Performance Improvement of Pump LDs for Industrial Fiber Laser Applications

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High-power LDs, which are applied as pump sources for industrial fiber laser systems, are required to achieve not only high output and high efficiency operation but also reduced beam divergence suitable for fiber coupling, as well as improved long-term reliability. In this report, we achieved high-power and high-efficiency operation with a light output of 27.9 W and a PCE of 66.5% at a driving current of 27 A and reduced vertical divergence angles by more than 30% by optimizing the waveguide structure. Furthermore, long-term aging tests demonstrated excellent reliability even under severe operation conditions. We aim to contribute to the advancement of next-generation industrial fiber laser systems through the development of these high-performance LDs.

1. Introduction

High-power LDs operating in the near-infrared wavelength range of 9xx nm are applied as pump sources for high-power fiber laser systems mainly designed for material processing applications. In recent years, development of high-power LDs has been focused on improving the output power per cost (W/$) and SWaP performance of multi-chip LD modules. To achieve higher output from a single emitter, development efforts have focused on approaches such as extending cavity length, widening emitter width, and optimizing epitaxial structure[1) 2) 3) 4) 5) 6)]. We have realized high-power, high-efficiency operation by adopting an extremely large asymmetric waveguide structure in the long cavity to minimize optical losses, and by optimization of the doping profile to reduce electrical resistance[7) 8) 9) 10)]. In this paper, while further improving the output and efficiency, we applied a new waveguide structure that reduces the vertical beam divergence, which is advantageous for integration into fiber-coupled LD modules. We report on the results of laser characteristic measurements and preliminary reliability tests of the newly developed LDs.

2. Modification of LD Structure for Performance Improvement

The most effective methods to improve the output power per single emitter of an LD are adopting a wide stripe and extending the cavity length. Expanding the current injection area reduces operating voltage and improves heat dissipation, which consequently leads to an improvement in the practical output power. The epitaxial structure of the LD employs an ADCH structure that is particularly advantageous for long-cavity LDs, as it reduces internal loss by minimizing the optical mode overlap with the highly absorptive p-doped layers through a strongly asymmetric waveguide[9)]. We first present the basic structure of our LDs, followed by a description of the design modifications and the expected performance improvements resulting from these changes.

For high-power LDs used as pump sources for fiber lasers, InGaAs/GaAs material systems capable of emitting at wavelengths near 970 nm are employed. The SAS structure is adopted as the basic configuration of the injection stripe in our high-power LDs. A cross-sectional view of the SAS structure is shown in Fig. 1. In SAS-LDs, the current injection stripe—which determines the emission width—and the non-injection region near the laser facets are simultaneously formed by etching the current blocking layer, thus simplifying the wafer fabrication process. In addition, the SAS structure features a relatively flat surface, which provides advantages such as mitigating the degradation of polarization purity caused by inhomogeneous strain when the LD is bonded epi-side down onto a high thermal conductivity submount[11)].

In the newly developed LD, the cavity length is extended from the conventional 4 mm to 5 mm to improve practical optical output. To significantly increase output power, it is essential to substantially reduce heat generation losses that limit the output. Therefore, efforts have also been directed toward improving power conversion efficiency (PCE). Specifically, the doping concentration of the p-clad layer is adjusted according to the optical density to suppress internal loss due to free carrier absorption while reducing the resistance of the p-clad layer[12)].

In addition to increasing the cavity length, the waveguide structure of the conventional structure was modified to reduce the vertical beam divergence. Reducing the vertical beam divergence of LDs is beneficial in fiber-coupled LD

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Abbreviations, Acronyms, and Terms.

LD—Laser Diode
PCE—Power Conversion Efficiency
SWaP—Size Weight and Power consumption
ADCH—Asymmetric Decoupled Confinement Heterostructure
One of the epitaxial structures of LD, suitable for high-power operation.
SAS—Self-Aligned Stripe
One of the current injection structures in LDs.
CoS—Chip on Submount
A device in which the LD chip is mounted on a submount.
CW—Continuous Wave
COMD—Catastrophic Optical Mirror Damage
A phenomenon in which heat generation by excessive output leads to instantaneous crystal melting at the LD emission facet, resulting in device failure.
QCW—Quasi Continuous Wave
FIT—Failure In Time
Failures per billion hours.
FFP—Far Field Pattern

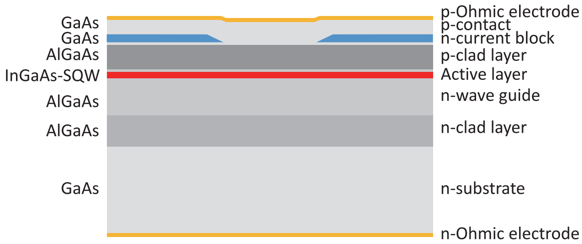


Fig.1. Cross-sectional view of LD structure.

modules because it decreases the beam size when multiple LD beams are stacked, thus contributing to more stable fiber coupling, higher brightness, and lower SWaP. Figure 2 shows the refractive index and optical intensity profiles of both the conventional and newly developed LDs. Although increasing the waveguide layer thickness generally reduces vertical beam divergence, it often leads to the emission of higher-order modes. To suppress higher-order mode emissions and achieve a reduction in vertical beam divergence, the waveguide thickness was increased while enhancing the asymmetry of the Al composition in the AlGaAs clad layers to determine the maximum waveguide thickness that allows only the fundamental mode to propagate. As described above, we fabricated LDs with a significantly revised epitaxial structure —including the waveguide structure and doping profile— in addition to increasing the cavity length. LDs were mounted epi-side down on ceramic-based, high thermal conductivity submounts to fabricate CoS devices, and their performance were evaluated.

3. Results of Performance Improvements in the Newly Developed LD

The extension of the cavity length has significantly improved the output characteristics. Figure 3 shows the light versus current (L-I) characteristics of the newly developed LD compared with those of the conventional LD. These measurements were conducted at 25 °C under CW operation, and exhibited improved linearity in the newly developed LD in the high current region above 20 A. This improvement in linearity is largely attributed to both the increased injection stripe area and the reduction of heat generation losses achieved through improvements in the epitaxial structure. Figure 3 also shows a comparison of PCE. While the conventional LD achieves an output of 22.0 W at a practical drive current of 22 A, the newly developed LD demonstrates a PCE improvement of more than 5 percentage points at the same drive current. Furthermore, at the practical drive current of 27 A for the new LD, an optical output of 27.9 W and a PCE of 66.5% were achieved.

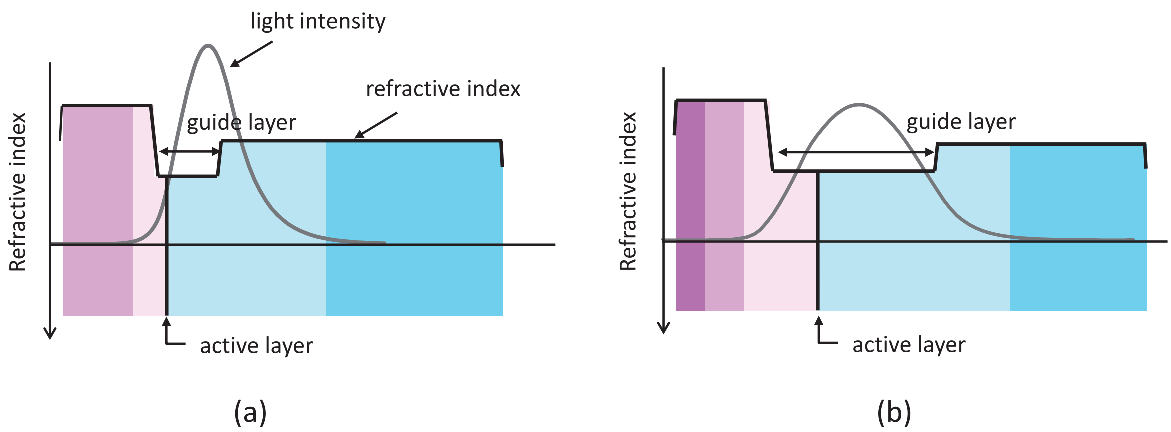


Fig.2. Refractive index profile and light intensity distribution of (a) conventional LD and (b) newly designed LD.

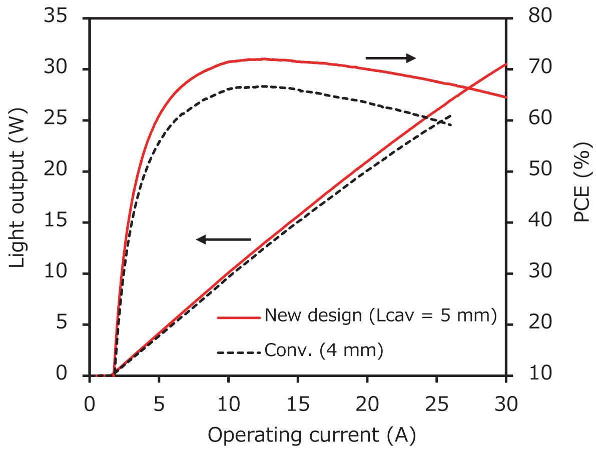


Fig.3. L–I characteristics and PCE of LDs.

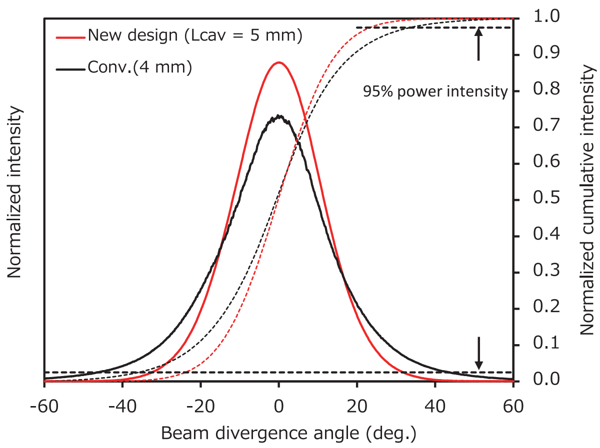


Fig.4. Vertical FFP of LDs.

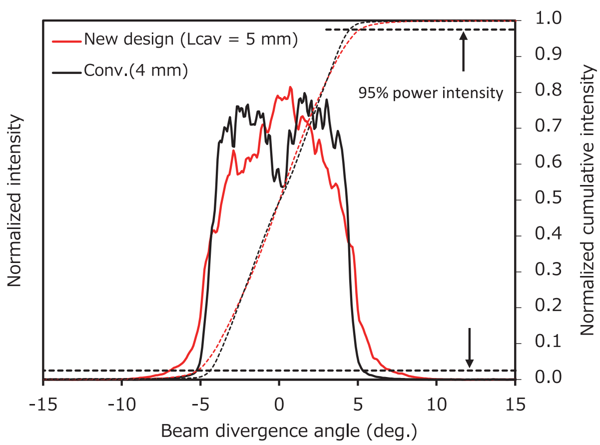


Fig.5. Horizontal FFP of LDs.

Figure 4 shows the reduction of vertical beam divergence achieved by the modified waveguide structure in the newly developed LD, compared with the conventional LD. The 95% vertical beam divergence, defined by the cumulative power intensity of 95%, was reduced to 47° in the new LD, showing reduction of over 30% from the conventional value of 69°. The beam profile exhibits a single-peaked Gaussian distribution, confirming that higher-order mode emissions are effectively suppressed. Figure 5 shows the horizontal beam divergence of the newly developed LD

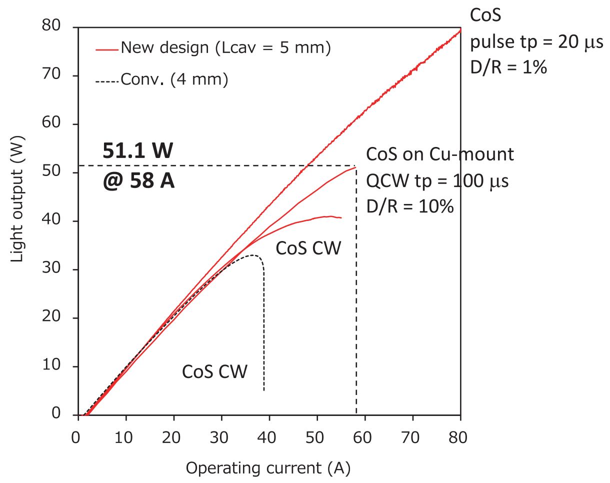


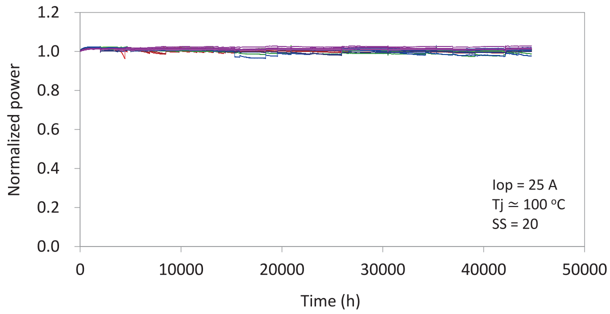
Fig.6. Results of maximum output power measurement of LDs.

and the conventional LD. In the newly developed LD, the injection stripe configuration is optimized to concentrate the optical intensity distribution within a low divergence angle range. Although the 95% horizontal beam divergence is slightly larger than that of conventional LD, the fiber coupling efficiency in multi-chip LD modules improved by approximately 2%.

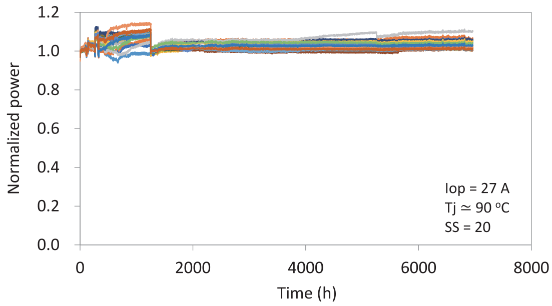
Figure 6 shows a comparison of L-I characteristics under CW and various pulsed operation conditions to evaluate the maximum output power of the newly developed LD. First, measurements on the CoS were performed under pulsed operation (pulse width 20 μs, duty cycle 1%) to avoid thermal saturation. Under pulsed operation, neither the new nor the conventional LD exhibited COMD up to 80A, which is the current limit of the LD driver. The newly developed LD demonstrated COMD-free operation, achieving maximum optical output of 79.7 W. Next, the maximum output power under CW operation were compared. Due to improved heat dissipation resulting from the extended cavity length, the newly developed LD achieved a maximum output power of 42 W, which is nearly 10 W higher than the 33 W output of the conventional LD. However, the output power saturated above 40 A under CW operation. The limitation of the maximum output is attributed to a significant increase in junction temperature caused by the high thermal contact resistance between the submount and the measurement stage. To avoid this problem, the CoS was bonded to a copper block with the temperature just below the emission surface maintained at 25°C under QCW operation (pulse width 100 μs, duty cycle 10%). Under these conditions, the newly developed LD achieved a maximum optical output of 51 W, demonstrating top-level output performance.

4. Demonstration of High-power and Long-term Operation

In addition to high power and high efficiency, LDs used in industrial fiber laser systems are required to exhibit extremely high reliability. We have advanced improvements in LD output power and efficiency while verifying long-term reliability through accelerated aging tests. Although we demonstrated COMD-free operation under high optical



(a)



(b)

Fig.7. Results of accelerated aging test of (a) conventional LDs and (b) newly designed LDs.

output conditions, it is crucial to verify long-term reliability under high-power operating conditions for industrial applications. As shown in Fig.7(a), the conventional LD demonstrated continuous failure-free operation for over 44,700 hours (approximately 5 years) under severe accelerated conditions, with a drive current of 25 A and a junction temperature equivalent to 100°C. This test was conducted on CoS devices and represents an exceptional long-term data set, directly demonstrating the stability of our LD manufacturing process. Similarly, high reliability has been confirmed through accelerated aging tests conducted on LD modules[10]. On the other hand, reliability tests for the newly developed LD are currently in progress, aiming for application in next-generation multimode fiber laser systems. Accelerated aging test results for the new LD, shown in Fig.7(b), confirm failure-free operation exceeding 6,900 hours under a drive current of 27 A and a junction temperature equivalent to 90°C, demonstrating excellent reliability even under severe operating conditions. Furthermore, device operating hours have been accumulated through ongoing long-term reliability tests of fiber-coupled LD modules. A failure rate below 1000 FIT is expected, which further confirms the high reliability of the newly developed LD.

5. Conclusion

We have developed an LD that employs a waveguide structure to reduce vertical beam divergence while significantly improving high output power and high efficiency compared to conventional LDs. At the practical drive current of 27 A, we achieved an optical output of 27.9 W and a PCE of 66.5%. By increasing the waveguide layer thickness and adopting a waveguide structure that supports only the fundamental mode, the 95% vertical beam divergence was reduced to 47°, representing a reduction of more than 30% compared to the conventional LDs. Accelerated aging tests of newly developed LDs have demonstrated failure-free operation exceeding 6,900 hours. Near-infrared LDs have made remarkable progress in power and efficiency, and their technology has recently reached maturity. We will continue to enhance not only the high-power and high-efficiency performance of LDs but also their functionality as pump sources for fiber lasers.

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