BY **MIKE WOOD**

How do white LEDs work?

FIRSTLY, WITH THE MERGER OF ESTA AND PLASA, I'd like to welcome the many new *Protocol* readers we have in Europe. Secondly, I'd like to let you know, if my articles are of interest to you, and you would like to take a look at any prior columns, you can find them on my website at www.mikewoodconsulting.com and in the *Protocol* archives through www.plasa.org/welcome/.

Last year I wrote a series of three columns on the basic principles and operating parameters of LEDs (Light Emitting Diodes), particularly as applied to entertainment lighting. I briefly mentioned white LEDs in that series but in no great detail. At that time, it didn't seem that white LEDs would be of much general interest to entertainment lighting. Perhaps they would be for a few specialized luminaires for TV and film but not for general use; after all we want colored light, so why would we use white LEDs and colored filters when we can have all those colors natively? How wrong I was! What I didn't foresee was how quickly white LEDs would pull away in efficacy and brightness from the monochromatic colored products. Today it's typical that a white LED will be at least two to three times as efficacious as a mix of colored LEDs in producing white light. This means that with pastel colors, even with a piece of gel for subtractive color in front of those white LEDs, they are likely still more efficacious than an additive mix of colored LEDs. In hindsight, I shouldn't have been surprised. Nobody but us cares about high intensity colored light, nobody but us cares about subtlety of color mixing, and nobody but us tries to make a color of light called chocolate! Well, perhaps I exaggerate slightly, but primarily, as far as the rest of the world is concerned, it's white light, and only white light, that matters. With entertainment lighting representing a minuscule percentage of the worldwide lighting market, it's inevitable that the major lighting companies, who stock the technology tables we scrape the crumbs from, are investing heavily in developing better and better white LEDs, while colors lag behind. Traffic signals are bright enough so why worry?

Fortunately, we're an inventive industry, not slow to take advantage of this government encouraged and funded spurt. High efficacy, extremely powerful, white LEDs are starting to appear in many products, either as light sources for luminaires using gel or dichroics for color, or as lumen boosters for units with additive color mixing. Thus, we need to understand the current white LED technology better and how its strengths and weaknesses might affect us. This article is intended to be a basic introduction to that technology.

You can make white LEDs by combining multiple differently colored LED dies in a single package, but that is complicated, inefficient, and the color consistency is not good. Therefore, the method we are concerned with here, which has become by far the most common, uses a single monochrome LED emitter, usually an InGaN blue die, and phosphors. The technique involves coating a blue LED (commonly called the pump, as it pumps light into the phosphor) with a phosphor, or mix of phosphors. The phosphor produces a broad-band yellow light that combines with the blue to create a spectrum we perceive as white light. The phosphor layer is semi-transparent so that some of the blue light passes through unchanged while some impinges on the phosphor particles. The high energy blue light photons are absorbed by atoms in the phosphor that are boosted into an excited state by the energy input. This high energy state is unstable and the phosphor atoms immediately drop back down and emit the energy again as another photon of light. However, the emitted photons typically have less energy than the absorbed ones and thus appear as a longer wavelength, or red-shifted, color. This wavelength change between the absorbed and emitted photons is commonly referred to as the Stokes shift of the phosphor material. It is this shift and energy change that transforms shorter (bluer) wavelengths into longer (redder) ones.

The name phosphor for these materials is perhaps a misleading one, as light is not emitted through phosphorescence but, instead, through fluorescence and scintillation. They are complex doped salts closely related to the materials used as the light emitting coating inside fluorescent tubes. They degrade over time and with heat, typically getting yellower and dimmer with age. Just like an old fluorescent tube.

Practical white LEDs first appeared in the nineties when Nichia used their newly developed blue LEDs as pumps for Stokes shifted phosphor whites. These were low-power devices and are illustrated schematically in **Figure 1**.

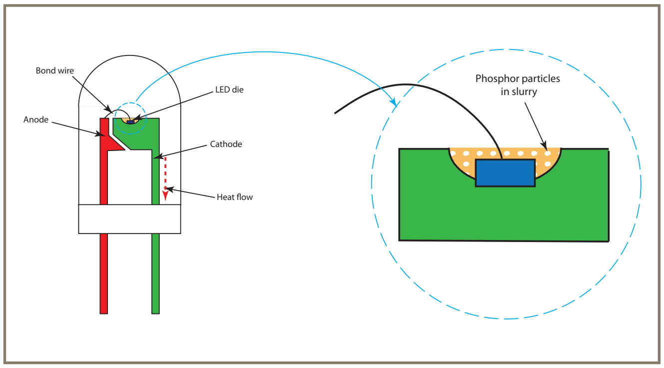

Figure 1 – Low powered white LED

The structure of the LED itself is the same as those we discussed in early articles in this series, so I won't repeat that discussion. The difference here is that the LED die is coated with a transparent epoxy resin containing particles of phosphor materials in a random slurry. The size and spacing of the phosphor particles control how much blue light will escape directly and how much will impinge on the phosphor. The denser the concentration of phosphor particles, the yellower the resultant light.

Figure 2 shows a more recent high powered white LED using essentially the same method.

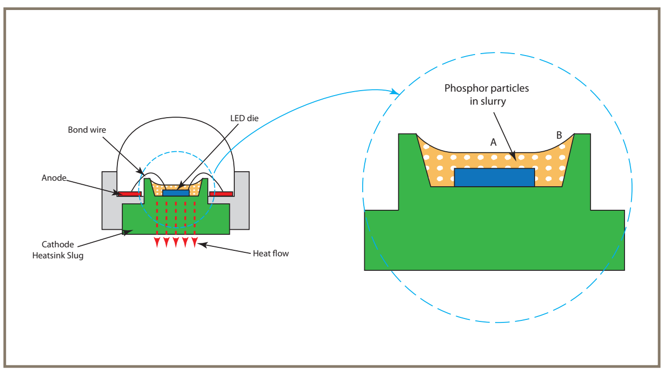

Figure 2 – High powered white LED

Again, randomly distributed yellow phosphor particles are held in epoxy or silicone slurry surrounding the blue LED die pump. The phosphor slurry is often contained within a reflective bowl that forms part of the light extraction mechanism for the package.

But what does this light that's concocted from two components look like? **Figure 3** shows measurements I took of the output spectrum of a typical cool white LED as compared with the white light spectra from a 3200 K incandescent lamp and 5600 K daylight.

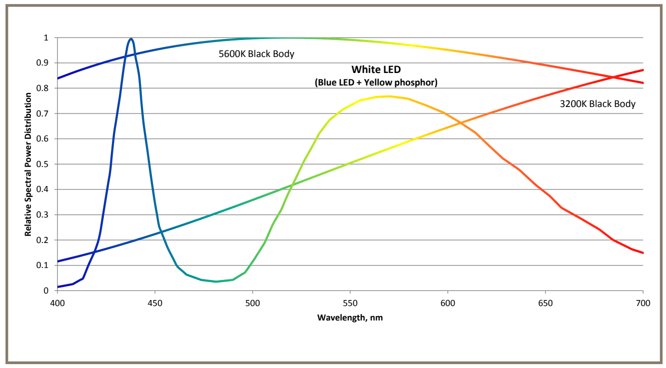

Figure 3 – White LED spectrum

You can clearly see the narrow blue spike centered at 440 nm from the blue pump LED die and the much broader peak from the phosphor mix centered on a 570 nm yellow. Although the resultant light appears white to the human eye, when you compare it with the incandescent and daylight spectra in **Figure 3**, it is clearly lacking in cyan and green energy and has almost no red at all. These spectral gaps result in light with relatively poor color rendering. Such cool white LEDs look fine on a white surface or as a task light, but can make colored surfaces or costumes look very strange. For warm white LEDs another, longer wavelength, phosphor with a wider Stokes shift is added into the mix to enhance the red output. This improves the color rendering, but is detrimental to the output, as these red phosphors with their extended Stokes shift are significantly less efficient. The good news for entertainment users is that it's not just us that dislike the poor color rendering of white LEDs, they look wrong in our houses as well, so a huge amount of research is going into improved phosphors with better outputs and broader coverage to fill the gaps in the spectrum.

Color rendering isn't the only concern with this phosphor technique. Take another look at **Figure 2** and you can see that the phosphor layer is much thicker around the edges (point B) than it is in the center of the die (point A), phosphor particles also tend to cluster around the edges of the die due to slumping during manufacture. In addition light going through the phosphor layer at an angle travels through more phosphor than a light beam that exits straight out. The result of all these inconsistencies is a light beam with a bluish-white center and a yellow ring around the outside. I'm sure you're very familiar with white LEDs that exhibit this problem! This slurry problem points up a very real manufacturing concern with all phosphor techniques. The proportions of blue and yellow light in the output beam, and thus the color of white light produced, are critically dependent on the accurate and consistent thickness of the phosphor coating on the die. Thick areas will be too yellow while thin areas will be too blue. Controlling this with sufficient accuracy with a simple slurry of phosphor particles is a quality-control nightmare and leads to the broad range of whites that you still see in many LED products. The cheaper white LEDs, such as those used in many flashlights, are particularly prone to this.

A number of methods are in use to try to alleviate the problem and produce a reliable coating thickness for the phosphor. This is a rapidly developing area, with big gains for the winners, so it is one of the busiest areas for patents and patent attorneys! **Figure 4**, for example, shows a conformal coating technique primarily developed by Philips Lumileds, but now used by many manufacturers, which produces very consistent coating thicknesses around the entire die. You still get some path length and angular differences near the edges of the die but, overall, this thin, well-controlled, layer significantly reduces yellow ring problems and ensures a much more homogeneous and consistent color across the beam.

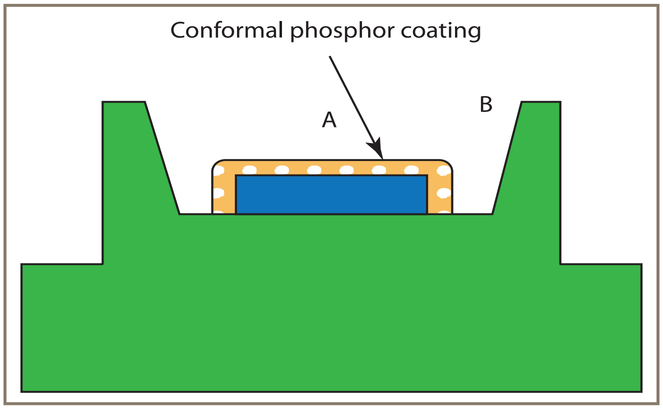

Figure 4 – Conformal coating

A more recent technique with similar goals is to remove the coating problem from the LED die manufacture and instead separately coat a piece of transparent ceramic which is bonded on to the die after manufacture. An advantage of this method is that the ceramic can be phosphor coated in large sheets with accurate process control and then cut up into the tiny pieces needed after coating. This gives improvements in manufacturing yields, reductions in production costs, and a much more durable result. **Figure 5** shows the concept.

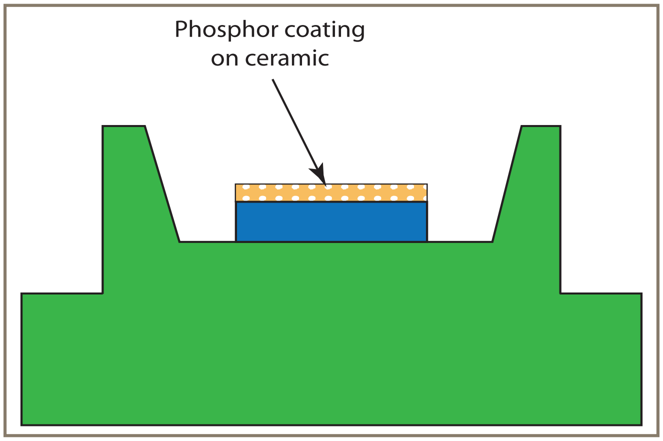

Figure 5 – Coated ceramic

All these direct contact phosphor methods suffer from another couple of problems which affect performance. The phosphor layer has a tangible thickness with particles suspended at different depths within it. Any of these particles that are hit by a blue photon will then radiate yellow light in all directions, not just upwards. Thus, on average, about half the yellow light ends up going in the right direction to be useful, but the other half goes straight back down towards the LED die and is wasted as heat. In addition a percentage of the blue light is also reflected back, without being absorbed at all, and also ends up as waste heat. **Figure 6** gives an idea about what's going on inside the phosphor layer. As much as 60% of the light never makes it out of the sandwich.

> **“As much as 60% of the light never makes it out of the sandwich.”**

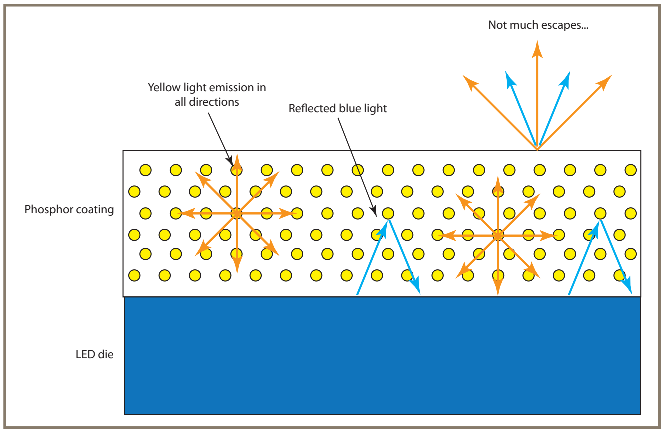

Figure 6 – Reflection losses

In order to try and minimize these losses, various techniques are being developed for recycling the reflected and wasted light. One that is seeing increasing use is the use of remote phosphors where the phosphor layer is removed from the die and reflective coatings are used to recycle reflected light before it gets reabsorbed in the die. **Figure 7** illustrates the basics; the blue LED pump is sitting in a bowl of light reflective material and is separated from the phosphor layer leaving an air gap between the two. Both blue, reflected, light and yellow, emitted, light that is heading the wrong direction now have a chance of bouncing off the reflective bowl and heading off in the right direction. Light that reflects straight back into the die will still be lost, but there is a significant overall gain in efficiency. The further away the phosphor is placed from the LED, then the greater the advantages, both from improved light recycling and from reduced temperature of the phosphor material, thus slowing down its degradation. Remote phosphor techniques are still in the early days of development but are expected to produce significant gains in package efficiencies over the next few years.

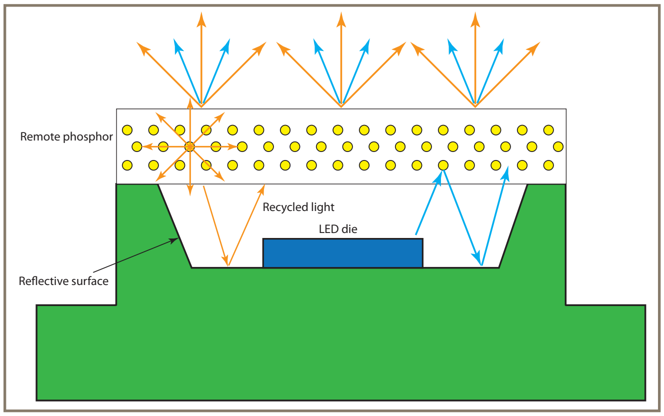

Figure 7 – Remote phosphor

The new Philips Endura LED domestic light bulb illustrated in **Figure 8** is an interesting example of the use of remote phosphor. In this lamp the internal blue LED is completely bare and the yellow phosphor is instead coated on the inside of the surrounding lamp envelope. The lamp may look yellow when it's turned off, but produces a warm white light when running and that yellow is combined with the blue from the LED pump. *Note that it's not a yellow filter, it's a yellow phosphor. The fact that, in this case, the phosphor looks yellow when unexcited is no indication of the color of light it will produce when energized.*

> **"If there were any lingering doubts that LEDs are a truly disruptive technology then that prediction should dispel them . . ."**

The rate of progress with white LEDs is absolutely staggering. In the few weeks between me writing this article and you reading it, chances are that some new development will have come along that makes my comments out of date. The US Department of Energy data currently predicts that commercial white LEDs will be achieving efficacies exceeding 200 lm/W within the next 10 years. Just to put that in perspective, current light sources range from 30 lm/W for the best incandescent lamp to around 100 lm/W for HID sources. Most telling of all is that the absolute maximum efficacy possible for white light at 5600 K when every electron flowing into the light source from the power supply ends up as one photon coming out as light is around 250 lm/W. With that as our metric, the predicted LED efficacy of 200 lm/W represents a staggering 80% overall efficiency. If there were any lingering doubts that LEDs are a truly disruptive technology then that prediction should dispel them. The question then is not if solid state light sources will dominate commercial lighting, but exactly when.

PHOTO COURTESY ROYAL PHILIPS ELECTRONICS

Figure 8 – Philips remote phosphor lamp

My fear, as someone passionate about theatre and entertainment lighting, is that we will allow efficiency to push quality and creativity to the side. We accept lower quality audio with MP3 compressed data every day—the convenience outweighs the quality for most people. Will the same happen with lighting? Will we accept lower quality white light and poor color rendering and skin tones for the sake of efficacy? I hope not. ■

Mike Wood runs Mike Wood Consulting LLC which provides consulting support to companies within the entertainment industry on product design, technology strategy, R&D, standards, and Intellectual Property. A 30-year veteran of the entertainment technology industry, Mike is the current Chair of the PLASA Governing Body, and Treasurer of the PLASA North American Regional Board. Mike can be reached at mike@mikewoodconsulting.com.