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Optical performance of a versatile illumination system for high divergence LED sources

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ABSTRACT

An efficient flat-top illuminating optical system optimized for an extended light source is presented. The source is a high-brightness high divergence light emitting diode (LED), sized 1 mm × 1 mm, producing monochromatic emission (525 ± 5 nm) with viewing angle of 130°. The design is based on a rotationally symmetrical catadioptric system, developed on a geometrical optics basis, and modelled with ZEMAX® software. The device consists of two optical systems: (i) a collimating system which, in turn, is formed by an aspheric lenses system (low numerical apertures, NA < 0.26) and two-mirror system (0.26 < NA < 0.86), and (ii) an external mirror (NA > 0.86) designed and optimized for each purpose. By itself, the collimating system works with a residual divergence of $\theta_C = 1.46°$. The external mirror can be adequately designed to produce some given conditions. For instance, a flat-top profile is obtained in the selected focusing plane, with a maximum transversal intensity variation of 2.5% over 18 mm. In addition, when the focusing mirror is allowed to move along the optical axis in a ±1 mm range, other interesting profiles can be reached for a given working distance, therefore increasing the versatility of the system.

1. Introduction

The advantages of LEDs as light sources include power consumption, lifetime or colour management and have produced an increase of their use in optical devices and general illumination systems. Nowadays LED technology is extending its domain from applications where high photometric levels are not needed [1] to other more demanding ones, rapidly replacing traditional lighting. In many applications, the light flux must be angular or spatially redistributed in order to meet the illuminating requirements of the case, and therefore a very convenient step in the design of a LED illuminating device is to produce a collimated beam. There are several types of commercial collimator optical systems for LED sources, that can be sorted into two groups: optical systems that are made up by an engineered thermoplastic lens that uses the total internal reflection mechanism to collimate the light [2–6], and collimator devices that are constituted by parabolic reflecting mirrors that would produce optimal collimation for point sources [1,7]. Some interesting examples of these systems are worth citing: Shatz and Bortz proposed a non-imaging TIR doublet-lens illumination system designed using inverse engineering approach [8,9]; Kudaev optimized some Compound Parabolic Concentrators (CPC-like) and other Complex Multi Reflectors (RXI-like) devices [3,9]; Chen and Lin proposed a freeform surface design based on total internal reflection (TIR) [10]; Munoz et al. presented a high efficiency LED collections lens, tailored with the edge-ray principle of non-imaging optics [11]; and Vázquez et al. described a parabolic elliptical-based collimator design by means of an analytical and numerical optimization method [2]. The efficiency of the system, defined as the fraction of the energy emitted by the LED source that is collected at the system output in the desired conditions, is proportional to the aperture of these systems [12]. The analysis of these solutions shows that, attending only to the capacity of collimating extended sources, non-imaging optics outperforms its imaging counterpart. However, in contrast to the well-known approaches of imaging optics, with all its broadly extended designing tools, design algorithms of non-imaging optics do not allow for an easy variation of its parameters when pursuing some specific change in its performance.

The purpose of this work is to obtain an optical system able to efficiently transform the light emerging from a specific extended source into a beam with good optical properties, in terms of spatial profile and collimation. The proposed design comprises the followings devices: (i) an extended high-divergence LED source; (ii) a lens system to collimate the rays with low numerical apertures (NA); (iii) a two-mirror collimating system for moderate NA and (iv) an external mirror for achieving a homogenization of the beam profile at a specific working distance (WD) for high NA. As will be shown, the system can either collimate a beam with high efficiency

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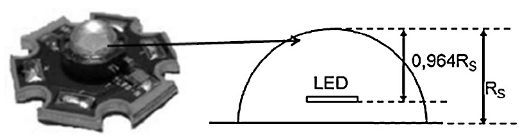

Fig. 1. LED mount with its silicone hemispherical protective lens (R_S = 2.7 mm). Right: lateral view.

or produce desired profiles at a particular distance as, for instance, a homogeneous flat-top profile. The optimization and performance of the system have been calculated with ZEMAX®, a well-known optical design software.

The paper is organized as follows: Section 2 describes the main considerations about the simulation of the LED source. In Section 3 the modelling of the optical system is described, as well as the optimization process used in order to achieve the desired requirements. Section 4 illustrates the results obtained by the proposed system in terms of beam quality and WD. Finally, in Section 5 the main conclusions are drawn.

2. The LED as an extended light source

The light source (depicted in Fig. 1) is a high brightness LED [13], that emits at λ = 525 nm with 15 nm of spectral bandwidth.

The source dimensions were measured by an optical microscope and realistically simulated with ZEMAX (Fig. 2). These correspond to the image produced by the LED silicone cover acting as a lens (R_S = 2.7 mm in Fig. 1). Although the real size of the source could be easily assessed by means of conventional geometrical optics, the image produced by the silicone cover acts as a real source for the rest of the system. Besides, the LED specifications in terms of intensity are given by the manufacturer taking into account this cover. 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 follow.

The directionality of the LED source (luminous flux versus angle of emission) has been modelled according to the emission specifications of the LED source [13] (dotted and solid lines in Fig. 3, respectively). The angle distribution LED is the same in both directions (*X*–*X* and *Y*–*Y*) and the maximum divergence of the LED emission is approximately 130° (viewing angle).

3. Optical system design

The system proposed in this work, and depicted in Fig. 4, consists of a collimating system and an external focusing (imaging) system. The light coming from the source will cross one or other depending on the NA of the emitted rays.

Rays emerging from the source with NA lower than 0.86 will find one of the following collimating systems: for NA < 0.26, collimation is made by a three lens system; for 0.26 < NA < 0.86, light is collimated through a two-mirror system. These two collimation

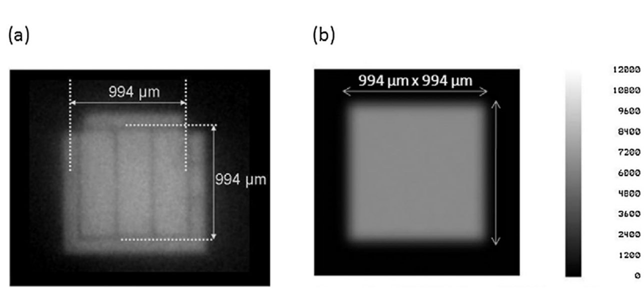

Fig. 2. Dimensions of the LED source seen through the silicon lens: (a) real image; (b) modelled by ZEMAX®.

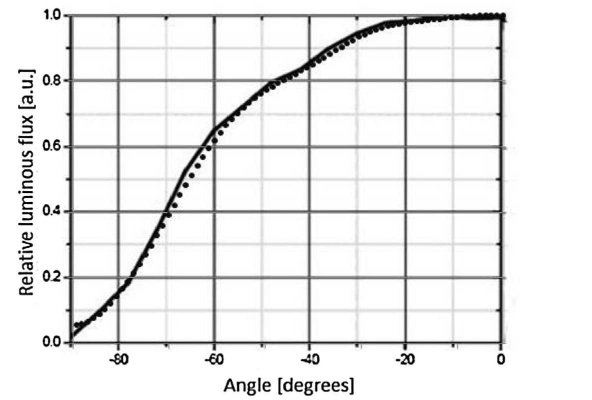

Fig. 3. LED emission profile in Cartesian coordinates, showing its forward directionality. Solid line: from LED data sheet. Dots: realistic directional model of the LED emission.

subsystems, being responsible of driving the light up to NA = 0.86, produce the basic profile of the output beam. Finally, rays with NA > 0.86 are focused by means of an external mirror that modifies the profile given by the collimating system. Depending on the desired profile at some given WD (i.e. distance from the last optical surface of the lens system to the detector plane along the optical axis of the system), the curvature parameters of this external mirror will be optimized. This degree of freedom introduces versatility on the system.

The shape of the mirrors is a conic that is optimized for each function. For the collimating system, we obtain a hyperbolic – parabolic pair (interestingly, this combination corresponds to the stigmatic perfect surfaces of real object + virtual image and image sent to infinity, respectively). For the external mirror, an elliptical shape is obtained (again, corresponding to the stigmatic solution of the case real object + real image).

3.1. Optimization technique

The optimization process of the various optical systems involved in our design is performed with ZEMAX® by using a nonlinear optimization algorithm (damped least square (DLS)) [14]. In order to define the Merit Function some parameters must be fixed at a desirable value (operands T_i). These are, for instance, the output angles from the back surface of each lens. Another set of parameters (variables V_i) will be fitted by the ZEMAX® optimization process for achieving the desired requirements (radius and conic constants of each optical surface, for instance).

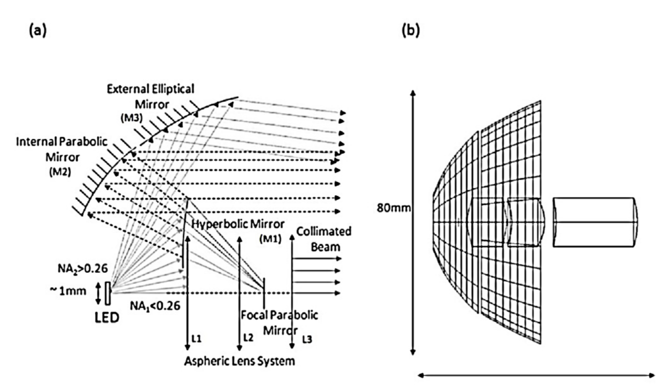

Fig. 4. (a) Schematic description of the different systems, each working for a different NA interval. (b) Cross section of the system, as shown in ZEMAX®.