Design and optimization of a collimating optical system for high divergence LED light sources

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ABSTRACT

This paper presents the design of an efficient collimating optical system for an extended light source, namely a high-brightness high divergence light emitting diode (LED), sized 1x1mm, and viewing angle of 130°. The design lies in a catadioptric rotationally symmetrical system, which modeling and optimization has been done by specific optical design software, ZEMAX®, and its development was based on geometrical principles. The device consists of two optical systems, one for the rays emerging from the source with low numerical apertures (NA<0.26) and another one for those emerging with NA>0.26. The system for rays with low NA consists of an aspherical lens system which parameters are optimized by means of standard criterion for collimation. The system for high NA rays is a combination of a hyperbolic and a parabolic mirror, being the first one the only surface shared by both system (refractive near-axis, reflective off-axis).

The result of this work is a system that reaches a collection efficiency of 80% of the LED emitted light. Moreover, the beam collimation quality has been analyzed obtaining a residual divergence of less than 2°. Thus, the results achieved by the proposed optical system improve those obtained with several commercially available devices and other previously proposed systems.

Keywords: LED source, collimation, high divergence, optimization, optical design, illumination, non-imaging optics.

1. INTRODUCTION

The use of LEDs as a light source in optical devices and general illumination offer significant advantages concerning power consumption, lifetime and colour management. For this reason, nowadays LED technology is used where high photometric levels are not needed [1]. Therefore, the first task of such design is to collect the maximum of light and produce a beam with good collimation. This problem is particularly important for system that must focus light in small spots. Analysis of available solutions shows, that non-imaging optics outperforms its imaging counterpart in collimation of extended sources. However, in contrast to well-know design approaches of imaging optics, design algorithms of non-imaging optics are often very sophisticated and some of them are even patented [2].

An important subject in the development of such optical systems is the optimization process. The designer has to provide a reasonable initial system prescription and a Merit Function (Error Function) for estimation of system performance. In this process, different nonlinear optimization algorithms (Damped Least Square (DLS)) are employed to find the best possible solution [3], i.e. the solution which produces a design with a lower Merit Function.

There are several types of commercial collimator optical systems for LED sources. In general, they can be sorted into two groups, optical systems that are made up by an engineering thermoplastic lens which use the total internal reflection mechanism to collimate the light [2, 4-6]. And, collimators devices that are constituted by parabolic reflecting mirrors which collimate the light [1, 7]. The aperture of these systems, i.e. the diameter of the parabolic mirror, is proportional to the efficiency of the system.

In this work, a collimation optical system for high divergence LED source is presented. The lighting system described here comprises the followings devices: an extended high divergence LED source, a lens system which collimates the

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light from source with low numerical apertures and a mirror system which collimates the light with high numerical apertures.

Section 2 presents the aim of the device developed and different considerations about the simulation of the LED source. Section 3 introduces the modelling of the optical system and shows the optimization process used in order to achieve the desired requirements. Finally, section 4 illustrates the results obtained by the proposed system and compares this design with other commercial collimator optical systems for LED sources.

2. AIM OF THE DEVELOPMENT

2.1 Origin of the Optical System Development

The starting point of this work came up from the idea of substituting a spatial laser source by LED source in interferometry. This implies the necessity of concentrating the output beam of the LED on pinholes of diameters of about 150μm.

In order to focus the LED light beam in a small area it is required to get a high level of collimation. This work is devoted to the collimating system, while the study of the focusing system and the final coherence of the light will be considered a further work.

2.2 Light source, LED

The selected light source had to fulfil two main conditions: i) to emit the same wavelength as the substituted source, and ii) to be intense enough to produce the required output.

Therefore, the selected source was a high brightness LED [8], which emits at 525nm wavelength with a 15nm spectral bandwidth. This LED emits with a divergence angle of 130°, and its geometry is shown in Fig.1, where it can be seen its hemispherical silicone protection surrounding it.

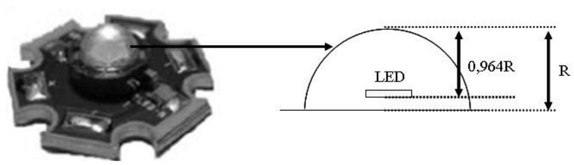

Fig. 1. Front and lateral view of the high of the LED source with its mount and silicon protective lens.

The dimension of the source was measured by an optical microscope (Fig.2). These are not the real LED dimensions, but those of the image produced by the silicone cover acting as a lens. The real dimension of the source is easy to estimate by means of conventional geometrical optics calculation of the magnification [9]. However, the image produced by the silicone cover acts as a real source for the rest of the system, thus being a very attractive idea to directly use this source in the simulation (Fig.2b).

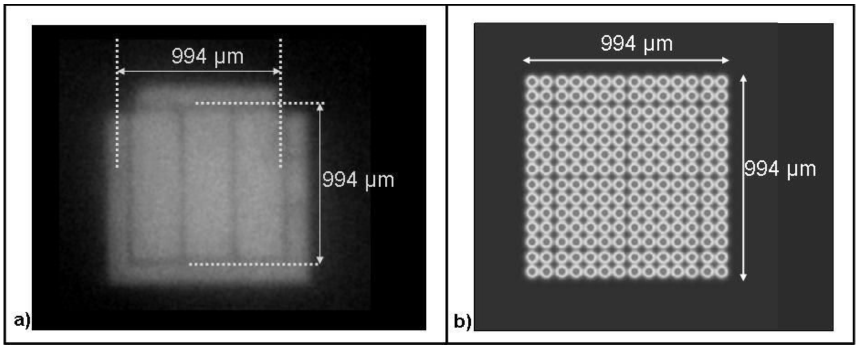

Fig.2. Dimensions of the LED source seen through the silicon lens in the case: a) Real; b) Simulation.

The advantage is clear, as getting rid of a surface in the presented system that was fixed and therefore useless for optimization. The only requirement was to place the source in the right place and keep the thickness of the silicone cover as a geometrical condition for the position of any other element that might contact it.

Once the dimensions and the position of the source have been fixed, other features must be implemented, like divergence and intensity profile. Briefly the LED source was considered as an array of 14x14 point diode emitters where each point emits with a uniform intensity profile and 130° of divergence (viewing angle).

3. MODELING OF THE OPTICAL SYSTEM

There are several commercial designs for collimating LED sources. These systems are based on different techniques. On the one hand, there are reflector systems [1, 7] that usually have parabolic shapes which can achieve efficiencies of about 90% and a residual divergence about 15-20°. On the other hand, it is possible to find another kind of the concentrator-collimator systems [2, 4-6] which use total internal reflections technique to collimate the light. These, in most cases, are made of acrylic plastic giving an optical efficiency up to 90% and a residual divergence of about 10°.

This work presents a catadioptric optical system with two parts; the first is made up of two mirrors, one hyperbolic and the other one parabolic and the second is an aspherical lens system located on the symmetry axis of the whole system. Both systems are dependent on each other, since the position and the shape of the hyperbolic mirror is a common surface to both systems (see section 3.2).

All components of the optical system, but the parabolic mirror, are held inside a Polymethylmethacrylate (PMMA) cylinder to make the system mechanically feasible.

In the modelling process of the optical system collimator (Fig.3a), each part has been dealt as: the aspherical lens system (for low NA) and the mirror system (for high NA) (Fig.3b)

Rays emerging from the source with numerical apertures lower than 0.26 are collimated through a lens system made up of three aspherical lenses, while rays that emerge with numerical apertures greater than 0.26 are collected by the hyperbolic mirror and are collimated through the parabolic mirror.

It is important to remark that the first refractive surface is hyperbolic, with the same shape parameters than the first hyperbolic mirror. This surface is mirrored only in a ring, from a certain distance to the axis, to the external border. This reduces the correction variables and makes the system more compact.

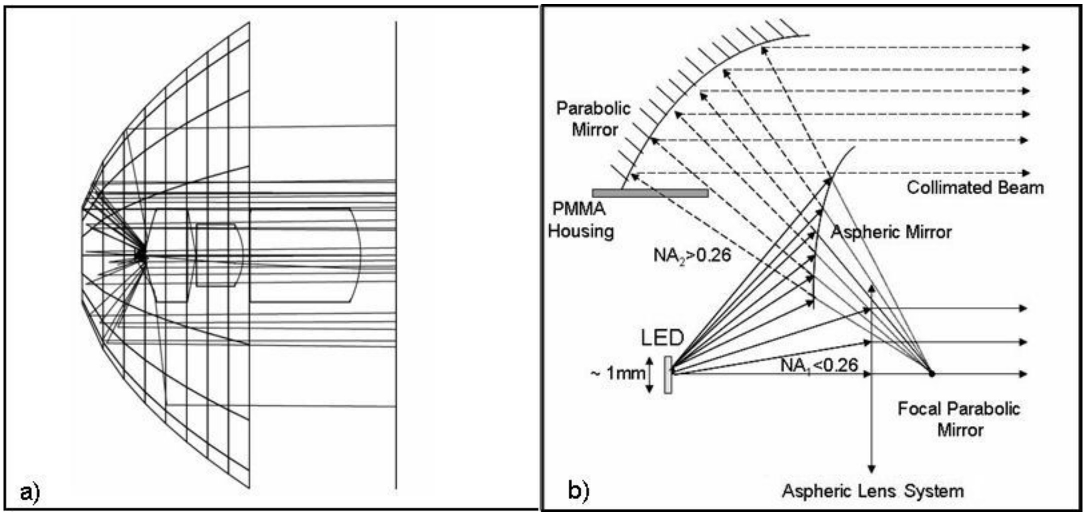

Fig.3. a) Cross transversal of the catadioptric optical system designed and b) different paths followed by low and high NA rays

It is important to point out that there has to be a minimum distance between the LED source and the hyperbolic mirror, 2.7mm, as the closest surface to the source allowed by the silicone cover (Fig.3).

The LED is located on the overall focus of the lens system with the aim of collimating its rays with the best quality. The same idea is applied to the mirror system, which parabolic mirror is placed so that its focus is located on the virtual image formed by the hyperbolic mirror which hence produces a located collimated beam.

To achieve the optical design that carries out these requirements ZEMAX® optimization process has been used. This tool is capable of improving lens designs given a reasonable starting point and a set of variable parameters. In the optical system presented the control parameters are the exit angles of each lens (see section 3.3).

3.1 Design of the lens system

For this system, the hyperbolic mirror acts simply as a diaphragm with a central aperture of NA<0.26. Rays actually find a hyperbolic surface as the first of a set of six aspherical surfaces.

The low NA system consists of three aspherical lenses, designed in such way that each of them deflects rays the same way, that is 1/3rd of the previous divergence, and the collimation is performed in a gradual way. The refractive indices of the lenses are commercial values from the Schott catalogue (BK7 and SF2).

As it has been said before these lenses are contained in a cylindrical PMMA tube (PMMA housing). The aim of the PMMA tube is to hold the system of lenses and the hyperbolic mirror, as a transparent housing, in order to make the system more feasible.

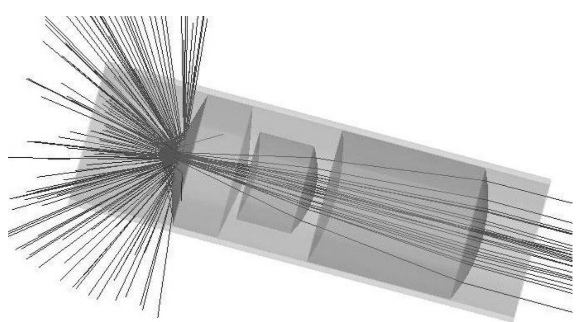

Fig.4. Lateral view of the PMMA housing inside which are the LED source and the aspherical lens system.

The design parameters of the surfaces (Fig.4) obtained in a process that is later discussed, are listed in table 1.

Table. 1. Design specifications for the low NA system of lenses together the hyperboloid mirror.

Surface	Curvature (mm)	Distance to previous surface (mm)	Media	Conic
1	14.55	2.66	Air / BK7	-11.96
2	-2.41	13.00	BK7 / Air	-30.00
3	-12.00	1.60	Air /SF2	-16.39
4	-13.90	10.63	SF2 /Air	-1.22
5	-35.15	3.80	Air / BK7	-1.57
6	-27.16	26.44	BK7 / Air	-0.40
Focal length	**12.84mm**			
Back focal length	**-48.35mm**			
Axial length de lens	**55.40mm**			
Diameter aperture diaphragm	**1.45mm**			

3.2 Design of the mirror system

The rays emerging from the LED with numerical apertures higher than 0.26 are collimated through the hyperbolic and parabolic mirrors (Fig.5). For the design of the hyperbolic mirror, a constraint on the first surface radius has been imposed so as to be a convex surface (see section 3.3). This constraint has been set since, in this way, the virtual image formed by the hyperbolic mirror will be located closer to the first lens edge than with a plane mirror. As a result, rays emerge from this mirror with higher angles preventing them being stopped by the LED mount.

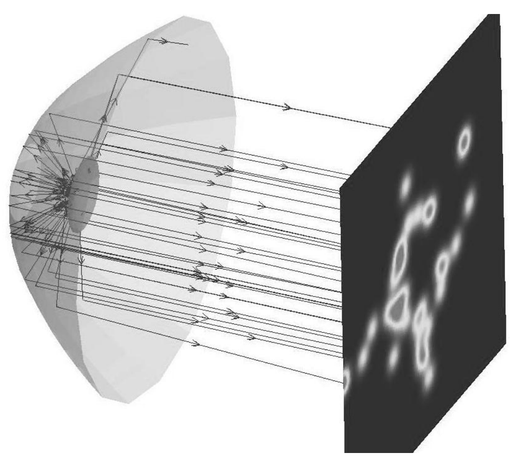

Fig.5. System of mirrors for the collimation of rays from LED with high NA.

The hyperbolic mirror is situated inside of the PMMA housing. The thickness of this tube is 1mm and it acts in a way similar to that of a plane-parallel plate. Though this is really correct only for meridians rays, i.e. rays crossing the axis, the ray-tracing software takes account of the exact trajectory. For this reason, in the manufacturing process of this tube it is important to take into account its optical quality characteristics. With regard to the mechanical design, it must provide the lowest possible roughness along the tube surface. Both homogeneity and roughness are quite important because the deviation that can be introduced by the PMMA tube of the rays with high NA (NA>0.26) could influence significantly the collimation quality.

The maximum aperture of the hyperbolic mirror has to be designed so that the rays can be reflected for the minimum aperture of the hyperbolic mirror and at the same time, to asses the maximum NA the system is reached. For the specifications (radius of curvature and conic constant) obtained from the optimization process (section 3.3), the maximum required aperture of the hyperbolic mirror was calculated by the equation below:

$$x = \frac{c \cdot y^2}{1 + \sqrt{1 - (k+1)c^2 y^2}} \tag{1}$$

Where $c = (1/radius)$ is the curvature at surface vertex, k is the conic constant, and, x and y are the aspherical surface coordinates. The parameters that characterize the mirror system are listed in the table 2, including the hyperbolic mirror maximum aperture.

The position of the parabolic mirror is set so that the distance between its vertex and the source (virtual image of the source given by the first mirror) is equal to its focal length. he basic configuration of this parabolic mirror (conic constant = -1) is enough to produce a good output collimation, while keeping a standard shape. Specifications of the mirror system are summarized in table 2.

Table. 2. Design specifications for the mirror system.

Mirror	Curvature (mm)	Conic	Minimum Radius (mm)/ Aperture	Maximum Radius (mm)/ Aperture
Hyperbolic	14.55	-11.96	0.72 / 0.26	12 / 0.92
Parabolic	40.00	-1.00	12.00	60.00

The complete collimation system is the joint of the lens system and the mirror system (Fig.6). These optical systems are not independent because, as mentioned before, the hyperbolic mirror is made by coating the outside ring of first surface of the first aspherical lens (common element of both systems). The position and the shape of this surface determines, firstly, the maximum aperture of the system, and second, the position of the parabolic mirror in order to collimate the beam light from the LED.

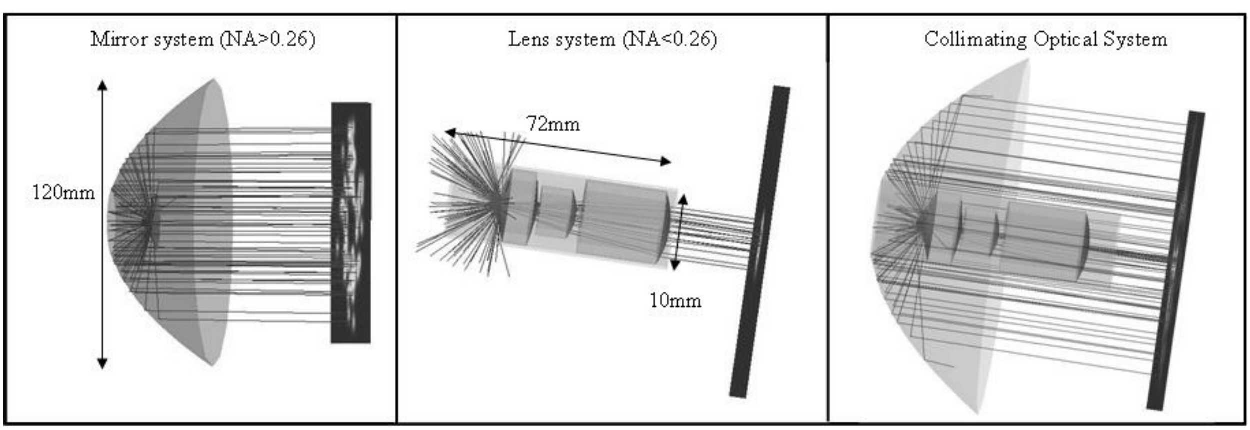

Fig.6. Design of the catadioptric collimating optical system which is made up of two optical systems.

3.3 Optimization technique

The whole optical system has been designed and optimized using different ray-tracing modes (sequential and non-sequential) provided by the optical design software used, ZEMAX®.

The lens system has been designed and optimized by a sequential ray-tracing mode where rays are traced from one surface to the next in a predefined sequence. The first step is the construction of the Merit Function which provides information about the quality of the optical system. The parameters required to define the Merit Function are the *operands* and the *variables*. The *operands* (or target values) are defined as the parameters that must be fixed at a desirable value. These parameters were the exit angles of every lens. The *variables* are defined as the system parameters which value will be fitted by the ZEMAX® optimization process achieving the desired requirements. It fits the curvature of the different surfaces, the thickness between surfaces and their conic constants in order to get the target values of the exit angles of each surface.

The joint system, has been designed by the non-sequential ray-tracing mode where rays may strike any group of objects in any order, or may strike the same object repeatedly, depending upon the geometry and properties of the objects.

Such optimization technique is similar to the one of imaging optics and can be performed by Damped Least Squares (DLS) algorithms, taking into account that the Merit Function has been expressed by Room Mean Square (RMS) deviation of ray angle relative to the target value for one dimension ray fan. DLS uses numerically computed derivates to determine a direction in solution space which produces a design with a lower Merit Function. This gradient method has been developed specifically for optical system design and is recommended for all optimization problems [2, 10].

4. RESULTS AND CONCLUSIONS

This section describes the behavior of some parameters that characterize the quality of the beam that emerges from the optical system. These parameters are the *collection efficiency* (ε_C) of the optical system and the *collimation quality* (E_θ) of the beam after passing through the system. They have been previously used to set the quality of several commercial collimation systems [2, 5-7]. To assess these parameters, the beam profile was measured by a virtual detector (60x60mm) (simulated by ZEMAX®) positioned behind the optical system at different distances (1, 200 and 400mm) after the last surface (Fig.6):

- ***Collection efficiency*** **(ε_C)**. It is defined as the fraction of the total energy emitted by a source that is collected at the system output. This parameter is quite important because it indicates the energetic performance of the optical system.

  The spatial distribution of the collected incoherent irradiance (I), irradiance proportional to impact density of rays, was analyzed on the detector and it is represented for the final system in the figure below:

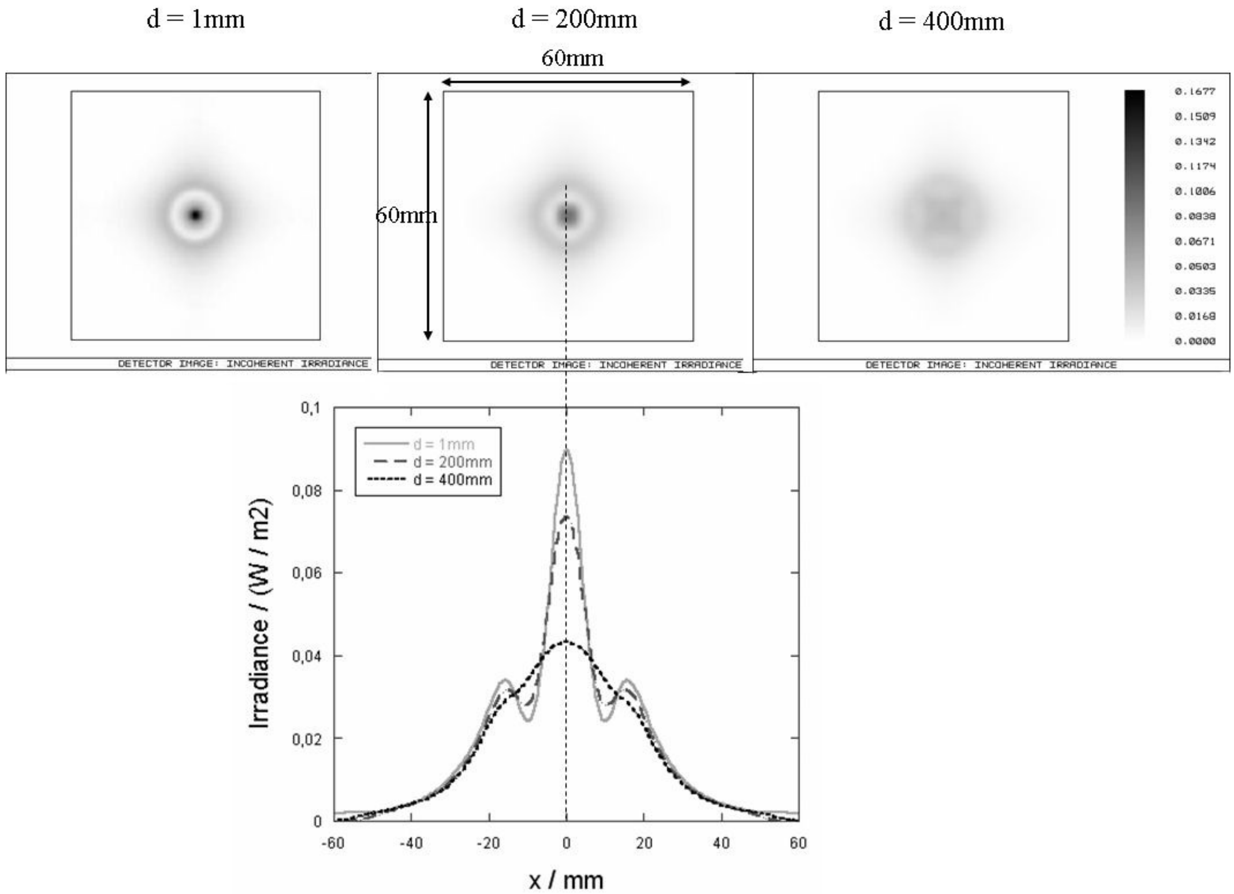

Fig.7. Spatial distribution and cross section of the incoherent irradiance through the collimation optical system (ZEMAX®, 10^6 rays-tracing) for three different position of the detector close to the optical axis.

In Fig.8 the cylinder symmetry of the system is clearly noticed, and from the analysis of this figure the following conclusions can be drawn:

- The collection efficiency *(ε_C)* of the overall optical system is approximately 80%, assuming that the reflective surfaces have an ideal aluminium coating with R>0.9 [11] in the spectral bandwidth of the LED source.
- The central peak of the incoherent irradiance profile comes from the lens system while the light around this peak comes from the mirror system. It is important to point out that this profile represents the density of rays over the detector. Then, the fraction of rays that travel through the lens system to the detector (13%) is smaller than the one through the mirror system (67%).
- The size of the virtual square detector was chosen in accordance to the size of the secondary mirror, which, in turn, is conditioned by the size of the LED mount and the need to avoid that rays might impact on it.

- ***Quality of collimation (E_θ)***. This parameter is defined as the fraction of rays with a residual divergence lower than a certain angle θ.

  E_θ is measured by the radiant intensity (Q) emitted from the source passing through the optical system versus the angle of the rays emerging from the system. By analyzing both Fig.8 and Fig.7 it is possible to conclude that the 80% of light emerging from the optical system has a residual divergence lower than 2° (E_θ<2°).

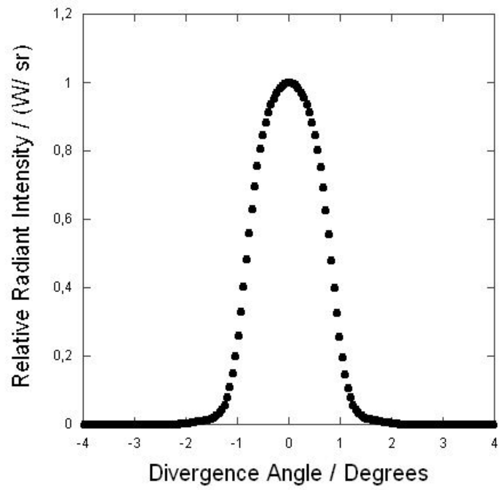

Fig.8. Normalized cross section of the radiant intensity from the LED source versus its divergence angle when emerges from the presented devices.

In summary, the results show that this optical design reaches an efficiency higher than 80%, and that more than 64% of the light emerging from the LED source exits the system with a residual divergence of lower than 2°. These means a reduction of the residual divergence with respect to several commercial devices which provide a residual divergence of about 10° [6, 7].

Regarding the collection efficiency, commercial systems provide an efficiency of 90% as compared to 80% of the system proposed. Nevertheless, the way in which the source has been simulated produces an over estimate of the losses. This is because is this simulations has been assumed a homogenous emission of the LED over its angular range, even for the light with high NA that has to be dealt by the most external zone of the parabolic mirror. For a realistic emitter (Fig.9), forward directionality, increases the light in directions for which system behaves very well, and gradually decreases towards the marginal directions.

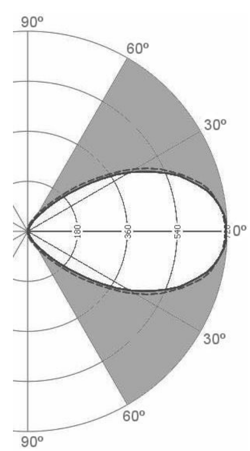

Fig.9. Realistic LED forward directionality (ovoid shape) and overestimated emission of simulated LED with a viewing angle of 130° (shaded shape).

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