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Analysis of the local temperature distribution in color conversion elements of phosphor converted light-emitting diodes

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ABSTRACT

Long-term stability, efficiency, and reliability of LED-based luminaires strongly depend on thermal management also inside the color conversion layer (CCE) which frequently consists of a transparent encapsulant with embedded microsized phosphor particles. Due to their limited quantum efficiency and Stokes-shift related losses these particles heat-up the CCE and need to be cooled just by heat conduction through the underlying LED chip which itself is heated by its own power loss. Significant research work has been devoted to determine the temperature distribution within the CCE using macroscopic thermal models by considering homogeneously distributed materials properties inside the CCE. By contrast, focus in this paper is to gain a deeper understand of thermal aspects on the base of microscopic thermal models considering the discontinuous set-up of the CCE. In turn, influences of degradation of the heat transfer between phosphor particles and encapsulant and between CCE and LED chip on the temperature distribution inside the CCE are studied in detail.

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1. Introduction

In the recent past enormous progresses in solid-state lighting have led to the development of light-emitting diodes (LEDs) producing luminous flux densities of up to an order of 1 W per square millimeter. For converting a primary (blue) light flux as it is generated by the LED semiconductor chip into "white" light at these density levels a sophisticated thermal management of the entire luminaire assembly is required to allow temperature control and long-term stable operation [1–7]. Based on this fact, as discussed in [8], it would be more accurate to call these devices ‚LED and phosphor", since the phosphor is actually generating more than half of the photons that we end up seeing. Therefore, a comprehensive discussion of thermal management of phosphor converted LEDs should besides the LED also include the color conversion element (CCE, phosphor in a silicone matrix) in particular, since it turned out that the highest temperatures of today's white LED packages are located within the CCE. For this reason, in the last years the temperature distribution inside the CCEs of phosphor converted LEDs due to power loss of the LED chip and due to self-heating by Stokes shift at different macroscopic boundary conditions has been analyzed in depth [9–16]. Most frequently, for this purpose the CCE has been considered as homogeneous and isotropic material. In this wise, for instance, the influence of thinning the encapsulant layer on the maximum temperature has been revealed for in-cup and chip-coated phosphor white LEDs [10]. However, in this way only spatially averaged thermal conditions can be studied. The effect of "thermal bridges" between single phosphor particles is considered in [7,14]. However, only little attention was paid on the local power loss and the temperature distribution inside the phosphor particles which are embedded in an encapsulant matrix with very low thermal conductivity and the effect of a change of thermal contact between particles and their surrounding encapsulant. It should be noted that the local temperature distribution of the phosphor particles is essential for both, the instantaneous effective color conversion parameters and an irreversible deterioration of the lumen performance mainly due to chemical degradation of the phosphor and/or encapsulant matrix. As discussed in [17] at high temperatures and long operating times, the materials in the package can discolor, crack, or delaminate, leading to lumen depreciation and color shifts. In order to gain a better understanding of the related coherences, this contribution is devoted to a thorough simulation based analysis of the temperature distribution inside the phosphor particles and the encapsulant matrix in the vicinity of the particles, considering, e.g., also the impact of materials delamination.

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2. Simulations

2.1. Macroscopic thermal model

The combined optical and thermal simulation procedure is described more in detail in a previous publication [7]. The LED assembly relies on a blue emitting LED die with a CCE having a flat surface on its top, see the inset in Fig. 1. The die has an active area of 940 µm × 940 µm which is located on a silicon substrate. The size of the silicon substrate is 990 µm × 990 µm and its height is 100 µm. The die is placed on a printed circuit board (PCB) by chip-on-board technology. The PCB comprises an aluminum substrate (height 1500 µm), a dielectric layer (80 µm) and a copper layer (70 µm). The LED die is mounted on the PCB by an adhesive layer (height 10 µm). This specific die design refers to a vertical thin film LED die like the EZ1000 (Gen I) from Cree. From the data sheet of this chip also the electrical and optical characteristics (voltage, current, corresponding radiant flux etc.) for the LED die under operation were deduced.

The dimensions of the CCEs are defined by a height of 400 µm and a width of 1040 µm in the lateral directions. The CCEs consist of phosphor particles embedded in a silicone matrix (10 percent by volume phosphor) with an overall thermal conductivity around 0.26 W/(m K) [7].

The optical simulations (ray-tracing) were carried out with the commercial software package ASAP™. Two wavelengths, representing the blue LED light (460 nm) and the converted light (565 nm) are used. The extinction coefficient of the phosphor particles is set to zero for 565 nm and to 10^{-3} for $\lambda = 460$ nm (only the blue LED light is absorbed). The mean diameter of the phosphor particles is 7.8 µm with a standard deviation of 4.2 µm. The refractive index of the matrix material is 1.4 and of the phosphor 1.63 for both wavelengths. The light scattering within the CCE is considered by the scattering model of Mie [18].

In order to determine the absorption profile of the blue LED light within the CCE the latter is divided into voxels (100 layers of voxels in vertical direction, each layer consisting of 260 × 260 voxels in lateral directions). That with, the absolute number of the blue radiant flux which is absorbed by each of the individual voxels can be determined from the datasheet [19] for currents of 200 mA, 800 mA and 1200 mA. These values were chosen to cover the whole range from low/middle power operation to high power operation and ultra-high power operation. Appropriate values of the radiative flux and the power for the value of 1200 mA were extrapolated from the data provided in the datasheet.

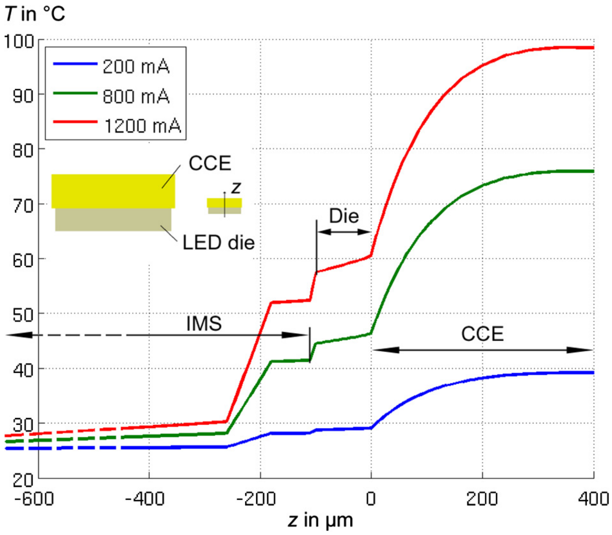

Fig. 1. Temperature distribution along the vertical symmetry axis of the module.

As a source for heat generation in the CCE the Stokes shift (for the two wavelengths of 460 nm and 565 nm) is considered in this study, while the quantum efficiency is assumed to be 100%. A quantum efficiency smaller than 100% would give reason for additional heat generation. However, present state of the art phosphor still reaches a quantum efficiency of 98%, so that the impact of this parameter on heat generation is comparably negligible (in particular in case that the temperature dependent reduction of the quantum efficiency is not that large).

The data on the number of absorption and color conversion processes that take place within the individual voxels are used as input parameters for the subsequent thermal simulations. For a macroscopic consideration of the temperature distribution, in which the CCE is considered as one block with a specific thermal conductivity and heat capacity, the GPL-software packages GetDP/Gmsh [20,21] are used. Using the symmetry of the model allows a reduction of the calculation effort and time by simulating only one eighth of the whole sample. At the symmetry planes of this reduced model space adiabatic boundary conditions were applied.

Within the defined model the steady-state heat equation has been solved with the finite element method (GetDP). As a boundary condition it is assumed that the bottom surface of the PCB (consisting of a 1500 µm thick aluminum substrate, an 80 µm thick dielectric and a 70 µm thick copper layer) is mounted on a perfect cooler. This cooler realizes a constant temperature T_{cool} (Dirichlet boundary condition) of 300 K at the PCB's bottom surface (not included in Fig. 1). All other boundaries of the model are subject to natural convection in air and radiation to the environment. For the average heat transfer coefficient a value of 20 W/(m^2 K) and an ambient temperature of 300 K have been chosen. This simplification appears justifiable by the fact that by far the major heat flow from the CCE is conducted through the LED chip [22].

Fig. 1 shows the temperature distribution along the vertical axis of the simulation set-up for the three current levels of 200 mA, 800 mA, and 1200 mA from a macroscopic point of view. From the absorption profiles and considering the power losses by the Stokes shift power loss distributions were calculated. The power loss density functions along the vertical symmetry axis in the CCE ($z = 0$ at the LED chip-to-CCE interface) for the different forward current levels are depicted in Fig. 2. It has to be mentioned, that throughout the whole study the same power loss distributions are used (in case of delamination the bottom surface of the CCE is simply shifted upwards by the assumed values of delamination width). In reality, such a delamination would cause slightly different absorption profiles and, therefore, power loss distributions. However these differences are negligible and have no impact on the general findings of this study.

2.2. Microscopic thermal model

For the microscopic consideration of the thermal behavior of the CCE the simulation tool Trescom was used. This self-developed tool allows developing thermal models with complex geometry in an easy way on the base of an orthogonal discretization and applies an advanced finite volume method on the heat equation [23].

In a local analysis at microscopic scale we consider spherical phosphor particles (Ce:YAG) with a thermal conductivity of 12 W/(m K) embedded in a transparent silicone matrix with a thermal conductivity of 0.2 W/(m K), as discussed in [7]. The conversion of the blue-light takes place in the phosphor spheres, only. Accordingly, the power loss is to 100% concentrated in the volumes of the phosphor particles. We study the temperature and power

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