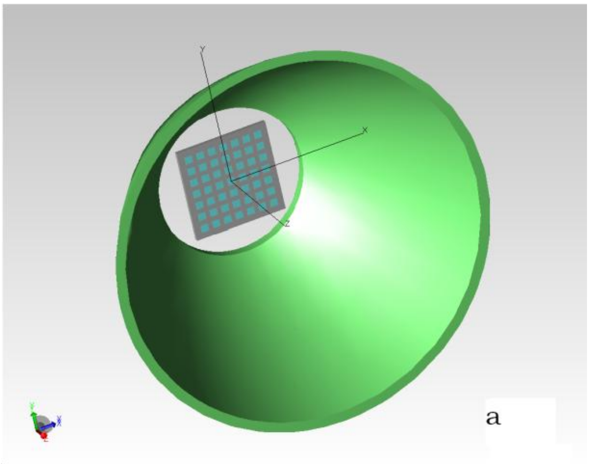
designed in such a way that the center of the LED device was positioned in the focus of the paraboloid and the front surface of the device coincided with the focal plane. The reflector was cut off at the focal plane because the LED device only emits light in the forward hemisphere. The inner radius at the base of the reflector was chosen to be 16mm, fitting tightly around the 20mm by 20mm LED matrix. The length of the reflector was chosen to be 40mm, a longer reflector would probably not be accepted for the intended application. The reflector surface was assumed to be specular reflective with a reflection coefficient $r = 0.75$ which is realistic for a commercial lighting reflector of medium quality. We modelled the LED dies in TracePro® as 49 square surfaces (1.9mm by 1.9mm) emitting a lambertian radiation pattern, 38 lumen per die, 1862lm in total. In each simulation 100000 rays per die or 4900000 rays in total were traced. The high number of rays is necessary because we used no smoothing in the presentation of the simulation results. Smoothing could easily mask subtle effects introduced by the use of many small, spatially separated, light sources.
Figure 1b and Fig. 1c show the radiation pattern and the illumination on a surface at 1m from the luminaire. As will be shown later, the very high central maximum in the radiation pattern is caused by the central LED that is positioned in the focus of the reflector. The rest of the radiation pattern originates with the 48 non central LEDs. The Light Output Ratio (LOR), the ratio between the flux exiting the luminaire and the flux emitted by the sources, is 0.87. From this, and assuming that light leaving the luminaire has been reflected once by the reflector or is direct light from the LED sources, an estimate can be made of the fraction of the light output that is controlled by the optics (1):

$$\begin{aligned} LOR &= \frac{\Phi_{direct}}{\Phi_{LEDs}} + \frac{\Phi_{reflected}}{\Phi_{LEDs}} \\ LOR &= \frac{\Phi_{direct}}{\Phi_{LEDs}} + r\left(1 - \frac{\Phi_{direct}}{\Phi_{LEDs}}\right) \end{aligned} \qquad (1)$$

From (1) we find: $\frac{\Phi_{direct}}{\Phi_{LEDs}} = 0.48$ and $\frac{\Phi_{reflected}}{\Phi_{LEDs}} = 0.52$
So only 52% of the emitted flux is controlled by the optics.
The illumination on a surface at 1 m from the luminaire consist of multiple bright and dark rings and is definitely not a well defined bright spot. In order to understand how the undesired radiation pattern originates a number of ray tracing runs are performed, in each run just one of the 49 LEDs is switched on, all others are switched off; 4900000 rays per active LED are traced. Tracing such a high number of rays results in high quality graphics without having to resort to extensive image processing. However, we did verify that the typical structures that will be shown in Fig. 3 and later in Fig. 7 are clearly identifiable if the ray tracing is performed with just 100000 rays as in the foundational simulation, this despite the fact that in the latter case the quality of the graphics is somewhat lower. In this paper only the high quality graphics are shown. In Fig. 2 the LEDs that are switched on in the different runs are marked a to g. The seven radiation patterns that are found are depicted in Fig. 3 in iso-candela plots: the point of view of the reader is located in the center of the LED matrix, the angles are the azimuth and zenith angle spherical coordinates and indicate the directions in which rays leave the luminaire. The center of a plot corresponds to zenith angle zero, rays travelling in that direction leave the luminaire perpendicular to the plane of the LED matrix. Figures 3a to 3g correspond to the radiation patterns of the LEDs marked a to g in Fig. 2. The

LED in the center of the matrix, positioned in the focus of the reflector produces an extremely narrow beam of light as can be verified in Fig. 3a. The light of the other LEDs leaves the luminaire in roughly ring shaped angular regions, in all these cases practically no light is sent in the central region of the iso-candela plot, see Fig. 3b to Fig. 3g. In this way the radiation pattern of the complete LED array (Fig. 1b) is explained, the central peak with a very small width originates from the one LED that is positioned in the focus of the reflector while the rest of the radiation pattern, including the minima that separate the central peak from the rest of the pattern, is a combination of the ring shaped radiation patterns originating from the 48 out of focus LEDs.

In an attempt to become a smoother radiation pattern we moved the LED array to several positions on the symmetry axis of the reflector. In total the radiation pattern for six out of focus positions were simulated: 0.5mm, 1.5mm and 2.5mm in front and behind the focus of the reflector. None of these simulations predicted a smooth radiation pattern. Clearly, defocusing the source is not a successful strategy.



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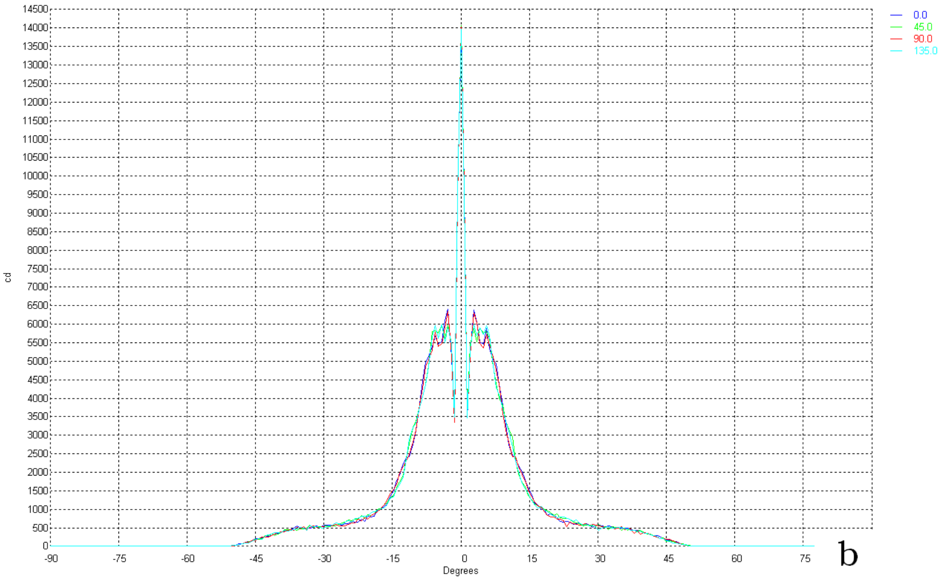

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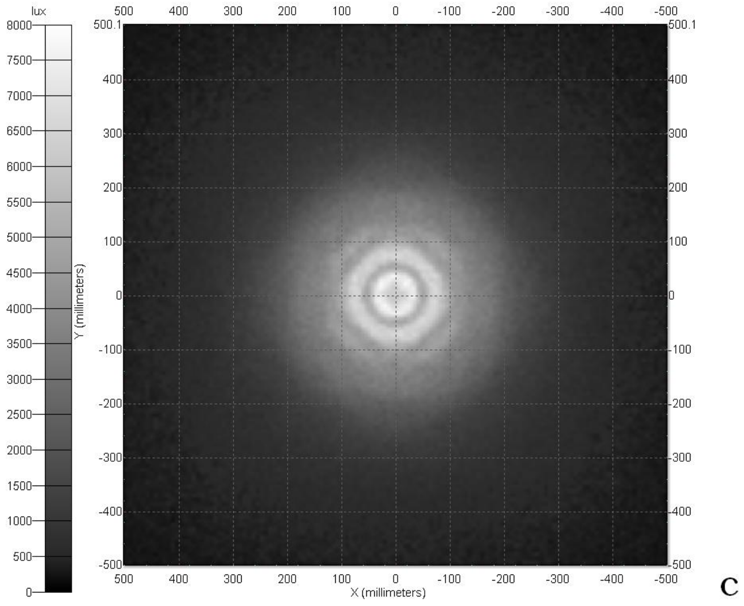


Fig. 1 a.The two dimensional LED array and the parabolic reflector. The LED in the center of the matrix is positioned in the focus of the reflector. b. The radiation pattern of the LED array in the parabolic reflector, candela versus zenith angle, the angle between the direction of the radiation and the optical axis of the luminaire. Four sections of the three dimensional radiation pattern are shown: azimuth angles 0 degrees and 90 degrees correspond to sections respectively in the xz-plane and in the yz-plane, azimuth angles 45 degrees and 135 degrees correspond to sections through diagonal planes. The Light Output Ratio (LOR) is 0.87. c. Illuminance map of a surface at 1m from the luminaire.

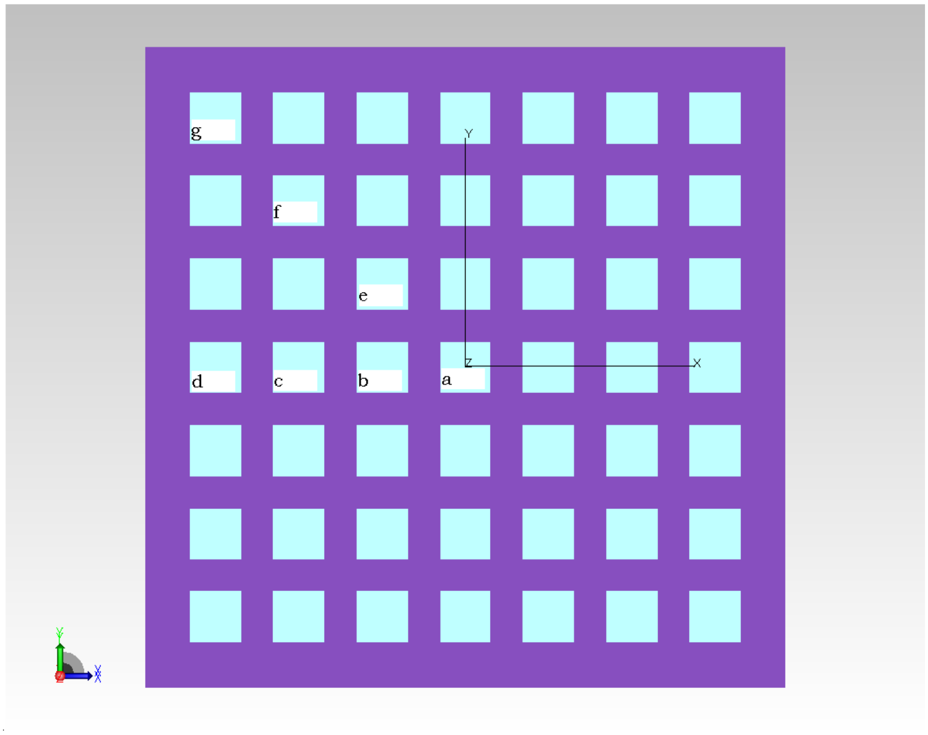
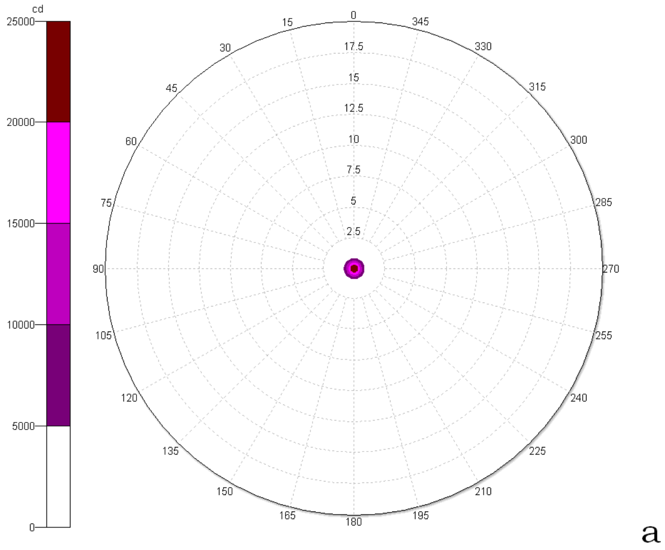
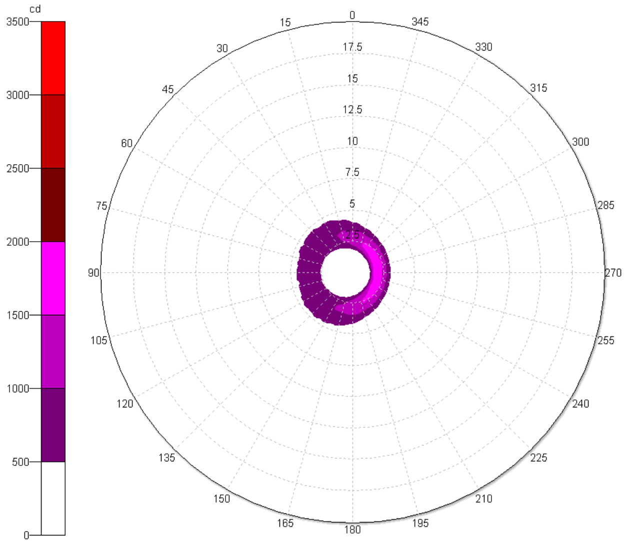


Fig. 2. Two dimensional LED array. The LEDs which were selectively switched on for ray tracing are indicated.

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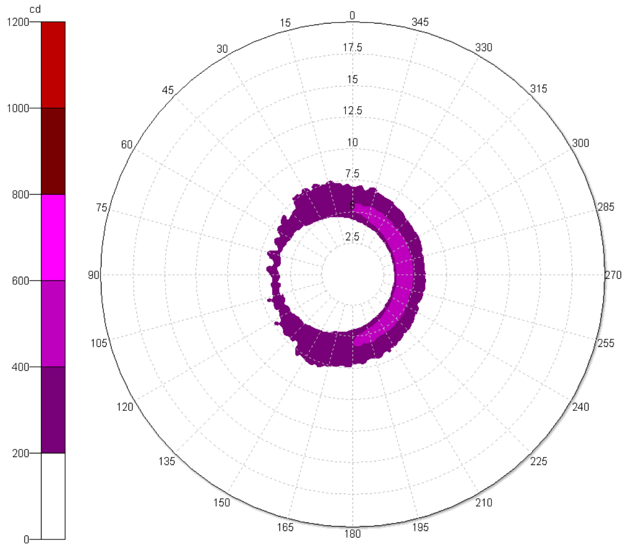
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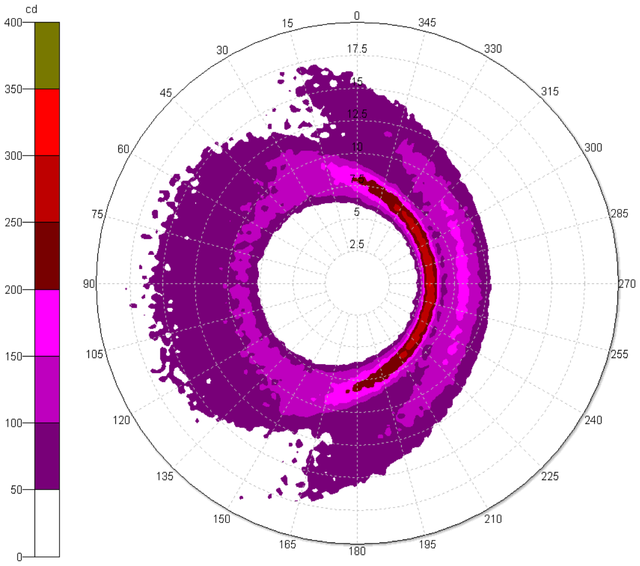
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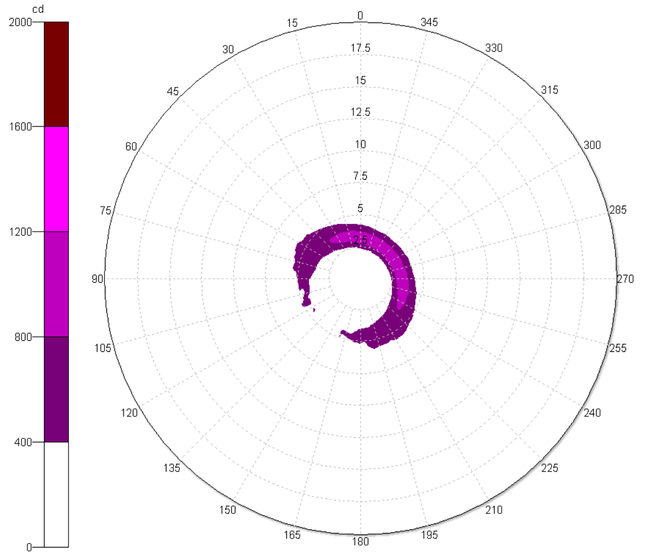
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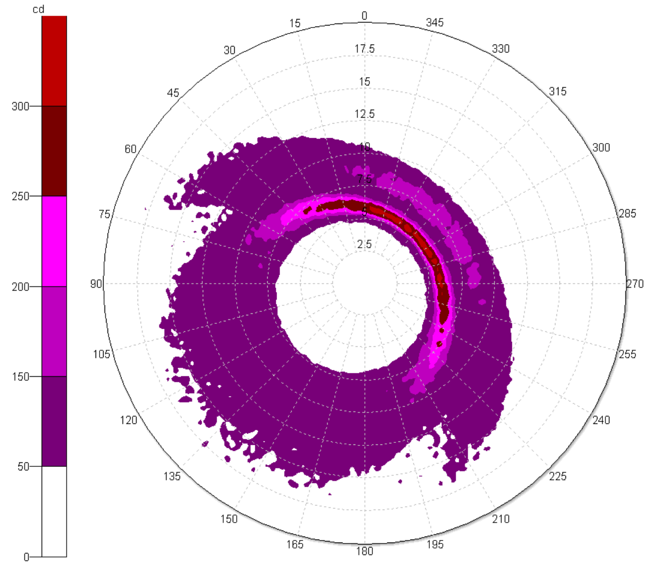
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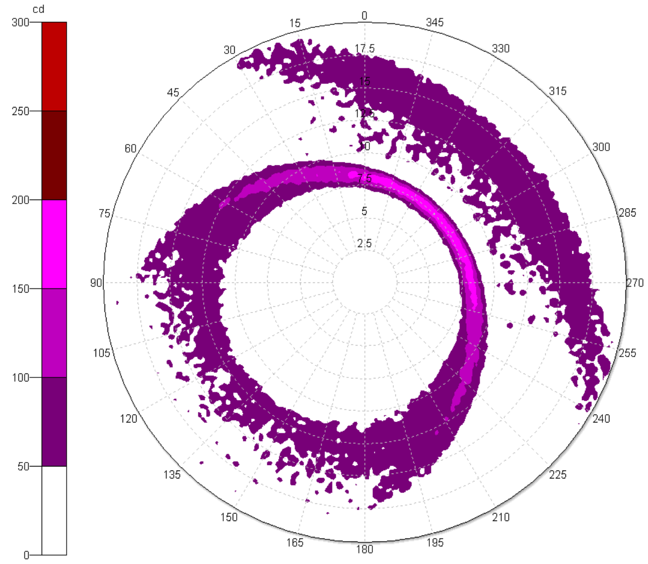
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Fig. 3. Radiation pattern of the first design with just one LED switched on at the time, 4900000 rays are traced in each case. The radiation pattern is depicted in a spherical coordinate system, the center of the plot coincides with the z-axis in Fig. 1 looking away from the LED array. The plots span an angular region up to 20 degrees from the z-axis. a. LED a, positioned in the focus of the reflector is switched on, the beam has a very high intensity and an extremely small width. b to g. LED b to g are switched on, in all these situations very little light is reflected in the central region of the plot, all light rays exit the luminaire in a roughly ring shaped pattern. The light flux exiting the luminaire is practically the same for each of these cases (approximately 33 lumens). Please notice that for practical reasons in visualising these iso-candela plots the candela scale is not the same in each subfigure.

2.3 The faceted parabolic reflector

It may be possible to transform the irregular radiation pattern of the original parabolic reflector (Fig. 1b) into a smoother one by tiling the reflector with facets (Elmer 1980, Casserly, David, Jenkins, Riser and Davenport, 2000). The size of the facets has to be chosen for functionality and not for aesthetics as is often the case with domestic lighting reflectors. In Fig. 4 the faceted parabolic reflector with base radius 16mm and height 40mm is shown tiled with 13 rings of 16 facets each. Notice that there are relatively few facets and that the facets are relatively large compared to the traditional halogen spots where 40 facets per ring are not uncommon. The facets were created with a standard TracePro® macro that tiles a given conic section reflector with roughly rectangular facets. Our simulations predict a fairly smooth and regular radiation pattern with a FWHM of 21 degrees for this particular reflector (Fig. 5a). The LOR and hence the fractions of direct and controlled flux are the same as for the original simple parabolic reflector. The illumination pattern on a surface 1 m from the luminaire is shown in Fig. 5b. Also noteworthy is that the radiation pattern is not very sensitive to the position of the light source, shifting the LED array 1.5mm out of the reflector focus, to the front or to the back, results in practically the same radiation pattern; the FWHM does not change noticeably and the peak intensity drops by only 4%. In our opinion this is an acceptable design for spot lighting. Numerous other simulations with the number of facets of the same order of magnitude also yielded acceptable results with a slightly less regular radiation pattern. However, when a small number of large facets was used a regular but broad radiation pattern with a low peak intensity resulted (Fig. 6a). On the other hand, if a large number of small facets is used the original, unfaceted, reflector is approximated and, although the central peak (Fig. 1b) has disappeared, the radiation pattern is not smoothed sufficiently (Fig. 6b). In order to increase our understanding of how the tiling of the reflector with facets results in a more acceptable radiation pattern we performed, analogously to the testing of the original parabolic reflector, a number of ray tracing runs in which just one of the LEDs in the array was switched on, the selected LEDs are marked a to g in Fig. 2. The radiation pattern of the central LED (Fig. 7a) is significantly broader than was the case for the original parabolic reflector (Fig. 3a). The radiation patterns of the non central LEDs all show a characteristic handprint shape in the iso-candela plot (Fig. 7b-7g) and for LEDs b,c and e the smoothing effect of the facets forces part of the flux in the central region of the iso-candela plot. The formation of a ring shaped illumination pattern is counteracted by the presence of the ‘fingers’ in the iso-candela plot, resulting in the illumination pattern shown in Fig. 5b.

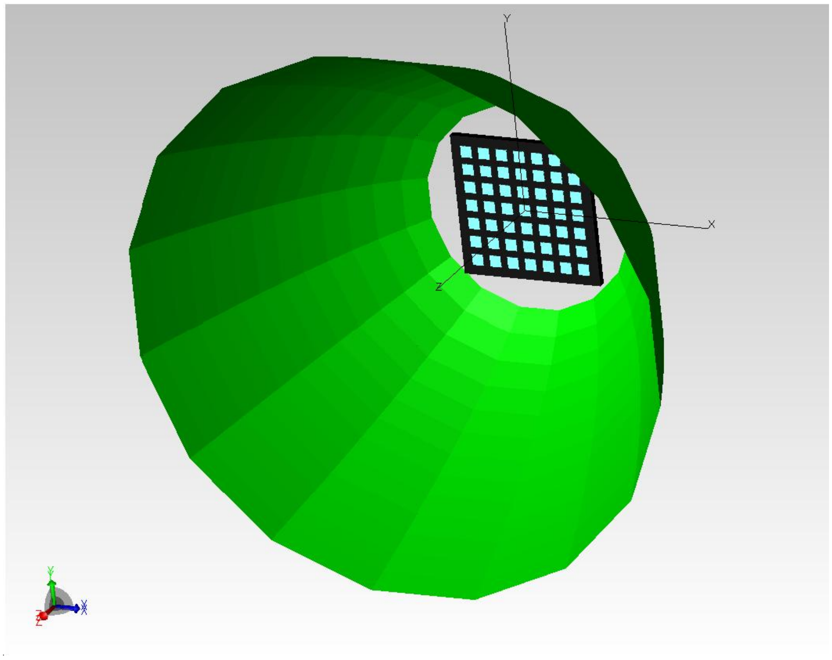


Fig. 4. Facetted parabolic reflector, base radius is 16mm, height is 40mm. There are 13 rings with 16 facets in each ring.

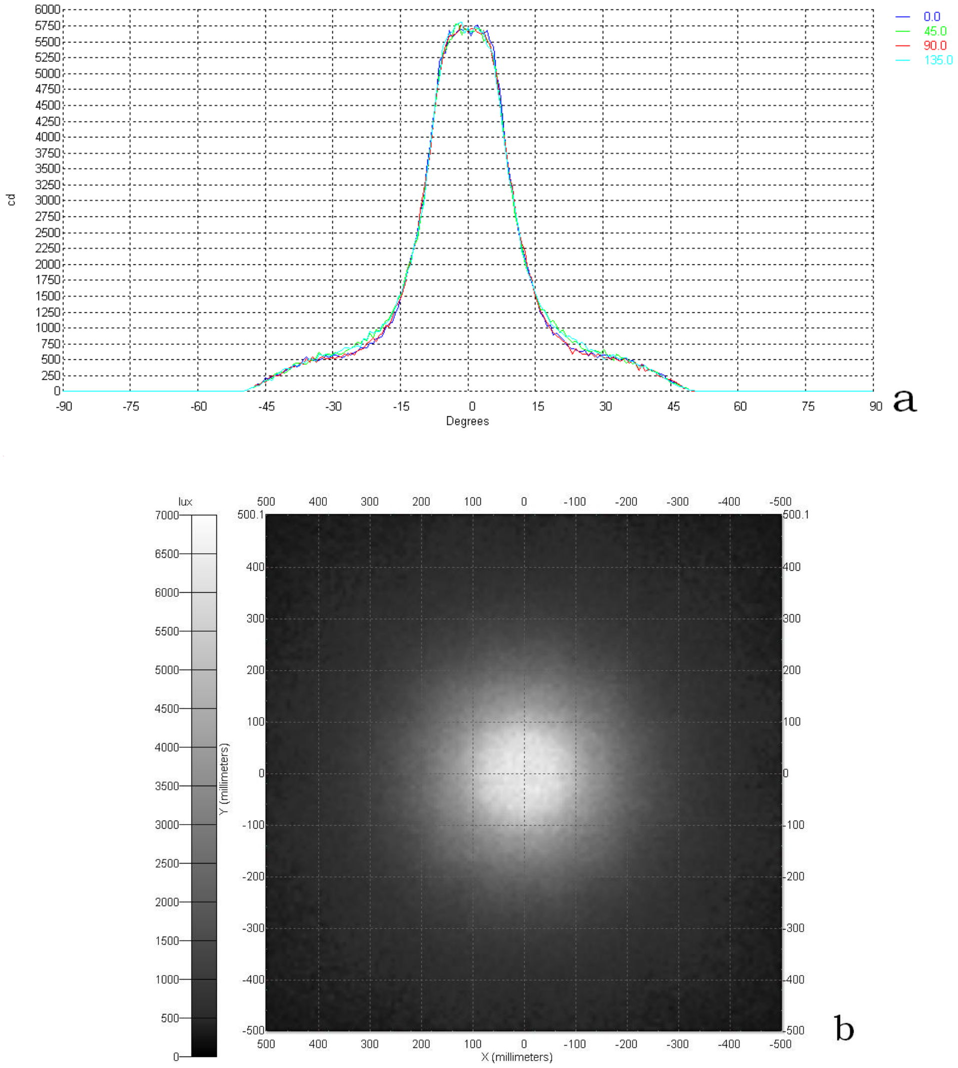


Fig. 5. a. Radiation pattern for the facetted parabolic reflector in Fig. 4. b. Illuminance map of a surface at 1m from the luminaire.

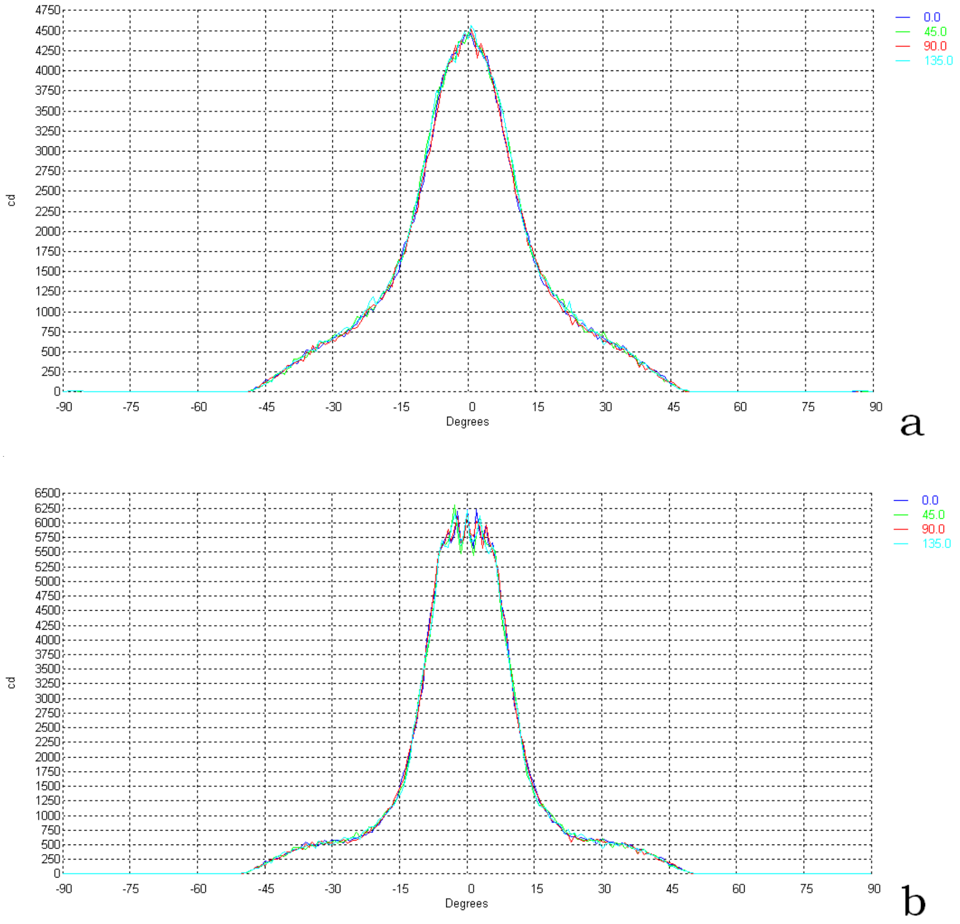
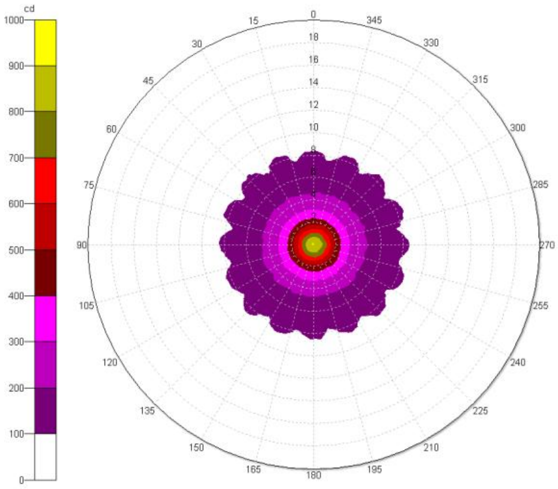


Fig. 6. a. Radiation pattern for a facetted reflector with 4 facet rings and 8 facets per ring. b. Radiation pattern for a facetted reflector with 34 facet rings and 36 facets per ring.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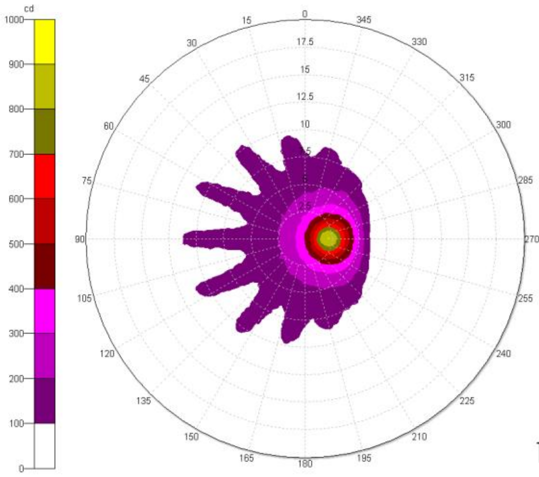
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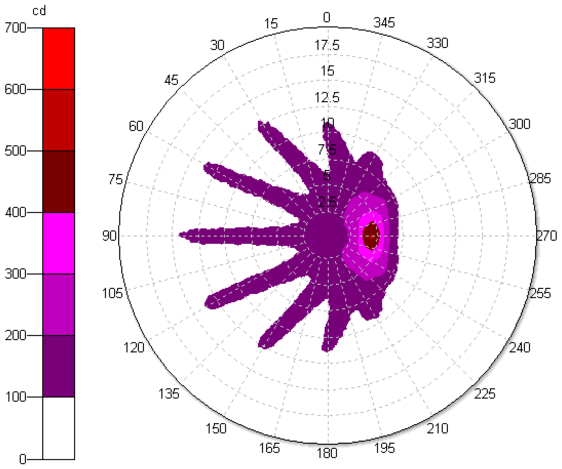
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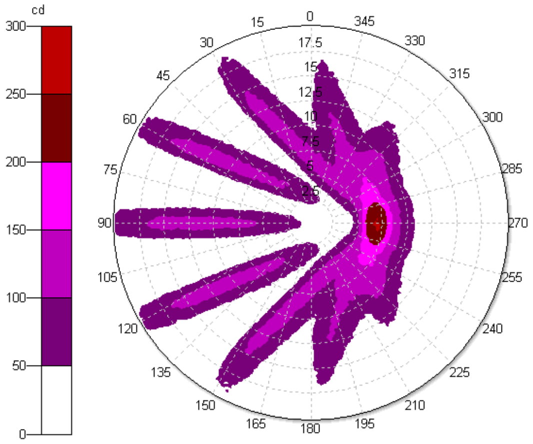
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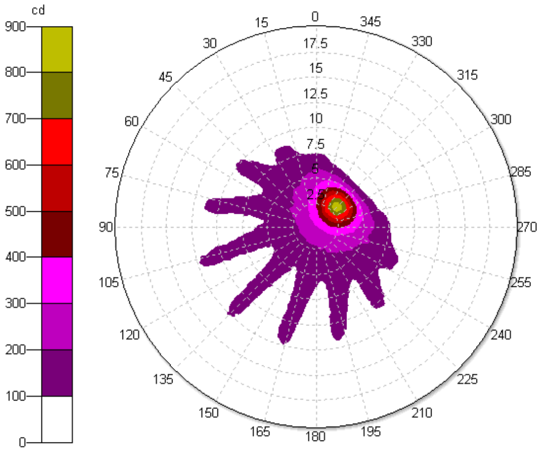
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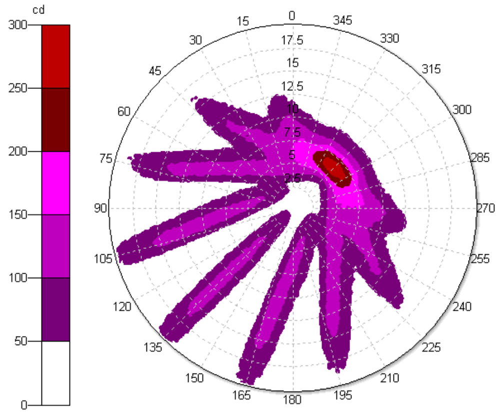
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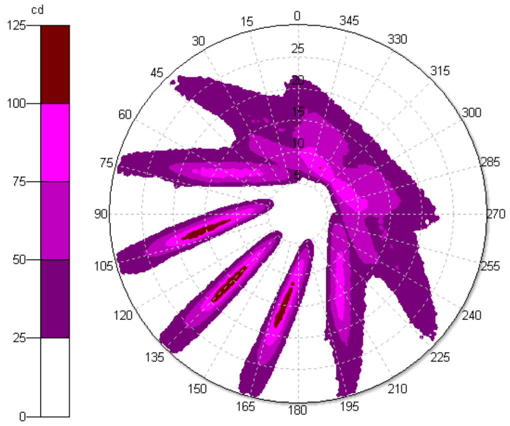

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Fig. 7. Radiation pattern of the facetet reflector, 16 facets per ring and 13 rings, with just one LED switched on at the time, 4900000 rays are traced in each case. The radiation pattern is depicted in a spherical coordinate system, the center of the plot coincides with the z-axis in Fig. 4, looking away from the LED array. All plots except g span an angular region up to 20 degrees from the z-axis. 7a. LED a, positioned in the focus of the reflector is switched on, practically all the light is emitted within a cone with 8 degrees half angle, which is a broad beam compared to Fig. 3a. 7b to g: LED b to g are switched on; the radiation patterns in these cases all show, some more explicit than others, a handprint shape in an iso-candela plot. The ring shaped patterns from Fig. 3 have completely disappeared. The light flux exiting the luminaire is practically the same for each of these cases (approximately 33 lumens). Please notice that for practical reasons in visualising these iso-candela plots the candela scale is not the same in each subfigure.

2.4 Effect of the radius of the reflector base

We investigated if it is possible to produce a light beam with a FWHM smaller then 21 degrees by modifying the base radius of the facetted reflector while keeping the length of the reflector constant at 40mm. A family of parabolic reflectors was constructed with different base radii, for each base radius we recalculated the reflector paraboloid in order to keep the central LED in the matrix positioned in the focus of the reflector. Each of these reflectors was tiled with rectangular facets in a pattern of 16 facets per ring, 13 rings per reflector. The simulated radiation patterns show a central peak on top of a broad, low intensity base, an example is shown in Fig. 8. Notice that practically the entire central peak is located within a cone with a half angle of 15 degrees. From (1) and with $LOR = 0.91$ it follows that only 36 percent of the LED output flux is controlled by the optics. As the base radius increases the peak intensity increases up to a maximum at base radius 40mm, then the peak intensity slowly decreases (Fig. 9a). The FWHM of the central peak drops rapidly to a minimum of 7 degrees (Fig. 9b). The LOR grows significantly but this is compensated by the fact that the fraction of the flux that is emitted within a 15 degree half angle cone - this can be calculated by integrating the intensity $I(\vartheta,\varphi)$ over the appropriate solid angle range (2) - spectacularly decreases with growing base radius (Fig. 9c).

$$\frac{\Phi_{cone}}{\Phi_{total}} = \frac{\int_0^{2\pi}\int_0^{\vartheta_{cone}} I(\vartheta,\varphi)\sin(\vartheta)\,d\vartheta\,d\varphi}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} I(\vartheta,\varphi)\sin(\vartheta)\,d\vartheta\,d\varphi} \tag{2}$$

For a reflector with a larger base radius a larger part of the emitted light never impinges on the reflector, this results in a smaller part of the flux being absorbed and thus in a bigger LOR. However, a larger part of the beam is uncontrolled by the optics which causes the broad base in the reflection pattern and may be the cause of glare if such a reflector is used in a real world application. As the dimensions of the reflector grow relative to those of the LED array a point source is better approximated so that light that does reach the reflector is better collimated. This results in a beam with a very small FWHM on top of a broad radiation pattern of direct light.

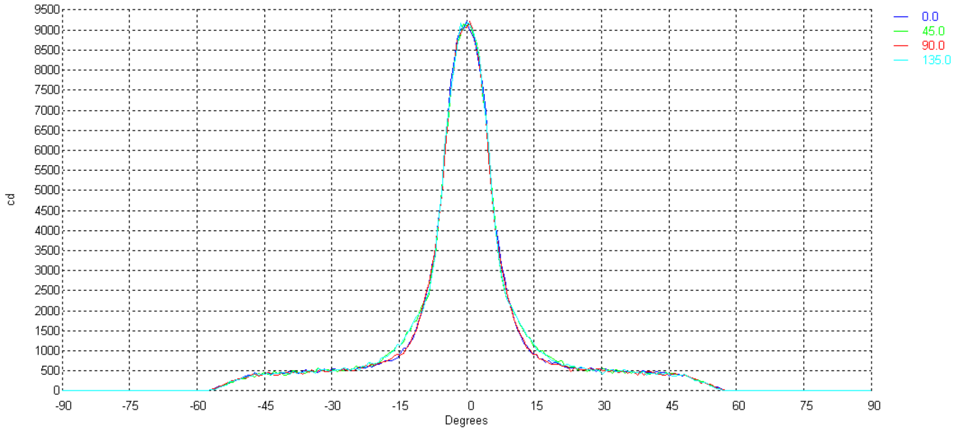
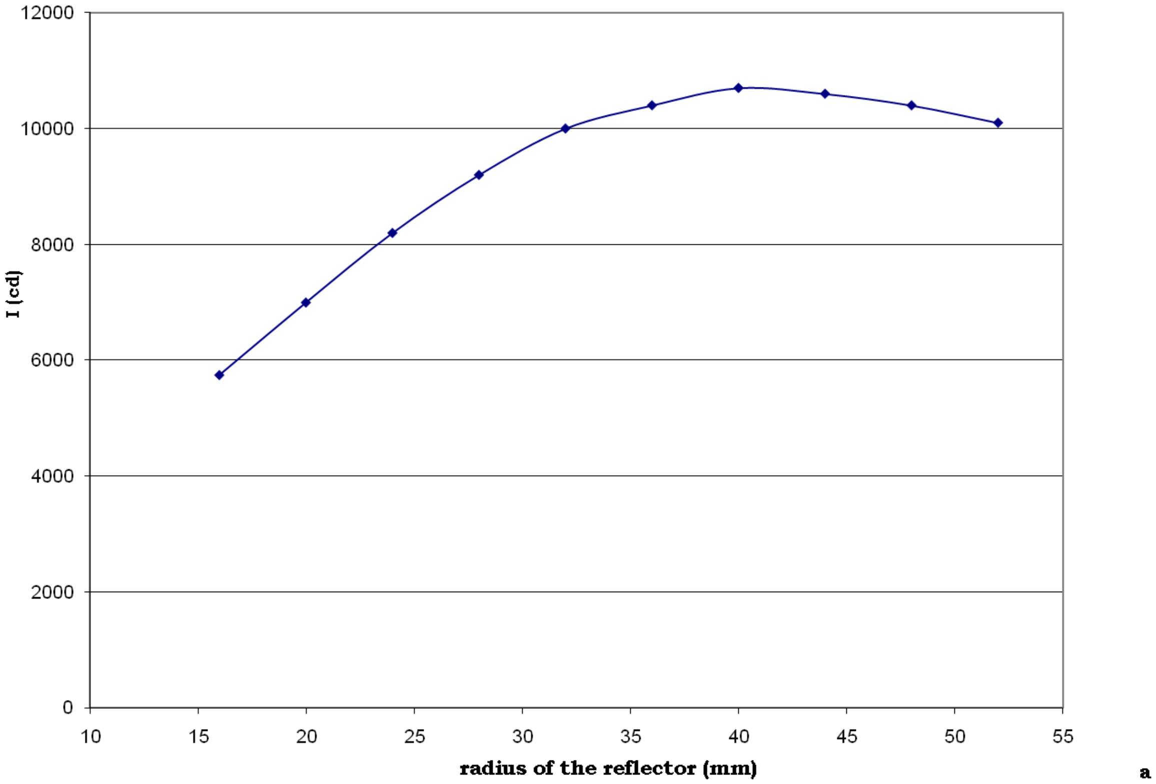
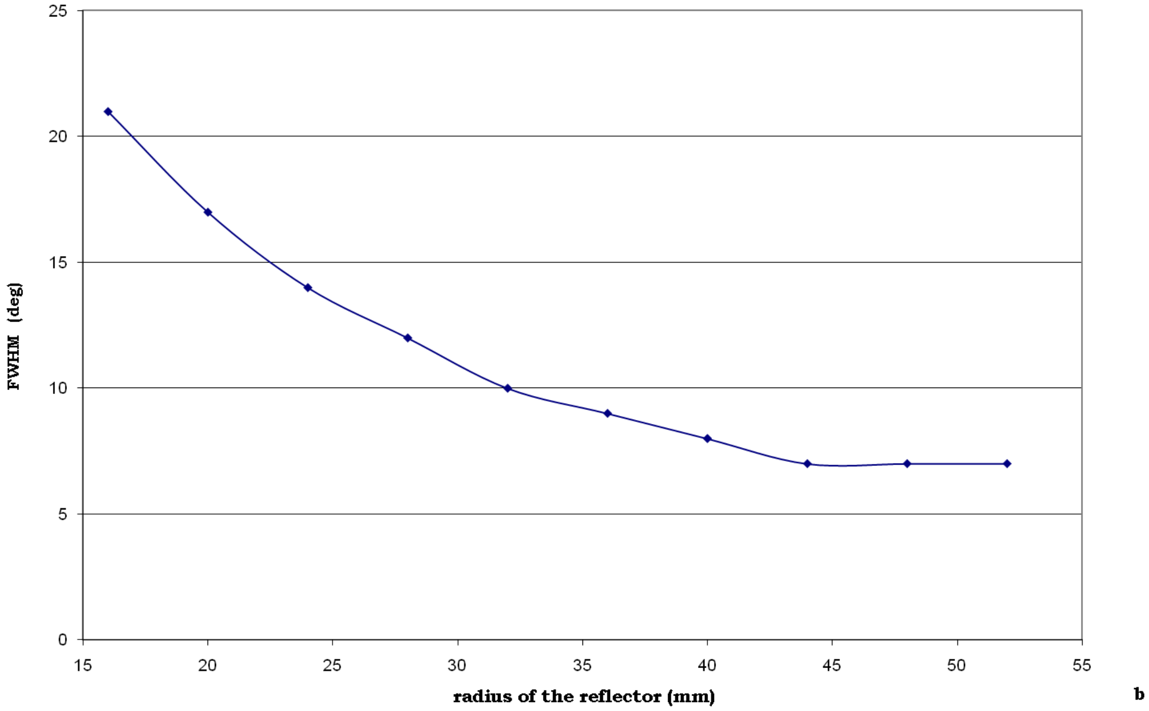


Fig. 8. Radiation pattern of the facetted reflector with base radius 28mm. A high intensity central peak with a small FWHM (12 degrees) sits on top of a broad low intensity base.


12000
10000
8000
6000
4000
2000
0
I (cd)
10
15
20
25
30
35
40
45
50
55
radius of the reflector (mm)
a


25
20
15
10
5
0
FWHM (deg)
15
20
25
30
35
40
45
50
55
radius of the reflector (mm)
b

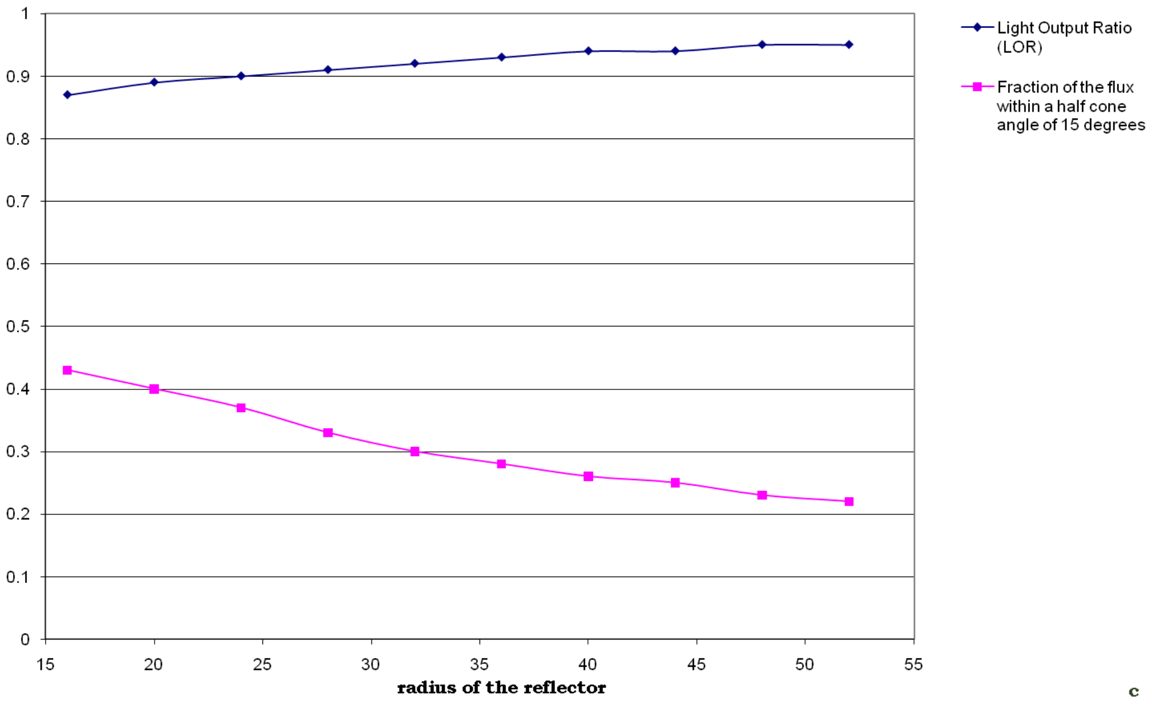


Fig. 9. Properties of the radiation pattern as a function of reflector base radius. a. Peak intensity versus base radius. b. FWHM (degrees) versus base radius. c. LOR (diamonds) and fraction of the flux within a half cone angle of 15 degrees (boxes) versus base radius.

3 Conclusion

A reflector was designed for a two dimensional array of 49 power LEDs so that this array can act as a light source for spot lighting. As a starting point we used a classic parabolic reflector which was modified by tiling it with relatively large facets. The facets were selected for functionality, not aesthetics. The reflector–light source combination produced a smooth radiation pattern with a FWHM of 21 degrees which was not very sensitive to the exact position of the light source. Increasing the base radius of the reflector did not yield satisfactory results because, although a central peak with small FWHM (7 degrees) was produced, a very large part of the light was not controlled by the reflector, possibly causing glare. If a radiation pattern with a very small FWHM is to be created, starting from a light source such as the one we used, it may prove necessary to use more advanced optics such as combinations of lenses, reflectors and holographic optical elements.

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