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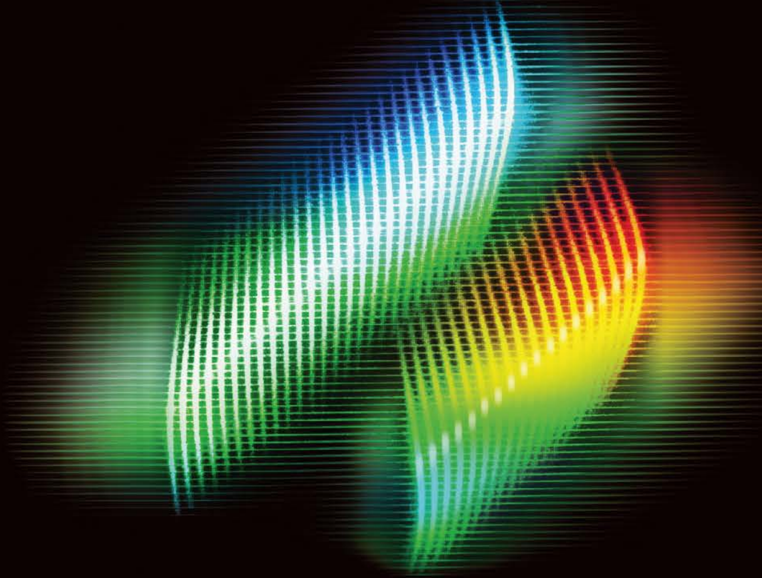

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Spectral Raydata for Simulation of Color Rendering Indices

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Abstract

Using wavelength information in optical simulations is receiving increased attention as measurement techniques emerge that are capable of producing suitable data and as simulation tools are able to handle these data. It is customary to work with raydata of light sources that contain a number of wavelengths up to a complete spectrum. Common raysets of white LEDs are often based on near-field measurements with two wavelength regions, one in the blue and one in the yellow spectral range. This data can be used for describing basic effects such as color-over-angle shifts encountered in many LED packages. However, the small number of only two near field measurements limits the simulation possibilities of these data.

More sophisticated LED – based systems require more detailed data in a simulation. An example is miniaturization where the size of the LED light source is comparatively large on the scale of the complete optical system.

State of the art raydata can be refined to meet the demands of such simulations. In a measurement, radiance images of the light source, taken with various bandpass filters, are combined with spectroradiometer data. This spectral information can be used to apply a scaling factor to the individual images and correct for effects caused by non-ideal optical bandpass filters.
The spectral information can also be used to divide the individual wavelength bands into smaller intervals, thereby generating spectral raydata limited only by the wavelength resolution of the spectroradiometer. These raydata can then be used to calculate color rendering indices (CRIs) in a simulation, a task that could only insufficiently be addressed by raydata containing a small number of wavelengths.

Introduction

Optics simulation plays a crucial role in designing optical systems. Practically all systems today undergo some simulation and evaluation process before manufacturing. This involves choosing a suitable light source and designing the optical elements that produce the desired light distribution. It also involves using measurement technology that can evaluate the characteristics of the light source as well as of the complete system.

The goal in optics simulation is modeling the system as realistically as possible. The data needed include the characteristics of the passive materials such as reflectivities and refractivities as well as the characteristics of the light source(s). A light source is characterized by a set of "rays", which, as an ensemble, fully describes the optical properties of the light source. One ray is associated with a number of physical quantities. It contains a set of coordinates in space where it originates and a direction. It is usually also associated with a radiant or luminous flux value.

Using this information can be sufficient to model a large number of systems.
For a complete model of such a light source, each ray needs to be associated with a wavelength and the ensemble of rays in a rayset needs to represent the spectrum of the light source. Based on such a rayset, refraction and dispersion effects can accurately be simulated. Also, the spectrum of the desired light distribution of the system can be evaluated and integrated values such as color coordinates or color rendering indices (CRIs) can be deduced from the spectrum.

As an example, consider a typical white light LED package consisting of LED chips of one or more colors that are combined with a luminescent coating: A part of the light of a blue LED chip is converted into higher wavelength regions by the coating and e.g. red LED chips can be used to tune the color temperature and the CRIs of the emitted spectrum of the package (see Figures below for typical spectra).

The shape of the spectrum of such a package usually depends on the observation angle. The ratio of the blue vs. the read peak

Figure 1: **Goniometric measurement setup with radiance camera and spectroradiometer. Sample LED (inset) mounted at the center of the setup (marked by the arrow)**

varies for different observation angles. Also, the spectrum depends on the point of origin on the light source and varies with the proximity to, e.g., a blue or red chip. These characteristics need to be accounted for in the data.

Today, the spectral characteristics of a light source are present in raysets to a still somewhat limited degree of detail. A common strategy is to measure a light source using two different spectral filters, one in the blue and one in the yellow, and produce a rayset containing two representative wavelengths. While this might be sufficient to model a certain degree of dispersion and account for an angular dependence of the spectrum of the source, it is insufficient to model colorimetric parameters of the light distribution. Another strategy is to include tristimulus values X, Y, Z with each ray. This permits simulating color coordinates, but cannot be used to simulate dispersion effects in the system or parameters that need to be derived from a spectrum like CRIs.

Simulations today usually suffer from a lack of comprehensive data that fully characterize the spectral emission properties of a light source. This paper intends to present an instrument and measurements that can extend the current state of the art of generating spectral raydata. As an example, a multi-chip white LED is used in a system that combines a TIR element and a condenser plate for color mixing. Colorimetric parameters of the system are simulated and compared to measurements of the actual system.

Measurements and Simulation

The LED sample used for the measurements and the simulations is depicted as an inset in figure 1. The photograph shows the LED package with its luminescent globe top and the connecting wires for 4 LED chips, one red and three blue ones. For the measurement, the LED is mounted on the goniometric measurement setup in figure 1 (see arrow).

The geometric location of the chips on the package is shown in figure 2. It shows radiance images that are taken with different bandpass filters. The image on the left shows an exposure taken with a blue filter that illustrates the location of the three blue chips. The image in the middle is taken with a red filter. It shows the location of the red chip as well as a radiance part emanating from the globe top. The image on the right shows the package imaged with photopic sensitivity (V(λ) filter). It contains contributions from the whole emission spectrum of the package.

Figure 3 shows the spectrum of the package for different emission angles. When viewing the package from the top (angle = 0°), the red peak of the spectrum exceeds the blue peak. As the viewing angle increases, the spectrum changes its shape to the extent that the blue peak exceeds the red peak when viewed from the side where the blue LEDs are located.

These two characteristics of the emission of such an LED package need to be accounted for in the data used for the simulation: The changing in shape of the emission

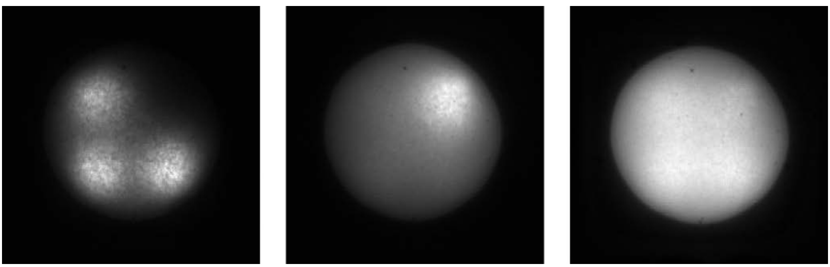

Figure 2: Radiance images of the LED package taken with blue (left), red (middle), and V(λ) filter (right)

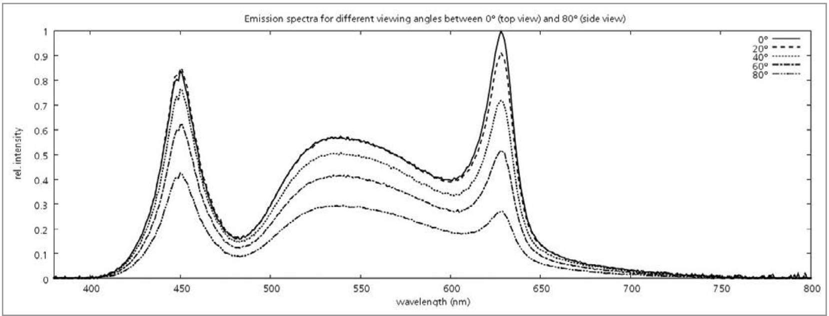

Figure 3: Emission spectra of the LED package for different viewing angles

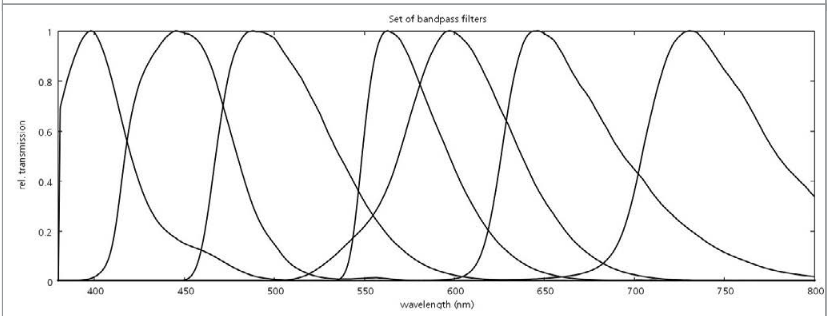

Figure 4: Set of bandpass filters for raydata generation

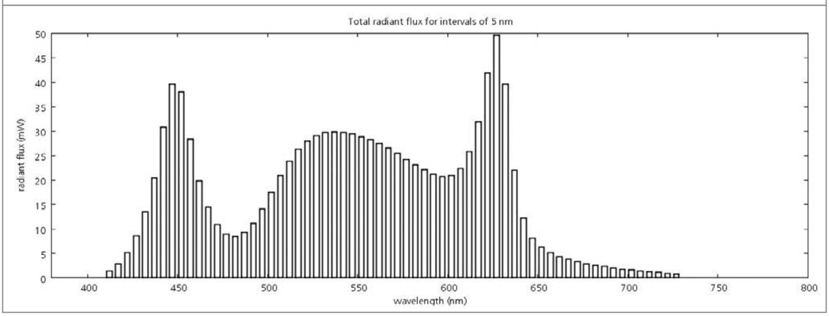

Figure 5: Total radiant flux for intervals of 5 nm

spectrum needs to be resolved for varying geometric points of origin on the LED package as well as for varying observation angles. To this end, luminance images of the sample are taken with a set of bandpass filters that are shown in figure 4. The figure shows the normalized transmission curves of the filters, which are approximately equally spaced over the emission range of the sample. For each filter, the radiance images are taken to generate an individual raydata set for the emission range of the filter. The emission ranges are separated where the curves of the filter transmission cross.

The set of bandpass filters is chosen as a compromise between a sufficiently large spectral resolution and a sufficiently large transmission, which affects the exposure time of the camera, and, hence, the total time for a measurement. Depending on the particular simulation task, it is also conceivable to generate data with a different set of filters. The set used for the measurements presented here contains the tristimulus filters X, Y, Z as a subset and complements it by an additional 5 bandpass filters.

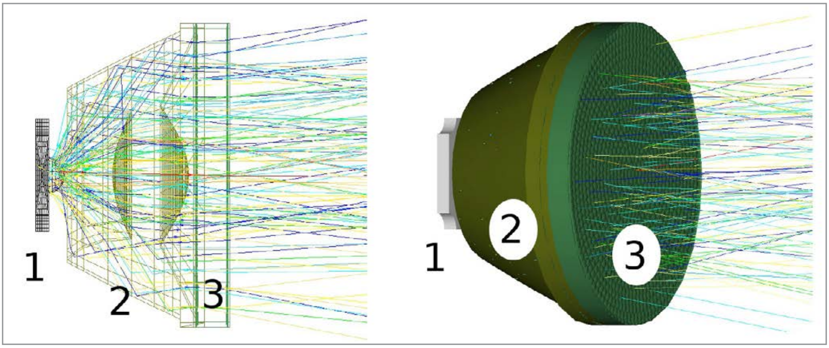

Figure 6: Optical system consisting of LED package (1), collimator optics (2), and condenser optics (3)

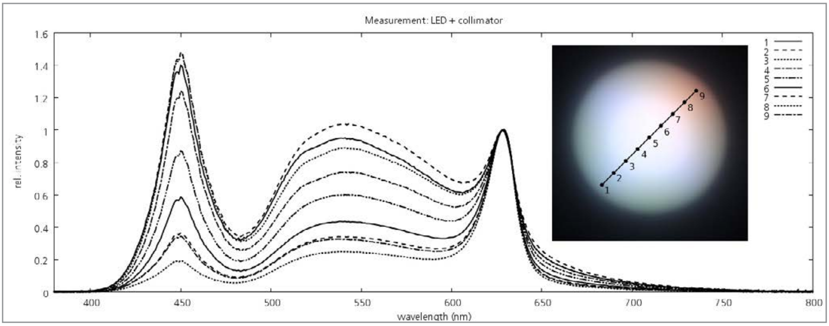

Figure 7: Measured spectra of LED package and collimator. Inset: Photo of the light distribution on the screen. Numbers indicate the measurement positions

For a complete simulation of the sample, the emission spectrum of the sample is recorded with a spectroradiometer that is mounted on a goniometric setup. The spectroradiometer data is integrated for intervals of widths of 5 nm and then summed up for all observation points on a hemisphere above the sample. This yields the total radiant flux of the sample in steps of 5 nm. Figure 5 shows a plot of these total radiant flux intervals. For a more detailed description of the measurement setup see [han12].

The interval width of 5 nm is chosen based on recommendations by various standards: A maximum interval width of 10 nm is required by [din6169]. [cie13] recommends a spectral interval of at most 5 nm.

Figure 6 shows drawings of the optical system that is modeled using these data. It consists of the LED package, a collimating optics using a lens combined with total internal reflection, and a condenser optics. The purpose of the system is to produce a uniform illumination distribution at the screen and ensure that the color coordinate remains constant throughout the screen. In the simulation, the screen is set at a distance of 1 m from the LED package.

Figure 7 shows a measurement of the actual system without the condenser optics. The collimator produces a light distribution at the screen that reflects the non-uniform distribution of the LED chips in the package. The inset in Figure 7 shows a photograph of the screen at a distance of 1 m from the LED package. The points 1 – 9 mark the spots where a spectrum is recorded. The distance between two neighboring dots is 5 cm. These measurement points are also used in figures 8 - 11. A big part of the screen is dominated by the light emitted by the blue diodes whereas a smaller part of the screen (upper right) is illuminated predominantly by

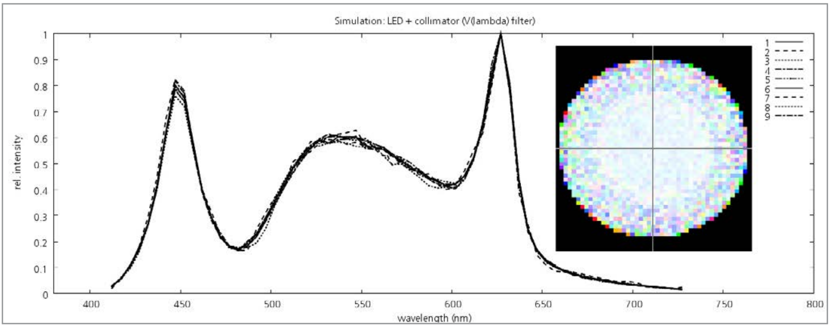

Figure 8: **Simulated spectra of LED package and collimator based on photopic raydata (V(λ)). Inset: Simulated light distribution on the screen**

the red diode. The spectra are normalized to the height of the red peak to show how the blue / red ratio decreases as we go from the blue to the red region on the screen.

This setup is modeled using two different sets of data of varying detail. Each set is based on 64 individual raysets that are composed in the following way:
For each of the 5 nm intervals shown in figure 5, we take the rayset that was generated using the filter that contains this interval and assign to it the integrated radiant flux value shown in figure 5.

In the first set, we use raydata that only relies on luminance images taken with photopic sensitivity (V(λ) filter). These data are commonly available for an LED package. This raydata set is complemented by the spectrum data shown in figure 5 to simulate the distribution on the screen. The simulation results are shown in figure 8. Since a raydata set that is based on a V(λ) filter does not geometrically resolve the origins of the differently colored LED chips, it cannot reproduce the variation within the spectrum across the screen and the normalized spectra are all identical in shape. The inset of figure 8 shows the light distribution as simulated on the screen. Slight non-uniformities in the image are due to different statistics; in the model more rays are used at the center of the image.

It has been common practice to improve the situation by supplying two raydata sets for an LED package, one for the blue and one for the yellow spectral region.
Two wavelength bands, however, still significantly limit the possibility of simulating a spectrum after an optical system.

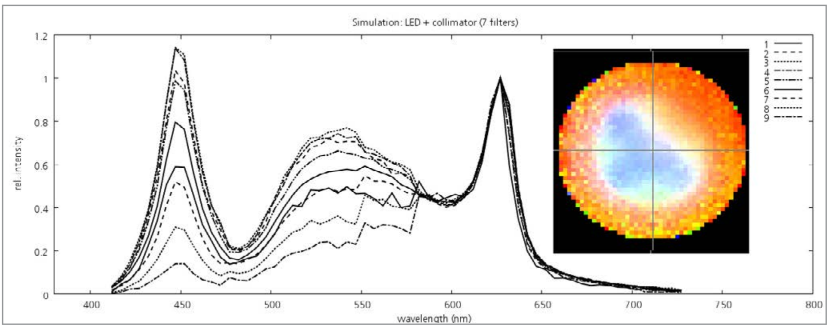

Figure 9: **Simulated spectra of LED package and collimator based on raydata generated with 7 bandpass filters. Inset: Simulated light distribution on the screen**

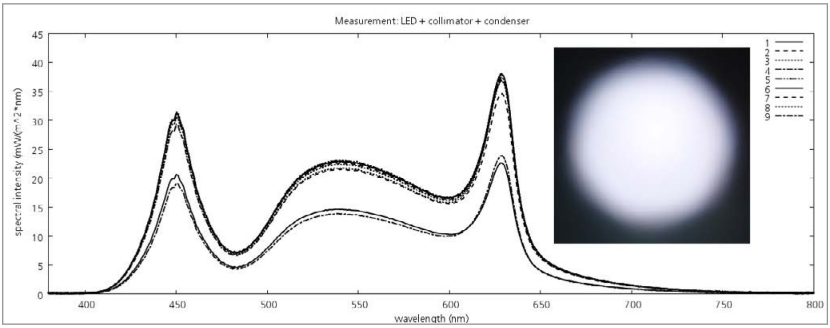

Figure 10: **Measured spectra of LED package, collimator, and condenser. Inset: Photo of the light distribution on the screen**

The second simulation is based on seven raydata sets that are taken with the filters shown in figure 4. It also uses the spectral data shown in figure 5. The simulation results are shown in figure 9. The simulated spectra are again normalized to the red peak.
In contrast to the simulation that only relied on the V(λ) filter, this time the spectral variation across the screen is accurately reproduced by the simulation.

In the next step, the system is extended by the condenser optics. The simulated results are again compared to a measurement. Figure 10 shows the measurement of the complete system of LED package, collimator, and condenser. The shapes of the spectra as well as the integrals over the spectra, which are a measure of the illuminance, remain identical across the screen.
Only at the edges of the light distribution (points 1 and 9), the spectra deviate from their uniform distribution. This scenario is accurately reproduced by the simulation, which is shown in figure 11.

The spectra which are produced by the simulation can now be used to calculate colorimetric information such as color coordinates or color rendering indices. As an example, consider the setup with the LED package and the collimator. The simulation with just the V(λ) filter cannot reproduce variations of the distribution on the screen and assigns a color temperature of 4800 K to the complete region. In the simulation with the seven bandpass filters, the variation of the colorimetric parameters is reflected in the data. Figure 12 shows the measurement positions across the screen in a color chart. Color temperatures range between 2400 K and 5900 K with the corresponding color

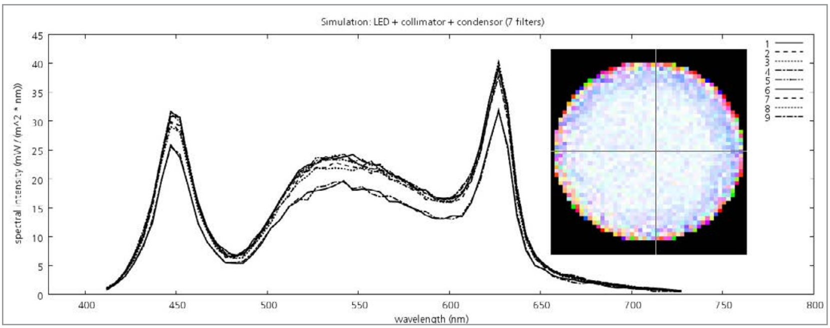

Figure 11: **Simulated spectra of LED package, collimator, and condenser based on raydata generated with 7 bandpass filters. Inset: Simulated light distribution on the screen**

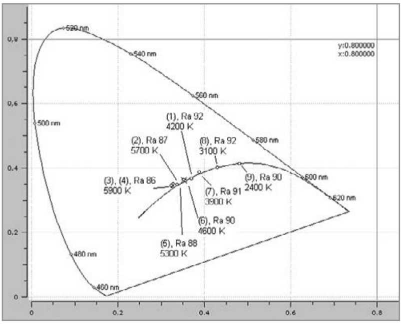

Figure 12: CRIs and color temperatures of the simulated spectra of Figure 9 displayed on a color chart

coordinates being close to the Planck curve. CRIs Ra vary between 92 and 86 with the one from the V(λ) simulation reaching a value of 89. These values can then be used in further application design if necessary.

In the simulations shown here, the raydata is scaled by an integrated spectrum over the whole hemisphere. This leads to results that well reflect the measurements done with the actual setup as long as the simulation is based on raydata measured with a large number of filters. The quality of the raydata can be further improved if the individual radiance images are scaled with the angular dependent spectrum before the raydata is generated.

One might also try to separate the blue and luminescent part of the spectrum from the red part by running two measurements, one where only the blue LEDs are turned on and one where only the red LED is powered. Such a strategy, however, is problematic in a number of ways: For a lot of LED packages, the chips cannot be individually powered. In any case, the operator needs special knowledge about the system to individually address the chips. But most of all, it is important to perform the measurement under the actual operating conditions in the application. Therefore, a measurement is needed where the contributions of the different emitters can be separated by optical filters.

Conclusion

The technique of using a larger number of raydata sets corresponding to different filters and combining these with a spectrum of the light source allows simulating the spectrum of a desired light distribution. It significantly enlarges the level of detail achievable in a simulation if compared to simulations based on raydata generated with two filters (blue / yellow) or based on tristimulus values. The strength of this technique is simulating light sources where the emitted spectrum strongly depends on the geometric point of emission on the source and where the shape of the spectrum can vary with the emission angle.

These conditions are usually present in white LED packages or packages that consist of multiple LED chips, maybe even of different color. For these cases, spectrally resolved raydata is needed to fully simulate the light distribution. Even if the same type of LED is used, their emission spectra might vary due to variations in manufacturing. For these cases, the LEDs are typically sorted into bins and the different characteristics of each bin can be modeled by using raydata specific for each of the bins. For all of these cases, color coordinates or color rendering indices can be deducted from the simulated spectra, thereby opening up the simulation possibilities to colorimetric parameters in complex LED systems found in many applications today.

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