The phosphor's optical properties - white light quality relationship of white LEDs

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Abstract— Based on optical ray-tracing simulations we discuss the effect of the extinction coefficient and the quantum efficiency of the phosphors on the color temperature and the angular homogeneity of the white light emitted from phosphor converted light-emitting diodes. The individual absorption profiles of the blue LED light and the related radiative loss mechanisms turn out to have a tremendous impact on the white light quality of the respective white LED sources.

I. INTRODUCTION

Today's most common approach for white light-emitting diodes (LEDs) relies on a combination of blue LED light and excited emission from a phosphor material [1]. The phosphor is embedded in a transparent matrix, typically a silicone type material and placed in the direction of the light emitted from the blue LED die. The overall device performance in terms of light output and quality of the white light critically depends on the appropriate shape and arrangement of such a color conversion element (CCE) within the LED package.

In order to avoid the need for experimental realization and inspection of a plurality of different configurations and compositions of the color conversion elements, recent progress in the simulation of the color conversion process and light propagation throughout the CCE offers a time- and cost saving alternative for studies aiming towards optimized configurations of the CCE with respect to efficacy enhancement and white light quality improvement of the LEDs [2 – 5].

In our recent publications we have presented such a simulation procedure [3,4] and have discussed the geometrical and compositional needs of the CCEs for improved white light quality. However, throughout these studies, the optical properties of the phosphor material were kept constant.

On the other hand, a large number of new phosphor materials are developed nowadays by materials scientists in order to cover the whole range of colors, improve the long-term stability and to enhance the extinction coefficient and the quantum efficiency of the phosphor materials. For a systematic approach in order to improve phosphor converted LEDs it is therefore imperative to gain a better understanding how variations of the extinction coefficient and the quantum efficiency and their mutual interactions affect the color conversion process and as a result the color temperature and white light quality of the LEDs. In the present study we therefore focus on the phosphors themselves and discuss how variations of their optical parameters vice versa affect the white light quality for a given geometry and composition of the CCE.

II. SIMULATION

The details of the simulation procedure can be found in our previous publication [3,4]. Generally, the simulation procedure, that was carried out with the commercial software package ASAP^{TM}, relies on the set-up of an appropriate simulation model for a blue emitting LED die, the implementation of a CCE on the top of the die, and a detector element of a favored shape surrounding the LED package (see Fig. 1 for a sketch of the simulation model).

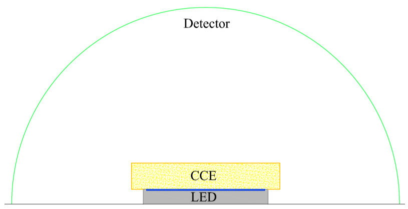

Fig. 1: The simulation model consists of a blue LED die with a square-shaped CCE placed on top of it and a hemispherical detector. The hemispherical detector is divided into 101 pixels along the two perpendicular main axes.

For the simulation process two wavelengths are considered, one representing the blue LED light (460 nm) and the other one the converted yellow light (565 nm). It is assumed that only the blue LED light is absorbed, therefore the extinction coefficient of the yellow phosphor particles is set to zero for 565 nm. Both the blue LED light and the yellow converted light are scattered throughout the CCE. The simulation of this scattering process is based on the scattering model of Mie and considers the particle size distribution of the phosphor, and the optical properties of both the matrix material and the phosphor. In the present study, both the extinction coefficient and the quantum efficiency of the phosphor material are varied, while the refractive indices of the silicone and the phosphor are kept constant at 1.4 and 1.63 for both wavelengths. The mean diameter of the phosphor particles size is kept constant at 7.8 µm with a standard deviation of 4.2 µm.

III. Results and Discussion

Fig. 2 shows the results for the mean of the averaged CIE x values for two perpendicular directions for CCEs having a constant width b = 1040 µm, a constant height h = 400 µm and a constant concentration of phosphor particles c = 10 vol. % in the matrix material in dependence of three different extinction coefficients of the phosphor material (5×10^{-4}, 1×10^{-3} and 2×10^{-3}), while the quantum efficiency is kept constant at 100%. Besides its tremendous impact on the overall color temperature, the variation of the extinction coefficient also has some impact on the angular variation of the color temperature.

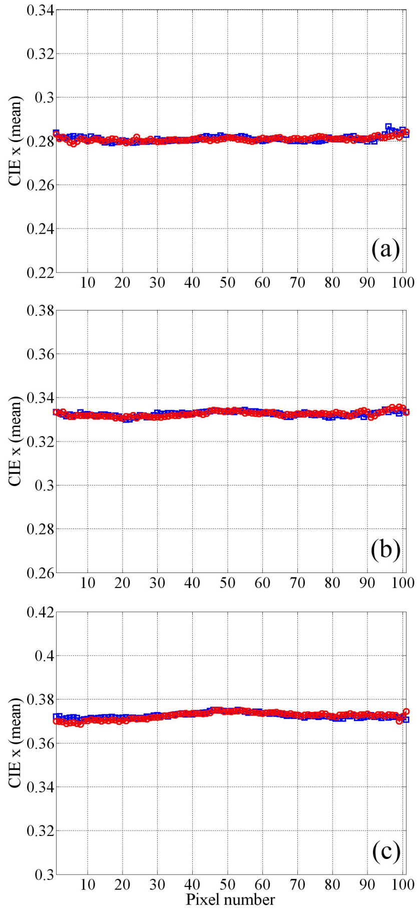

Fig. 2: Mean of the averaged CIE x values for two perpendicular directions for a CCE having a constant width b = 1040 µm, a constant height h = 400 µm and a constant concentration of phosphor particles c = 10 vol. % in the matrix material, as well as a constant quantum efficiency of 100 % while the extinction coefficient of the phosphor is varied from (a) 5×10^{-4}, to (b) 1×10^{-3} and (c) 2×10^{-3}.

This behavior is even more pronounced in case of a quantum efficiency of only 50 % and extinction coefficients of 1×10^{-3} and 2×10^{-3} (see Fig. 3).

The variations of the absorption profiles of the blue LED light throughout the CCEs for the different extinction coefficients as well as related loss mechanisms for the light (backscattering and reabsorption in particular of that portion of light which is absorbed and converted in close proximity to the blue LED die, nonradiative recombinations,…) as well as the respective light scattering throughout the CCE determine the radiative properties of the white LED light: the correlated color temperature, the angular variation of the color temperature as well as the radiant fluxes of the LEDs, for which, based on a comparison of a broad range of extinction coefficients and quantum efficiencies, suitable combinations of these parameters can be determined.

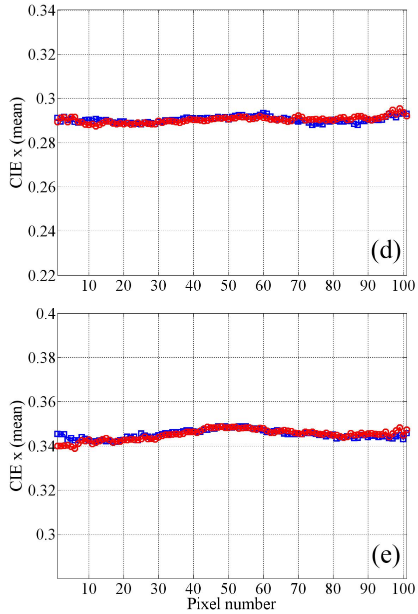

Fig. 3: Mean of the averaged CIE x values for two perpendicular directions for a CCE having a constant width b = 1040 µm, a constant height h = 400 µm and a constant concentration of phosphor particles c = 10 vol. % in the matrix material, as well as a constant quantum efficiency of 50 % while the extinction coefficient of the phosphor is varied from (d) 1×10^{-3} to (e) 2×10^{-3}.

IV. Acknowledgements

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