High Efficiency and High Power Broad Area Laser Diodes

Ryozaburo NOGAWA,[1] Kyohei YOSHIDA,[1] Yoshikazu KAIFUCHI,[2]
Toshiyuki KAWAKAMI,[1] and Yuji YAMAGATA[1]

As light sources of fiber laser system, which is spreading rapidly in the material processing field, high power and high efficiency 9xx- nm LDs are strongly demanded. In order to improve PCE by reduction of electrical resistance, vertical designs of LD are optimized. As a result, the newly designed LD successfully demonstrates the high PCE of 73.6% which is comparable to the world record. Furthermore, high efficiency of 66.6% is obtained even at high injection current of 25 A by extension of cavity length based on optimized vertical design. The practical output power is successfully increased.

1. Introduction

High-power laser diodes (LDs) lasing in 8xx-9xx nm wavelength band have been widely used in material processing applications such as light sources for fiber laser systems and direct diode laser systems [1) 2)]. The fiber laser systems have achieved over 10 kW in output power and have enabled high speed and highly accurate processing [3)]. Since a large number of pumping LDs are used in a fiber laser system, LDs have a huge impact on the heat generation, long-term reliability and operating cost of the total system. Therefore, the power conversion efficiency (PCE) as well as output power becomes the essential parameter of LDs. We have reported the achievement of high power and high reliability operation in LDs with our original design by optimizing the cavity length, injection stripe width, and heat dissipation [4) 5)]. In this paper further optimization of vertical structure is studied focusing on improvement of PCE through the reduction of inner electrical resistance of LDs.

2. Structures of LD

LDs in this study, which consist of GaAs / AlGaAs / InGaAs epitaxial layers, metal contacts, and facet coating etc., were fabricated utilizing metal organic chemical vapor deposition (MOCVD) and semiconductor processing technology. Figure 1 shows schematic images of the LD's vertical structure, refractive index profile and optical field of the emission. The structure has the feature of an asymmetric waveguide that the center of optical mode is in the n-doped side, which enables the reduction of an optical loss [6)]. The reduction of optical loss in waveguide contributes to increasing the slope efficiency, which enables long cavity design focused on high-power operation. In order to improve the PCE, it is necessary to reduce the driving voltage, i.e. electrical resistance, in addition to the optical loss. It is effective to increase the carrier concentration by higher impurity doping for reducing the electrical resistance of the semiconductor layers in the LDs. On the other hand, increasing the carrier concentration in the optical field makes a trade-off between optical loss and electrical resistance. Therefore, in order to achieve high PCE, both doping profile and optical field distribution in the structure of LD must be carefully designed. Figure 2 shows the characteristics of

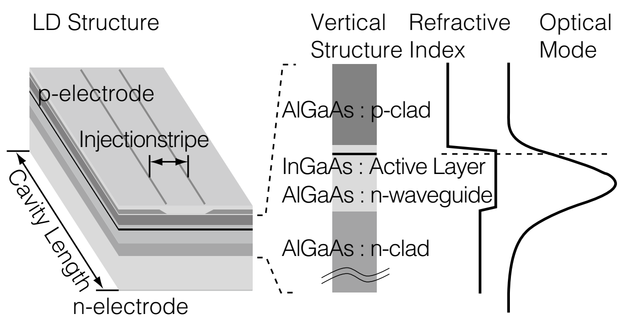

Fig. 1. Schematic structures of LD, refractive index profile and optical profile.

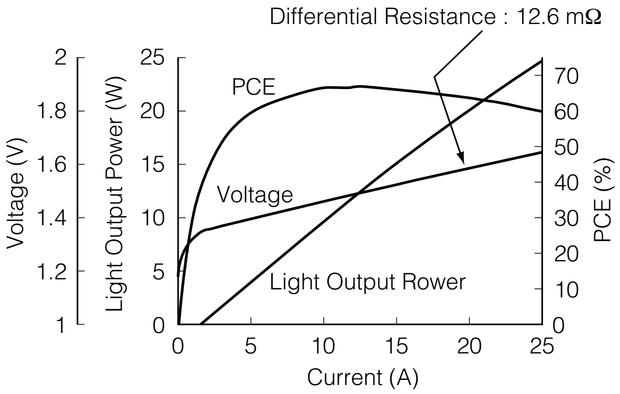

Fig. 2. Light output power, voltage and PCE versus injection current characteristics of conventional LD.

1 Optical Device Research Department
2 Optoenergy Inc.

Panel 1. Abbreviations, Acronyms, and Terms.

LD—Laser Diode
PCE—Power Conversion Efficiency
A ratio of the light output to electrical input
GaAs—Gallium Arsenide
One of the materials of LD
AlGaAs—Aluminum Gallium Arsenide
One of the materials of LD
InGaAs—Indium Gallium Arsenide
One of the materials of LD
MOCVD—Metal-Organic Chemical Vapor Deposition
One of the method of crystal growth
Vertical Structure
Profiles of thickness, refractive index and doping in the LD
Slope Efficiency
A ratio of optical output power to the injection current
Differential Resistance
A ratio of a small change in driving voltage to the corresponding change in injection current
CoS—Chip on Sub-mount
A LD chip bonded on high thermal-conductivity sub-mount
Active Layer
A layer emitting light with quantum well structure
Clad Layer
A layer confining light to a waveguide layer with low refractive index

light output power versus injection current (L-I), driving voltage versus injection current (V-I) and PCE versus light output power, which were obtained from conventional products of chip-on-sub-mount (CoS). A differential resistance is about 12.6 mΩ in the linear part of the V-I characteristics. Figure 3 shows the pie chart of resistance element of conventional design of the CoS, such as bulk resistance of the epitaxial layer, or the surface wiring resistance on the sub-mount. Epitaxial layer accounts for 75% of the total resistance, especially p-doped AlGaAs cladding layer with high aluminum content accounts for 37% of the total. In this paper, LD design focusing on improvement of PCE by reducing the resistances is studied experimentally. Two types of LDs, one with a cavity length of 4 mm, which is same with the conventional product, and the other with a cavity length of 5 mm, were fabricated in order to verify the effect of the optimization

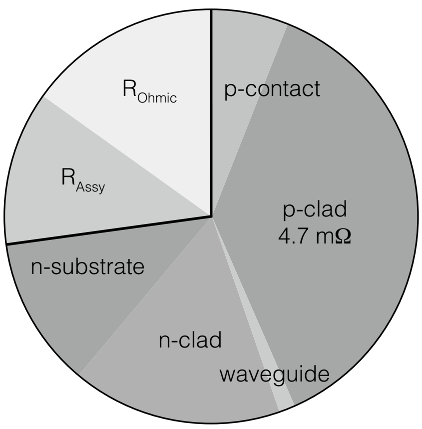

Fig. 3. Pie chart of resistance element of conventional design.

of the vertical structure and the extension of the cavity length, respectively. In order to obtain stable operation at large current injection, LDs were bonded by junction-down on ceramic based high thermal-conductivity sub-mounts.

3. PCE improvement approaches

3.1 Reduction of resistance of p-clad layer

Figure 4 shows the doping profile and the optical mode profile in the p-clad layer of a conventionally designed LD and newly designed LD. Because of the high intensity of light field in the region close to the active layer in the p-clad layer, the carrier concentration must be kept low to avoid internal losses by light absorption. On the other hand, in the region far from the active layer with lower intensity of light field, it is necessary to increase the carrier concentration in order to reduce the resistance. In these points of view, the optical mode and the doping profile were redesigned focusing on reducing the resistance of the p-clad layer. First, the waveguide structure was redesigned to strengthen the asymmetry of the optical fields in the p and n layers, and the optical field in the p-clad layer was reduced compared to the conventional design. Next, the doping profile of the p-clad layer was redesigned to maximize the PCE in this newly designed waveguide structure. As a result, the low carrier concentration region in the whole p-clad layer was successfully reduced to about 10%. In addition, the carrier concentration in the region of 70% from the far end of the active layer in the p-clad layer was increased one order of magnitude compared to the conventional design. The resistance of the p-clad layer in the new structure was simulated to be reduced to 25% compared to the conventional structure.

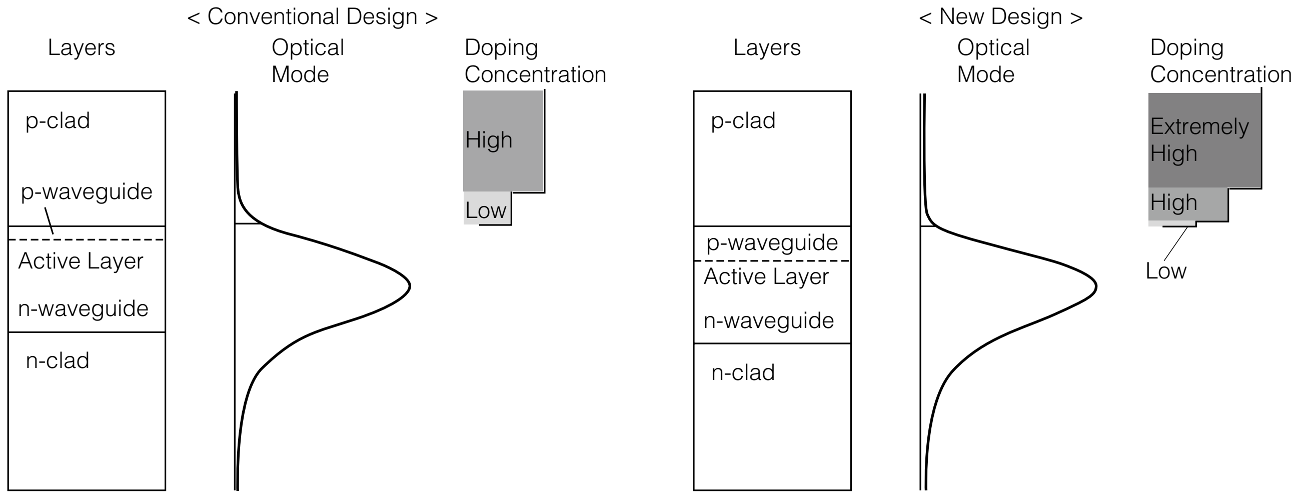

Fig. 4. Schematic diagram of optical mode profile and doping profile comparison of conventional design (left) and new design (right).

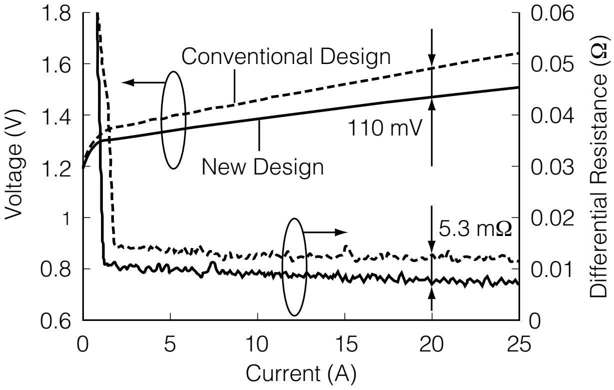

Fig. 5. Voltage versus injection current characteristics comparison of newly designed LD (solid lines) and conventionally designed LD (dashed lines).

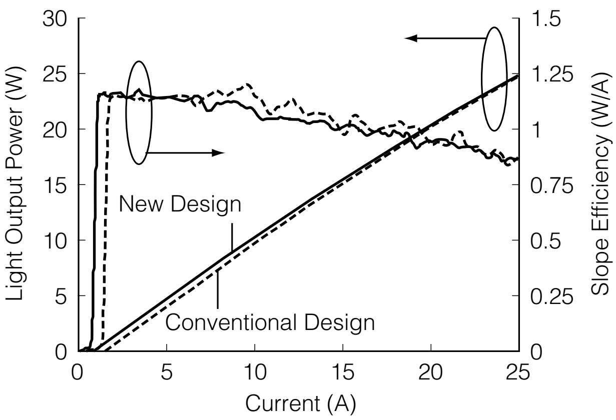

Fig. 6. Light output power versus injection current characteristics comparison of newly designed LD (solid lines) and conventionally designed LD (dashed lines).

3.2 *Demonstrations of newly designed LDs*

Figure 5 shows comparison of V-I characteristics between newly designed and conventional LDs. The voltage of the newly designed LD was remarkably decreased compared with conventional LD. The differential resistance was successfully reduced by 5.3 mΩ at 20 A from conventional structure by redesigning of the doping profile. As a result, the driving voltage was reduced by 110 mV. Figure 6 shows comparison of L-I characteristics between newly designed and conventional LDs. In the L-I characteristics, the slope efficiency curve of the newly designed LD and the conventional LD overlapped. This result means that the increase of optical loss in the waveguide due to the change in the doping profile was negligibly small. As a result, the light output power of the newly designed LD was comparable or better than that of the conventional LD in the whole operating current range. Figure 7 shows comparison of PCE versus light output power (PCE-L) characteristics between newly designed and conventional LDs. As a result of the

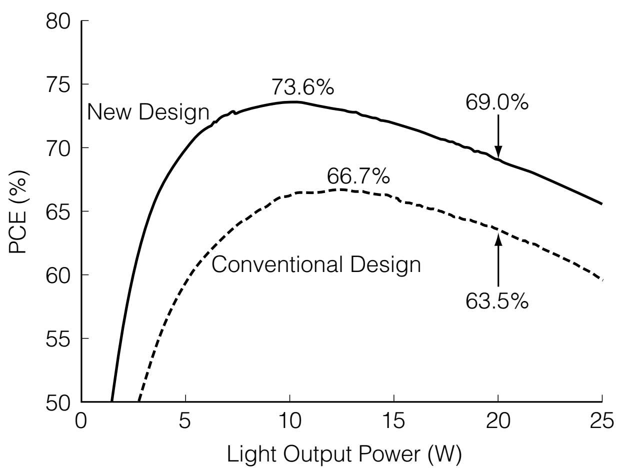

Fig. 7. PCE versus light output power characteristics comparison of newly designed LD (solid line) and conventionally designed LD (dashed line).

reduction of resistance and suppression of optical loss, the PCE was significantly increased compared with conventional LD. In particular, the peak value of PCE increased significantly, reaching 73.6%. This value is 7.0 points higher than that of the conventional LD, which is comparable to world records [7]. The PCE value of 69.0% was achieved even in the high power range of 20 W which is 5.5 point higher than the conventional LD, showing both high power and high efficiency.

4. Dependence of PCE on cavity length

Based on the new vertical structure focusing on improving PCE, the LD design was modified to increase the light output power furthermore. Higher output power of pumping LDs creates value of fiber laser system such as higher output, cost reduction by reducing the number of components, and space saving. In this chapter, the effect of extending the cavity length up to 5 mm from conventional 4 mm was investigated. Heat dissipation and electrical conductivity could be improved by enlarging the contact area between the LD and the sub-mount by extending the cavity length. Therefore, the long cavity LD is expected to increase an output in the high current region that is used for commercial systems compared to the short cavity. On the other hand, since extending the cavity length is expected to decrease the slope efficiency and increase the threshold current, the cavity length should be selected accordingly to the required performance. Figure 8 shows the L-I and PCE-I characteristics of LD with cavity length of 4 and 5 mm. The vertical structure of these LDs are designed identically. The L-I curve of the 5 mm LD was almost identical to that of the 4 mm LD, and the increase in the threshold current and the decrease in the slope efficiency due to the extension of cavity length was small. Due to the lower threshold current, LD with 4 mm cavity length was higher than 5 mm in PCE at low injection current. On the other hand, the PCE of 5 mm-LD was higher than that of 4 mm-LD in the high injection current above 20 A. The PCE of 5 mm-LD was 66.6%, which was 1.0 point higher than that of 4 mm-LD at 25 A. The improvement of output power at high injection current due to the increase of the heat dissipation and the reduction of the current density by the extension of cavity length was confirmed.

5. Conclusion

The doping profile and the optical field distribution of the LD were redesigned, focusing on the maximization of PCE, and the power consumption was successfully reduced without deterioration in slope efficiency. As a result, the PCE was improved in whole output power region compared to the conventional LD, especially maximum PCE value of 73.4% in the 4 mm LD was comparable to world records. Additionally, LD with extended cavity length of 5 mm showed improved PCE at high output power compared to cavity length of 4 mm. The performances of new designed LDs were successfully demonstrated, which is expected to contribute to increase the output power and improve the PCE of fiber laser systems.

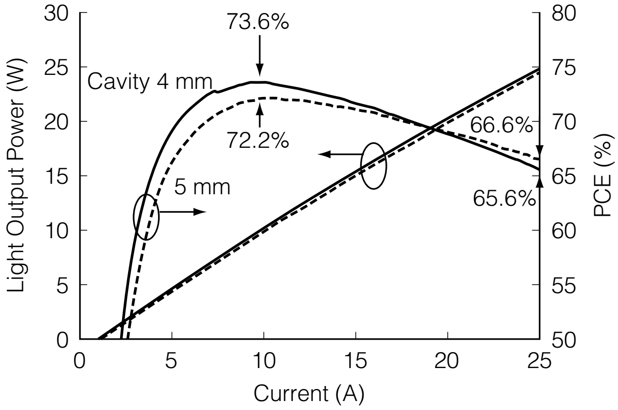

Fig. 8. Light output power and PCE versus injection current characteristics comparison with 4 mm (solid lines) and 5 mm (dashed lines) of cavity length with newly designed vertical structure.

Reffernce

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