

Precise optical model of multi-chip white LEDs

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Abstract: A single-chip white light LED is commonly modeled by considering the phosphor coating as a homogeneous Lambertian light source. However, this approach leads to an incorrect optical simulation of phosphor-coated multi-chip LEDs due to the presence of a previously unreported spatial distribution of emission spots across the phosphor layer. We introduce “weighting” factors based on position-dependent light strength across the phosphor surface in order to improve the model accuracy. Following the modeling algorithm in the mid-field region, we have built up a precise and practical optical model by using Monte Carlo ray tracing and weighting factors. We measure the LED radiation distribution at several representative distances to test the model performance. In all cases, the accuracy is higher than 99.5% in normalized cross correlation between the simulated pattern and experimental measurement.

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1. Introduction

An LED (Light Emitting Diode) has more advantages than a traditional light source, e.g., vivid colors, long lifetime, faster response, environmentally friendly, etc [1]. Therefore, LEDs have been regarded as the best potential light source for next-generation lighting. To achieve the high flux level required for most lighting applications, several chips are integrated in a single package.

The addition of a phosphor wavelength converter to the short-wavelength primary emitter is the most common method used to produce LED-based white light [2]. In available

commercial phosphor-coated multi-chip LEDs, the phosphor is dispersed within an epoxy resin that surrounds a chip array. This type of LED emits a light pattern difficult to model with conventional design tools.

A precise optical source model is necessary and very important for analyzing and applying white LEDs [3-7]. An LED model is traditionally used to design both an improved package and a compound optical system, e. g., projection optics. In most applications, like illumination, simulation software is used to assist the optical system design. Because each type of LED has a specific radiation pattern (due to a particular chip structure, package, and other factors), it should be precisely modeled. Otherwise, simulation results cannot be trusted.

2. Conventional model

Ideally, a model for multi-chip white LEDs should trace several millions of rays from every chip through the phosphor layer and then throughout the encapsulant lens. However, the computation required to model the light pattern is overwhelming.

This approach has been implemented to simulate a single-chip white LED [7]. Although useful to model the color angular distribution, this method demonstrated that there is practically no difference between using a complex phosphor model or a simple Lambertian model for the stimulation of the radiation pattern. Therefore, for the general case, when trying to model a single-chip white LED, the top surface of the phosphor layer is traditionally regarded as the starting Lambertian light source for Monte Carlo simulation.

However, for a phosphor-coated multi-chip LED, the traditional Lambertian model does not accurately reproduce the experimental measurements. The problem is depicted in Fig. 1 for an 8 chip LED with sizes: chip side 1 a.u., phosphor disc diameter 6.5 a.u., chip spacing 0.5 a.u., and spherical cap with both an 8 a.u. radius and a 4.2 a.u. tip height. It can be noted that the conventional method does not agree with the off-axis data. As we explain in the next section, the main consideration missing for this problem is the energy distribution across the phosphor surface, which depends on geometric conditions, phosphor layer thickness, phosphor particle diameter, absorption of phosphor and so on.

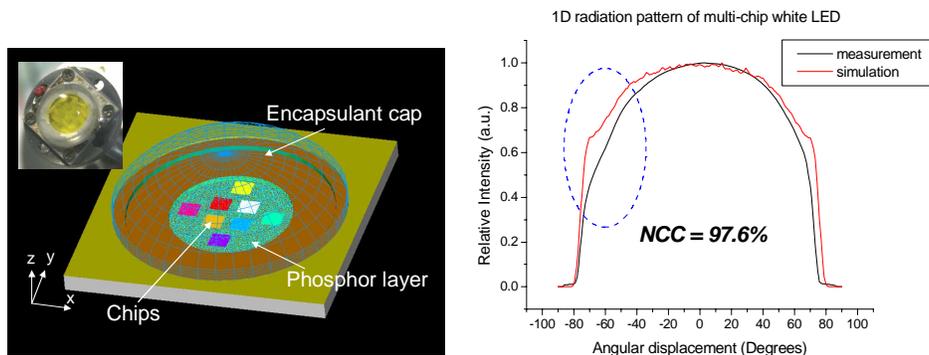


Fig. 1. LED package used to illustrate the proposed optical model (left). Comparison between experiment and the angular distribution simulated with the conventional method (right).

3. Observing the energy distribution

In an attempt to identify the cause of the failure of the conventional method in the multi-chip case, we performed several experiments. It was not evident at first glance that the light emission is significantly not uniform across the phosphor surface. Furthermore, as far as we know, this characteristic of multi-chip white LEDs has not been reported before. To observe such a distribution, we required taking an image of the top surface of the phosphor layer by a CCD camera with LED operating under low power. The energy distribution can also be measured when the LED is operating at high power by using a set of filters. However, we experimentally found that the relative distribution does not significantly vary with power,

changing less than 15% over the full power range. Therefore, we recommend the measurement at low power because it is easier to perform.

Additionally, we observed the relative light strength across the phosphor surface under different observing angles. We wanted to know whether the relative strength is the same at different angles or not. If the relative strength varied, we could not regard the phosphor surface as an array of Lambertian emitting spots, thus leading to a very complicated model.

After taking the image of the top surface of the phosphor layer by a CCD camera, when LED is operating under low power, the relative light strength is obtained by image processing. From Fig. 2 we can find out that the relative light strength at the same position does not significantly vary with observing angle. Therefore, we treat it as a new Lambertian emitting surface with an energy distribution given by the weighting factors.

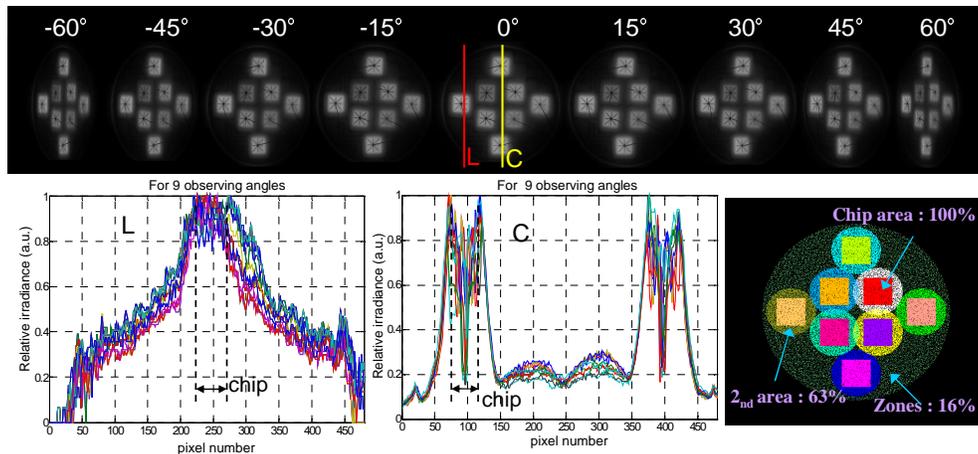


Fig. 2. Constancy of weighting factors over viewing angle. CCD images of multi-chip white LED with flat encapsulant for 0, ± 15 , ± 30 , ± 45 , $\pm 60^\circ$ (top). Corresponding weighting profiles along two representative sections of processed images (bottom, left and center). Set up of the weighting factors for sample simulation (right bottom).

4. Precise model and measurement

In radiometric (or photometric) terms, what we mean by “weighting factor” is a redistribution of the flux (or luminous flux) emitted by unit area of the light source [8]. In Monte Carlo ray tracing, this is equivalent to trace differently weighted rays from different sections of the source [3]. After image processing (Fig. 2 bottom, left and center), an average weighting profile of a single chip can be calculated from the image cross section along each one of the chips. Therefore, the relative light strength along the entire emitting surface can be defined by assigning a weighting profile in each chip position.

To simplify the simulation, we split the chip weighting profile into two flat sections: the first one corresponding to the chip area, and the other to the surrounding area (2nd area). The size and weighting value of the secondary area can be chosen arbitrarily within certain limits. However, we recommend taking these average values when the slope of the image profile suddenly increases after the chip region. For example, in Fig. 2, the size of the secondary area can be determined from pixels 200 and 300 (bottom, left), and from pixels 55 and 140 (bottom, center). After averaging, we chose 0.86 a.u. as the radius of the secondary region.

Figure 2 (bottom, right) shows the average weighting factors used to simulate the example LED: chip area 100%, surrounding chip zone 63%, and the remaining area 16%. According to the relative light strength, weighting factors are assigned to the phosphor surface which is considered as a segmented Lambertian source for Monte Carlo simulation (see Fig. 3). In the following simulation, we assume that all the chips have equal performance, but random values can be used to determine some manufacturing tolerances.

Figure 4 shows simulations and experimental measurements of the 1D radiation pattern of the tested LEDs across the x - z plane for several mid-field distances. All intensity measurements were performed with LED operating under mid-power.

In order to determine the similarity between the simulated pattern and the measured pattern, we apply the normalized cross correlation (NCC) [6]:

$$NCC = \frac{\sum_n [I(\theta_n)_e - \bar{I}_e][I(\theta_n)_s - \bar{I}_s]}{\sqrt{\sum_n [I(\theta_n)_e - \bar{I}_e]^2 \sum_n [I(\theta_n)_s - \bar{I}_s]^2}}, \quad (1)$$

where I_s and I_e are the simulated and experimental values of relative intensity, respectively. θ_n is the n -th angular displacement, and \bar{I}_s and \bar{I}_e are the mean values of simulation and experiment across the angular range. The NCC between the simulation and experimental measurement at different distances in the mid-field is also shown in Fig. 4 for a $\pm 90^\circ$ angular range. It can be observed that the NCC is always larger than 99.5%. From our experience in designing LED lighting systems for industry, we know that an LED model with a NCC higher than 99% gives enough accuracy for most applications [6]. Figure 5 shows a comparison of the NCC of simulation and the NCC of two other samples with respect to a reference sample. The model accuracy could be improved by considering a more realistic profile (see Fig. 2) of weighting factors or by using color filters to measure blue and yellow weighting factors. However, such an improvement is very small because, as shown in Fig. 5, the manufacturing variability among LEDs of the same type limits the precision of any model.

Our source model offers a fairly excellent precision for optical design and is much less time-consuming than an exact model. Using our model, the simulation speed is about 40 million rays per hour with a common desktop computer.

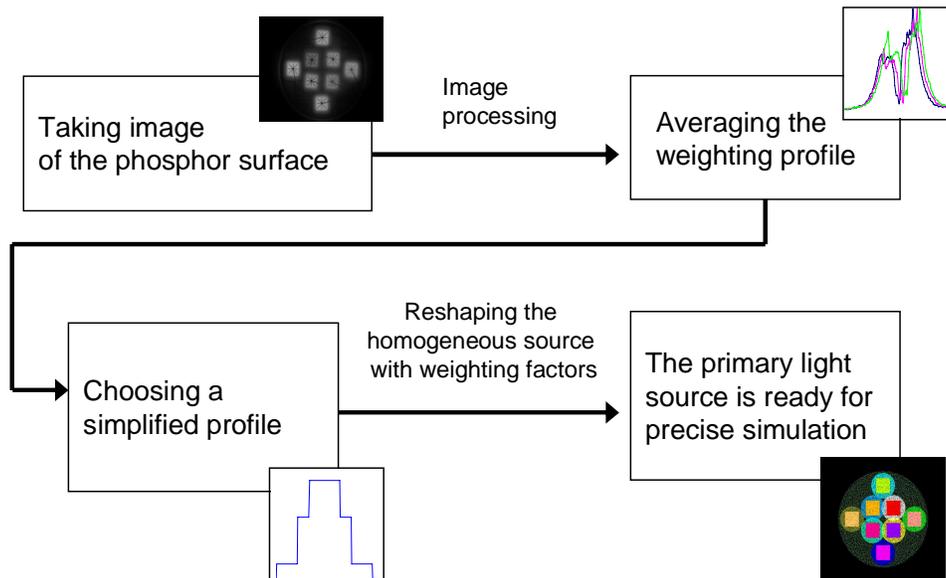


Fig. 3. Summary of light source modeling.

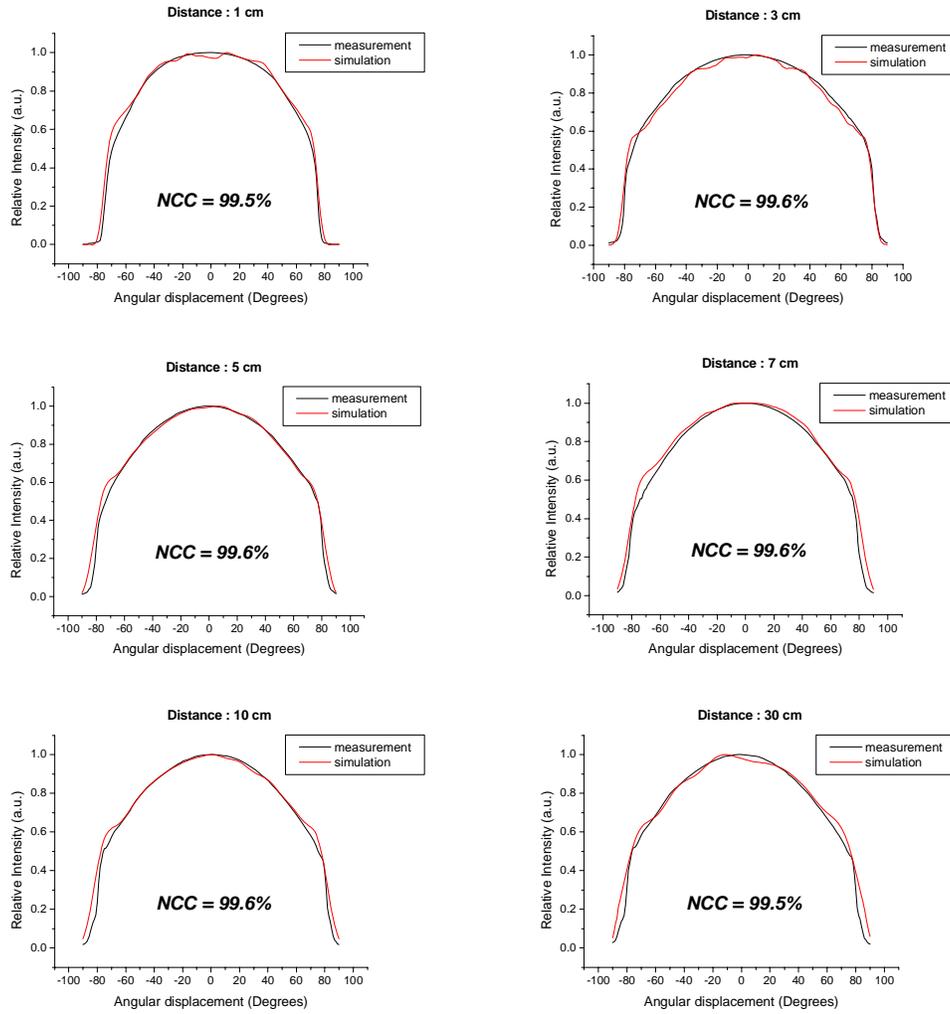


Fig. 4. One-dimensional light pattern at different distances: 1, 3, 5, 7, 10 and 30 cm. This distance is defined as the separation between the bottom of the LED package and the detector aperture.

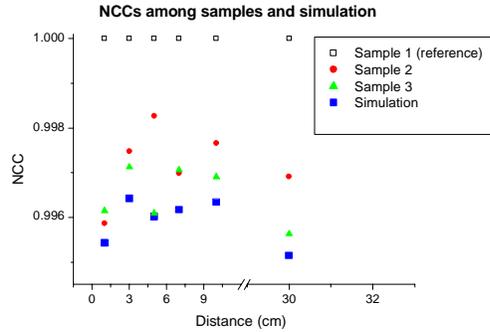


Fig. 5. NCC graphed in function of the measurement distance for the simulated LED and for three sample LEDs of the same model. The NCC variation among samples shows that the level of fabrication repeatability limits the model precision.

The model also can be used to compute the color angular distribution by using color filters to measure the two different energy distributions over the phosphor layer (or three in the case of UV/RGB phosphor LEDs), which are due to both the wavelength converted light and the short-wavelength primary emission. However, in this case the blue and the yellow weighting factors should be measured for every operating power.

5. Conclusion

A new, simple yet highly accurate optical model for a phosphor-coated multi-chip LED was proposed. Weighting factors based on position-dependent light strength across the phosphor surface which redefine the energy distribution of the conventional Lambertian light source used in the traditional Monte Carlo simulation were introduced. We successfully demonstrated the model against measurements at several mid-field distances. NCC was used to compare the similarity between the modeled radiation pattern and the patterns of several sample LEDs, showing that the NCC is always larger than 99.5%. This high model performance and the fabrication variability of LEDs indicate that our model yields essentially the same results as the more exact yet much more time-consuming approach. However, its simpler form and implementation make it easier to understand, apply, and perhaps improve for color applications.

This optical model can be applied to any other phosphor package arrangement [7,9], because non-uniform phosphor emission due to multiple chips surely will be present. Another possible application of our model is the precise computation of color angular distribution by measuring the weighting factors of both blue emission and yellow-converted emission by using color filters. Additionally, as we have done before for single-chip GaN-based LEDs [10], our method can be applied in a similar way to analyze the light extraction efficiency of a multi-chip white LED in function of both the configuration and the packaging density of the chip array. This approach can also be useful for determining some manufacturing tolerances.

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