Advances in High Brightness Light Emitting Diodes in Underwater Applications

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Abstract- **Light Emitting Diodes (LEDs) continue to make headway in the undersea world as efficient and durable light sources. Previous papers by the authors have discussed differences and advantages over gas discharge lamps** [1], [2], [3]. **Undersea lighting designers continue to follow the rapid development of LEDs for general commercial illumination. In addition to improvements in LED technology, electronic drivers have become more compact and increasingly efficient, providing options to end users for thermal roll-back, dimming, AC/DC, or variable voltage input with constant current output. DeepSea Power & Light® (DSPL) engineers have devised techniques to pressure compensate both the LEDs and the driver electronics, successfully testing LED arrays and drivers to 20,000psi. Using a component integration matrix, new configurations of light systems are rapidly emerging for many diver, manned submersible and unmanned vehicle applications.**

This paper will summarize advances in High Brightness LED lighting systems, in-house and field testing methods, and suggest where ongoing developments will take us next. Recent at-sea experiences are discussed.

DeepSea Power & Light® (DSPL) has been involved in advanced underwater lighting since the company's inception 25 years ago, and with applications of LED lighting in harsh environments for over 10 years in a line of Pipe Inspection Video Cameras.

I. Introduction

A. About LEDs

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.

An LED is a diode consisting of several layers of semiconductor material. Light is generated when electrical power is driven through the semiconducting material, where bound electrons capture, then release,

Figure 1. DeepSea Power & Light®'s LED-MultiSeaLite® is the most advanced solid state undersea light on the market today. The LED light is rated for 6,000m and 2,000 lumen output, and retains the slender form of DSPL's popular MultiSeaLite®.

electrical energy as monochromatic light. Different doping materials in the semiconducting material, called a "die," produce different colors of light. Most white LEDs utilize a single phosphor compound over the die to absorb monochromatic blue light, and reradiate it as broad spectrum white light.

An LED is one component in an electronic circuit. The portion of the circuit between the LEDs and the power source is called the "driver."

Important metrics associated with LEDs include:

Brightness: High Brightness LEDs (HB-LEDs) produce light in the 70 to 120/lumen per watt range. Manufacturers are now placing a "Vision Advisory Claim" safety warning in the specification sheets. For one, Cree warns, "The consumer of this Cree product should be aware that one should not stare directly into the light beam." [4]

Lumens versus watts: LEDs are about five times more efficient in producing white light than incandescent lamps, so a more practical measurement of the white light output of the lamp is lumens (L) rather than power input of watts (W). A "lumen" is a measure of light as perceived by the human eye. The human eye is most sensitive to the green segment of the spectrum, as characterized in the C.I.E. Chromaticity Diagram. Because of this variability of the human eye in sensitivity to different colors, the output of any monochromatic light source is best stated in milliwatts (mW).

Heat: LEDs, though very efficient, still produce heat. The heat generated by an LED must be conducted via the shortest path to the cool ocean to prevent overheating and failure.

Efficacy and Efficiency: Efficacy is The ratio of the amount of light (lumens, "L") produced by a light source, to the energy used to produce it, measured in watts (w), and expressed as L/w. [5] Efficiency of a light source is calculated as the ratio of visible energy output (watts) to energy input (watts), or watts/watts, a dimensionless number.

Most LED manufacturers prefer to report maximum light output under ideal circumstances, typically optimized with a short electrical pulse and an instantaneous light measurement. Others, including DSPL, prefer to allow the LEDs to reach thermal equilibrium, then report that value. The latter method records less light, but is a more realistic measurement, reporting what the operator will see in the field.

Reliability: LEDs are solid state devices without shock sensitive elements, such as glass envelopes or thin wire filaments, providing an extremely long life span.

Lifetime: 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 [6].

While manufacturers publish estimated life ratings for individual LEDs up to 50,000 hours or even more, these are best case scenarios running cool in a controlled laboratory test environment. Dense LED arrays can suffer from overheating, for example, if left running in air on a hot deck. DSPL incorporates a thermal rollback circuit to reduce current and dim the LEDs, which lowers heat without shutting off the light completely.

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

Reflectors: LEDs inherently direct their light forward in a "Cosine" or "Lambertian" distribution requiring edge light to be redirected. DSPL has devised compact reflectors that are optimized to create either a spot light for maximum forward penetration, or a uniform floodlight needed for videography.

II. Advancements in LED Technologies

In the past year, the principle advances in LED technology have occurred in the area of A) increase in light out for power in (lumens/watt), B) multi-chip packages, and C) drivers.

A. Improved Efficacy

A year ago we reported efficacies on the order of 80-lm/watt for the best cool white LEDs. Today we are looking at 120-lm/watt @ 350mA as the best commercially available. As more light is pumped out the front, less heat is pumped out the back, and the design challenges get easier.

As more current is passed through an LED, the light output increases, but the output is not linear, actually producing less lumens/watt. With a decrease in lumens/watt, there is a corresponding increase in the waste heat/watt. As a result, there is a diminishing return for currents higher than peak efficiency generally found at about 1W per 1mm^2 chip.

B. Multi-chip packages

To maximize light output from a package at the highest lumens per watt, LED manufacturers have begun packaging multiple LED dies onto a single platform, and housing them under a single silicone dome. This allows a higher density of LED dies, each operating at their point of maximum efficiency, creating the most light with the least heat in the smallest package. Some of the contenders for this market segment are Osram OStar (6 dies), Cree MCE (4 dies), Seoul Semiconductor P7 (4 dies), and Seoul Acriche. The Cree MCE has 4 dies, each producing a maximum of 120-lm per watt, yielding a brilliant 480-lm per LED package at 4 watts. The Seoul P7 produces 90-lm/watt. The Acriche utilizes two parallel strings of 36 tiny LED dies, 72 total per part, to run directly off AC current using just a current limiting resistor. While this circuit is the ultimate in simplicity, it does not lend itself to a wide range of dimming options, is susceptible to overvoltage transients, and may produce flicker problems with some video systems. The best Acriche

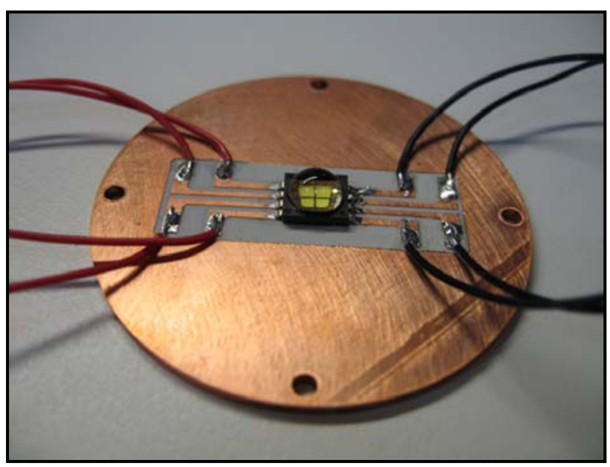

Figure 2. A Cree MCE multi-chip LED is shown on a test fixture during testing at DSPL. Multi-chip LEDs allow for more light from a single package while operating at the most efficient current.

produces about 80-lm per watt.

C. LED Drive Electronics and Dimming Circuitry

DSPL has developed a series of highly efficient drive electronics to accommodate the wide range of power sources available in undersea manned and unmanned vehicle applications. Low voltage DC, in the 9-32V range, accommodates a wide range of battery voltages. Special-application, high-voltage AC/DC inputs, universal (85-265VAC 50/60Hz) inputs, isolated flyback and non-isolated buck/boost converters, power factor corrected inputs have all been successfully developed. Miniaturization, both for compactness and reduced compressible air volume, has been a driving design constraint. DSPL has developed compact drivers that achieve high output power. Efficiency is the key, and DSPL switchmode regulators deliver precise and constant current to the LED array at efficiencies exceeding 93%.

Temperature monitoring circuitry reduces the drive current to maintain the LEDs within their safe operating limits, as excessive heat significantly reduces the LEDs lifespan. This temperature compensation is paramount in achieving the usability required by demanding undersea applications. Concerns of light fixtures overheating without water-cooling are eliminated, as are Start-up/cool-down requirements of HID and Xenon ballasts. The LED luminaire becomes as easy to use as a flashlight, and DSPL has produced such deep-water-capable LED lights at over 5000 lumens of light output in an impressively compact and rugged package.

Certain applications require dimming, and DSPL has developed a modular approach to accommodate the numerous dimming interfaces encountered, including isolated and non-isolated control voltage (0-10VDC), current loop (4-20mA), PWM and serial communications. In video applications, constant-current without phase blanking is often required to avoid black video frames. In other applications, phase-blanking is perfectly acceptable. DSPL works with an end-user to define and deliver the LED lighting system most appropriate for their application.

III. Field Experiences

A. DSV ALVIN

DSV ALVIN, Woods Hole Oceanographic Institution's famed manned submersible, has operated at sea with DSPL's 2000-lumen LED-SeaLites® since June 2007. The efficiency of the LED lights over the Xenon allow WHOI pilots to operate three times the lights with half the power. Dives conducted in March 2008 on the 9-North hydrothermal vents allowed the pilots to navigate 6km on the seafloor with all lights running continuously, an operational first.

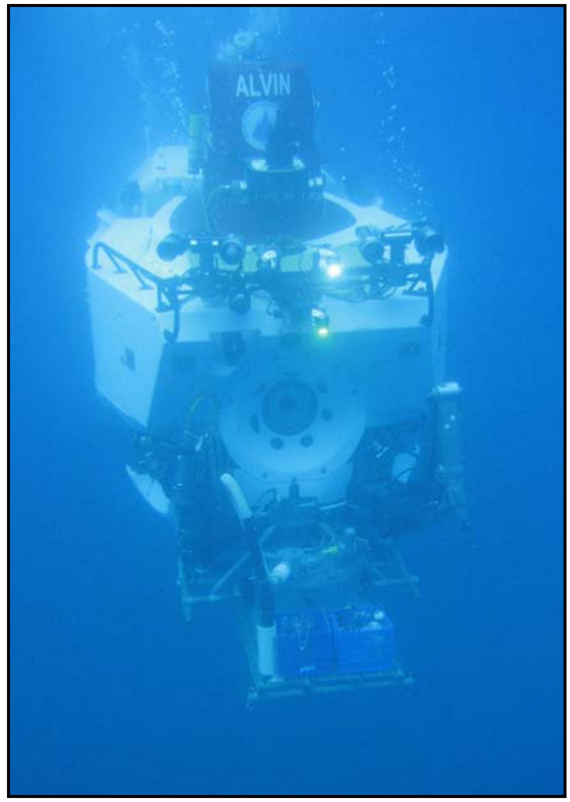

Figure 3. Woods Hole Oceanographic Institution's famed submersible ALVIN leaves the surface off San Diego, CA, USA, on the start of a 1-mile dive with DSPL's new high power LED-SeaLites® lights. Photo by Rod Catanach/Mark Spear, WHOI ALVIN Group.

DSPL recently developed a prototype Cree multichip MCE ultra-high brightness LED-SeaLite® for DSV ALVIN for operations on the Juan de Fuca Ridge off the coast of the State of Washington. DSV Alvin pilot Mark Spear reported, "The light has been on the front of the sub for three dives now acting as a basket / fwd light. It is side by side with the pilot's 400w HMI. So far we are very happy with it and I'll get you more feedback as the cruise progresses."

B. ROV ROPOS

Figure 4. Canadian Scientific Submersible Facility - ROPOS ROV before an evaluation dive with DSPL's 2000-lm LED-MultiSeaLite® (red arrow), and other lights. Photo by Reuban Mills, ROPOS

DSPL provided the Canadian Scientific Submersible Facility - ROPOS (http://www.ropos.com/) with a pair of 2000-lumen LED-SeaLites® for evaluation and comparison to DSPL 150 w and 400w HID lights.

Reuben Mills, Mechanical systems design /Pilot, reported "Lights are great, should be perfect for instrument deployments with that efficiency. The HD video with the 400w's, the 150w's & the LED's is pretty stunning."

He added, "We were very impressed with the beam control on the spot unit, like a large laser pointer! I have these lights spec'd for an 8 camera 3D imaging array we're building for the University of Alberta this winter."

C. Diver

Wildlife Filmmaker and Underwater Frontiersman, Scott Cassell, (http://www.sea-wolves.com/), recently paired a DSPL low light camera with two LVDC LED-SeaLites® for dives to film his favorite subject, the voracious Humboldt Squid.

Using the DSPL LED-SeaLites®, Scott believes he has a greater chance of getting the shots he needs in the dark and green waters off Santa Rosalia, Sea of Cortez, Mexico. DSPL has also donated the use of a prototype Night Vision Camera system to film a new Discovery documentary that will air in late 2008 called "Squid Invasion," produced by Creative Differences. With this new camera technology, Scott was able to non-invasively film the Humboldt Squid, unobtrusively imaging them display natural behaviors. The night vision camera documented previously unseen behavioral patterns of the squid, and demonstrated new ways to study the species.

Scott called the white DSPL LED-SeaLites®, "incredibly awesome," and looks to "film a feeding frenzy of Humboldt Squid at night in white light to compare their behavior filmed with the DSPL Night Vision camera. It is suspected they will behave more aggressive in white light because they will be more hurried."

Figure 5. Undersea film maker and explorer, Scott Cassell, holds a live 7-ft Humboldt Squid. Scott has experimented with prototype DSPL LED lights and cameras in his filming. Photo copyright by Ivo Kocherscheidt, 2007. Used with permission.

"That light is the finest light I have ever used," said Scott. "It is durable, broad beamed and clear white color. It worked perfectly for use with the night vision system (I would spot the squid with the light, then turn it off for the NV to capture images). What I found is that it is perfect for HD video."

Tests of the affects of monochromatic LED light on animal behaviors are slated for the Fall 2008 in the Sea of Cortez.

IV. Future developments

DSPL continues advanced development projects on the next generation of deep ocean, light weight LED lights. Alternate methods of pressure compensating are being evaluated for performance and robustness, and their adaptation to large area panel lights. Novel methods of pressure compensating drivers and elegant methods of heat dissipation will create some of the most unique lights made by man ever seen below the surface of the sea. One light design uses a shape cast window to blend the light fixture into the leading edge of a dive plane.

V. Conclusion

LED lights continue to make inroads into the world of underwater illumination. Semiconductor lights provide safety, flexibility, and efficiency. Applications will continue to be found as designers gain experience and confidence.

Acknowledgments

The authors gratefully acknowledge and thank the WHOI ALVIN Group, particularly Rick Chandler, Pat Hickey, Mark Spear, Bruce Strickrott, and Rod Catanach for their continued interest in deep ocean LED lights. These men continue the best seafaring traditions of oceanography.

The authors also thank Jerry Kolansky, Cree Inc, (Durham, NC), for providing us the opportunity to test the earliest beta releases of the multi-chip MCE device.

Thanks to Reuben Mills, ROPOS for his field test feedback on beta versions of the LED-SeaLites®. Honest feedback from men at the sea helps steer our final design.

Special thanks to Scott Cassell for his harrowing and inspiring work with the powerful Humboldt Squid. Scott is a favorite with DSPL employees as he personally shares his tales of adventure, and their implications, with the folks who work here.

FOOTNOTES

[1] "High Brightness Light Emitting Diodes for Ocean Applications," K. R. Hardy, M. S. Olsson, J. R. Sanderson, B. P. Lakin, J. E. Simmons, P. A. Weber, Oceans2007 Proceedings, Vancouver, Canada

[2] "Underwater Application of High-Power Light Emitting Diodes," M. S. Olsson, K. R. Hardy, J. R. Sanderson, Sea Technology Magazine, August 2007, Vol. 48, No. 8, pp 31-34

[3] "Submerged Application of High Brightness Light Emitting Diodes," Intervention 2008 K. R. Hardy, M. S. Olsson, J. R. Sanderson, B. P. Lakin, J. E. Simmons, P. A. Weber, Underwater Intervention 2008 Proceedings, New Orleans, LA

[4] Cree X-Lamp 7090 XR-E Series LED, Data Sheet, CLD-DS05.001, 2006,
pp 7

[5] <http://en.wikipedia.org/wiki/Efficacy>

[6] ASSIST, the Alliance for Solid State-State Illuminations and Technologies
www.lrc.rpi.edu/programs/solidstate/assist/index.asp

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