High-Power GaN-based Laser Diodes for Next Generation Applications

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Abstract

We present a new class of laser-based light sources based on state-of-the-art gallium nitride (GaN) violet and blue emitting laser diodes. Using semipolar GaN, we demonstrate high-power, high-efficiency continuous-wave laser diodes with wall-plug efficiencies of over 40% and optical output powers of over 5 watts in both the violet and blue wavelength ranges. By combining the high-efficiency blue laser diodes with high-efficiency wavelength converters, we present LaserLight white light sources with 10-100X higher brightness than LEDs, enabling styling and integration not previously possible with solid state light sources. With the capability to illuminate, sense, and communicate, LaserLight sources will revolutionize the future of lighting in mobility and smart infrastructure.

Introduction

Gallium nitride (GaN) based laser diodes (LDs) were first introduced in Blu-ray optical disc storage for increased data density. In 2010, GaN-based laser diodes emerged in the display market where high-power blue LDs serve as the light engine in laser-pumped phosphor projection display systems. More recently, high-brightness solid state LD sources have been combined with phosphor converters to generate white light sources that overcome the fundamental brightness limitations associated with LEDs known as efficiency droop.

With a brightness of 10-100X higher than LED-based sources and the opportunity for drastically higher delivered lumens per watt, LaserLight is ideal for many existing applications and will drive the future of solid-state lighting. The high brightness of LaserLight allows for a drastic (1/10) size reduction in optics for styling not possible with LED, a beam distance and range increase of 10X, and efficient white light fiber-coupling. By leveraging the fast temporal response of the GaN LDs along with the inclusion of infrared LDs, the light sources can be configured for high accuracy sensing and ranging, LiDAR imaging, and high-speed data transmission of over >100 Gb/s in LiFi communication systems.

In this paper, we first provide a performance overview of state-of-the-art semipolar high-power GaN LDs. Next, we describe LaserLight products that leverage the high efficiency LDs to generate white light and IR light to deliver the next generation of lighting with sensing and communication.

High power Semi Polar Laser diodes

Utilizing semipolar GaN to mitigate the internal polarization fields present on c-plane and enable a drastically increased design space, we present blue and violet LDs with over 5 W output power under continuous wave (CW) operation. In the blue wavelength range of 440-455 nm, LDs deploying a cavity width of 45 µm and a cavity length of 1.2 mm packaged in TO-9 cans demonstrate a peak wall plug efficiency (WPE) of ~41% as shown in Figure 1. In the violet wavelength range of ~405 nm, LDs deploying a cavity width of 30µm and a cavity length of 1.2 mm packaged in a TO-9 demonstrate a peak WPE of ~42% as shown in Fig. 2.

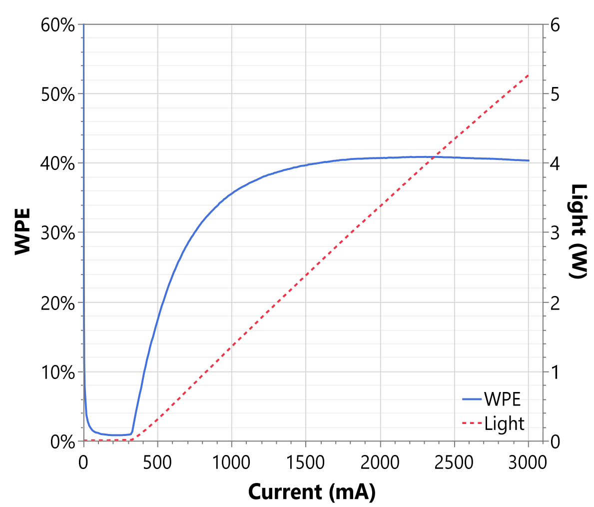

Fig. 1: CW measurement at 20°C base of a blue (440-455 nm) laser diode (threshold (Ith)=300 mA, slope efficiency (SE)=2.0 W/A)

Current production high-power blue LDs operated at an optical output power of 3.5W packaged in TO-9 cans with a 60°C base temperature (Junction Temperature, Tj of 110°C) demonstrate a projected L70 (light output degradation of 30%), mean time to failure (MTTF) of more than 11 khrs. The next generation high-power blue LDs operated at an optical output power of 4.5 W with a Tj of 100°C demonstrate a projected L70/MTTF of about 25 khrs. Recent process breakthroughs are expected to provide both an improved WPE and a lifetime increased by a factor of 2.5 to 3X.

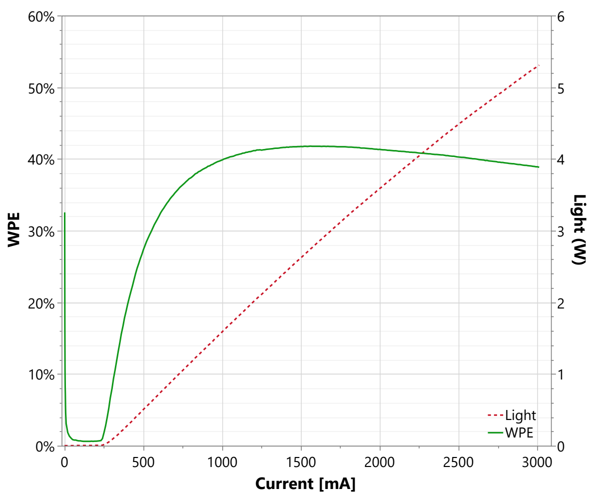

Fig. 2: CW measurement at 20°C base of a ~405 nm violet laser diode (threshold (Ith)=250 mA, slope efficiency (SE)=2.1 W/A

LaserLight Phosphor pumped Light Source

By combining the high-power, highly-efficiency semipolar blue GaN LDs with high-efficiency phosphor wavelength converters we have commercialized a reliable, eye-safe, compact (7 mm x 7 mm) white light source in a surface mount device (SMD) package as shown in Figure 3. The eye-safe, fully hermetic SMD LaserLight source architecture utilizes a reflective mode phosphor excited by blue LDs to generate high brightness white light. The white light SMD products can deliver over 1000 lumens of flux and a luminance of >1500 cd/mm^2, from an emission spot on the phosphor with <300 µm full width half maximum (FWHM).

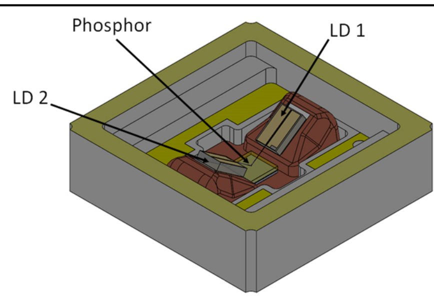

Fig. 3. Schematic of laser SMD package including LD chips and phosphor material

The reflective SMD architecture enables the integration of multiple LDs to provide a wide range of product capability options as shown in Figure 4. For example, configurations with only a single-blue-LD can provide 500 lumens of output while configurations with dual-blue LDs can enable >1000 lumens of output. Moreover, the architecture enables the integration of alternative wavelength LDs to create a collinear source of white light and alternative wavelength light. In one such configuration, a single blue LD is combined with an infrared (IR) LD to create a LaserLight white + IR (WIR) SMD with both white and IR light emitting from the same source spot on the phosphor. These WIR sources combine the powerful white light LaserLight emission with IR emission for night vision illumination, sensing, and communication.

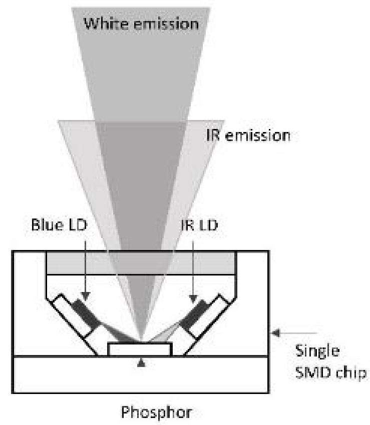

Fig. 4: Cross-section schematic of a WIR-SMD consisting of dual wavelength collinear emission from blue and IR LDs in an SMD package.

By leveraging the fast temporal response of the integrated blue and/or IR LDs, LaserLight sources can generate short pulses of light for time-of-flight (ToF) depth sensing, ranging, and full three-dimensional light detection and ranging (LiDAR) imaging. These sources can be deployed to augment current sensing suites in mobility applications. Figure 5 presents a demonstration of full 3D LiDAR imaging using LaserLight SMD sources equipped with an 850 nm LD. Using an integrated 905 nm LD, we have demonstrated distance detection and ranging of more than 250 meters with only a 1% RMS root mean square of error.

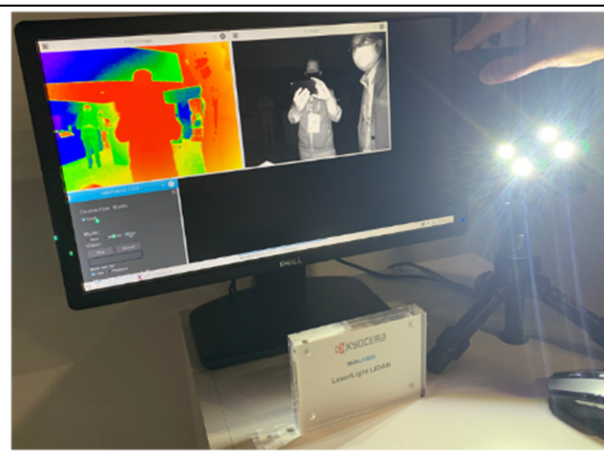

Fig. 5: Demonstration using 4 WIR-SMD combining white light illumination, night vision (grey scale image) and depth sensing (colored image) functions

LaserLight spotlights

The LaserLight SMD can be easily coupled with a small diameter (35 mm) parabolic reflector or lens to create a highly collimated source with divergence angles of 1-2 degrees enabling light weight, compact, ultra-long range (> 1 km with only 500 lm source) spotlights. With low power consumption, the spotlights can be used as a battery-operated long-range flashlight or as a LaserLight Microspot shown in Fig. 6.

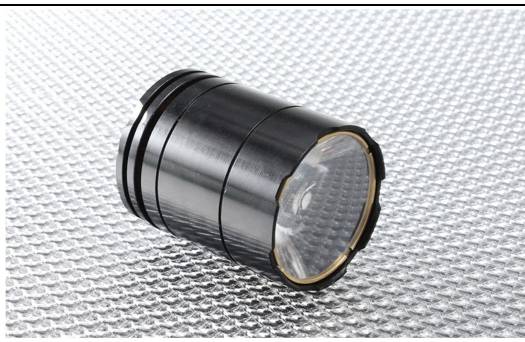

Fig. 6: LaserLight Microspot

LaserLight Microspot sources can be arranged in an MxN array to aggregate the light output and form exceptionally powerful, lightweight, and very high light output spotlights capable of ranges over 10km. Fig. 7 presents an array comprised of 100 SMDs to generate 50,000 lumens. These high-power spotlights can be leveraged in many applications including defense, security, search and rescue, entertainment lighting, and industrial lighting.

Fig. 7: LaserLight spotlight (50,000 lumens, 25 million cd) with 10km beam range

LaserLight Fiber Coupled SMD (FC-SMD)

The very high brightness of the LaserLight SMD sources enables high coupling efficiency of the white light into small diameter fibers. Such efficient white light coupling is not possible with LEDs where the efficiency is about 1/10 of what can be achieved using the LaserLight sources. In Fig. 8 we present a fiber-coupled SMD (FC-SMD) light source wherein the white light from the SMD is coupled into a ~1 mm diameter glass fiber with high efficiency. The fiber can be configured to transport and deliver the white light to a remote location, or to emit the white light along the length of a fiber to create a 1-dimensional emissive fiber light source.

Fig. 8: FC-SMD with associated optical connector.

In Fig. 9 we present a FC-SMD using a small diameter (<1.5mm) side emissive fiber. In this configuration an illumination level of 8000cd/m^2 over several meters of fiber has been achieved.

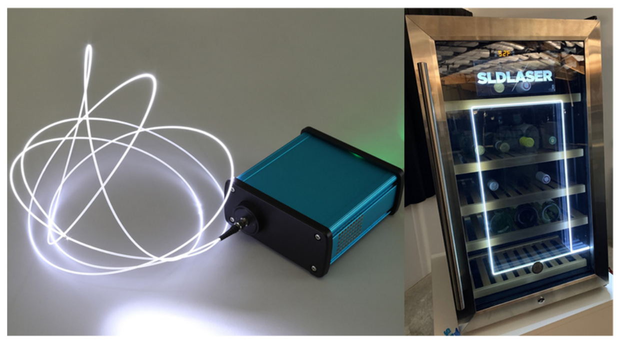

Fig. 9: (left) FC-SMD configured with a side emissive fiber, (Right) Example of commercial application

The FC-SMD light source enables a wide range of applications in interior and exterior automotive, architectural lighting, underwater lighting, tunnel lighting, and lighting in harsh environments such as within appliances or industrial application. When connected to a transport fiber the FC-SMD can be used as a safe long distance remote white light source with maintenance advantages and increased safety in various types of sensitive environments.

LiFi Applications

Using the high modulation bandwidth of the LDs within the LaserLight SMD, the light source is ideally suited for deployment in light fidelity (LiFi) wireless communication systems. Serving as LiFi transmitters, the SMDs enable the illumination and communication functionalities to be fused into a single device. The sweeping benefits over conventional radio frequency (RF) based communication systems have positioned LiFi to play a critical role in future wireless networks. These benefits include increased data security, elimination of electromagnetic interference concerns that limit current RF-based communication systems, abundantly available spectrum to accommodate the inevitable explosive demand for bandwidth, and substantially increased data rates over state-of-the-art 5G networks. Example applications that will benefit from LiFi include automotive and avionic communication systems, smart factories, smart homes, smart infrastructure, and government and defense communications.

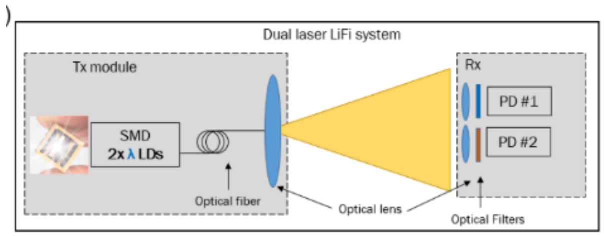

Fig. 10: Schematic of single SMD dual channels based LiFi system

By utilizing a single LaserLight WIR-SMD source and combining the orthogonal frequency division multiplexing (OFDM) data encoding scheme with wavelength division multiplexing (WDM) [1] wherein both the blue LD and the IR LD were modulated for communication, we demonstrated data rates over 25 Gbit/sec at a distance of 5 meters. Fig. 10 presents a schematic of this system. In more recent work we demonstrated a LiFi systems with over 100 Gbit/sec comprised of 10 SMDs applying OFDM and WDM. This world record LiFi data rate, readout shown in Fig. 11, represents 100X the speed of state-of-the-art 5G wireless networks. In other notable LiFi embodiments, over 2 Gbit/sec was demonstrated from a FC-SMD with a side emissive fiber, which has a wide range of interesting applications.

Fig. 11: >100 Gbit/sec LiFi Demonstration

Conclusion

We presented state-of-the-art high-power, high-efficiency blue and violet wavelength LDs fabricated on semipolar GaN. By integrating these LDs with high-efficiency wavelength converters to form bright white LaserLight sources, we introduced novel products and applications enabled by the unique capabilities of LaserLight technology and not possible with LEDs. These products include the high brightness SMD source, the FC-SMD, the LaserLight Microspot, and arrays of LaserLight sources to generate high-flux, long-range spotlights capable of illuminating targets at distances over 10 km. With the inclusion of IR based LDs in the SMD, the light sources can serve both visible illumination and night vision illumination. Finally, with fast temporal response LDs serving as the light engine, the LaserLight sources enable beyond illumination capabilities that include sensing, range finding, LiDAR, and high-speed LiFi communication sources. In summary, LaserLight technology based on GaN LD technology offers an all-in-one fusion of illumination, sensing, and communication to drive the future of lighting in mobility, smart infrastructure, and defense and security.

Acknowledgements

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Acronyms

CW: Continuous Wave
FC-SMD: Fiber Coupled SMD
GaN: Gallium Nitride
IR: Infra-Red
Ith: Threshold current
LD: Laser Diode
LED: Light Emitting Diode
LiDAR: Light Detection and Ranging
LiFi: Light Fidelity
LIV: Light/Current/Voltage
MTTF: Mean Time To Failure
RMS: Root Mean Square
SE: Slope Efficiency
SMD: Surface Mount Device
ToF: Time of Flight
WPE: Wall Plug Efficiency
WIR: White + IR