High Brightness Light Emitting Diodes for Ocean Applications

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***Abstract-* Light Emitting Diodes (LEDs) are emerging in the undersea world as a reliable, efficient light source capable of narrow or wide chromatic bandwidth. Use of gas discharge lamps as light sources in the deep sea is complicated by the need to pressure protect the sealed bulbs. LEDs provide a viable alternative for many diver, submersible, and unmanned vehicle applications. While they are proving versatile, they also have unique characteristics that require designers to think differently. This paper will highlight those differences, draw similarities, offer common language, and suggest future developments. At sea tests with Woods Hole Oceanographic Institution's DSV ALVIN will be described.**

DeepSea Power & Light (DSPL) has been involved in severe environment LED lighting for over 10 years in a line of Pipe Inspection Video Cameras and has been involved in advanced underwater lighting since the company's inception 25 years ago. DSPL has successfully tested LED arrays to pressures in excess of that found in the deepest ocean trenches.

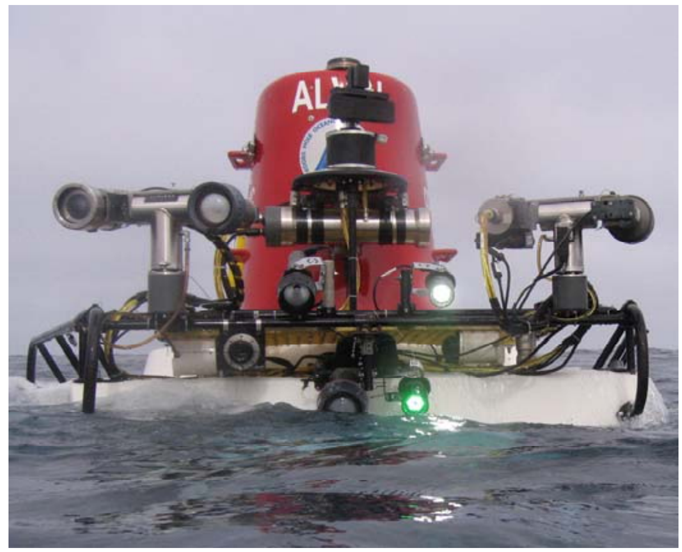
Figure 1. Woods Hole Oceanographic Institution's submersible ALVIN begins a 1-mile dive with new high power LED (light emitting diode) lights. Photo by Rod Catanach/Mark Spear, WHOI ALVIN Group.

I. Introduction

A. A Time of Change

This is a very dynamic time in the lighting world. LEDs, known largely as function indicators, are bringing revolutionary change to general lighting. It is expected that the efficiency of commercially available High Brightness LEDs (HB-LEDs), which just recently doubled, will double again in the next 12 months[1]. The evolution continues to happen at an exponential rate. Already, manufacturers are placing warnings on single chips to not stare at a fully powered LED or risk eye damage.

LEDs are quickly catching up to other forms of lighting in terms of total light output and efficiency. They have the potential to offer many significant advantages over currently available under water light sources, but require that a number of design challenges be addressed before these benefits can be realized. LEDs are very different from traditional light sources, and new design methods must be employed for optics, heat management, dimming control, and other characteristics.

DeepSea Power & Light, known for adaptation of the most advanced lighting technologies to professional undersea applications, recently tested its new underwater LED-SeaLites® on DSV ALVIN, Woods Hole Oceanographic Institution's iconic, pioneering manned submersible.

B. LEDs versus filament or gas discharge lighting

LEDs offer significant advantages over traditional incandescent or gas discharge lighting, including: 1) rapid on-off switching without damage; 2) increased efficiency to maximize battery life; 3) dimming without changing their emitted color, 4) ruggedness, vibration and shock resistance; 5) very long operating life (reduced total cost of ownership); 6) pressure tolerance; 7) choice of emitted spectrum; 8) unconstrained light array shape; 9) ability to run lamp in air without risk of damage to the lamp and reflector elements; and 10) smaller, lighter fixtures.

LEDs present unique challenges to system designers. Heat dissipation of high density LED arrays will remain the number one problem. Next, the large light emitting surface of high density LED arrays requires a new approach to reflector design. Other challenges include the high initial cost of components, an intimate knowledge of magnetic core inductors, and qualifying components tolerant of pressure compensation. Electronics are sensitive to electrostatic discharge and reverse breakdown voltages if not properly protected. LEDs and their driver circuits may cost more up front than traditional incandescent or gas discharge lamps of equal lumen output, but as technology improves, those costs will come down. Even with today's higher initial cost, use of

LED lights can provide significant cost savings compared to HID or halogen lamps when the total cost of ownership is considered. Some of the hidden costs associated with HID or halogen type lamps are: 1) routine re-lamping of the bulb as often as every 2000 hours of use; 2) cost of replacement lamps can range from a few dollars to several hundred dollars for high wattage lamps; 3) training technicians on the intricacies of seals, o-rings, and lubricants during lamp replacement; 3) high cost of repair for damage caused by accidental air burn; 4) and most importantly, and usually the most expensive, operational down time while a lamp is being replaced.

II. About LEDs

A. How LEDs work

An LED is a diode consisting of several layers of semiconductor material. Light is generated when the LED is forward biased, and electrical power is driven through a semiconducting material, where bound electrons capture, then release electrical energy as a narrow spectrum or monochromatic light. Different doping materials in the semiconducting material produce different colors of light. Most white LEDs utilize a single phosphor compound to absorb light emitted in the blue band, and reradiate it as broad spectrum white light.

B. Power measurement

Today's lighting fixtures operate with significantly higher efficiencies than fixtures of the past. The amount of power that goes into a lighting fixture as "watts" is not in itself a good indication of how much light you can expect to get out of the fixture. Light output depends on the combined efficiencies of the control electronics + lamp + optics, specifically in the `case of an LED light, drivers + LEDs + optics.

C. Lumens

The preferred method of classifying light output of a luminaire, or light fixture, is by its visible energy output, typically called out in "lumens" (L).

A "lumen" is a measure of light that can be perceived by the human eye. Other familiar light appliances, including liquid crystal display (LCD) projectors, describe their products in lumen output, that is, their total projected visible light. Other metrics, including "lux" and "candlepower" are directional intensity measurements and don't measure a light's entire useable output. The same light fixture, fitted first with a spot reflector, then a flood, will have the same lumens, but different lux values depending on how the light is focused. The best way to measure total lumens is with an integrating sphere, such as manufactured by SphereOptics (Concord, NH). An integrating sphere captures all the light emitted from a fixture inside a highly reflective sphere, removing any affect of a reflectors or optics, producing a measurement of total light (including the visible spectrum) known as "Radiant Flux." The human perceptible portion (lumens) of the total radiant flux is then derived, usually by software, from the measured radiant flux.

Underwater light fixtures gain a slight increase in light output due to water contact with the outside face of the pressure window or port. This causes less light to be reflected back into the fixture and results in an increase of a few percent.

D. Efficacy and Efficiency

Within the lighting industry, efficacy is a ratio of the amount of light (L) produced by a light source, to the energy used to produce it, measured in watts (w), and expressed as L/w. [2]

The theoretical maximum efficacy of an LED light source is 683 L/w for pure monochromatic 550nm, yellow-green light.

The maximum luminous efficacy of an "ideal" white source, defined as a radiator with a constant output over the visible spectrum and no radiation in other parts of the spectrum is approximately 220 lumens per watt. [3]

Efficiency of a light source is calculated as the ratio of visible energy output (watts) to energy input (watts), or watts/watts, and hence a dimensionless number.

Efficacy and efficiency are sometimes interchanged in published sources, generating some confusion.

There is some disagreement among LED manufacturers on how to measure and report efficacy. Most prefer to report maximum light output under ideal circumstances, typically optimized with a short electrical pulse and an instantaneous light measurement. Others, including DeepSea Power & Light, prefer to allow the LEDs to reach thermal equilibrium, then report that value. The latter method records less light, but is a more honest measurement that takes the net efficiency of the total light generating system into account and is consistent with how the LEDs will be operated in the field.

Using the latter method, the efficacy of the current generation of LEDs is about five times greater than incandescent light bulbs and is on par with all but the highest efficacy fluorescent sources.

E. Heat

LEDs, while very efficient, still produce heat. Unlike traditional sources which radiate heat as infra-red light from the source, the heat generated by an LED stays inside the semiconductor material and must be extracted via conduction and dissipated to prevent overheating and failure.

Excessive heat within the LED can cause reduced lumen output, color temperature shifts, and lower life expectancies. Fortunately, the sea provides an ideal heatsink. Transferring heat from the back of the LED to the ocean volume must be done through the shortest path and fewest thermal barriers. Metal Core Printed Circuit Boards are becoming standard practice, and methods to tie those to the housing challenge designers to minimize thermal transitions. Engineering physics of "solid state diffusion" and "barrier metals" are likely to enter the designer's thinking and vocabulary.

F. Reliability

Because LEDs are solid state devices, there are no shock sensitive elements to be broken, such as glass envelopes or thin wire filaments. If designed and constructed properly, LED arrays are highly reliable and have an extremely long life span.

G. Useful Lifetime

Because LED's rarely fail catastrophically but simply have a degraded output over time, engineers created a new set of metrics to properly characterize LED's used in their designs. The LED industry group "Alliance for Solid-State Illumination Systems and Technologies (ASSIST)" established LED life, or "lumen maintenance," as the time it takes for an LED to reach 70% of its initial light output[4]. Lumen maintenance can exceed many tens of thousands of hours. It is more likely an operator will change an LED light engine to upgrade because of improved lumen output than from failure of an LED string.

While manufacturers publish estimated life ratings for individual LEDs in enormous numbers of hours, a fixture using a large array of LEDs may not have anywhere near this life rating. Individual LEDs can be rated at 50,000 hours or even more, running cool in a controlled laboratory test environment. But dense LED arrays can suffer with inadequate heat sinking while left running in air on a hot deck. A good design will include a thermal sensing unit that rolls back the current and dims the LEDs when an elevated temperature is detected, reducing the supplemental heat generated by the LEDs and driver circuit, and insuring long life of the fixture.

H. Color Temperature

The "whiteness" of light is often tied to something called "color temperature" in degrees Kelvin (K). The surface of the sun is about 5880 Kelvin (5605 Celsius) which gives daylight its characteristic "whiteness". A higher temperature white (7000K), emits white light that has a bluer tint to it, while cooler temperature white (4000K) emits white light that has a redder tint to it.

High power LEDs producing narrow spectrum Red, Green, Blue, UV, IR, and other colors are currently available, giving the designer a virtually limitless palette to easily tailor the color output of the light. Color temperature is no longer fixed to a specific element or material in the lamp manufacturing process. Colors may be selected for a specific application by choosing an appropriate LED or combination of LEDs. With the advent of LEDs the designer is not required to use traditional light filters to block unwanted colors, robbing the end user of available light output and wasting energy.

I. Pressure compensation

Unlike traditional vacuum and gas-based light sources, LEDs are solid-state devices, packaged in epoxy or silicone, making them inherently resistant to pressure affects. DeepSea Power & Light has successfully driven its LED light engines and custom drivers to 20,000psi, studying the mechanics of phosphor contamination and pressurization. Satisfactory solutions have been found, while advanced research continues to characterize alternative approaches.

J. Drivers

LEDs are best operated as current-driven devices. While voltage remains relatively constant, average current is varied to control light output. DeepSea Power & Light incorporates temperature compensation circuitry to reduce drive current when LED temperatures exceed a critical level which would cause damage or degradation to the LEDs. When operating from AC mains, power factor correction circuitry becomes important, particularly in higher-power fixtures. Power efficiency is paramount in reducing heat and minimizing burden on the power source. DeepSea Power & Light drivers are extremely efficient and support nearly any power source including wide-range DC (Direct Current), high-voltage DC, and universal AC (Alternating Current) mains. Efficiencies exceed 95% in some cases, with power factor correction near unity.

K. Compact Reflectors

LEDs intrinsically direct their light forward in a "Cosine" or "Lambertian" distribution requiring only compact reflectors to redirect edge light. Still, the design of the LED reflector will make the difference between a spot light for maximum penetration, and the uniform floodlight needed for videography.

L. System Design

Together with the core knowledge described above, a complete LED underwater light design will incorporate housing, window, reflector design, heat sinking, power and control elements. Advanced designs may pressure compensate both LEDs and driver circuits in architectures completely driven by the form of the craft.

III. Future Applications

While LED arrays can create near daylight spectrum, their real gift may be in the ability to generate narrow bands of pure monochromatic light. In the UV, oil leaks fluoresce, a powerful observational tool when matched by a camera sensitive to the re-radiated light. Deep sea animals see primarily in the blue-green, having narrowed their sensitivity through natural selection to favor dominant bioluminescent colors, so lights in the red or near infrared may not disturb the natural behavior of some species, or attract them to the light source. It may be possible for marine biologists studying animal behaviors or ROV operators working on wellheads to see without being seen.

Additionally, recent test dives with the Woods Hole Oceanographic Institution's submersible, ALVIN, showed less backscatter and greater penetration in turbid bottom water using green LED lights compared to white. During ALVIN dives in June 2007, light bar tests and other performance metrics were taken to help evaluate the new LED lights. Observing the green LED light first hand at depth, Anton Zafereo, with the Woods Hole Oceanographic Institution's ALVIN Group, wrote: "Lighting up the Abyss, a new light-emitting diode (LED) system—built by Deep Sea Power & Light—was recently tested on the Alvin submersible during engineering dives in June off San Diego. The green lights appear to help pilots when the water is murky with particulate matter; the light does not necessarily penetrate farther, but there is less reflection than with white lights. The LEDs use about one-tenth of the power consumed by traditional Xenon, leaving more battery power for other things."[5]

Figure 2. Green LED lights show less backscatter than white lights, improving the pilot's ability to see ahead. Parallel red lasers on the left are used to provide scale to objects within the field of view.
Photo by Anton Zafereo, WHOI ALVIN Group.

DeepSea Power & Light has a number of LED projects working their way through Research and Development, including high power "bottle cap" LED-lights for mini-ROVs, diver helmet lights, and flat panel light fixtures for the next generation of deep ocean free vehicles. Powered by light weight pressure-compensated batteries, the LED panels can provide light for long term timelapse remote filming. One day, panels of LED lights may surround a submersible or ROV, and the vehicle pilot can swivel a camera while sequential panels illuminate a sector, following the camera motion. A submersible, maintaining constant course, depth, and speed, can pass a hydrothermal chimney, filming it with constant illumination as the active vent approaches, passes, and recedes from view.

Other emerging topside marine applications of LEDs include oil platform, ship, buoys, safety, general lighting, and survival systems. LEDs are well suited for unattended operation, battery back-up, or hazardous environments.

DeepSea is adapting flat panel arrays of LEDs for deep ocean free vehicles. Powered by pressure compensated batteries, the LED panels are cooled by the great ocean interior.

IV. Conclusion

LED lights have created new opportunities for manned and unmanned vehicle designers. No longer constrained by circles, spheres, and cylinders, designers can create hydrodynamic shapes and incorporate LEDs in a freeform manner that are able to survive even the crushing pressures of deep ocean trenches. While not all traditional lights can be replaced by LEDs as of today, that time is coming.

Acknowledgment

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Footnotes

[1]Cree, Inc (Durham, NC), estimate, 2007
[2] http://en.wikipedia.org/
[3]IES reference volume, 1984, Section 2-6, Luminous Efficacy of Light Sources
[4] ASSIST, the Alliance for Solid State-State Illuminations and Technologies
[5] http://www.whoi.edu/page.do?pid=10897&i=2741&x=209

References

[1] Among many good background references on LEDs components and systems is Rensselaer Polytechnic Institute, Lighting Research Center, (http://www.lrc.rpi.edu).