Recent Progress in High-Power Laser Diodes and Laser Packages for Projection Display Applications

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Keywords: High-power laser, blue LD, green LD, LD package, RGB Laser.

ABSTRACT

The wall-plug efficiency of blue and green Laser Diode (LD) chips for laser projection display applications exceeding 48% and 21% respectively was achieved. Our development laser package with 24 blue LD chips installed has achieved an optical output power of 124 watts.

1 INTRODUCTION

After the first development of InGaN-based LDs in 1995 [1], the characteristics of LDs, such as optical output power, efficiency and reliability, have been improved. Now that our products with InGaN-based LDs cover a wide range of wavelengths from UV to green, the LD applications and markets have been expanding accordingly. InGaN-based LDs are used in consumer applications such as optical disc drives, industrial applications such as lithography equipment, more recently in display applications such as laser projectors, and automotive laser headlights.

Especially for display applications, lasers are unique light sources with high monochromaticity. RGB LDs enable the ultimate display with a wide range of color reproduction. Following the development of watt-class green LDs [2], high-power LDs for the three primary colors of RGB are now available. RGB laser light sources are widely used for high luminance light sources for digital cinema projectors, large laser projectors, projectors for businesses and laser TVs. Light sources combining high luminance blue LDs with phosphor are very efficient in projecting light and are now used in laser projectors and laser TVs. Traditional lamp based light sources with relatively short life and high-power consumption are being replaced with lasers. Particularly, by using low-etendue LDs as light sources, energy-saving, high-brightness and high-efficiency systems are realized.

In these ways, LDs have many merits and great potential for use in displays. Improving the performance of LDs is essential for the advancement of these applications. This paper reports the latest device performance, such as optical output power, voltage, and lifetime of high-power blue and green LDs [3]. Furthermore, the latest LD packages equipped with multiple LD chips targeting projector and display applications [4] are also disclosed.

2 PROGRESS OF BLUE AND GREEN LD

We developed the first blue LD in 2001 [5], which had an optical output power of 5 mW. Also, we developed high-power blue LDs on GaN substrates, which had an optical output power of 200 mW in 2005 and 500 mW in 2006 respectively. By adopting a TO-9 CAN package instead of a TO-5.6 CAN package for reducing the thermal resistance, 445 nm blue LD had an optical output power of 1.17 W in 2009. 3.75 W was achieved in 2012 by heat dissipation improvements, such as junction down mounting and so on. We increased the optical output power to 4.7 W in 2017 [6] and 5.25 W in 2019 [7] through further improvements. Figure 1 shows the development history of the wall-plug efficiency of our high-power blue LDs. The wall-plug efficiency of our blue LDs was doubled from 21.7% in 2006 to 43.4% in 2019 [7] by optimizing the structure of epitaxial layers, device structures and packages. In this time, we reached over 48% wall-plug efficiency at 455 nm.

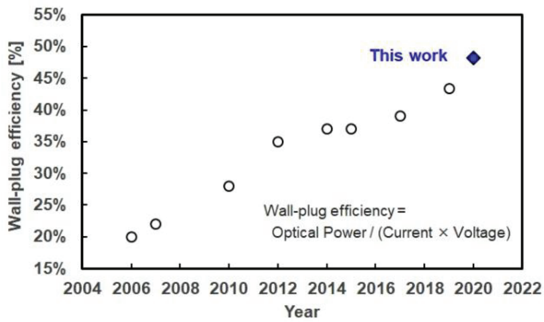

Fig. 1 Development history of the wall-plug efficiency of high-power blue single emitter LDs

On the other hand, for use in digital cinema projectors, watt-class green LDs are needed to realize wider chromaticity. Figure 2 shows the development history of the wall-plug efficiency of our high-power 525 nm green LDs. In 2012, we reported the first watt-class 525 nm LDs, and the optical output power and wall-plug efficiency of 525 nm LDs were 1 W and 14.1% [2]. We have already reported further efficiency development of 525 nm green LDs, which had a wall-plug efficiency of 15% in 2015 [8] and 15.9% in 2017 [6] respectively. By optimizing the epitaxial structure and device structure, the wall-plug efficiency of the 525 nm LDs was 18.1% in 2019 [7]. In this report, we developed the wall plug efficiency of 525 nm green LDs exceeding 20%.

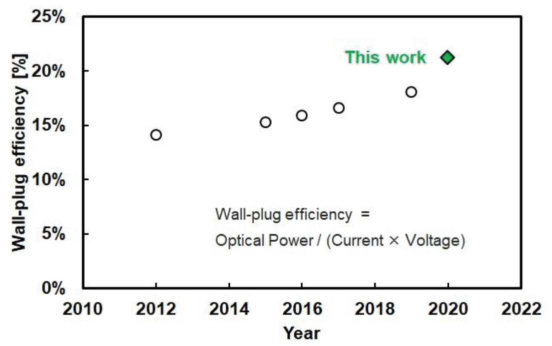

Fig. 2 LD history of the wall-plug efficiency of high-power 525 nm green single emitter LDs

3 HIGH-POWER BLUE AND GREEN LDs

3.1 Fabrication of Blue and Green LDs

We optimized the epitaxial and the device structures for high efficiency, high optical power and reliability of LDs. The epitaxial structures of LDs including n-type, active and p-type layers were grown by metal organic chemical vapor deposition (MOCVD) on C-plane free-standing GaN substrates. The structures were separate confinement heterostructure (SCH) which was based on cladding layers, guiding layers and quantum wells. Quantum wells of green LDs were thinner and higher Indium composition than those of blue LDs. A ridge type structure and electrodes of the n-type and p-type were formed. The ridge widths of blue and green LDs were 45 µm and 20 µm respectively, and both LDs have cavity lengths of 1,200 µm. Dielectric mirrors were deposited on front and rear mirror facets, which were obtained by cleavage at the m-plane surface. Each LD chip was mounted on a heat sink using a junction down mounting method on a thermally optimized TO-9 CAN package for reducing thermal resistance.

3.2 Results of High-Power Blue LDs

We fabricated high-power, multiple longitudinal mode blue LDs with peak wavelength of 455 nm. Figure 3 shows optical output power-current (L-I) and the voltage-current (V-I) characteristics of 455 nm blue LDs under continuous wave (CW) operation at 25 ºC. The threshold current was 0.30 A. The optical output power and voltage were 5.67 W and 3.93 V at 3 A respectively. The wall plug efficiency was 48.1% at 3 A and the peak wall-plug efficiency was 49.1% at 2 A. As far as we know, the wall-plug efficiency of the high-power blue LD we developed is the highest reported so far.

3.3 Results of High-Power Green LDs

We fabricated high-power, multiple longitudinal mode green LDs. Figure 4 shows the L-I and V-I characteristics of the 525 nm green LDs under CW operation at 25 ºC. The threshold current was 0.19 A. The optical output power and voltage were 1.75 W and 4.35 V at 1.9 A respectively. Wall-plug efficiency was 21.2% at 1.9 A and the peak wall-plug efficiency was 23.3% at 1.1 A.

On the other hand, the first watt-class pure green LDs emitting at 532 nm were developed in 2015. 532 nm LDs are promising light sources for conforming to the green primary color of ultra-high vision standard Rec.2020. Figure 5 shows L-I, V-I curves of our latest 532 nm LDs. The optical output power and voltage were 1.53 W and 4.35 V at 1.9 A respectively under CW operation. The wall-plug efficiency of the 532 nm LD was 18.5% at 1.9 A. At an optical output power of 1 W, this data shows the forward current and the voltage of 1.2 A and 4.2 V corresponding to a wall-plug efficiency of 20%. And we assume that these both types of green LDs will have sufficient lifetime for projector applications.

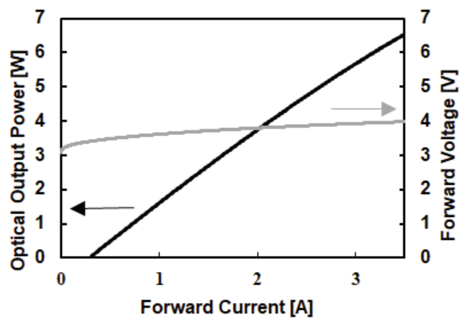

Fig. 3 L-I & V-I characteristics of a 455 nm blue LD

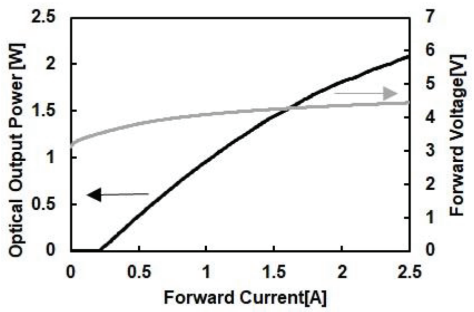

Fig. 4. L-I & V-I characteristics of a 525 nm green LD

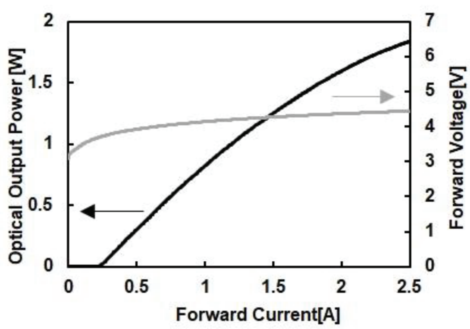

Fig. 5 L-I & V-I characteristics of a 532 nm green LD

4 MULTI-CHIP LD PACKAGE

4.1 Outline of Multi-chip LD Package

Realizing higher optical output power over several tens of watts or more, we developed a multi-chip LD (MCL) package [7], which was named "OctoLas®". This LD package, shown in Figure 6, equips 24 LD chips in metal-based package. Accounting for thermal dissipation and beam qualities such as the deviation of beam tilt angles and divergence angles of each LD beam, we set the dimension of OctoLas® as W 29 mm (except electrode terminals) x L 47.5 mm x H 10.8 mm.

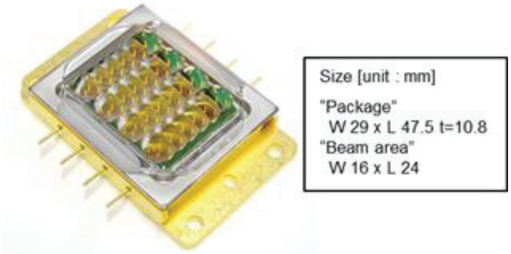

Fig. 6 Outline Image of OctoLas® package

4.2 LD Characteristics of Multi-chip LD Package

Figure 7 shows the beam images and the distribution of beam tilt angles of OctoLas® packages with 24 LD chips. Each beam tilt angle was 0.4 ° or less, and results from the multi-axis alignment of the lens array. These small deviations of OctoLas® beams are sufficient for the optical design of laser projectors and laser display systems.

Figure 8 shows the L-I characteristics of an OctoLas® package equipped with 24 blue LD chips developed in 2018 when the module temperature was set from 25 °C to 85 °C. At the module temperature of 25 °C, the optical output power and wall-plug efficiency were 124 W and 41.8% at a current of 3 A under CW operation. Even at higher module temperatures of 65 ° C and 85 °C optical output powers were 108.8 W and 98.1 W respectively at a current of 3 A under CW operation. The wall-plug efficiencies at 65 °C and 85 °C were 38.1% and 35.1%, respectively. With this single OctoLas®, for example, a laser projector of over 4,000 lumens combining blue LD and phosphor can be achieved.

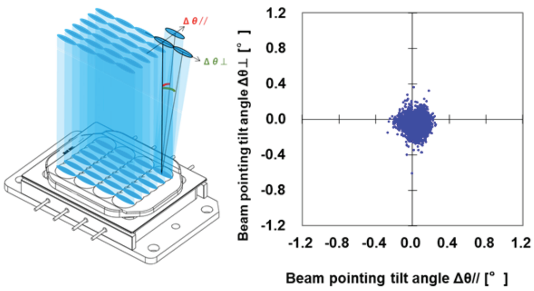

Fig. 7 Beam pointing tilt angles of OctoLas®

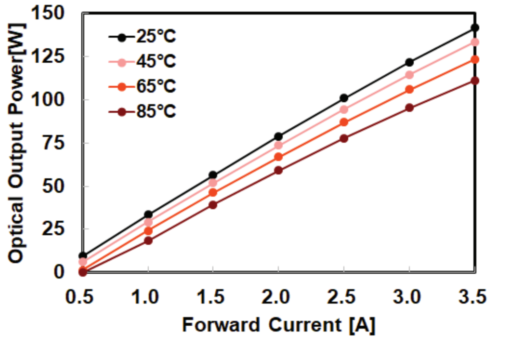

Fig. 8 L-I characteristics of 24 LD chips OctoLas®

4.3 Lifetime test of Multi-chip LD Package

Figure 9 shows the lifetime test results of OctoLas® equipped with 20 blue LD chips under an operating current of CW 3 A at Tm 75 °C for 10,000 hours. The estimated lifetime was over 30,000 hours. OctoLas® shows durability for light sources of projectors. In addition, the type and number of chips mounted in OctoLas® package can be easily changed. The OctoLas® package offers many advantages as the LD light source in laser projectors and displays.

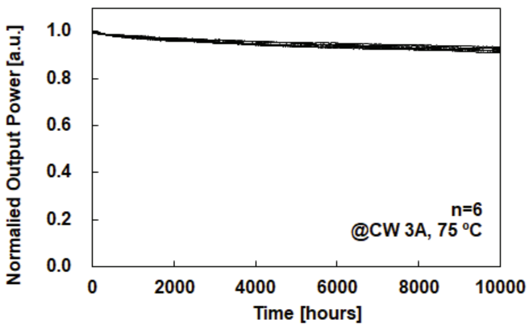

Fig. 9 Lifetime test of blue OctoLas®

4.4 Small type of Multi-chip LD Package

Figure 10 shows the appearance of the recently developed compact OctoLas® package that can be mounted up to 14 chips, side by side with the conventional type of OctoLas. This compact OctoLas® has the dimension as W 29 mm (except electrode terminals) x L 30 mm x H 10.8 mm, and a beam area of 16 × 12 mm, which is half of the conventional type. This OctoLas® is suitable for smaller projectors and laser display applications. The heat dissipation characteristics, the beam characteristics, and the life characteristics are the same performance in both types of packages. Therefore, these things help to easily combine or replace both types of OctoLas® in an optical unit of the laser projector engine.

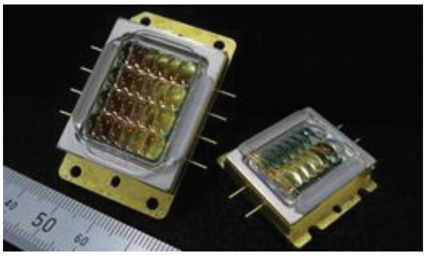

Fig. 10 Image of Small OctoLas® (right)

5 COMPACT RGB 3-IN-1 LD PACKAGE

We fabricated a compact small RGB LD package incorporating red, green and blue LD chips. For the LD package frame material, we employed a ceramic suitable for large-scale production and miniaturization of LD package. The LD chip area is fully hermetic sealed to ensure the reliability of the LDs. This LD package can emit collimated RGB LD beams by mounting a lens on the package. Figure 11 shows the outline image of this compact RGB 3-in-1 LD package.

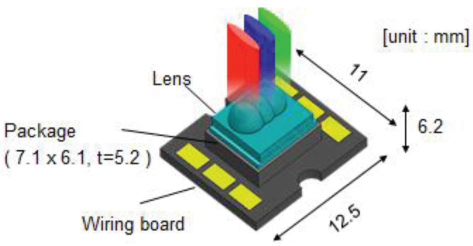

Fig. 11 Outline of Compact RGB 3-in-1 LD Package

For small projectors, Liquid Cristal on Silicon (LCoS) or Digital Mirror Device (DMD) are mainly used for Spatial Light Modulator (SLM) devices and light of each RGB color is sequentially projected at tens of hertz or more. Therefore, we drove this LD at 120 Hz and set operating currents of each RGB LD chip to get white light at D65 white point under 45 °C control. The driving conditions and LD characteristics of each red, green, and blue LD are shown in Table 1. In this table, the output luminous flux from this LD package reaches 413 lumens at driving currents of 3.4 A, 2.1 A, and 2.1 A, respectively.

Table 1 Luminous flux of 3-in-1 LD package adjusted to D65 with 45 °C pulse operation

	Spectrum	Current (duty cycle)	Optical power	Luminous flux
Red	642 nm	3.4 A (48 %)	2.1 W	413 lm
Green	526 nm	2.1 A (34 %)	1.5 W	
Blue	466 nm	2.1 A (18 %)	2.3 W	

6 CONCLUSIONS

We succeeded in fabricating further-improved high-power blue and green LDs grown on c-face GaN substrates. The optical output powers of 455 nm blue LDs and 525 nm green LDs were 5.67 W and 1.75 W, and the wall plug efficiencies were 48.1% and 21.2% respectively. In addition, 532 nm green LDs reached 1.53 W optical output power and 18.5% wall-plug efficiency. We also developed a 124 W LD at 25 °C with OctoLas® package by mounting 24 blue LD chips. Lastly, an over 410 lumens LD light source at 45 °C with a new compact RGB 3-in-1 LD package was developed. We have been constantly improving the wall-plug efficiency and the optical output power of LDs. Our LD packages will extend the use of LDs in projector and display systems. We hope that these results will contribute to the expansion of display markets based on LD technologies.

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