BY **MIKE WOOD**

It's not easy being green

More about the efficiency of color LEDs

IT'S NOT EASY BEING GREEN—a phrase that, at least in my mind, is inextricably associated with an image of a green frog singing a song in a nasal voice while sitting under a tree on a sound stage at the ATV Studios in Elstree. Kermit the frog was singing the song of course and I'm sure Jim Henson had a hand in it somewhere too. Isn't it strange how it was always Kermit you watched even when they were doing an interview and Henson was in clear view next to him? The mark of a great performer I guess.

However, putting thoughts of frogs to one side, this phrase has acquired a whole new meaning in recent times and, strangely enough, has two very different but equally important meanings when applied to solid state light sources. Both meanings of the phrase impact the topic of this article—the efficiency of LEDs and the misunderstandings that are rife.

> "... performance figures for these products are sometimes hyped ..."

Let's look first at "It's not easy being green" in the sense of "It's pretty tough to make a light source that emits green light." Hiding behind this is an unfortunate and deeply frustrating aspect of current mass produced LED technology. There are two main classes of semiconductor material types used in common light emitting diodes. (In reality there are many more than two, but manufacturing costs and efficiencies drive this problem as much as physical possibilities.) Those constructed around the gallium arsenide chemistry (GaAs) are really good at producing long wave length colors such as the reds and oranges while those using indium gallium nitride (InGaN) and related families tend to be highly efficient in the short wave length blues and blue-greens. Neither is particularly good at the yellow to green range of the spectrum. In fact, although there are many LED chemistries which emit light in this region, none of them are as easy to manufacture, accurate or as efficient as those making red and blue light.

Why is this frustrating? Well, if we take a look at the standard CIE curve representing the ability of the human eye to see different colors of light we see that the eye is most sensitive to light right in that yellow-green area that LEDs are so poor at producing! (See **Figure 1** - CIE Photopic Curve)

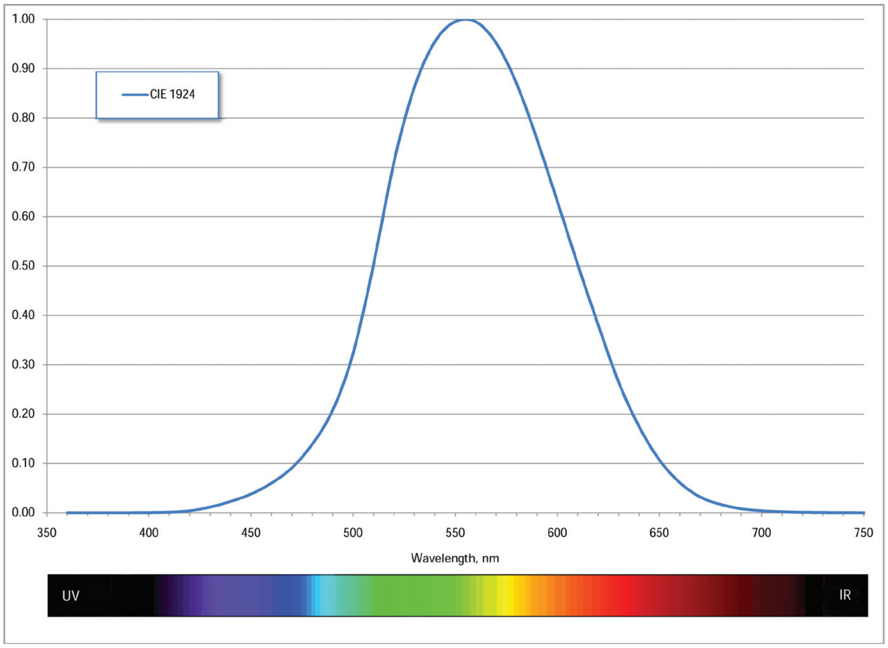

Figure 1 – CIE Photopic curve

Figure 2 is another way of showing the same thing. This represents the spectra of the seven colors of LEDs most commonly offered by LED manufacturers and shows the large gap between green and amber around 550 – 570 nm. Given that amber LEDs aren't that efficient anyway this can be a real frustration for the lighting product designer. (See **Figure 2** – Common LED spectra)

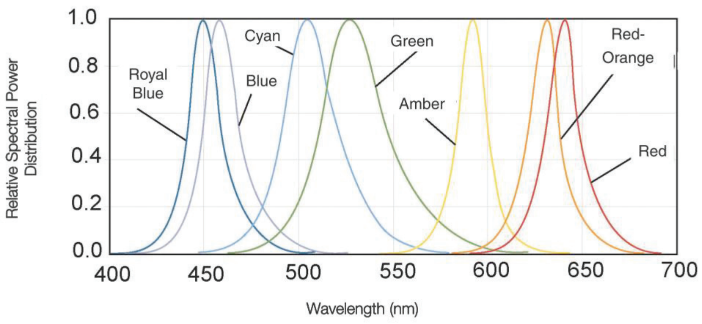

Figure 2 – Common LED spectra

As an aside, phosphor converted LEDs are just starting to appear on the commercial market which produce amber and other difficult colors using a blue LED coupled with an efficient phosphor. These show great promise as way of filling in this gap and improving overall efficiencies and color rendering.

This links nicely in with my main theme and the second meaning of the phrase where "It's not easy being green" refers to the difficulty in making energy efficient products. The natural assumption is that, if we are using an LED based product, then we must be doing a great job of energy efficiency and we can sit back and stop worrying about global warming. Often that's true and LED based products can be highly energy efficient, however they aren't always and unfortunately one of the areas where they aren't so good is slap bang where the entertainment industry wants to use them.

"Hang on a minute," you say, "surely LEDs have energy efficiencies that are many times better than incandescent lights and are bound to be more efficient!" Well—yes and no. It's certainly true that individual LED dies are highly efficient, however it doesn't automatically follow that the final output from the luminaire is equally efficient under all circumstances. It's the usable output from the luminaire and not that from the die that matters to us so we need to base all our real efficiency figures on the light produced by the luminaire related to the power supplied to that same luminaire. Largely driven by marketing needs I'm sure, the performance figures for these products are sometimes hyped with incorrect figures without a disclosure of the measurement techniques. A common problem is that a fixture datasheet may quote the efficiency levels for an individual LED whereas, within the fixture itself, depending on the quality of its design, optical and electrical losses can easily reduce that efficacy by 50% or more. There's a lot going on between that LED die and the final output so let's work through all the stages and see where the losses are and what a reasonable expectation should be.

Firstly, the LED die itself has an efficiency figure quoted by the die manufacturer and these are getting stunningly good with some colors exceeding 50 lm/W and even getting up to 70 or 80 lm/W (soon to be 100 lm/W in commercial products I'm sure). To put these figures into perspective the best theatrical incandescent lamps are around 15 - 20 lm/W while a metal halide lamp might be 70 – 80 lm/W. However these figures for LEDs are quoted with the die running at room temperature or 25°C which never happens in a real product. To take these measurements the LED manufacturers power the die with an extremely short duration pulse so it never has chance to warm up. There's nothing wrong with this technique and the LED manufacturers are very open and honest about their process and do this for very understandable reasons. They need to have a known and repeatable measurement point and this method allows them to test dies on the production line without having to attach them to a heatsink.

The rise in temperature in the real product over the quoted 25°C can have a huge impact on the output and thus the efficiency. **Figure 3** shows the change in output for a green die. If we assume our operating temperature for the die when run in a luminaire under steady state conditions is around 80°C (could be more could be less) then the output has dropped to about 92% of its rated output at 25°C – not too bad. However **Figure 4** shows what happens with amber and red dies which are much more sensitive to temperature, at the same 85°C the red die has dropped to around 60% output while the amber, by far the worst color, has dropped to around 35%! LED luminaire manufacturers are very well aware of this effect and do their best to mitigate it by keeping things cool but it's realistic to expect double digit losses in real efficiency here.

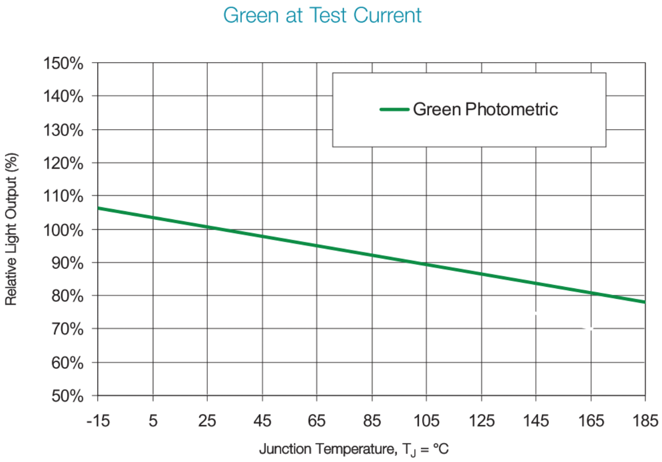

Figure 3 – Green LED output with temperature

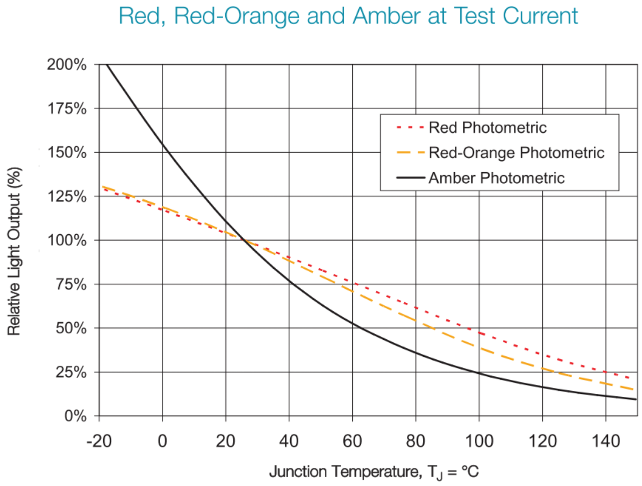

Figure 4 – Red/Amber LED output with temperature

Irrelevant but interesting aside: This effect is a real problem with the use of amber LEDs in traffic signals, their extreme temperature sensitivity means that amber LEDs tend to dim as the day gets warmer and brighten as the night cools down, which is exactly the opposite of what you want! Traffic signals should instead brighten in the daytime and dim at night to maintain balance with the ambient light. It also means that, if no adjustment were made, traffic signals would be significantly brighter in Alaska than they are in Texas.

That LED die has power supplied to it by a driver and power supply. With modern switching supplies and drivers these components can be highly efficient but again it wouldn't be unusual to see 10% - 20% losses in the electronics—it varies widely from manufacturer to manufacturer and while some are definitely better, some, sadly, are dramatically worse. Additionally you might see the use of power supplies with inadequate power factor correction creating hidden but expensive reactive power losses in the power supply chain that distort the data.

That gets us light output from the LED die but what happens next? That light is probably emitted in a Lambertian distribution pattern, which essentially means it's sent everywhere in a 180° hemisphere. The LED manufacturers (like all light source manufacturers) capture every last lumen of this in an integrating sphere to provide the data published in the specification. Although that broad spread of light can be directly usable in some luminaires most will add some kind of optic to control and direct the output. Most commonly seen are the small molded TIR (total internal reflection) lenses which constrain the output into a manageable beam. These TIR systems are highly efficient however, once again, we might expect losses of at least 10% or more. In many luminaires that's the end of the chain, however in those that use additive color mixing from multiple different colored sources, most commonly RGB, it's not uncommon to have some homogenization component—perhaps a diffractive diffuser of some kind. They work well but introduce more loss.

Add all these losses up and we get a very different answer from the 50 lm/W we started with. In reality the useful light output from a currently available RGB based LED luminaire producing white light is likely to be produced at an efficiency level of around 10 - 15 lm/W at best. Of the many color mixing LED entertainment lighting units I've tested from a wide range of manufacturers the best overall efficiency from power cord to wall in white light was 13.5 lm/W while the worst was under 7 lm/W with the average falling around 9 lm/W.

Before LED manufacturers get up in arms about this please note the caveats:

- These figures are for entertainment lighting luminaires which contain optical systems offering at least some beam control. These aren't 180° output floods with no dimming or control—these fixtures have controllable, usable light output and we pay a price for that.
- I'm considering cases where an RGB color mixing luminaire is used to produce white light which is clearly not the best use for such a unit. I would expect a luminaire with just white LEDs to give better results. White LEDs are nowhere near as sensitive to temperature as red or amber for example and they don't need the same levels of homogenization.

- I'm only considering energy consumption here, not total cost of ownership.

So using a color mixing LED based luminaire to produce white light probably isn't green at all, in fact with current technology they are often less efficient than incandescent lamp units and hugely less efficient than discharge lamps. Is that surprising? It shouldn't be as the major manufacturers make this very clear in their literature. The problem is that nobody reads the manual and we tend to associate LEDs with energy savings automatically whether it's true or not.

However this tale has a flip side. Use those same luminaires to produce colored light and it's a whole different story, particularly when we get to the saturated tones. This is where LED based units do really well and outperform their incandescent cousins. If we take that same RGB LED unit that gave us 10 lm/W in white and, instead, make a saturated red then the efficiency changes very little—it may still provide 10 lm/W. In fact we might be reducing the power consumption of the blue and green emitters almost to zero in order to mix that deep red color. On the other hand to make the same color in our incandescent fixture we leave it at full power and put a colored filter in front of it. Deep colored subtractive filters like a deep red gel may only have a 10% transmission so this effectively reduces the efficiency from the initial 15 lm/W down to 1.5 lm/W, much lower than the LED unit.

Figure 5 illustrates this diagrammatically; the red line illustrates the predominantly flat efficiency of an LED based additive color mixing system as we vary color saturation while the blue shows the drop off of a subtractive filter incandescent system. In white light the incandescent wins, while in deep color the LED is well ahead. Somewhere in the middle, in the mid-tones, the two will be the same. This chart is illustrative only—in practice different colors will produce different curves however the general trend will be similar.

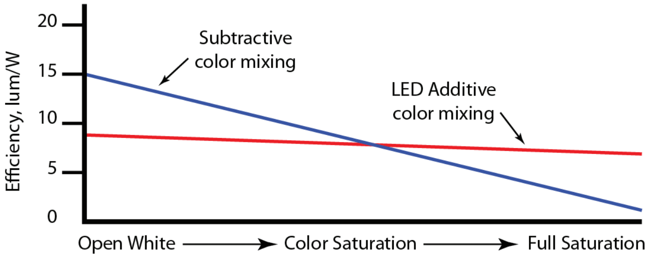

Figure 5 – Efficiency with color saturation

Of course there are many reasons why a designer might choose an LED based unit over an incandescent one and vice versa, each have their pros and cons which are well known and understood, so this isn't the whole story. Additionally LEDs are improving all the time with, historically, a doubling in efficiency occurring about every 36 months. (This exponential increase in efficiency is due to ongoing development and discoveries is often called Haitz's Law and has been true since the sixties.) So, if you are reading this sometime after the end of 2008 when it was written and Haitz's Law is still in effect then the LED figures I mention above are very likely to have changed for the better!

I'm a huge fan of LED technology and its enormous potential and I feel privileged to be part of the first generation for well over a hundred years to be able to use a fundamentally new mass market light source. I'm also a believer in reducing energy consumption wherever we can. However, whatever anyone might tell you, you should listen to Kermit; it's not easy being green. ■

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