An Overview of High Brightness Light Emitting Diodes

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***Abstract*—High brightness LEDs have been paving the way towards more efficient illumination. Whether in household applications or professional settings, HBLEDS are providing the next step in solid-state lighting. Presented here is an overview of the areas HBLEDS have already improved and the challenges that require solutions before tis technology can take the next step forward. Included is a history of other lighting types as a method of comparison to LED technology. The review will conclude with several promising technologies being explored by the LED lighting industry for more efficient illumination.**

***Index Terms*— HBLEDS, Entertainment Lighting, Architectural Lighting, LED replacement lamps**

I. INTRODUCTION

High brightness light emitting diodes (HBLEDs) have grown rapidly in popularity since their development in 1993. Since the first InGaN high-brightness blue LED was developed, a wave of research into "white" LEDs has followed and ultimately led to the development of replacement lamps for traditional halogen, sodium, tungsten, and fluorescent fixtures (1). The use of HBLEDs has grown due to their high luminous output compared to the power they consume. Most HBLEDs are producing 75 to 125 lumens per watt of energy consumed. While applications vary, one of the first industries to begin utilizing various colors of HBLED was the entertainment industry. Whether it is for lighting a stage or lighting your home, HBLEDs have reshaped the future of efficient lighting practices.

Why not fluorescent lighting? Since the early 2000's there has been a push to use fluorescent lighting replacements in homes to replace traditional tungsten bulbs. While these fixtures are efficient, the luminous output per watt and lifetime pale when compared to the output of a similar LED fixture. In table 1, the output of various lamp types are shown side by side.

In this review, the use of HBLEDs in the entertainment industry will be explored along with the challenges posed in the application of LEDs as a replacement to traditional lighting sources. One of the early adopters of solid-state lighting as a replacement source was the entertainment industry with Color Kinetics (now a Philips subsidiary) introducing the Color Blast fixture as early as 2001 (2). Earlier fixtures using "super bright" LEDs were available but not widely used due to poor color quality.

A brief overview of high-output lighting sources will be discussed in Section II. This will be followed by a discussion of high-brightness LEDs and their uses in Section III. After this, Section IV will feature a discussion of the current challenges facing the use of HBLEDs in the entertainment industry. This will include a discussion of both the technical problems and a brief discussion of the industry reaction to LEDs. Finally, Section V will close out with an overview of high-brightness LEDs in other applications, such as in-home solid-state lighting.

Table 1: Types of Lamps, Outputs, and Luminous Efficacy

Type	Lumens	Lumens/Watt
100 W Tungsten	1500	15
25 W Compact Fluorescent	1500	60
55 W Halogen	1500	27.3
150 W High Intensity Discharge	5000	33.3
180 W Sodium Street Light	27,000	150
9.5 W Cree Soft White LED	800	84.2

II. HIGH-OUTPUT LIGHT SOURCES

In the 1860's and 70's, theaters were using limelights as their source for high-output lighting. These units used a flame focused on a piece of lime to produce a brilliant white light that could then be focused on the stage. These units were eventually phased out in favor of the carbon arc lamp. This lamp, which was open to the air, consisted of two carbon rods with a high voltage and current flowing across them. Once the arc was started, light would be emitted from the carbon rods, but the distance had to be maintained as the arc vaporized the rods (4).

Eventually, the entertainment industry moved to gas discharge lamps as a source for projectors, follow-spots, and other high-output fixtures. Lower output fixtures still relied on tungsten or halogen lamps as sources.

A. Tungsten/ Halogen Lamps

For many years, the entertainment industry relied on improvements to instrument optics to increase the overall efficiency of a unit. Rather than making the tungsten and halogen lamps more efficient, the amount of light exiting the system was improved.

In 1992, Electronic Theater Controls (ETC) released the first major improvement to Ellipsoidal Reflector Spotlights (ERS) with the introduction of the Source 4 Ellipsoidal. This unit used a compact filament 575 W halogen source paired with a dichroic reflector (rather than aluminum) to output light equivalent to a 1000 W fixture (5). The lamp, shown in Fig. 1, features a compact filament layout. Having a small filament allows the optics to treat the light as a point source, which helps produce a more even beam of light. This fixture still remains the standard in the United States for electronically dimmable lighting. Simply by updating the design of the High Performance Lamp (HPL) and redesigning the optics, the company managed to match the output of older fixtures with almost half of the power consumption.

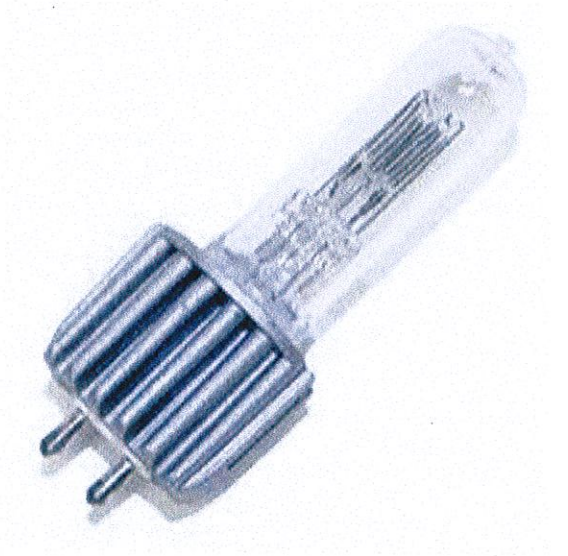

Figure 1: The HPL lamp used in the ETC Source 4 Ellipsoidal and Source 4 PAR. Designed in 1992 and still used today, this 575 W lamp has an equivalent output to a 1000 W fixture.

ETC followed this success with the development of a 750 W lamp, which fit the same fixtures (shown in Fig. 2a) and produced even more light. However, these lamps still lose most of their energy output to heat, rather than light. When it comes to high-output projection and concert lighting, the lamp of choice has been and still is the xenon short-arc lamp.

B. Xenon Short-Arc/ HID Lamps

These lamps are the focus of many projection systems. Xenon Short-Arc lamps are the popular lamp of a subset which are considered High Intensity Discharge, or HID. These gas discharge lamps have very high luminous outputs for the power they consume, but are not dimmable via electronic means. Instead, the lamp output level must be controlled using mechanical systems.

In a Xenon short-arc lamp, high-pressure glass envelops a xenon gas environment where two thoriated tungsten electrodes meet with a gap in between. The environment is usually filled with xenon gas to a pressure of up to 25 atm. Using a high voltage and current, the lamp is struck and the arc between electrodes is created. On the cathode, a small cloud of plasma is created where the electrons are leaving. When the electrons hit the anode, they cause it to heat up very quickly. In extremely high-powered cases, the anode must be liquid-cooled to prevent over-heating. This pinpoint sized ball of plasma creates the majority of the light output for the lamp (6-7).

While these lamps have tremendous outputs, their power draw is also quite large. Italian lighting company Clay Paky manufactures an instrument (shown in Fig. 2b) using a 1.5 kW xenon short-arc which has a system output of over 135,000 lumens for white light. While this provides a phenomenal 90 lumens per watt, the lamps also feature short life spans of only a few thousand hours (typically around 1200-2000) (8).

Figure 2: (a) The ETC Source Four Ellipsoidal spotlight, which uses a 575 W lamp outputting 16,500 lumens (28.7 lm/W). (b) Clay Paky's Alpha Spot 1500, which uses a 1500 W HID lamp outputting 135,000 lumens (90 lm/W).

In addition to the short life spans, the high-pressure envelope of the lamp makes them dangerous to handle. Even with lower wattage lamps (150w to 575w), the pressure is high enough to cause the lamps to explode if mistreated. In addition, the natural operation of the lamps weakens the integrity of the lamp housing; meaning that the lamp is most delicate when it is in need of replacement.

Another downside to these lamps is the large amount of UV light emitted. Because of the nature of the fused quartz glass, which makes up the lamp, all UV produced (and there is quite a bit produced) is transmitted out of the source. This can result in exposure to high levels of UV if not properly shielded and a build-up of ozone produced by the emissions. Both are considerations that must be dealt with when using HID lamps.

1) Extremely high-output lamps

Most of the factory-produced HID xenon short-arc lamps fall into the range of 75 W to 12 kW. However, for Omnimax projection systems (domed IMAX theaters) a special 15 kW lamp is produced. This lamp, pictured in Fig. 3, has liquid cooled electrodes and is pressurized with pure xenon gas to 25 atm. The glass encasing this lamp is actually fused quartz, which is the only economically feasible material that can withstand the temperatures and pressure present in the lamp and remain optically clear. In addition to protective eyewear, people replacing IMAX and Omnimax lamps are required to wear protective bodysuits in case of lamp failure (7).

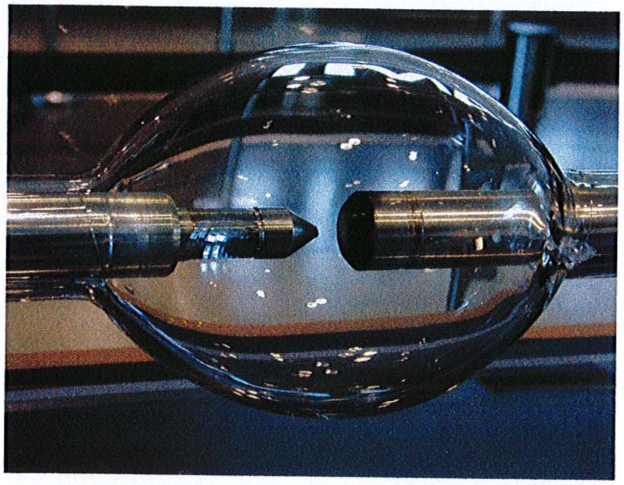

Figure 3: The 15 kW xenon short-arc lamp used in the Omnimax projection system consists of liquid cooled electrodes and an optically

C. Sodium Vapor Lamps

Referring to Table 1, it may seem wise to use sodium-vapor lamps for high-output devices given the extremely high luminous efficacy. However, the most electrically efficient version of the lamp is the low-pressure sodium light. Unfortunately, this type of lamp emits near monochromatic light with an average wavelength of 590 nm. With no way to alter the light to produce a full spectrum of visible light, it is not ideal for use in entertainment beyond parking-lot illumination or for special effects (9).

III. HIGH BRIGHTNESS LEDS

High output lamps are associated with immense amounts of heat and electricity. Running a music festival with dozens of fixtures using 1.2 kW HID lamps and hundreds of 575 W halogen lamps can result in total loads in the 300 MW range; an expensive and large-scale problem. It was not long after Shuji Nakamura's 1993 production of a "candela-class" blue LED that the first 1 W LEDs were being produced (1).

As observed by Dr. Roland Haitz of Agilent Technologies, every 10 years, the price of LEDs will drop by a factor of 10 and the output over that same period will increase by a factor of 20. Also known as Haitz's Law, this means that in the future, LED product generation lifetimes are going to be months rather than years. Figure 4 shows this in graph form as a function of flux per unit and cost per lumen. Already, we have begun to see this, not only in the laboratory, but also with commercially available products. In fact, since the late 1990s, these rates have gone up. Mainly attributed to the widespread demand for high-brightness LEDs and increasing competition, this could result in low cost LED replacement bulbs within the decade (10).

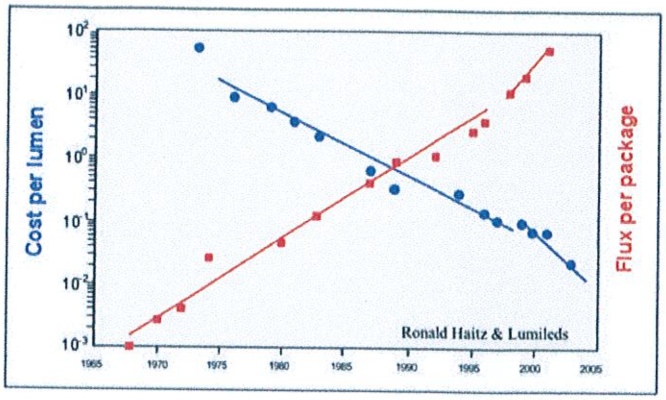

Figure 4 – A graph showing Haitz's law for LEDs. Notice that the y-axis is logarithmic, indicating rapid cost reduction and flux increase. Also note the increased rates of change starting in the late 1990s.

In 2010, Cree marketed an LED boasting 1000 lumen output at 130 lumens/W. That same year, they announced a prototype LED with an efficacy of 208 lumens/W. In the following year, a prototype was released producing 231 lm/W at a draw of only 350 mA. Currently available on their website is an LED array (shown in Fig. 5) measuring 3cm x 3cm with an output of up to 18,000 lumens giving an efficacy of approximately 120 lm/W (11).

Figure 5: Capable of 18,000 Lumens, the 3cm x 3cm Cree CXA3590 is one of the brightest available on their website.

A. Basic LED Theory

Before discussing the problems associated with using these LEDs in the entertainment industry, a solid understanding of how a solid-state device produces light is necessary. Many of the high-brightness LEDs discussed here are hetero-junction devices made up of multiple materials to obtain a higher overall efficiency. During the discussion of the basic LED theory, we will act as though our LED is merely a P-N homo-junction device.

1) Spontaneous Emission

LEDs emit light through a radiative transition process called spontaneous emission. In a semiconductor, photons may be emitted when an electron and hole recombine via a direct band-to-band recombination process. High brightness LEDs are made using direct band-gap materials to exploit this process.

When a forward bias is applied across the P-N junction, electrons and holes are injected into the space charge region. Within this region, the electrons and holes become the minority carriers and begin to diffuse into the neutral semiconductor regions. Once they have moved to the neutral regions, they begin to recombine with the majority carriers and emit photons. The wavelength of the light emitted is dependent on the band-gap of the material as shown in Fig. 6. This process is known as spontaneous emission because it happens spontaneously when an electron and hole recombine in a direct band process. While the wavelength of the emitted photons is not singular like in stimulated emission, the bandwidth of emissions is only 30-40 nm wide, so that the light emitted is perceived as nearly monochromatic.

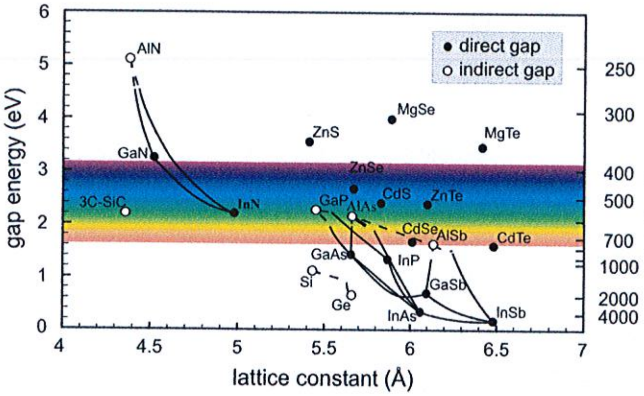

Figure 6 – The band-gap energy for most semiconductor materials. Note that the higher the band gap, the shorter the wavelength. Black lines indicate materials that can be hybridized for custom band-gap energies.

The photons emitted by a wide band-gap device will be higher energy and have a shorter wavelength. Using the equation listed here, we can determine the wavelength based on band-gap or vice versa. Gallium Nitride, a wide band-gap material, is used in the production of LEDs ranging from UV to cyan (12).

$$E_g(eV) = \frac{1.24}{\lambda\ (\mu m)}$$

2) Band-Gap Tuning

Using Fig. 5, we see that there is a semiconductor material for many colors in the visible light spectrum. However, sometimes a color is desired that is not perfectly aligned with the band-gap of a pure semiconductor. In Fig. 5, there are black lines connecting some types of semiconductors. These lines indicated that they can be combined (since they have elements from the same group in them) to produce a hybrid semiconductor with a band-gap somewhere in between the two materials.

In a recent paper on the design of a royal blue LED, I address the problem of reaching the desired wavelength by using a combination of GaN and InN to form InGaN. The mole fraction of Gallium compared to Indium in the semiconductor directly relates to the final band-gap of the material. Using Vegard's Law (shown below), the band-gap of the material can be fine tuned to emit light at a desired wavelength (13).

$$E_g(x) = xE_g^A + (1-x)E_g^B - x(1-x)E_b$$

In the above equation, the term E_b is the bowing coefficient. This accounts for the fact that there is not a linear relationship between the band-gaps and the mole fraction. In fact, the true relationship exists between the lattice constants for various materials. However, since the lattice constant is directly proportional to the band-gap energy for a semiconductor, Vegard's law can be manipulated to obtain the band-gap directly. The bowing constant has been found for many different types of InGaN materials (14).

B. From Monochromatic to Full Spectrum

At this point the reader may begin to notice an issue with using high-brightness LEDs as a replacement for high-output lighting sources. There is no such thing as a band-gap capable of producing anything other than monochromatic light. In other words, there is no native "white-light" HBLED. When discussing sodium-vapor lamps, the monochromatic nature of the light was seen as a disadvantage. This raises the question of how LEDs could be used to efficiently replace HID or even tungsten sources.

1) RGB Color Mixing

One method of manipulating the monochromatic output of an LED into a full spectrum of visible light is be combining multiple LEDs into one unit. Using a separate red, green, and blue (RGB) LED die and placing them within close proximity will give the perception of an output of white light. In Fig. 7, a "smart" RGB LED is seen with each color helping to produce an approximate white. This method, also known as additive color mixing, often results in more complex electronics due to the need to drive various LEDs at different currents and voltages to produced the desired white color (15).

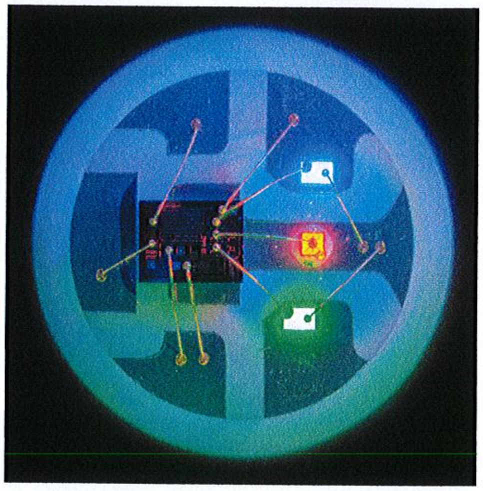

Figure 7 – A "smart" RGB HBLED capable of interpreting an input signal and adjusting the output color of the device.

2) *Phosphorescent Coatings*

A heavy emphasis has been placed on the importance of the blue high brightness LED. While red and green LEDs have made steady progress for high-output applications, it was not until the last two decades that blue HBLEDs came along. Blue LEDs are not just important for completing the RGB color-mixing spectrum. The most important thing they are used for is the production of white-light LEDs.

Much like fluorescent fixtures, placing a phosphorescent coating on the top of the LED can alter the output of a blue LED. The coating allows a portion of the blue light to pass, but absorbs and re-emits the light in a broad spectrum of wavelengths. Using an Yttrium-Aluminum-Garnet (YAG) glass ceramic coating doped with Cerium, the blue light can be turned into a full-spectrum white LED. Of course, different color temperatures of white LEDs may be produced using different types of phosphor coatings. Many different types of coatings have been tried, but YAG-based coatings have proven time and again to have the highest efficiency (16). Since the light must be passed through a coating, it is thought that the highest possible efficacy for blue to white LEDs will be 251 lumens/W (11).

C. Applications for HBLEDS

With the knowledge that LEDs may be produced in any color, including white, it is time to see how they can be used in the real world. It should be noted that these applications are specifically for High Brightness LEDs and not all LEDs. Many applications were left off because, in the author's opinion, the LEDs are not being used in an application where high output devices are needed.

1) Wash/ Architectural Lighting

The first application category involves illuminating an area where ambient light spill is not important. While the beam angle of the fixture will matter for getting light to its destination, the "edge" of the light may be soft and diffuse. Lighting that falls into this first category includes streetlights, building lighting, and security lights. Most of these lights are not necessarily more efficient than their sodium vapor counterparts, but do provide a much longer lifetime and higher reliability.

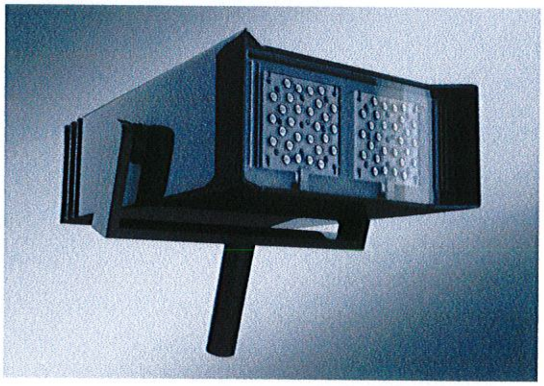

Figure 8 – The LED North America SuperSport LED unit for arenas. With a more focused output, fewer units are needed.

One new producer of wash fixtures suiting these purposes is LED North America; a Knoxville, TN based company producing high-output, high-reliability wash lights. Using fixtures like the one shown in Fig. 8, the company is replacing arena lighting and streetlights with LED lights that are outperforming their predecessors (17).

Wash lighting is also prevalent in the entertainment industry. Earlier, the ETC Source 4 PAR was discussed. This instrument uses a 750 W lamp in conjunction with a parabolized reflector and lens to provide a soft edged wash of light. In the mid-2000s, the Selador series of LED fixtures was released as a replacement for these traditional halogen fixtures. With brightness matching the output from the traditional 750 W lights, these wash units not only provide energy savings but also color changing abilities that are not available from a white light source.

LED color changing units, as they are called in entertainment, allow for rapid color changes and the use of fewer instruments overall. In the pursuit of a wash fixture that behaves like traditional halogen sources, many color-mixing schemes have been developed, building on the original principle of RGB. The most popular units use Red, Green, Blue, White (RGBW) or Red, Green, Blue, Amber, White (RGBAW) mixing. Most of the units use individual LEDs with independent lenses, but this will be discussed more in the next section.

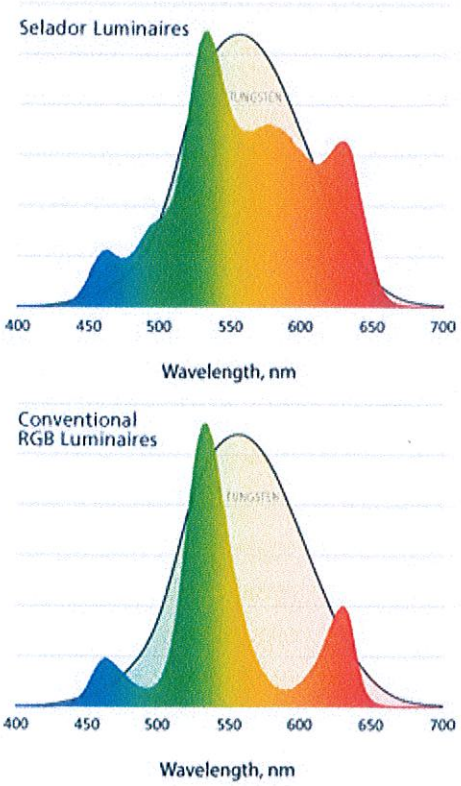

Figure 9 – The x7 color system spectrum (top) compared to a unit using only RGB leds (bottom). The faded curve in the back shows a comparison to the approximate curve of a tungsten fixture.

The Selador series has continued to evolve under the watchful eye of ETC, who has perfected what is called the x7 system. Using Red, Red-Orange, Amber, Green, Cyan, Blue, and Indigo LEDs, engineers have been able to provide a near-tungsten distribution of wavelengths from the fixture. In Fig. 9 we see a graph of the wavelength distribution available from the x7 system versus a traditional RGB unit (15).

2) *Profile/Projection Lighting*

As discussed in Section II, large numbers of high-output lamps are used in projection systems and entertainment lighting. For these applications, a hard-edged, well-focused and defined light beam is desired. Being able to project a precise image is easy when you have a source like an HID lamp with an approximate point source of emission. Designing precision optics for these systems is simplified by the point source approximation.

a) *Profile Lighting Instruments*

For a good reference of what a profile lighting instrument needs as a light source, we look back to ETC and the Source Four Ellipsoidal instrument. Named for its ellipsoidal shaped reflector, the instrument focuses the light through an optical shaping system and then out through a series of beam adjustments. With a variable focus system, the instrument can project clean, hard-edged images on a surface from virtually any distance. Figure 10 shows an example of the desired edge for profile instruments with a template in the instrument to show focusing across an even field.

Figure 10: A tree template projected onto a wall using a halogen sourced Source 4 Ellipsoidal unit. The hard edges around the edge of the light and the template are desired for profile instruments.

In Section II, we noted that the compact filament layout of the fixture resulted in an even field of light. Given a color mixing system, the various LEDs must be small enough and bright enough to emulate a point source for the optics. In addition, the system must be designed in such a way that the LEDs mix well and do not produced multiple images based on their location with respect to any optics. This challenge and several proposed solutions are addressed later in Section IV.

b) *Projection Lighting*

Section II discussed the use of HID lamps in projection and the need for a very bright source. One of the reasons for using high-output lamps is because of the losses experienced within projectors. Modern white-source projectors split white light into RGB before sending the light through a digital light projection (DLP) system, recombining the light and then sending it through a focusing system. This inefficient use of optics means that your source may be producing much more light than actually reaches the screen.

Since HBLEDs are semiconductor devices, they can be turned on and off extremely fast. Some modern LED projectors use this to their advantage by flashing the red, green, and blue LEDs faster than the eye can see and sending the images to the screen nearly simultaneously. This reduces the amount of optics needed to project and image. When combining an increase in optical efficiency with a more efficient light source, the end result needs a less powerful LED to replace the equivalent HID output (18).

IV. CHALLENGES FOR AN EMERGING TECHNOLOGY

Many of the challenges facing HBLEDs are a result of the applications for which they are destined. Some challenges, such as heat transfer, are universal for all HBLEDs. Others, such a color fringing or multiple images, are more important on profile instruments than wash fixtures. This section will address several of the pertinent challenges facing HBLEDs today and some of the current proposed solutions.

A. *Thermal Transfer*

Heat destroys LEDs and causes problems with their reliability. Even when resistance in the LED is minimized, large amounts of heat are still produced by the current passing through the junction. The increased heat on the junction can cause drops in brightness and color drifting. Caused by the expansion and contraction of the band gap (due to temperature changes), color drifting poses a severe problem to projection systems that have fine-tuned color temperature settings (2).

In addition to output problems, overheating LEDs are less reliable and experience shortened lifetimes. With different thermal expansion coefficients between the LED substrate and the copper heat sink, cracking and separation can occur over time. Should the LED delaminate from its heat sink, the overheating problem can become exacerbated and result in the premature failure of the LED.

One proposed solution is the use of direct plated copper (DPC) ceramic substrates rather than directly bonded copper (DBC) substrates. Plating the contact between the LED and the attached PCB allows better heat transfer off of the device. The process for DPC described in (19) also occurs at a lower temperature, inducing less residual stress in the copper and copper/substrate interface. When combined with a high performance metal core printed circuit board (MCPCB), the result is a HBLED package with much better heat transfer capabilities.

The high performance MCPCB brings the metal core to the surface of the PCB at the places where the copper plated LED substrate would attach. This way, heat can transfer directly into the thermally conductive metal rather than needing to diffuse through PCB before reaching the metal (19). While providing better heat transfer away from the LED junction, this method does not help the speed of thermal transfer in the heat sink.

Developed at [redacted] and licensed for use by [redacted], graphite foam thermal technology provides HBLED designers a heat sink with thermal conductivity four times greater than that of copper. The traditional heat sink material, aluminum conducts heat at a rate of 237 W/m*K. A copper heat sink conducts heat at a rate of about 400 W/m*K; indicating that a copper heat sink about half the size of the aluminum heat sink can do the same amount of work. This results in a smaller and lighter instrument, with a sharp increase in cost since copper is quite expensive.

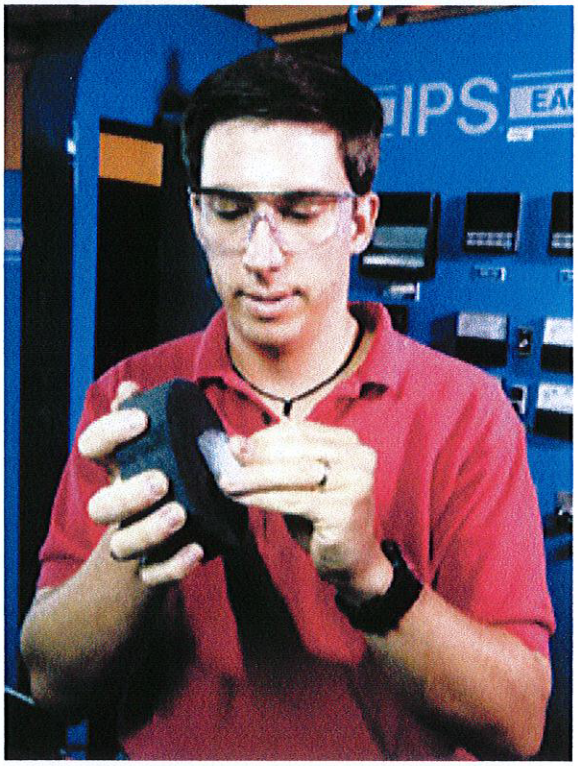

Figure 11 – The coldness of ice can be felt nearly instantaneously on the other side of the graphite foam (shown here with its creator) due to the very high thermal conductivity.

The graphite foam thermal technology shown in Fig. 11 transfers heat at a rate of 1700 W/m*K. Given a thermal conductivity four times greater than copper, this technology allows for brighter LED arrays since heat can be wicked away from the HBLEDs faster with a much smaller instrument profile and weight (20).

Already being used by LED North America on streetlights and the SuperSport arena light shown in Fig. 8, foam graphite thermal technology has solved some of the thermal management problems in LEDs for the time being.

B. LED Array Design

Due to the physics of the p-n junction, individual LEDs in a HBLED module are kept in the mm^2 range to improve quantum efficiency. Creating an array of smaller LEDs on one LED chip increases total system output. LED "dies" are arranged so that they provide the optimal forward voltage and current requirements when attached to a driving circuit. When designing a compact LED array driver as shown in (21), this works well enough. Large variations in the production of LEDs can cause issues with inconsistent forward bias voltages and current requirements, but most of these can be averaged out for single color fixtures (21).

In wash and profile fixtures where color mixing is desired, the design of an array becomes more complex. For the time being, color fringing will not be considered an issue and only the electrical challenges will be considered.

As mentioned above, LED forward voltage drops and current drops can vary wildly, not just between color types (which is to be expected with various band-gap energies), but also from LED to LED. The authors of (22) detail the problems caused by attempting to use RGB LEDs to create white light. Ideally, one driver circuit could be used to operate an LED fixture. However, the authors address the problem with using arrays of LEDs by explaining that differences in voltage and current requirements can end up shortening the overall life of the LEDs if not handled carefully (22).

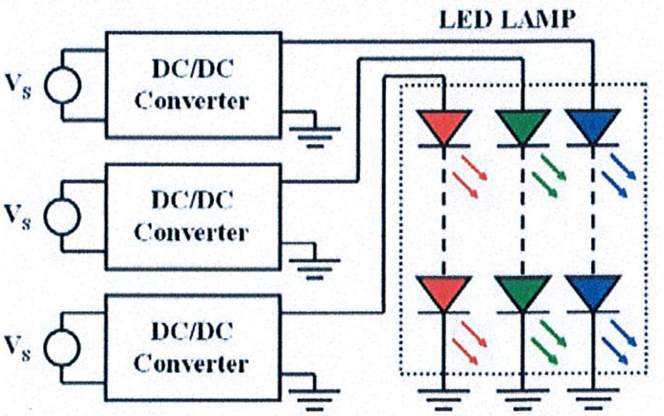

Figure 12 – An example LED array with individual drivers for each color. More drivers increase unit cost but also increase lifetime by more closely matching the needs of individual LEDs.

With this in mind, the ideal solution appears to be driving each LED separately like the circuit shown in Fig. 12. However, the cost of electronics to mediate this problem would quickly increase to the point where it would be better to shorten the life of the LEDs. While the heat transfer challenge is nearly solved, the design of LED arrays still has a way to go. One of the problems closely tied to this is color fringing in profile and projection systems. The size and arrangement of an LED array will have a significant impact on the methods used to drive the LEDs.

C. Color Fringing

Early LED wash units for entertainment use had a nasty habit of creating multiple shadows on stage due to the spacing of LEDs on the fixture. An example of this effect is shown in Fig. 13. While exacerbated by wide spacing of the sources, the same effect is achieved by having instruments with many LEDs spaced like those shown in Fig. 14. To the untrained eye, these small color fringes may have been unnoticeable, but in the production world, it made LEDs wildly unpopular at first.

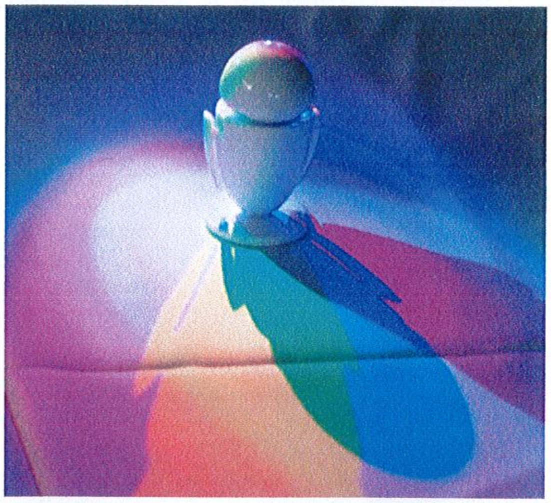

Figure 13 – An exacerbated demonstration of color fringing. When three sources produced three different shadows, it results in colored, overlapping shadows.

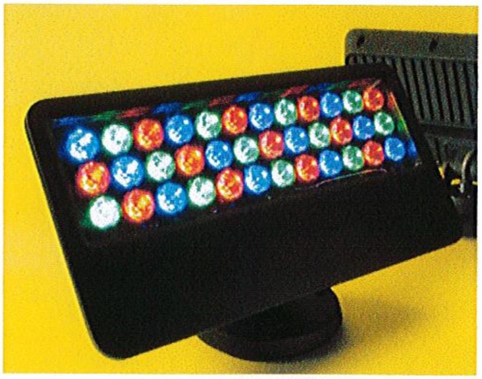

Figure 14 – The Color Blast 12 RGB LED unit. The unit had bad color-fringing problems as a result of poor LED placement

Eventually, this problem was solved by more complex arrangements of LEDs on the instruments and better optics. Another solution came in the form of RGB, RGBW, and RGBAW LED arrays on single chips. Rather than needing to arrange multiple LEDs in precise arrays, the colors would pre-mix in the on-board optics and leave the unit as one color. Wash units, like the one in Fig. 15, using this technology has increased the popularity of LED fixtures by eliminating any color fringing issues. However, the question of color changing profile systems still remains. In projection systems, LEDs can be finely tuned to overlap perfectly, like in (18). With profile wash fixtures, a color-changing instrument capable of matching the output of a halogen fixture is still desired.

Figure 15 – The Elation Opti Tri Par with 5 W RGB LEDs. Using single chip RGB LEDs eliminates color-fringing issues.

One unit that has made waves since its release in early 2012 is the Selador Lustr+ from ETC. Built around the same optical system as the Source Four, the unit rivals the output of a 375 W halogen fixture. Using the x7 color system described earlier, the unit can reach deep hues and nuanced pastels, but still has some issues with color fringing when focused sharply.

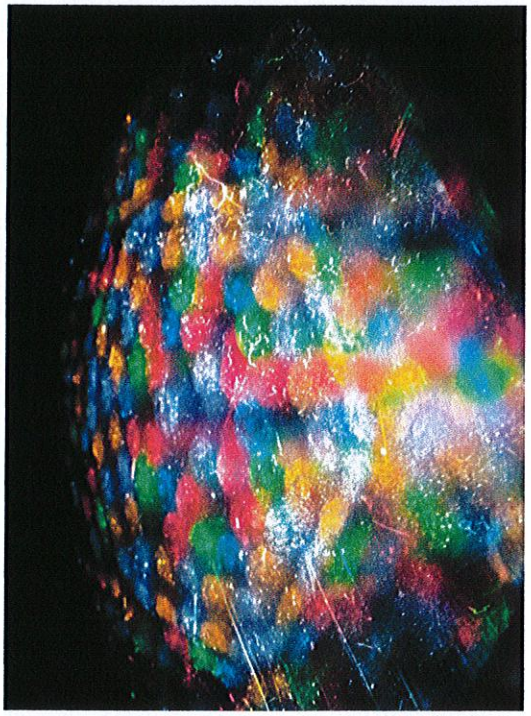

Figure 16 – The LED pattern from the color engine on the ETC Lustr+. The optics are focusing the light in such a way that each individual LED die is imaged on the lens before passing through.

In addition to color fringing, another challenge arises when using multiple sources and precision optics. Figure 16 shows the pattern of LEDs in the color engine of the Lustr+ as it appears on the optics of an instrument. Having the light focused at such a point that the optics act as a microscope and show the individual LED dies causes this. While having the fixture project light from a distance solves this problem, the challenge still remains to have an LED fixture that behaves the same as a Halogen fixture in all aspects.

V. OTHER APPLICATIONS AND CONCLUSIONS

While the applications and challenges explored for high-brightness LEDs in this review are centered on the entertainment and architectural industries, LEDs are rapidly gaining traction as replacements in many other areas. One of the most notable examples is the 60 W warm white replacement lamp now being offered by Cree for $13. This relatively inexpensive lamp consumes a mere 9.5 W while promising a lifetime of 50k+ hours.

As Haitz's Law states, LED prices will continue to drop in the next decade as output from these devices rises. While several of the challenges facing LED applications have been tentatively solved, many more remain. With increasing array density, better on-chip thermal management will be needed so that the graphite foam thermal system has heat to remove. More precise production systems also need to be developed to prevent mismatch issues as LED chip arrays increase in size.

Pending solutions to these challenges, projection systems may be able to some day replace their 12 kW HID sources with 500 W LED sources. With an LED profile fixture capable of matching the output of a 1200 W HID lamp, the entire super-bowl half-time show could only draw 100 MW, rather than 4 to 5 times that load.

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