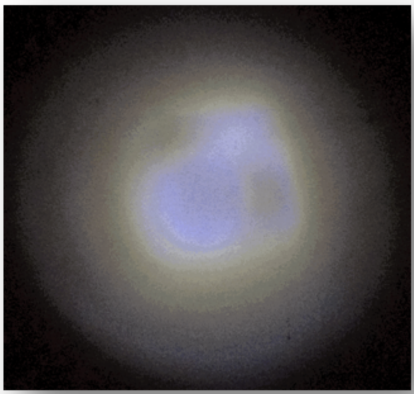
Color Modeling in Solid-State Lighting

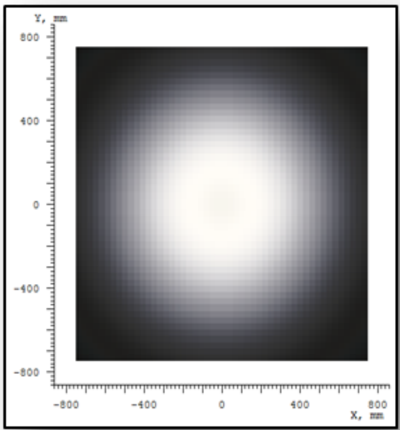
Thomas Davenport, Systems Engineer, Optical Solutions Group at Synopsys (www.synopsys.com)

Often with traditional, non-LED sources (e.g., incandescent, fluorescent tubes, or CFL) the source color is not the largest design challenge faced. With these sources, you can often use a single wavelength for designing the luminaire, perhaps evaluating it at the end of the process using a single, full-spectral distribution, and the design will meet specifications and please customers. The designer can often assume the manufacturer has provided an angularly and spatially color-homogenous source to design with. In other words, the spatial and angular distributions of the luminous radiation are important, but you don't have to worry that the color might be different over those distributions.

The same was once true for LEDs when they were constrained mostly to monochromatic, specialty lamps. Designers possibly had to worry about smearing out the electrode structure in the output distribution, but the color was more or less homogenous. Now that phosphor LEDs are being used for general illumination, however, a higher level of LED model fidelity is often required for luminaire design. For instance, consider the beam distribution of an LED flashlight shown in the top image below. The blue light from the chip is much more pronounced in the center of the distribution, whereas the outside of the distribution appears yellow, since most of that light is coming from the phosphor alone. This is a case where the designer could have benefited from modeling the color distribution and changing the optical design to help mix the color. Contrast that with the true color model image on the bottom, where the designer incorporated color information into the LED design.



Beam pattern from a phosphor-LED flashlight



Modeled true color image of a flashlight distribution

There are lots of possibilities when modeling LED color. For instance, one method for better color model fidelity now gaining traction with vendors* is to create two separate ray file sources to represent the blue (chip) and yellow (phosphor) portions of the light from an LED source. Each one of the sources has a separate spectrum. This definitely helps, but it limits each of the ray sets to have the same spectrum for all rays in the ray set, and so does not capture the full possible non-uniformity of the color. It is also possible to use tristimulus filters with separate detectors to do a simultaneous goniometric scan of a given source, and then provide those tristimulus values for each ray in a ray file. This is helpful, but does not provide enough information to account for the dispersion directly in a model. In other words, the wavelength or range of wavelengths for a given ray is necessary information to calculate refraction angle, Fresnel losses, etc. at optical surface intersections, and the tristimulus values do not provide enough information to calculate those wavelengths directly. The best ray file solution (from a designer’s point of view) would be one in which each ray has its own wavelength. This would be very difficult to measure, however.

A potentially higher-fidelity approach than using ray files is to model the LED structure directly. The chip can be modeled with a volume emitter inside a high-index volume (representing the P-N junction where the light radiates from), and then the phosphor can be modeled directly. To model the phosphor correctly, one needs to characterize items such as the phosphor's absorption spectrum, its quantum yield, the emission spectra, the particle number density of the phosphor particles (using a Mie model or otherwise), and the intensity distribution of unconverted radiation. This type of model is now available in some commercial optical modeling software packages.**

Moving forward, with the increasing fidelity of color modeling, designers can take advantage of these software tools to create a more pleasingly lit environment for people to use, free of distraction caused by poor lighting designs. It is especially important to design LED luminaires with care, since they are typically used much longer (and cost more) than the sources they are replacing. At any rate, we should see fewer beam patterns like the one shown in the image above left, and more like the one above right.

*See, for instance, the optical simulation data provided by OSRAM at http://catalog.osram-os.com/applications/applications.do?folderId=0&act=showBookmark&favOid=0000000200034c80025d0023 [1]

**See, for instance, the white paper, "Modeling Phosphors in LightTools," http://www.opticalres.com/white%20papers/ModelingPhosphorsInLightTools.pdf [2]

Links:
[1] http://catalog.osram-os.com/applications/applications.do?folderId=0&act=showBookmark&favOid=0000000200034c80025d0023
[2] http://www.opticalres.com/white%20papers/ModelingPhosphorsInLightTools.pdf