New lamps for old . . .

Mike Wood takes a look at the current state of play with light source technologies . . .

We are privileged to be living at this time in history. You and I are members of the first generation for 200 years to be part of a dramatic change in the technology we use for lighting. Incandescent lamps are 150 years old and arc/discharge and fluorescent lamps even older (admittedly not quite as we know them today).

You don't need me to tell you about the pressure to improve the energy efficiency of our lighting and save energy. Much of the rhetoric is the stuff of tabloid headlines rather than the pages of a journal like this one. Let's take all that as read and accept there is a need for change and, what's more, a clear willingness for that change to occur - except perhaps from companies mining tungsten and even they may still yet be needed.

The current pace of change is dramatic and as important to the history of lighting as when Swan (or Edison, depending on which side of the Atlantic you were) first turned on the light.

The goal with any lighting is pretty clear, it's to enable us to see and our eyes have evolved to be most efficient in the light wavelengths present in sunlight. That is light with a spectrum primarily between 400 and 700nm with our eyes peaking in efficiency at 550nm in the green. All lighting is essentially some form of daylight substitute and we do our best to maximise the output between those wavelengths and eliminate everything else. A timeline of the various technologies and their efficacies is shown in *figure 1*.

The various core technologies are shown against a timeline with the left axis showing the luminous efficacy of these technologies expressed in lumens per watt on a logarithmic scale. Lumens are a statistical measure of the human eye's response to a lighting stimulus and are therefore wavelength dependent. You can have all the power you like, but if it's in the Infrared or Ultraviolet wavelength and we can't see it, then there are no lumens.

The right axis shows the possible power conversion efficiency for a 3900K RGB-based white light source for comparison. For this theoretical source 100% efficiency would correspond to 400 lm/W. (Sunlight, by way of comparison, has an efficacy of about 93 lm/W.)

The first artificial light source was fire in the form of oil and kerosene lamps, gas light and gas mantles. This technology primarily produces non-visible heat and peaked in efficiency at around 1 lm/W. Incandescent lamps started off at similar efficiencies with carbon filaments (which really aren't much more than heaters either) but the introduction of tungsten filaments increased this to around 10 lm/W in the early 20th Century. As far as domestic light bulbs go, that's pretty much where it stayed - a light bulb in your house is still only 10-15 lm/W which represents an overall power efficiency of less than 5% - not great. We do somewhat better than that in entertainment lighting, where current tungsten halogen incandescent lamps increase this to 20-25 lm/W or around 5-6% conversion efficiency (*see figure 2*).

Modern fluorescent and HID lamps have significantly higher efficacies. Although these are both older technologies than incandescent, their domestic use wasn't widespread until relatively recently so they don't appear on this chart before 1950 - not many people had carbon arc lamps in their kitchens! Base efficacies have stayed fairly static and these light sources are our current leaders, approaching 100 lm/W for an overall efficiency of 25%.

However, this graph is missing some important information for our application. The data here is for diffuse or ambient light sources and what it doesn't show is how luminaire efficiencies for theatrical fixtures with highly developed optical systems have improved over the same period. With compact filaments and improved optical systems we've seen incandescent theatrical spotlights go from 25% to 60% optical efficiency in the last 30 years and the introduction of short arc lamps has provided similar improvements with discharge-based fixtures. Include that and current theatrical lamps start to look a whole lot better. Any new lamp technology not only has to have better luminous efficacy but it also has to be compact enough to work efficiently with such optical systems.

Can Incandescent lamps be improved?

With pending legislation in many countries to ban the humble incandescent lamp because of its inefficiency (and I hope that Governments ban lamps on the basis of efficiency levels, not just blindly based on technology) is there anything to be done to improve it to an acceptable level?

Well incandescent lamps aren't just rolling over and dying. There is significant work from a number of quarters on improving them. In February of this year GE announced that it was working on a 'HEI' (High Efficiency Incandescent) lamp with initial targeted efficiencies around 30lm/W, or twice as efficient as current lamps. They have long term goals for the technology of 4 times the efficiency of current lamps which would take them to a level comparable with CFL (compact fluorescent lamps).

It is unclear precisely which technologies are expected to provide this improvement, although there are two main contenders. The first is based around improvements to thin film coatings inside lamps. Such coatings are designed to reflect Infrared back onto the filament rather than letting it escape as wasted energy. This reflected heat keeps the filament hot and can significantly improve the overall efficacy of the lamp. Lamps using early versions of this technology have been available for quite some time and have been particularly successful in low voltage airfield and automotive applications where efficiencies of nearly 40 lm/W have already been achieved. Osram, Philips and others are

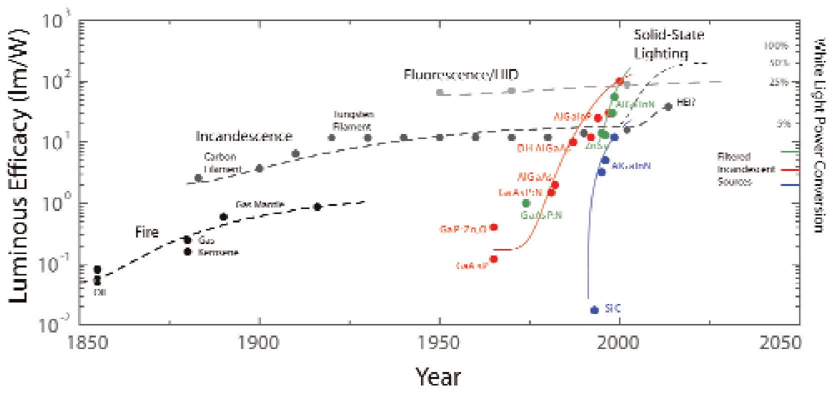

Figure 1: Evolution of luminous efficacy.

(Thanks to Jeffrey Tsao of Sandia Labs for permission to reproduce this graphic)

using this technology in other low voltage, low power lamps to achieve over 30 lm/W (*see figure 3*).

So far we haven't seen this technology being used in higher power, higher voltage lamps. Problems with coatings and temperature at higher wattages make this difficult to achieve, but I have every expectation that there will be success and we will see improved incandescent lamps using this technology in higher power lamps in the entertainment sector. In fact David Cunningham (the well-known inventor of the ETC Source Four and Sensor Dimmer) recently published a patent application on improvements to lamps which incorporated this technique. What progress is with its development I have no idea but, with Dave involved, I'm sure it will be interesting.

The second potential breakthrough with incandescent lamps is the use of photonic lattice technology. Originally developed by the Department of Energy's Sandia Labs in the US, this is a technology which, instead of wasting or recycling the infrared energy, actually converts that invisible infrared energy up into visible light frequencies. This technique could raise the efficiency of an incandescent lamp from the 5% figure we saw in Figure 1 to greater than 60%. Unfortunately, after initial press releases and fanfare in 2003 this technology has gone very quiet. I understand there were significant difficulties in scaling down the nanotechnology far enough to reach the visible region and it is awaiting improvements in the manufacturing technology before it can be a realistic proposition. It was hoped that the spin-off from improved semiconductor manufacturing techniques would help this get back on track, but I'm afraid that all those R&D dollars are now being spent on LED research instead. (To give some idea of the scale in the photograph, the tungsten rods are 1.2 microns in diameter!) (*see figure 4*).

Ironically the same technology that Sandia used here, photonic lattice crystallisation, is now being used for waveguides in LEDs to make them more efficient. Since LEDs are already more efficient in the first place, it's hard to see the commercial justification for the research, even though some of us in the entertainment industry would love those black body, wide band 100 CRI sources. Sadly, I think it is unlikely we will see this technology any time soon.

Fluorescent Lamps

Currently, fluorescent lamps are the leaders in the lighting efficiency race. Although domestic fluorescents have issues with colour rendering, units designed for the professional market have no such concerns. The broad spectrum phosphors with excellent CRI and the flicker-free ballasts used by manufacturers such as Kino-Flo, Flolight and Videssence in their fluorescent-based washlights give excellent results. The flat, large sources that these lamps are used in are ideal for television and film use and meet a need for low energy, low heat fixtures in these environments. They are also perfect fixtures for lighting the blue and green screens

Figure 2: Theatrical lamp.

Courtesy of Osram

Figure 3: IRC Lamps.

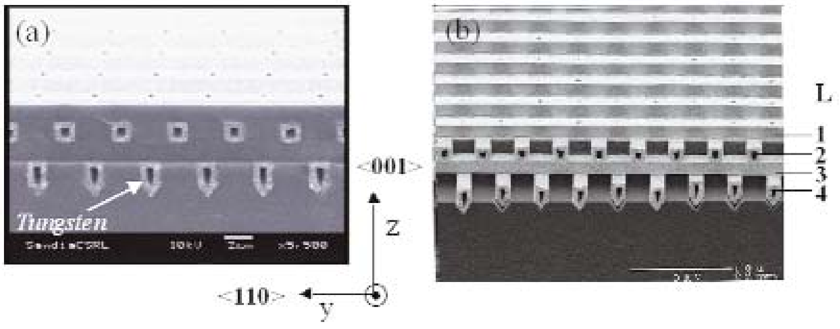

Figure 4: Sandia Tungsten Photonic Lattice.

used in colour matting video and film photography. Unfortunately, their naturally diffuse and broad output, coupled with limited dimming capability compared to incandescent sources, have perhaps made them less suitable for longer throws in theatre or other live performance venues (*see figure 5*).

There are also colour mixing products using multiple fluorescent tubes, although I suspect that LED-based systems will marginalise those niche products fairly quickly.

Improvements in fluorescent phosphors continue, ironically partially because of the use of the same or similar phosphors in white LEDs, and it seems likely that fluorescents will remain viable in those specialised markets where they are already in use. However, those same markets are already starting to adopt LEDs because of their ruggedness and ability to control colour.

HID Lamps

HID lamps are perhaps the high-efficiency light sources that we are most familiar with in the entertainment industry. HMI, MSR, and other High Intensity Discharge (HID) lamps are in daily use everywhere. Their combination of efficiency and small source is hard to beat in spotlight fixtures or most automated luminaires where there is a need to focus the light down through a small aperture and illuminate an image for projection by output optics. HID lamps are fundamentally a very old technology whose core efficacies haven't changed significantly in recent years. What has improved, however, are their colour rendering, colour temperature, stability and life - all parameters which help make them more suitable replacements for incandescent lamps. One of the more recent developments has been the introduction of ceramic arc tubes in smaller lamps designed for architectural use. These lamps, such as the Philips MasterColor, Osram Sylvania Powerball or GE Constant colour offer significantly improved colour rendering with lifetimes up to 25,000 hours. These ceramic arc tube sources are large, so are better suited for wash units rather than imaging fixtures (*see figure 6*).

This is perhaps a good place to discuss the concept of fixture efficiency as opposed to light source or lamp efficacy. It's no good having the most efficient light source on the planet if the size and shape of that light source makes the light output unusable. Clearly you can't replace a short arc discharge lamp where the light is emitted from a 5mm arc with a 2.4m fluorescent tube and expect the same output. This is an extreme example but the same calculations have to be considered when looking at any new light source. The brightness of the source is important, but only half the story. How and where that light is emitted is equally critical to the lighting fixture. HID lamps are the current leaders in output coupled with small size. One extreme example is the Xenon lamp - Xenon lamps don't have that high an efficacy but they have the smallest light emitters around, with arc sizes down to less than 1mm. That tiny source makes for highly efficient optics so the overall result is an efficient lighting fixture. On the other hand, using a Xenon lamp in a broad wash unit would likely be a waste of time as the optics in such a unit cannot make use of the small arc.

Such considerations make edicts by legislators on banning certain lamp technologies highly suspect. The goal should be to achieve a certain agreed level for luminaire efficiency. After all, what we really care about is the amount of energy consumed versus the amount of useful light generated. That efficiency is affected by all the components involved; lamp, luminaire and optics and it's the combination that should be judged. Some of those combinations are hard to beat - a fluorescent lamp in a wash fixture or an HID in a spotlight, for example - but most of what we deal with falls in between these limits and it's not always obvious how luminaire efficiency relates to the efficacy of the light source. Recent papers from the DoE in the US thankfully recognise this issue and deal with luminaire efficiency rather than light source efficacy.

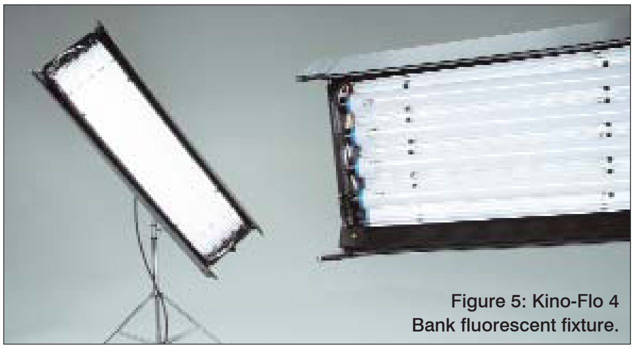

Figure 5: Kino-Flo 4 Bank fluorescent fixture.

Figure 6: Philips Mini Mastercolor ceramic metal halide.

Figure 8: Cree XLamp, 75 lm/W white LED.

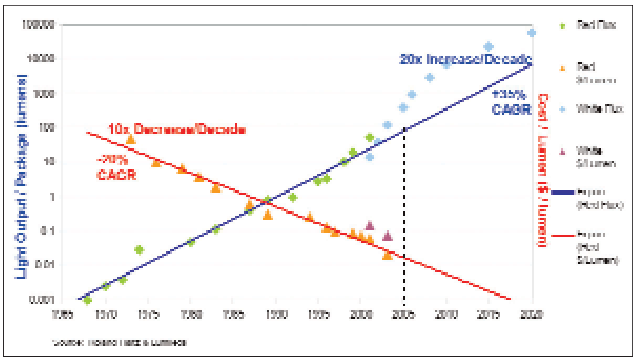

Figure 7: Haitz's Law (CAGR = Compound Annual Growth rate) (US DoE report March 2007).

LEDs

Be honest, you knew we were going to end up with LEDs didn't you? Unlike the other technologies discussed above which are at a point of their development where only slow improvement is likely, LEDs are a new technology which continues to show enormous potential. Major breakthroughs and the introduction of completely new chemistries promise to keep this technology on a rapid upwards slope.

By now, most people will have heard of Haitz's Law, the LED corollary to Moore's Law of semiconductors. Named after Roland Haitz (now retired from Agilent Technologies), the law forecast that every 10 years the amount of light generated by an LED increases by a factor of 20, while the cost per lumen (unit of useful light emitted) falls by a factor of 10. These are pretty steep curves but, so far, not only have these forecasts been fulfilled but in recent times with the injection of large amounts of R&D funds from government seeking energy efficiency, it's possible that they have actually been exceeded (*see figure 7*).

Colour	Luminous Output	Wattage	Luminous Efficacy	CCT/Dominant Wavelength	CRI	Lifetime
White	45 lm	1 W	71 lm/W	5500 K	70	50,000 hr
Warm White	20 lm	1 W	30 lm/W	3300 K	90	50,000 hr
Green	53 lm	1 W	53 lm/W	530 nm	N/A	50,000 hr
Blue	16 lm	1 W	16 lm/W	470 nm	N/A	50,000 hr
Red	42 lm	1 W	58 lm/W	625 nm	N/A	50,000 hr
Amber	42 lm	1 W	50 lm/W	590 nm	N/A	50,000 hr
Incandescent	850 lm	60 W	14 lm/W	2900 K	100	1,000 hr
Fluorescent	5300 lm	32 W	83 lm/W	4100 K	78	20,000 hr
HID	24,000 lm	400 W	80 lm/W	4000 K	65	24,000 hr

Figure 9: Typical performance of LED Devices and Conventional Technologies. (US DoE report March 2007)

Figure 10: eWCove Powercove - Color Kinetics.

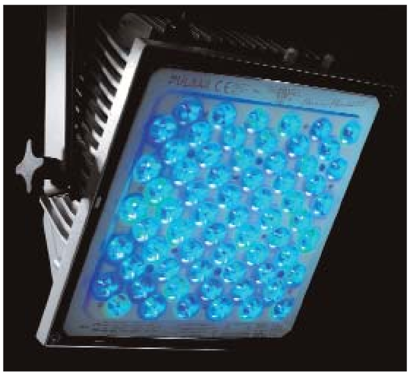

Figure 11: Pulsar TriColour.

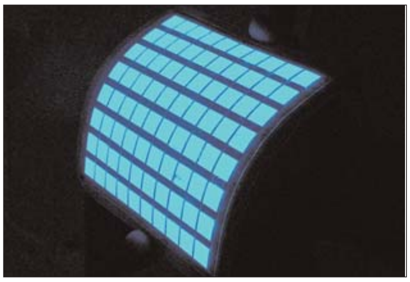

Figure 12: GE OLED-based unit.

Today's top-of-the-range white LEDs are now fast approaching the efficacy of fluorescent lamps (around 80 lm/W) (*see figure 8*) and it is predicted that they will break the 100 lm/W barrier within the next two years.

The 2006 data for the efficacy of light sources published by the US Department of Energy in *figure 9* shows LEDs, for the first time, becoming a viable alternative to incandescent lamps and that soon, if Roland Haitz continues to be correct, will become a competitor to fluorescent sources.

But what does this mean to us in the entertainment business? Clearly we are seeing large inroads from LEDs into the wash and display end of our market and some are showing high enough output to start to compete with more conventional units in lighting (as opposed to decorative) applications. *Figure 10* shows the eW Cove Powercore unit from Color Kinetics which, it is claimed, is now an impressive 5x the efficiency of equivalent incandescent strip lighting. This is clearly designed to be a functional product, not just decorative.

The Pulsar TriColour shown in *figure 11* is a current example of the RGB-based colour mixing units which are making huge inroads into every type of production. Television was the first to embrace these but they are rapidly becoming ubiquitous. It was hard to find a lighting booth at PLASA this year that didn't have an example. Many of these, like the Pulsar unit, are based around the Lumileds Luxeon emitters which seem to have found their home in entertainment products. However, there are some interesting high-density packaged emitters coming from many smaller companies such as Lamina and Enfis. Companies to watch I think.

This is clearly the tip of the iceberg and LED-based products will continue to improve, first in wash and diffuse lighting and eventually in spot and imaging optics. We are really still seeing first generation products with, in my opinion, still some way to go in colour control. Three-colour RGB is fine for lighting backgrounds and cycs but doesn't give the CRI and colour range that we'd like for the critical lighting of skin tones. However, RGBW, RGBA, RGBAW and those with even more letters in their acronym are coming, and there's absolutely no doubt that the colour subtlety will get to where it needs to be, the only question is how quickly.

What about OLEDs?

The core products we are seeing today, almost without exception, use conventional, inorganic LEDs, but we are just starting to see promising developments in OLEDs (Organic LED). OLEDs are a really interesting technology: they can be produced by very simple manufacturing techniques totally unlike the methods used to make conventional semiconductor-based inorganic LEDs. In fact, a simple inkjet printer might be enough to lay down an OLED layer. An OLED emits light from its entire surface at a relative low lumen density so they could be well suited as a source for large washlights and provide competition for the fluorescent-based soft lights we talked about earlier. They also have a much wider range of colours than inorganic LEDs which has great potential for entertainment use. The large source size means it's unlikely they'll be the source in a spotlight, but they could make the best cyc lights ever. In fact, if prices drop enough, the whole cyc could be one big OLED emitter. That would be fun!

The biggest current problem with OLEDs is their relatively short life - the organic materials degrade relatively quickly. However, GE and others are investing heavily in OLED research as a way of achieving government energy efficiency standards and I look forward with interest to OLED-based products in our industry (*see figure 12*).

Is that it?

We've talked about the mainstream light sources but there are other, peripheral, light sources which may yet prove to be significant players. RF/induction lamps have been around for a while with only limited success, but there have been some recent breakthroughs that make this technology interesting, particularly for small source projection and spotlight units. Plasma and microwave lamps could also make a return. The pressure is on for energy efficiency and consequently R&D dollars are available - not only available but plentiful. One thing is for sure, as I said at the beginning, we are privileged to be working in lighting at a time of unprecedented change and invention, and whatever happens is going to be exciting!