The Fujikura Group’s High-power Semiconductor Laser Technologies

Yohei Kasai,[1] and Toshiyuki Kawakami[1]

The Fujikura Group has accumulated in-depth technology and know-how to develop products such as high-power semiconductor lasers and laser modules. In addition, we also have expertise to grow high-quality III-V compound semiconductor crystals, enhance power and efficiency of laser diodes by optimizing the structure, multiplex beams, mount parts on substrates, and dissipate heat. This paper introduces the technologies and performance of high-power semiconductor lasers developed by the Fujikura Group.

1. Introduction

The optical output power of semiconductor laser diodes (LDs) and fiber coupled modules (LDMs) at 9xx-nm wavelengths have increased remarkably in the last 10 years. That is because the kilowatt-class fiber lasers have replaced CO_2 lasers in the laser processing market1), and thus the demand for LDs and LDMs as a pump source has also increased. Furthermore, because of the increase in both optical output power and brightness of LDs and LDMs, direct diode lasers (DDLs), which directly use output power from these devices as a heat source, are also in increasing demand. Therefore, each company can be said to have made significant progress through active development efforts in parallel with the rapid growth of the market2-7). The Fujikura Group also started developing LDs and LDMs more than 10 years ago and, in terms of optical output performance, has always been in the top group in the world8, 9). Fig. 1 shows the improvement in optical output power of our LDs and LDMs. Compared to the initial development stage, the power has increased three times in the LDs and five times in the LDMs. The long cavity structure and the optimization of the epitaxial-layer design are the main reasons for the improved output power of the LDs. These LDs also have achieved a significantly high power conversion efficiency (PCE) value under high-power operating conditions as well as at peak. Such high-power, high-efficiency LD technologies are described in Chapter 2. For LDMs , improvements in beam multiplexing technology have enabled the devices to have many emitters in the package and to combine the beams into a fiber with a higher output power. Combining polarization beams is another technique utilized to improve beam brightness, and it has become commonplace for dozens of beams to be combined into a single optical fiber. Heat dissipation technology is also an important factor that contributes to maximizing LD performance considering several hundred watts of heat could be generated in a palm-sized package. These packaging technology for high-power LDMs is described in Chapter 3. Furthermore, since the reliability of laser devices is an extremely important characteristic that determines the product operational period in industrial applications, the reliability of LDs will be discussed based on long-term accelerated aging test data in Chapter 4. The conclusion is given in Chapter 5.

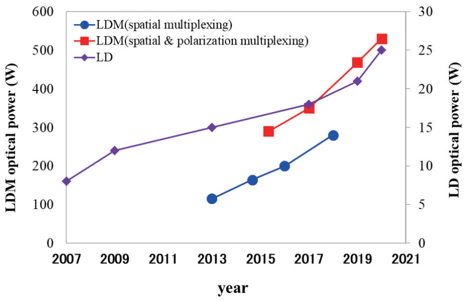

Fig. 1. Improvement in optical output power of the Fujikura Group’s LDs and LDMs.

2. Technologies on high-power high-efficiency operation of laser diodes

Since an extremely large number of pumping LDMs are used in fiber laser systems, the fundamental characteristics of the LDs, such as output power per single emitter and PCE, have a significant impact on the total system performance. Therefore, improvements in output power and PCE of LDs have always been a high-priority development issue. Fujikura has worked on the development of the 9xx-nm-wavelength LDs with the world’s highest output power and efficiency in cooperation with our group company, Optoenergy Inc.11-13). Recently, we have successfully developed the 9xx-nm LDs with the world’s highest level PCE at over 20 W output power. This section reviews the approaches to improve the power and

---

[1] Optical Device Research Department Optical Technologies R&D Center

Panel 1. Abbreviations, Acronyms, and Terms.

LD—Laser Diode
CoS—Chip on Submount
LDM—Laser Diode Module
DDL—Direct Diode Laser
PCE—Power Conversion Efficiency
SAS—Self-Aligned Stripe
ADCH—Asymmetric Decoupled Confinement Heterostructure
FAC—Fast-axis Collimation Lens
SAC—Slow-axis Collimation Lens
BPP—Beam Parametar Product
NA—Numerical Aperture
FFP—Far-Field Pattern
NFP—Near-Field Pattern
AR coat—Anti-Reflection Coat
VBG—Volume Bragg Grating
SWaP—Size, Weight, and Power consumption

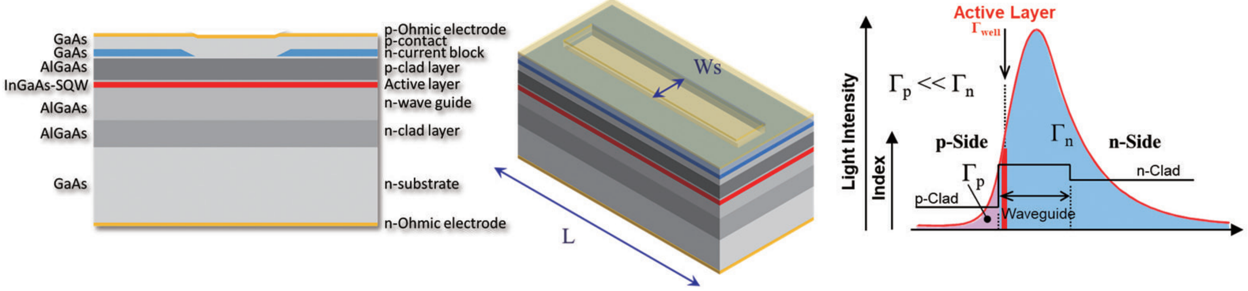

Fig. 2. Schematic LD structure (a) cross section, (b) perspective view, (c) Index guide structure and mode profile.

efficiency of LDs, and then explores the possibility of design optimization according to each application field.

2.1 Basic structure of LDs

Fig. 2 (a) and (b) show a schematic of structure of our LDs in cross section and a perspective view, respectively. The LD structure composed of InGaAs/AlGaAs-based materials with an emission wavelength of 9xx-nm was epitaxially grown by MOCVD on an n-GaAs single-crystal substrate. A self-aligned stripe (SAS) structure consisting with an n-type current-blocking layer was used for controlling the stripe width of the emitter. The merits of SAS structure include increased polarization purity of emitting light by the use of a flattened surface, which avoids mounting stress[14)], simultaneous formation of a lateral current confinement structure and non-current-injection window at the facet[15)], reductions in the resistivity of p-type ohmic contacts. These are important factors that affect the performance of our LDs.

Fig. 2 (c) shows a schematic of an index guide structure and mode profile of our LDs for the vertical structure. By the use of an asymmetric decoupled confinement heterostructure (ADCH), the optical confinement ratio of the p- and n-doped layers (Γp, Γn) and the confinement factor of the active layer (Γwell) can be optimized individually. This allows us to flexibly design a low-loss waveguide, the optimal Γwell value to achieve high-power, high-efficiency operation in long cavity LDs. For an InGaAs/AlGaAs-based material system, it is essential to suppress the p-type doping level because the free carrier loss of the p-doping layer is more than twice that of the n-doping layer. On the other hand, since the carrier mobility of the p-type layer is one order of magnitude lower than that of the n-type layer, reducing the p-type doping simply increases the operating voltage and results in a low efficiency of LDs. Therefore, the basic strategy is to reduce the free carrier loss by decreasing the Γp-Γn ratio, and at the same time, to decrease the electrical resistance by reducing the thickness of the p-type layer or increasing the amount of the p-type dopant in the layer far from the mode distribution peak. In order to further improve the PCE, it is also effective to increase the Γwell value within an appropriate range taking into account the trade-off with reliability, and to eliminate the excess voltage components generated at the ohmic contacts and interlayer regions to reduce the operation voltage.

2.2 Improvement of efficiency and output power of LDs

In accordance with the strategy explained in section 2.1, the following investigations were conducted to improve the performances of the LD: 1. reductions in internal loss by adjusting the Γp-Γn ratio, 2. efficiency improvement by adjusting the Γwell value and balancing gain with loss, 3. resistance reductions by minimizing the p-type layer thickness and increasing the doping level for the p-type layer far from the mode distribution peak, 4. reductions in excess voltage due to the band-discontinuity between each epitaxial layer[8,13,16)]. Fig. 3 shows the trend of the PCE improvement in our LDs. Each data was obtained by measuring the LDs with a cavity length of 4 mm at 25 deg. C. The PCE values at peak and an output power of 20 W were plotted. As can be seen from the plot, the peak PCE value has increased significantly from 67.0% in 2016 to 73.5% in 2020, and PCE at 20 W increased from 63.0% to 69.0%, the highest level in the world.

High reliability of LDs is also required for high-power fiber lasers. Fig. 4 shows the optical output power versus the drive current (L-I) characteristics of the newly developed LDs (cavity length of 4 mm) driven in pulsed

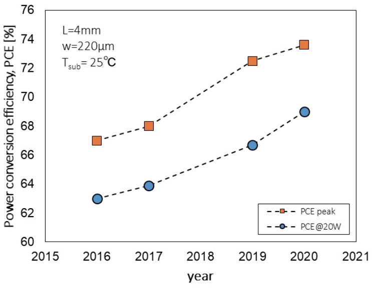

Fig. 3. Advancement in Power conversion efficiency of LDs.

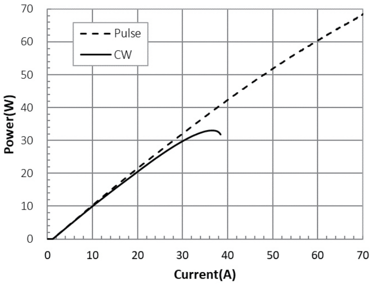

Fig. 4. Pulse and CW L-I characteristics of developed LDs.

operation (width of 20 μs and duty 1%) and CW operation. A COD-free operation of more than 69 W was verified under pulse. On the other hand, a high output power of 33 W was obtained under CW conditions, although it was lower than that by pulse due to a limitation of heat dissipation[16).

2.3 LD design according to the application fields

In the application of LDs, their characteristics are prioritized according to the fields. For example, for LDs for fiber laser systems, output power per single emitter might be the first priority. On the other hand, high conversion efficiency will be more important for application in optical power transmission systems. It is possible to provide LDs suitable for each requirement by changing the cavity length according to the application. For applications that require high output power, expanding the cavity length is effective. Increasing the cavity length enhances practical output power because it decreases current density, improves heat dissipation[13), and reduces series resistance[12). On the other hand, the peak efficiency of an LD decreases as the cavity length becomes longer. This means that there is a trade-off between practical output power and peak efficiency[13). However, for LDs with a long cavity design within a permissible range, the merits of low series resistance and high-heat dissipation enable the devices to operate at high power. Therefore, employing a long cavity design should provide significant advantages in LDMs in terms of cost reductions and brightness improvement by reducing the number of LDs and beam shaping optical parts. For applications which needs higher PCE, they can be equipped with short cavity LDs with high peak efficiency and operated under the current at peak efficiency. Fig. 5 shows the PCE versus operating current characteristics of the LDs with the highest efficiency described in section 2.2 for the cavity lengths of 2 mm, 4 mm, and 5 mm. The solid line represents the measured characteristics, and the dotted line the calculated results, respectively, and the data for the LD with a 4 mm cavity is shown for reference. A high peak PCE of 75.5% was obtained for the 2-mm-cavity LD, and a high PCE of 66.6% at a practical output power of 25 W was achieved for the 5-mm-cavity LD as shown in Fig. 5[17). These results show that we are able to provide LDs that demonstrate the world's-highest-level performance in a wide output range for various applications.

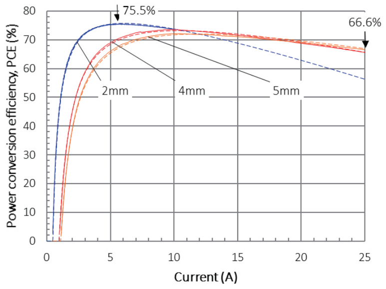

Fig. 5. Dependencies of Current-PCE characteristics on cavity length.

3. Packaging technology of high-power semiconductor laser

Although LDMs are one of the components of a fiber laser system, they use a wide variety of elemental technologies compared to other optical components, so LDMs can be regarded as a system unit. This report introduces the spatial optical system and heat dissipation system, both of which are particularly important for high-power LDMs.

3.1 Spatial optical system

Beam multiplexing is an essential technology for increasing fiber output power of LDMs. This section explains collimated beam forming, fiber coupling, and beam multiplexing (space, polarization, and wavelength) as optical technologies required to combine beams emitted from plural single-emitters into a single optical fiber.

3.1.1 Fast-axis and slow-axis collimation

To achieve high-density spatial multiplexing, converging radiated beams from LD into approximately parallel beams with collimation lenses is necessary, since LD radiation beams have a large divergence angle in both horizontal and vertical directions. In terms of optical design, the larger the focal length of the collimation lens, the smaller the divergence angle of the collimated beam. Therefore, a slow-axis collimation lens (SAC) is designed with a focal length as long as about 1 cm to suppress the effect of the large beam parameter product (BPP) in a horizontal direction due to the wide emission width. On the other hand, the vertical direction does not require a large lens because the BPP is relatively small since the waveguide of the LD is as thin as the order of the wavelength. Rather, the vertical emission beam has a large divergence angle, so the fast-axis collimation lens (FAC) needs to be placed very close to the LD facet to capture beams as much as possible.

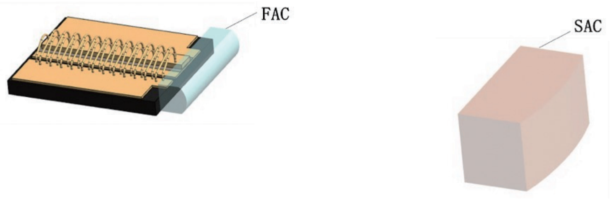

Fig. 6. Schematic view of the FAC and SAC collimation system.

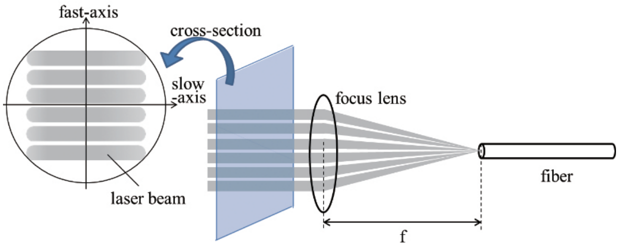

Fig. 7. Schematic diagram of coupling the collimated multiple beams into the fiber.

Therefore, the FAC is designed with a short back focus of about 0.1 mm, and uses an aspherical lens to converge high numerical aperture (NA) beams into a collimated beam. Comparing the focal lengths, the FAC is about two orders of magnitude smaller than the SAC, in other words, FAC requires about two orders of magnitude more precise alignment than that of SAC. Therefore, the position of the FAC needs to be adjusted actively while the collimated beam image is monitored with a camera.

As mentioned above, it is difficult to integrate FAC and SAC because the optimum dimensions differ greatly depending on the near-field pattern (NFP) and far-field pattern (FFP) of an LD. For this reason, separate cylindrical lenses are used for FAC and SAC as shown in Fig. 6.

3.1.2 Optical fiber coupling

As shown in Fig.7, the collimated multiple beams are coupled into the optical fiber by a focusing lens. If the optimum lens curvature sizes differ significantly in the horizontal and vertical directions, separate cylindrical lenses need to be placed, but one condenser lens may suffice depending on the design. In designing a focusing lens, it is important to set the focal length f so that the BBPs of the focused beam in horizontal and vertical directions are equal. This is because the shape of the optical fiber core is circular, which is the condition for the highest brightness19). In addition, as the number of combining beams increases, spherical aberration becomes a problem because the distance from the optical axis of the outermost beam increases. To avoid this problem, an aspherical focusing lens is preferably used.

The entrance face of the optical fiber is anti-reflection (AR)-coated for the purpose of suppressing transmission loss and return light to the LD.

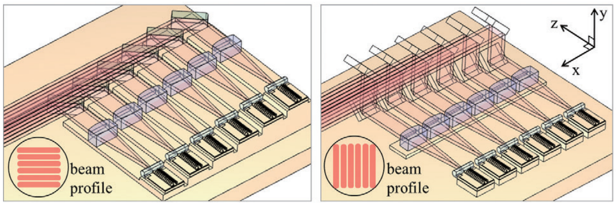

Fig. 8. Schematic diagram of beam layouts.

3.1.3 Spatial multiplexing and mirror alignment

Reflecting the BPP difference of the LD between slow and fast axis, the collimated beam width is also much larger in the horizontal direction than in the vertical direction. Therefore, in spatial multiplexing, collimated beams are stacked in the vertical direction as shown in Fig. 8. Beam alignment is performed by adjusting the mirrors prepared for each beam. In a typical layout, as shown on the left side of Fig. 8, LDs are lined up on a stepped package, and the beam traveling direction is bent 90 degrees by the single mirror. The step height is set slightly wider than the vertical width of the collimated beam so that the beams do not overlap. As another layout option, Fujikura have the patented structure of the unique mirror layout shown on the right side of Fig. 818). In this layout, LDs are mounted on the same plane, and the beam traveling direction and the beam aspect are rotated by 90 degrees by a pair of upper and lower mirrors. There are two advantages in this structure. One is that since the LDs are mounted on the same plane, the heat dissipation distance to the heat sink is the same for each LD, and the temperature of each LD becomes uniform. The other is that there is an axis that cannot be adjusted with a single mirror in principle, but with the pair of mirrors, the position and angle of the beam is completely adjustable to the target, which results in higher fiber-coupling efficiency.

3.1.4 Polarization multiplexing

Spatial multiplexing, which was described in the previous section, is a technique that combines as many beams as possible into a single optical fiber, but not that improves the entire brightness of the bundled beam. To increase the beam brightness, polarization and wavelength multiplexing techniques are often used. This section introduces polarization multiplexing.

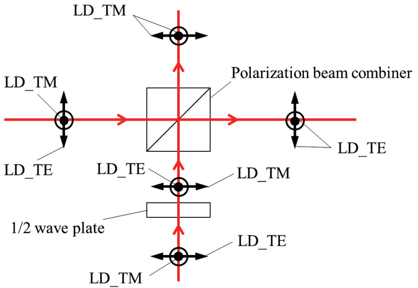

Fig. 9. Schematic diagram of polarization multiplexing system.

Polarization multiplexing can double the brightness when two different beams with orthogonal polarizations that do not interfere with each other are spatially multiplexed. This is achieved by using a polarization beam combiner that utilizes the polarization dependence of the reflectance. Specifically, as shown in Fig. 9, the dielectric multilayer film of a polarization beam combiner utilizes the property that reflects a horizontally polarized wave and transmits vertically polarized ones[19)]. Since the LD emits a beam mainly in TE mode, the polarization is perpendicular to the dielectric multilayer film, and it transmit through the polarization beam combiner (the ray traveling from left to right in Fig. 9). When another beam is incident as a wave is polarized horizontally with respect to the dielectric multilayer after the polarization is rotated by 90 degrees using a 1/2-wave plate, the beam is reflected (the ray traveling from the bottom to the right in Fig. 9), resulting in polarization multiplexing of the two beams. As can be seen from Fig. 9, the TM mode beam of the LD is a loss in polarization multiplexing, so high polarization purity is advantageous to accomplish higher output power and higher efficiency of the device. Fujikura has realized polarization multiplexing with the lowest possible loss by adopting the SAS structure as a basic structure of LDs, which ensures high polarization purity[14)].

3.1.5 Wavelength stabilizing and wavelength multiplexing

There are two methods for wavelength multiplexing, one is to use the wavelength dependence on the reflectance of an object, and the other on the reflection angle. The former has two methods using either a dichroic mirror or volume Bragg grating (VBG).

In wavelength multiplexing, wavelength separation is important because spectral overlap causes loss. However, the emission spectrum width of a high-power LD is generally several nm, and the wavelength shifts due to the temperature rise caused by current injection is also several nm. Therefore, wavelength stabilization technology is also required for wavelength multiplexing of laser pumping within the narrow excitation band of an ytterbium-doped fiber laser. We realized wavelength multiplexing of high-power LDs with narrow spacing as shown in Fig. 10 using wavelength stabilizing technique. While polarization multiplexing can only use two orthogonal polarizations, wavelength multiplexing can combine beams with many different wavelengths, making it a promising technology for the development of ultra-high-power laser sources.

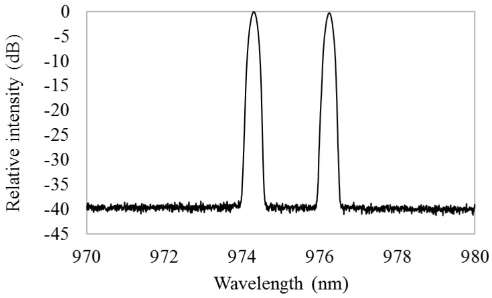

Fig. 10. Output spectrum of the LDM with wavelength multiplexing.

3.2 Heat dissipation system

As one of the limiting factors for the optical output power of LDs, heat management is one of the most important issue to be addressed. In this section, we will discuss three of the most important topics in package heat dissipation technology.

3.2.1 Solder bonding

Solder bonding of high-power LDs must be highly reliable mechanically, physically, and chemically, and the solder must have good wettability. AuSn, a lead-free eutectic solder with a high melting point, is used to meet these requirements. AuSn has eutectic points at 80 and 10 weight percent of gold, and the former is used for LD bonding because it has a higher melting point and better thermal conductivity because of higher gold content.

In LDM fabrication, solder bonding is performed for CoS and sub-mount bonding. To prevent the solder used in the previous process from re-melting, solder with a lower melting point is selected in the subsequent process. In recent years, copper, which has the highest thermal conductivity among commonly used metals, has come to be used as a packaging material to cope with higher power of LDs. On the other hand, copper has a significantly different coefficient of thermal expansion from LDs and thus high thermal stress is applied to the solder joint. To relieve the stress, solder with a low Young's modulus and a high flexibility is used as a buffer layer.

3.2.2 Heat dissipation sub-mount

There are two types of heat dissipation sub-mounts: the LD sub-mount on which an LD chip is mounted, and the optical system sub-mount on which an LD sub-mount and optical components are mounted. The heat dissipation sub-mount has various functions in addition to the capability of efficiently transferring the heat from the LD to the heat sink.

First, to transfer heat, it is essential that the material has high thermal conductivity, and that materials with less than 100 W/m/K are not used in high-power LD sub-mounts. Besides that, it is also important to prevent the formation of voids, which degrade thermal conductivity extremely, and to reduce the thickness of the solder layer, which has relatively low thermal conductivity, as much as possible. Therefore, heat dissipation sub-mounts require

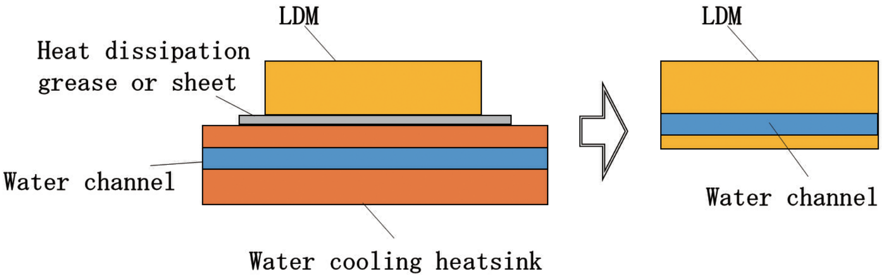

Fig. 11. Schematic view of a conventional water-cooling structure (left) and a direct water-cooling structure (right).

improvements in surface roughness and flatness. The metallization of the sub-mounts is also necessary to enhance solder wettability.

Another point required in designing sub-mounts is to avoid distorting the LD. If the thermal expansion coefficient of the LD and the heat dissipation sub-mount are different, thermal stress will be applied during solder bonding, causing distortion of the LD. The distortion affects the characteristics and reliability of the LD. Therefore, the coefficient of thermal expansion must be close to that of the LD.

Furthermore, electrical insulation is an important factor in designing LD sub-mounts. Some kilowatt-class laser systems, where dozens of LDs are connected in series, may need to withstand hundreds of volts. Therefore, to avoid current leakage, which can lead to dielectric breakdown, and major troubles such as fiber laser system halting, designing of such systems and selecting materials as well as mounting of parts must be done carefully.

For sub-mounts, where optical components are mounted, the thermal expansion coefficient must be close to that of the package, and the flatness must be good to prevent the misalignment of the optical components.

Examples of materials used in the heat dissipation sub-mount include molybdenum, tungsten, alloys of copper and these materials, ceramics, cladding materials composed of ceramics and metals.

3.2.3 Package

The design concept of the package to deal with challenges including heat transfer and thermal stress are similar to the heat dissipation sub-mount. On the other hand, since the package interfaces with the outside components, it needs toughness, and thus uses the metal materials among those listed in the previous section. In recent years, as a result of prioritizing higher power and lower cost, the use of copper as a package material has become common, as described in the previous section. Moreover, a simple structure to which the CoS is directly bonded without a sub-mount between the CoS and the package is commonly employed.

In a recent development trend, the low size, weight, and power consumption (SWaP) package has become known. This is attributable to the increasing demand to move the laser system to various locations and use it there, not only at a fixed place in a factory. However, kilowatt-class fiber lasers use a huge number of LDMs, and their cooling systems are also large, so their weight becomes a problem. Therefore, there is a growing demand for high-efficiency LDMs from the viewpoint of mobility not just of energy savings. One of the options to satisfy such demands is a structure that allows cooling water to flow directly into the LDM package[3]. Conventionally, a heatsink for cooling the LDM package was placed separately as shown in the left illustration of Fig. 11, but in the direct water-cooling structure, a water channel is formed in the LDM package as shown on the right side of Fig. 11. This makes it possible to reduce the size and weight of the laser device and also to improve the efficiency of heat dissipation by eliminating the contact thermal resistance between the package and the heat sink. Fujikura have recently adopted the direct water-cooling structure for LDMs that are in mass production.

4. Reliability of high-power semiconductor lasers and its modules

Industrial LD applications, such as fiber laser systems, require high output power and long-term stable operation. Our LDs have undergone accelerated aging testing and proven so reliable that they are operable for a long period. Since the reliability of LDs is affected by the packaging conditions, heat dissipation, and the atmosphere, the evaluation of product reliability should be performed in the form of an LDM, as well as a CoS. In addition, since ON-OFF operation is frequently performed in actual use such as in laser material processing, thermal stress should be higher than in continuous operation. Therefore, it is also necessary to conduct testing to verify that the LDM is sufficiently resistant to the repeated thermal stress caused by ON-OFF operation in long-term testing.

Table 1 shows the long-term reliability test data of the LDMs that are currently mass-produced. The test was performed under acceleration conditions at various optical output power and junction temperatures. To accumulate enough device hours, 103 modules for continuous operation, 8 modules for ON-OFF operation, and the total number of over 1400 emitters were used.

The accumulation time in Table 1 is the product of the number of the LDs and the time of driving the LDMs. The longest elapsed time has reached 12,000 hours for some cells, and the test is still ongoing. The actual device time in Table 1 is the product of the accumulation time and the acceleration coefficient, which means the driving time

Table 1. Data of long-term aging test of LDMs.

Continuous driving test

Optical Power (W)	Jucntion Temperature (℃)	Accumulation time (h)	Device time (h)	Number of failure
21.0	71.0	169,000	169,000	0
21.0	78.5	345,592	441,634	0
22.2	76.8	157,196	258,567	0
21.9	81.8	630,760	1,127,035	0
24.1	84.1	157,196	503,308	0
23.7	89.1	3,669,321	12,682,992	5
25.6	94.9	359,004	2,206,155	1
	Total	5,488,069	17,388,690	6

ON-OFF driving test

Optical Power (W)	Jucntion Temperature (℃)	Accumulation time (h)	Device ON-OFF cycle number (h)	Number of failure
21.0	78.5	309,082	3,671,888,220	0

under the maximum actual operating conditions (21 W, 71 degree C) for the fiber laser systems. The results of 6 LD failures occurring within 17 million hours indicate that the LD failure rate under operating conditions is less than 1000 FIT with a 90% confidence level.

The ON-OFF driving test was performed under the maximum current operating conditions on the systems. The accumulation time of ON-OFF operation in Table 1 is the product of the number of LDs and the duration of LDMs in the ON state while the ON-OFF cycle number of the device is the product of the accumulation time and ON-OFF frequency. The fact that no LD failure occurred even after 3.67 billion ON-OFF operations shows that our LDMs are sufficiently reliable for laser material processing applications.

5. Conclusion

This report has discussed the high-power, high-efficiency laser technologies as well as the world's highest level of performance and reliability of LDs and LDMs based on those developed by the Fujikura Group. With the progress of technological development in the last decade, LDMs have become more commoditized, and it seems to be becoming more difficult for each company to demonstrate their originality of packaging technology. However, as a future prospect, technological frontiers are expanding towards higher-brightness fiber output, improvement in heat dissipation, wavelength stabilizing, wavelength multiplexing, and low SWaP packaging. We are convinced that the evolution of high-power LDs and LDMs will continue.

References

1) A. Nogee, ed., The Worldwide Market for Lasers: Trends and Five-Year Forecast (2019-2025), Strategies Unlimited, Mountain View, CA, Chapter 3, 2020

2) N. Moshegov, I. Berezin, A. Komissarov, P. Trubenko, D. Miftakhutdinov, I. Berishev, V. Chuyanov, N. Strougov, A. Ovtchinnikov, and V. Gapontsev, Highly-Efficient High-Power Pumps for QCW Fiber Lasers, Proc. SPIE Vol.10900, 109000G, 2019

3) M. Kanskar, C. Bai, L. Bao, Z. Chen, C. Chiong, M. DeFranza, K. Fortier, M. Hemenway, S. Li, E. Martin, J. Small, B. Tomakian, W. Urbanek, B. Wilkins, and J. Zhang, High Brightness Diodes and 600W 62% Efficient Low SWaP Fiber-coupled Package, Proc. SPIE Vol.11262, 112620A, 2020

4) D. Xu, D. Ma, Z. Yu, L. Xu, and X. Chen, Kilowatt Wavelength-Stabilized CW and QCW Diode Laser, Proc. SPIE Vol.11262, 112620C, 2020

5) M. Hemenway, Z. Chen, M. Kanskar, W. Urbanek, D. Dawson, L. Bao, M. DeVito, K. Fortier, R. Martinsen, K. Welch, and R. Ballaban, Wavelength Stabilized Fiber-coupled Laser Modules for DPSS and Fiber Laser Pumping, Proc. SPIE Vol.11262, 112620I, 2020

6) G.G. Werner, J.J.M. Ponsoda, V. Raab, G. Safont, C. Bree, M. Radziunas, C. Cojocaru, and K. Staliunas, 1 kW cw fiber-coupled diode laser with enhanced brightness, Proc. SPIE Vol.11262, 1126202, 2020

7) R. Paoletti, S. Codato, C. Coriasso, F. Gaziano, P. Gotta, A. Maina, P. De Melchiorre, G. Meneghini, G. Morello, G. Pippione, E. Riva, M. Rosso, A. Stano, and M. Gattiglio, High power wavelength stabilized multiemitter semiconductor laser module using highly manufacturable DBR diode lasers, Proc. SPIE Vol.11262, 112620K, 2020

8) Y. Kaifuchi, K. Yoshida, Y. Yamagata, R. Nogawa, Y. Yamada, and M. Yamaguchi, Enhanced power conversion efficiency in 900-nm range single emitter broad stripe laser diodes maintaining high power operability, Proc. SPIE Vol.10900, 109000F, 2019

9) Y. Kasai, T. Aizawa, and D. Tanaka, High-power fiber-coupled pump lasers for fiber lasers, Proc. SPIE Vol.10514, 105140J, 2018

10) A. Sakamoto, H. Ogawa, S. Sakamoto, Y. Yamagata, and Y. Yamada, High Power Laser Diode Module for Fiber Laser Pumping Source, Fujikura Technical Review, No.44, pp.11-15, 2015

11) Y. Yamagata, R. Nogawa, Y. Kaifuchi, S. Sato, and Y. Yamada, High Power Semiconductor Laser Diode for Fiber Laser Pumping, Fujikura Technical Review, No.46, pp.46-49, 2016

12) R. Nogawa, K. Yoshida, Y. Kaifuchi, T. Kawakami, and Y. Yamagata, High Efficiency and High Power Broad Area Laser Diodes, Fujikura Technical Review, No.50, pp.23-26, 2020

13) Y. Yamagata, Y. Kaifuchi, R. Nogawa, K. Yoshida, R. Morohashi, and M. Yamaguchi, Highly efficient 9xx-nm band single emitter laser diodes optimized for high output power operation, Proc. SPIE Vol.11262, 1126203, 2020

14) R. Morohashi, Y. Yamagata, Y. Kaifuchi, K. Tada, R. Nogawa, Y. Yamada, and M. Yamaguchi, High polarization purity operation of 99% in 9xx-nm broad stripe laser diodes, Proc. SPIE Vol.10514, 105140B, 2018
15) Y. Yamagata, Y. Yamada, M. Muto, S. Sato, R. Nogawa, A. Sakamoto, and M. Yamaguchi, 915nm high-power broad area laser diodes with ultra-small optical confinement based on Asymmetric Decoupled Confinement Heterostructure (ADCH), SPIE Vol.9348, 93480F ,2015
16) Y. Kaifuchi, Y. Yamagata, R. Nogawa, R. Morohashi, Y. Yamada, and M. Yamaguchi, Ultimate high power operation of 9xx-nm single emitter broad stripe laser diodes, Proc. SPIE Vol.10086, 100860D, 2017
17) R. Nogawa, Y. Yamagata, K. Yoshida, T. Kawakami, and Y. Kaifuchi, High Efficiency 9xx-nm Broad Area Laser Diode, Proc. OPJ (2020)
18) Y. Kasai, Y. Yamagata, Y. Kaifuchi, A. Sakamoto, and D. Tanaka, High-brightness and high-efficiency fiber-coupled module for fiber laser pump with advanced laser diode, Proc. SPIE Vol.10086, 1008606, 2017
19) R. Morohashi, Y. Yamagata, Y. Kaifuchi, R. Nogawa, Y. Kasai, K. Tada, and Y. Yamada, High Polarization Purity High Power Laser Diodes, Fujikura Technical Review, No.48, pp.28-32, 2018