BY MIKE WOOD

How do LEDs work? – Slice of lime with that?

THIS IS, I THINK, PART 6 of an occasional series dealing with LED development, the last one being in the *Protocol* Winter 2013 issue covering chip-on-board LEDs. It continues to amaze me how quickly progress is being made in the LED world and how you can blink and miss something. It was not quite a year ago in this column, in the Summer 2014 issue, that I was talking about the possible maximum efficacy of various LED types and mixes. We talked about the maximum possible efficacy of a light source with the spectrum of an incandescent lamp being 153 lm/W, and that for daylight being around 250 lm/W.

> "How wrong could I be?"

The question at the time was, if that's true, how is Cree making an LED which they advertise as 300 lm/W?

That article then went on to discuss the theoretical improvements that could be made to maximum efficacy by using discontinuous spectra rather than the continuous ones we are used to with traditional light sources.

For example, what has now become the norm for white LED packages is a blue pump LED with a broad yellow phosphor as shown in **Figure 1**.

The yellow peak has been chosen to be close to the peak in the photopic curve, giving highest output at the green-yellow color where the human eye is most sensitive with less wasted energy in the areas where we don't see well. By designing to the curve like this, we get a maximum possible efficacy, if everything else were perfect, of 336 lm/W. The light still looks white, but we've beaten that 250 lm/W barrier.

By tweaking our system we can get even better results. If we hypothesize perfect individual red, green, and blue emitters in a familiar RGB layout we can get outputs with efficacies above 400 lm/W. **Figure 2** shows one example of a close to optimal result of 404 lm/W.

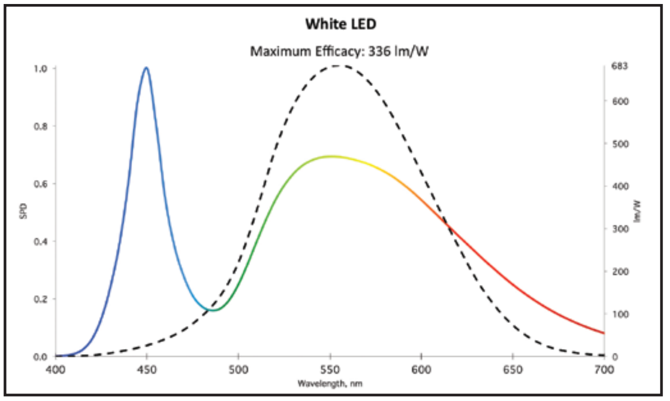

Figure 1 – White LED

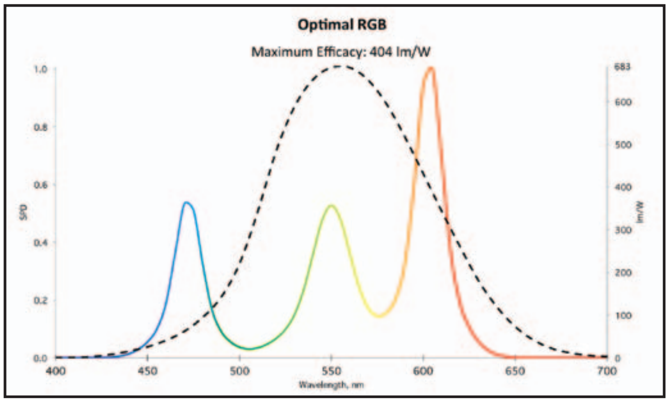

Figure 2 – Optimal RGB

The problem with both these solution, the blue LED with a yellow phosphor, and a mix of RGB, is that the color rendering of such mixes is often poor. This is particularly true of an RGB mix made as shown in **Figure 2**, where the three emitters have narrow spectra and there are large gaps of missing colors. Very little cyan, much reduced amber, and no deep reds longer than 625 nm. The end result is a very efficient light, but one that is not very pleasing to the eye. Kind of reminds you of compact fluorescents doesn't it? Great light output but horrible lighting.

My conclusion only a year ago was that we were unlikely to see very high efficacy whites without correspondingly poor color rendering in the immediate future.

How wrong could I be?

Just as I was writing that article in early 2014, Lumileds released information on a new phosphor-based LED that they were calling Lime. This was a blue pumped broad phosphor LED designed to address precisely this problem. How do we maximize efficacy and still get a light that's worth using?

Lumileds introduced this Lime LED in February 2014. (Osram has a similar product which they call Mint). Perhaps the most unusual aspect of this product is that, although Lumileds designed it for white light production, you can't use it on its own, it's green! **Figure 3** shows the SPD (Spectral Power Distribution) of a Lime LED.

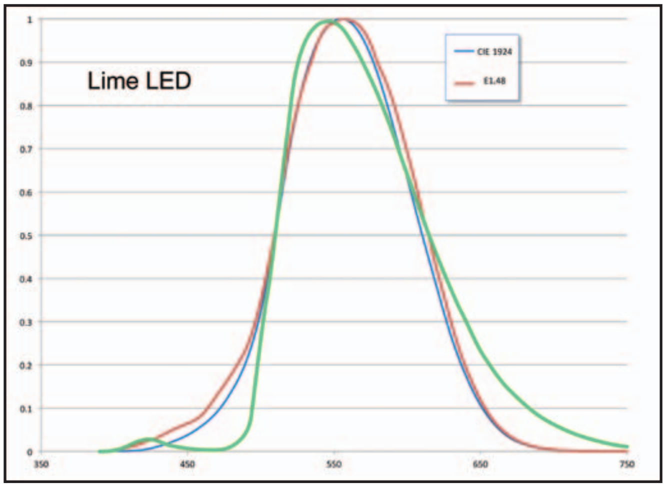

Figure 3 – Lime LED

I've shown it superimposed over the top of the photopic curve (both the old familiar CIE 1924, and the new E1.48) to show you how good a fit it is. It peaks at just over 560 nm, right about where the human eye is most sensitive, and follows the photopic curve very closely on either side. In other words, this is an LED designed to be as efficacious as it possibly can be. A perfect match to the human eye response is as good as you can get when you want to make visible light. Every part of the spectrum is used, no wasted energy. On its own the current chips are over 200 lm/W, however, as I've already mentioned, they are green. What do we do about that? Well, actually you don't need to do very much. Mix this high efficacy lime green with an amber LED or a red LED and you get a very, very, good white. High efficacy and good color rendering. Philips commented at the time of release, "Colour tuning of 2,250 - 2,950 K can be achieved with an R9 > 90, CRI > 90 and efficacy of 90 lm/W using Luxeon Z combinations. When using a similar combination of red, green, and blue LEDs to create 3,000 K white light, the CRI is close to 20. Alternatively, tuneable white light with high efficacy can be achieved from 1,800 - 6,500 K along the blackbody curve."

The Lime LED is similar to the phosphor white LEDs in that it uses a royal blue pump LED, however they allow very little of that royal blue to escape. Most of it is used to drive the mix of phosphors producing the broad green peak with just enough escaping to give the result a nice tail into the blue.

"… it's green!"

Philips' first use for the Lime LED, before they started shipping it to other customers, was in their own product, the Philips Hue Lamp. As I expect you know, Philips Hue is a Zigbee color-changing lamp system that allows you to control domestic lighting from a smart phone or tablet. When Hue first came out I had assumed that it used RGB emitters but that isn't the case. Instead, each Hue bulb has five lime-green, four red–orange, and two royal blue LEDs. **Figure 4** shows a Hue circuit board with the 11 emitters. The center and four corner emitters are the limes.

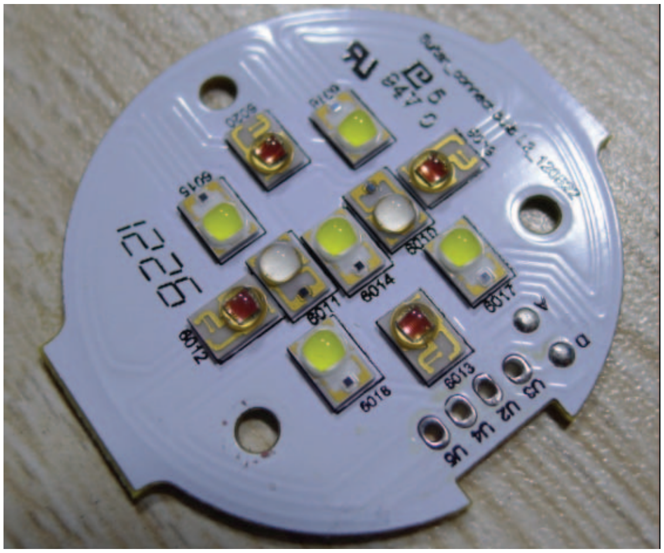

Figure 4 – Philips Hue

Now that the Lime emitters are commercially available, a number of companies in our industry are using them in their color mixing units. It seems strange that you deliberately pick a greenish white when green is the color we always seem to want to avoid, but the results are impressive. High output and high color rendering. The good quality white that we strive for in the entertainment lighting industry. If ever a LED source was to seriously challenge the quality of incandescent lighting, then the lime mixes are some of the best we have available.

The trade off with moving to these broad phosphor-based emitters, because trade off there always is, is that they cannot provide access to saturated colors. You can't make a color-mixing luminaire with solely broadband colors. If you do then you will forever be mixing pastels. Of course, that might be what you want, and, indeed, much of theatre lighting is in the pastels. However, I'm not sure we are prepared to give up on access to saturated colors just yet.

I see this as the next step in our journey. As we approach 300 lm/W the development curve is inevitably becoming less steep. When the absolute maximum is 400 lm/W there just isn't the room for the large leaps we've seen in recent years. However, watch this space, I'm confident I'll be back here in a year's time eating my words again as I report the latest breakthrough. ■

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 35-year veteran of the entertainment technology industry, Mike is the Immediate Past Chair of the PLASA Governing Body and Co-Chair of the Technical Standards Council. Mike can be reached at mike@mikewoodconsulting.com.

An observation . . .

If you'll forgive me going off on a tangent for a moment. A year ago Lumileds was a Philips company. They had acquired it by buying out their original partners Hewlett Packard and Agilent. As I'm sure you know this is no longer the case, and 80% of Lumileds has been sold for $2.8B to an investment consortium called GO Scale which, in turn, is funded by a raft of venture capital corporations. It also looks like the rest of Philips Lighting will be similarly spun-off over the next year or so, likely through an IPO. This, yet again, brings home to me how truly disruptive the rise of LED technology has been. Philips, up until very recently a household name (in every sense of the word) in lighting is apparently exiting the field. (They might argue that they aren't completely exiting it, but it looks like that to me). Would Philips do that if they thought that lighting would remain a profitable venture for them? I don't think so. Whatever rhetoric may be used to explain the sales, Philips is a well-run, responsible company, and if they are exiting lighting, it's probably for good reasons. Perhaps as simple as they just have no idea how to migrate to a solid-state lighting future and continue to make money. This isn't being in any way derogatory towards Philips. I'm sure that all the large lamp manufacturers Osram, Ushio, et cetera are having similar doubts. How do we recover the revenue we made from selling replacement incandescent lamps with a technology that, if the life claims are to be believed, we only sell once? The math just doesn't work any more. LEDs aren't just making the buggy whips redundant; they are replacing them with a new fangled buggy whip substitute that never wears out. It's great for a few years while we sell these new LEDs, but what do we do when every socket is filled with a light source that shouldn't fail for 10 years or more?