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Combined experimental-numerical identification of radiative transfer coefficients in white LED phosphor layers

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ABSTRACT

An inverse analysis of the phosphor layer of a commercially available, conformally coated, white LED is done based on tomographic and spectrometric measurements. The aim is to determine the radiative transfer coefficients of the phosphor layer from the measurements of the finished device, with minimal assumptions regarding the composition of the phosphor layer. These results can be used for subsequent opto-thermal modelling and optimization of the device. For this purpose, multiple integrating sphere and gonioradiometric measurements are done to obtain statistical bounds on spectral radiometric values and angular color distributions for ten LEDs belonging to the same color bin of the product series. Tomographic measurements of the LED package are used to generate a tetrahedral grid of the 3D LED geometry. A radiative transfer model using Monte Carlo Ray Tracing in the tetrahedral grid is developed. Using a two-wavelength model consisting of a blue emission wavelength and a yellow, Stokes-shifted re-emission wavelength, the angular color distribution of the LED is simulated over wide ranges of the absorption and scattering coefficients of the phosphor layer, for the blue and yellow wavelengths. Using a two-step, iterative space search, combinations of the radiative transfer coefficients are obtained for which the simulations are consistent with the integrating sphere and gonioradiometric measurements. The results show an inverse relationship between the scattering and absorption coefficients of the phosphor layer for blue light. Scattering of yellow light acts as a distribution and loss mechanism for yellow light and affects the shape of the angular color distribution significantly, especially at larger viewing angles. The spread of feasible coefficients indicates that measured optical behavior of the LEDs may be reproduced using a range of combinations of radiative coefficients. Given that coefficients predicted by the Mie theory usually must be corrected in order to reproduce experimental results, these results indicate that a more complete model of radiative transfer in phosphor layers is required.

1. Introduction

Solid state lighting has become dominant in industrial and household settings, primarily on account of the very high luminous efficiency of solid state lighting devices [1]. Phosphor-converted (also referred to as dichromatic or binary-complementary) white light emitting diodes are particularly common. These LEDs consist of a diode emitting blue light, typically in the 380–490 nm band [2] and a so-called phosphor layer in which a part of the blue light is converted into yellow light (peak wavelength between 530 and 570 nm) [3–5]. The wavelength conversion of the blue light happens via a phenomenon called the Stokes Shift [6]. Theoretically, dichromatic white LEDs can have over 400 lm/W luminous efficacy of radiation (i.e. luminous flux divided by optical power) [6] and already, white LEDs with luminous efficacy of source (i.e. luminous flux divided by input electrical power) above 200 lm/W have been demonstrated [7]. The resulting high energy efficiencies and low costs, along with the color tunability, high responsiveness and multi-functionality [1,2] make white LEDs very attractive for lighting applications.

The phosphors are typically either synthetic garnets i.e., garnets with the silicate replaced by metal oxide ions, or oxynitrides, or

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sulphides [5,8,9]. Among phosphor materials, $Y_{3-x}Ce_xAl_5O_{12}$, Cerium doped Yttrium Aluminum Garnet (YAG:Ce), has been the widely used for white lighting applications [5,9,10]. The phosphor layer in white LEDs is also called the color conversion element (CCE) or the wavelength conversion element (WCE).

In white LEDs, conformal phosphor and remote phosphor arrangements are typical [6,11]. The conformal arrangement consists of a phosphor layer coated directly onto the diode, while the remote arrangement has a phosphor layer separated from the diode by a radiatively non-participating material. Phosphor layer features such as the encapsulant and phosphor materials, volume or mass concentration and size distribution of particles, matrix blending, etc. can be adjusted to meet the package size and color requirements [12–16]. Each adjustment can have a measurable effect on the overall behavior of the phosphor layer.

A good model of the phosphor layer is important not only in optical design, but also in the thermal management of an LED package, since the energy lost in the wavelength conversion is dissipated as heat within the package [17]. Various approaches have hitherto been applied to model the phosphor layer. Experimental analyses of standalone phosphor layers using single or double-integrating sphere arrangements have been widely reported in literature [12,15,18–22]. In these analyses, the concentration, particle size distribution and matrix material of the phosphor layer are varied and the corresponding effects on the behavior of the phosphor layer are reported. However, in order to use the results of these analyses, exact knowledge of the properties of all constituent materials of the phosphor layer is a must.

For numerical simulation of the phosphor layer, model parameters often rely on experimentally measured values. Some early analyses make use of a 1-D, two-flux model [12,23]. The use of a rigorous model of the phosphor layer based on the Mie Scattering theory [15,16,24–28] is more typical. However, optical properties of the medium such as the absorption coefficient, scattering coefficient and the scattering phase function obtained from the Mie theory often deviate from the experimentally observed behavior [15,21,25,28,29]. An explanation for this may lie in the quantum mechanical nature of the Stokes Shift, which is physically different from the wave-mechanics underlying the Mie theory [30]. Other factors include the non-sphericity of the actual phosphor particles, particle aggregation and non-uniform particle distribution in the layer. Therefore, the accurate optical/radiative modelling of the phosphor layer in numerical simulation of white LED optics remains a challenging task. As a result, correction factors often need to be applied to the absorption and scattering coefficient values used in simulations [15,25,29]. If measured behavior of the finished device is then inconsistent with the theoretical models, even after corrections based on measurements of standalone phosphor layers, then the parametric modelling results would no longer be useful.

In this paper, we perform an inverse analysis of the phosphor layer in a commercial LED. First, we determine the geometry of the LED package using tomographic scans of multiple specimens. Following that, we perform integrating sphere measurements, as well as gonioradiometric measurements of the angular spectra at recommended operating parameters of the LED for 10 samples from the same color bin of the series. Using ranges for the absorption and scattering coefficients within a two-wavelength model of radiative transfer, we then establish the applicable values of those parameters for a radiative transfer simulation of the LED. Not only do these analyses provide insight into the effect of each of the radiative parameters studied, but they are also useful for further studies such as coupled optical-thermal modelling of the package, redesign of lens geometry or repurposing of the phosphor composition for other LED packages. Since the thermal performance, and ultimately durability, of LEDs is heavily dependent on the heat generation in the phosphor layer [17], the method used here can provide guidelines for the thermal management of luminaires making use of a given LED. The method demonstrated is applicable to any two-wavelength model of an LED, as long as it is assumed that the excitation spectrum and the re-emission spectrum of the phosphor have little overlap. Thus, it is widely applicable in case of dichromatic phosphor-converted LEDs using yellow phosphors such as YAG:Ce [9], with the advantage being that further details of the composition (e.g. particle sizes) are not required. The inverse analysis does not require any strict assumptions with respect to the type (e.g. spherical) and composition of the particles contained in the phosphor layer. Thus it also avoids problems such as those with reconciling the Mie theory with quantum mechanics or adapting it for non-uniformities in particle shapes and sizes. However, as a purely empirical method it makes no attempts at explaining the underlying mechanisms and is only applicable to the samples investigated.

2. Methodology

2.1. Experimental

2.1.1. LED packages

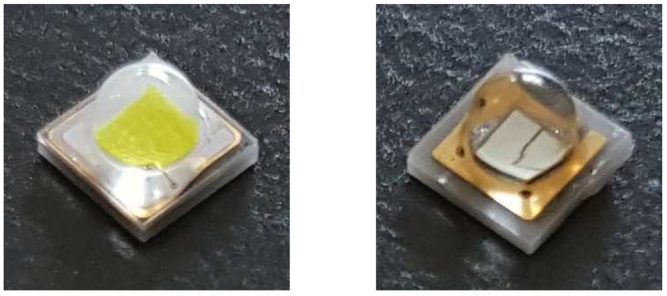
In this study, white and blue LEDs from the OSRAM™ OSLON® SSL 80° series are used. These consist of a surface-mount-technology (SMT) ceramic package with a silicone lens [31]. The details of the LEDs used are given in Table 1 and specimen packages are depicted in Fig. 1. The angular radiative characteristics for these LEDs are provided in the series documentation [31]. Since there is no phosphor layer in the blue LED, it serves as a control sample for determining the refractive index of the lens material via angular radiative characteristic matching.

2.1.2. Tomographic measurement, LED geometry extraction and mesh generation

Tomographic measurements to obtain the accurate LED package and component geometry are done using a GE™ Phoenix Nanotom m Microtomograph [32,33]. The tomographic scans are done using 60 kV acceleration voltage, 200 μA tube current and a 1.7 μm focal

Table 1
Specifications of OSRAM™ OSLON® SSL 80° series packages.

	White LED	Blue LED
Product Number	LUW CR7P type JQ	LB CP7P type GZ
Color bin	1	4
Viewing angle at 50% q	80°	80°
Measured mean radiometric yellow-to-blue	(0.2775,0.7225)	(1.0,0.0)



(a) (b)

Fig. 1. Specimen samples of a (a) white LED, (b) blue LED from the OSRAM™ OSLON® SSL 80° series.