High-brightness laser diode module over 300 W with 100 μm / NA 0.22 fiber

Yohei Kasai*[a], Shinichi Sakamoto[a], Yukihiko Takahashi[a], Ken Katagiri[a], Yuji Yamagata[b], Akira Sakamoto[a], and Daiichiro Tanaka[a]
[a]Advanced Technology Lab. Fujikura Ltd. 1440, Mutsuzaki, Sakura, Chiba 285-8550, Japan
[b]Optoenergy Inc., 1440, Mutsuzaki, Sakura, Chiba 285-8550, Japan

ABSTRACT

High-brightness laser diode module over 300 W with 100 μm core / NA 0.22 fiber has been developed by integrating the several tens of optimally designed single emitter laser diodes in a newly designed package. We employed the Asymmetric Decoupled Confinement Heterostructure (ADCH) and the wide strip width to increase the durability for the catastrophic optical damage. High fiber-coupling efficiency was obtained with the uniquely designed micro-optical system. In addition, low thermal resistance made it possible to operate higher power. As a result, 300 W power was achieved without thermal rollover at 15.5 A with significantly high reliability. The high-brightness modules have a great advantage for high power fiber lasers such as 10 kW and beyond.

Keywords: Laser diode module, high-brightness, high-power, single emitter, package, spatial multiplexing

1. INTRODUCTION

The market demand for fiber lasers has been increasing in a laser processing area because of their competitive properties such as high conversion efficiency, good beam quality and small-footprint compare to CO_2 lasers or YAG lasers [1]. The fiber lasers with over kilowatt are widely used for the metal cutting or welding. Tens of laser diode modules are used in those high-power fiber laser systems for pumping sources. So brightness of the module is the most critical issue to achieve the competitive fiber laser properties [2, 3, 4].

High-power, high-brightness fiber coupled modules are realized by means of the spatial multiplexing of beams from multi emitters into the fiber. There are two methods to increase the power and the brightness of the modules - one is to increase the number of emitters and the other is to increase output power of each emitter. However, as the number of emitters increases, it becomes more difficult to focus the light from the laser diodes on the core of the fiber. On the other hand, as the output power of each emitter increases, random failure rate raised because of Catastrophic Optical Damage (COD). In addition, high-power operation would cause the negative cycle of reduction of efficiency and elevation of heat. As the results thermal rollover could happen. In either case high-efficiency and high-brightness laser diode modules are difficult to be achieved.

To overcome these limitations, we have developed following technologies.

- Laser diode chip; Single emitter diodes with ADCH structure and wide stripe width. Significantly high COD level of the laser diodes was obtained and it became possible to operate at high current without degradation of the efficiency.
- Spatial optics; Optical system for aligning the beams with high accuracy and high-precision alignment machine realizing that system. The spatial density of the beams was maximized. Polarization multiplex technique was also used to double the brightness.
- Package; High efficient heat dissipation with the high-heat conducting materials for base materials of the package. Low thermal stress with the sub-mount multilayer structure. The thermal resistance of the modules was reduced and also the thermal stress to the laser diode chip was suppressed.

As a result of these developments, 300 W power and 50% efficiency was achieved without thermal rollover at 15.5 A with 100 μm core / NA 0.22 fiber. In this paper, detail of the module designs and their performance are discussed.

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2. MODULE DESIGN

2.1 Laser diode design

There are two general approach to increase output power of a laser diode. One is to elongate the length of the cavity. The other is to make the emitter width wider. For both methods, the temperature of the active layer is lowered because the decreasing of heat resistance and light density, and then reliability is improved. But in case of long cavity length, power conversion efficiency generally decreases because a longer cavity length result in increasing of internal loss and threshold current. Now then we adopted the design as widening the stripe width of a laser diode over 100 μm while the cavity length remains conventional one. As stated above, it is possible to increase the output power by widening the stripe width. First, heat and electrical resistance decrease with increasing cross-section area of the active layer, so temperature rising is suppressed, and then CW high-power operations can be possible without thermal rollover. Second, because optical power density at the front facet of a diode decreases, COD level increases. These features brings higher power operation with high reliability. These properties can be estimated by calculating mean-time-to-failure (MTTF) represented by the following formula

$$\frac{MTTF_1}{MTTF_0} = \left(\frac{SW_0}{SW_1}\right)\left(\frac{P_0 / SW_0}{P_1 / SW_1}\right)^n \exp\left(\frac{E_a}{k_B}\left(\frac{1}{T_1} - \frac{1}{T_0}\right)\right) \quad (1)$$

where SW is stripe width, P is output power, n is power acceleration multiplier, E_a is activation energy, k_B is Boltzmann constant, T is the temperature of the active layer, and subscript 0 means reference condition.

It should be noted that beam-parameter-products (BPPs = half stripe width times half beam divergence angle) become larger as widening stripe width. That means the amount of increased stripe width is greater than the reduction of beam divergence angle due to thermal lens effect. In other words, the concept of high-power operation offers essentially rising BPPs. We optimized laser stripe width giving the highest coupled power to 100 μm core NA 0.22 fiber by our spatial optical design and high-precision alignment techniques.

To increase the reliability at higher power operation, we have also utilized ADCH structure for laser diodes [5]. Optical confinement becomes small to the extent possible by changing the position of active layer. This is synonymous with p-side optical confinement becomes smallest, so internal loss is minimized with reducing absorption loss of p-doped layer utmost. Significantly high COD level is also realized for optical density reduction.

ADCH structure and widened stripe width realize extremely high reliability. In addition, our laser modules do not use a laser bar but single emitter lasers, there is no thermal interference between the adjacent emitter. MTTF of developed laser diodes is estimated by acceleration test to be over 1,000,000 hours at 15 W, 80 degrees C at p-n junction. Power conversion efficiency is over 60%.

2.2 Spatial optical design

The originally designed micro-optics such as lenses and mirrors are used to couple the laser light emitted from wide stripe single emitter laser diodes into the fiber most efficiently. The collimated beams from tens of laser chips are stacked in the fast axis direction because a beam diameter of fast axis after the collimating lens is smaller than that of slow axis direction reflected the near field pattern of a laser diode. Figure 1. shows a typical beam profile image of part of the beam column in the module. Optimum value of beam alignment pitch along to the fast axis direction was decided under the following reason. When the beam pitch is too narrow, laser light eclipses with the adjacent mirror. While on the other hand if the beam pitch is too wide, fiber coupling loss arises because the focusing angle of the beam located on the edge of the plurality of beams exceeds critical angle of the fiber. However it's difficult to achieve perfect optimal value of beam alignment pitch on the ray tracing simulation because very high alignment accuracy and dimensional precision of the members are required. Then it is usually designed in consideration of the manufacturing tolerances, which means that power loss has been compromised. But we designed optical system that can correct the deviation of die-bonding position, beam alignment, and dimension of the member by the mirrors. In addition, high-precision custom self-aligning machine has been developed to support this optical system. Ideal layout of beam stack in the fast axis direction was realized. And also optical axis of the beams were aligned to the fiber axis with high precision, i.e. center of the beams for the slow axis direction were aligned as shown in Figure 1. It is possible to couple efficiently the large BPPs from wide stripe laser diodes for the slow axis direction. Polarization multiplex technique was also used as well as spatial multiplexing to double the brightness.

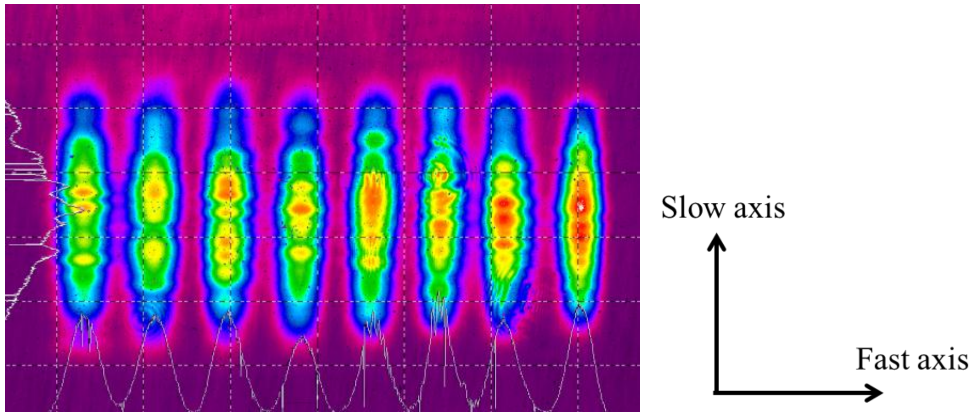

Figure 1. Typical beam alignment profile image of part of the beam column in the module.

2.3 Package(thermal) design

It is very important to achieve following two properties at the same time in the module. One requirement is high thermal conductivity from a laser diode chip to the heatsink. The other requirement is less stress design to the laser diode chip. Coefficient of thermal expansion (CTE) of high-heat conductive materials usually doesn't match with that of a laser diode. If a chip on sub-mount bonded to the CTE mismatch materials, thermal stress enlarges the point defects inherent in the crystal, and then internal failure mode called dark line defect (DLD) may occurs. DLD have a concern about degradation of the reliability of laser diodes. We managed the thermal stress by employing the sub-mount multilayer structure using gold-tin solder and indium solder. Therefore the appearance of DLD has been suppressed.

Appearance of manufactured the 300 W module is shown in Figure 2. It is a compact size of about 10 cm × 10 cm. And also not necessary to provide a micro-water cooling channels because it uses single emitters rather than laser-bars. This compact high-brightness module have a great advantage for reducing the size and cost of kilowatt fiber laser systems.

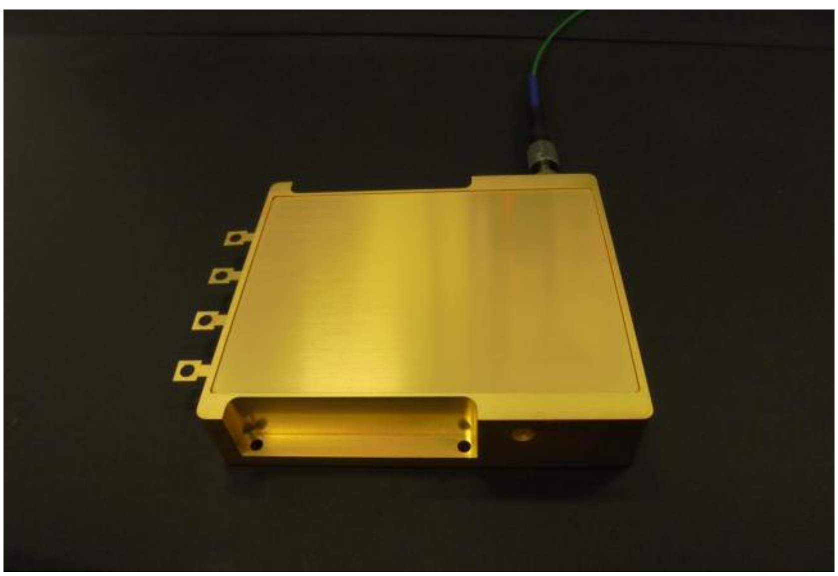

Figure 2. Appearance of the 300 W laser diode module.

3. PERFORMANCE OF THE MODULE

3.1 Optical and electrical characteristics

Optical power and forward voltage of the module as the function of current are shown in Figure 3. 300 W has been achieved at 15.5 A at the heatsink temperature 25 degrees C. Linearity of the L-I curve is maintained to 16 A and there is very few thermal rollover. Power conversion efficiency over 50% at 300 W was achieved as shown in Figure 4. The reduction of the efficiency at high current range is markedly small. In addition, the capability of heat dissipating is more directly shown by center wavelength shit of the module as Figure 5. Shift amount is less than 1 nm/A even at 300 W. That clearly shows a benefit of newly developed widening stripe width and high-thermal conductive package design.

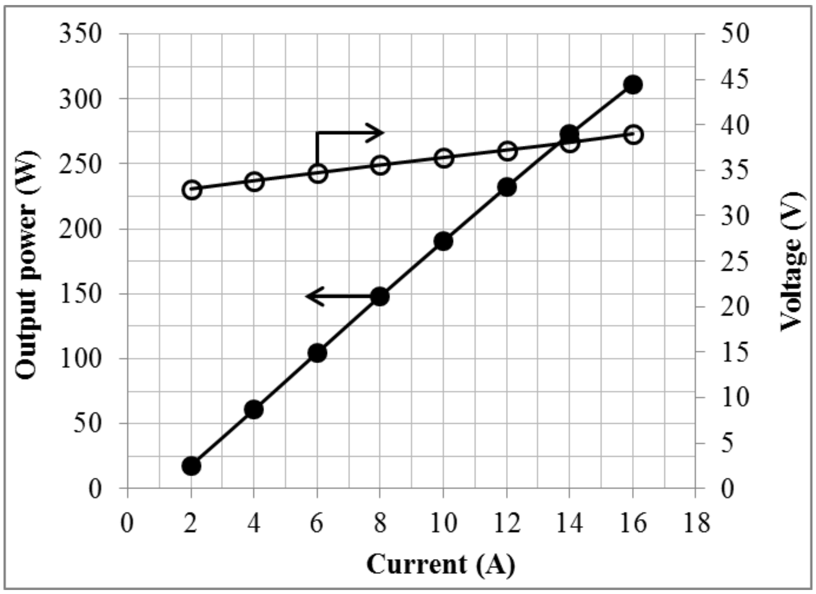

Figure 3. L-I and V-I characteristics of the module.

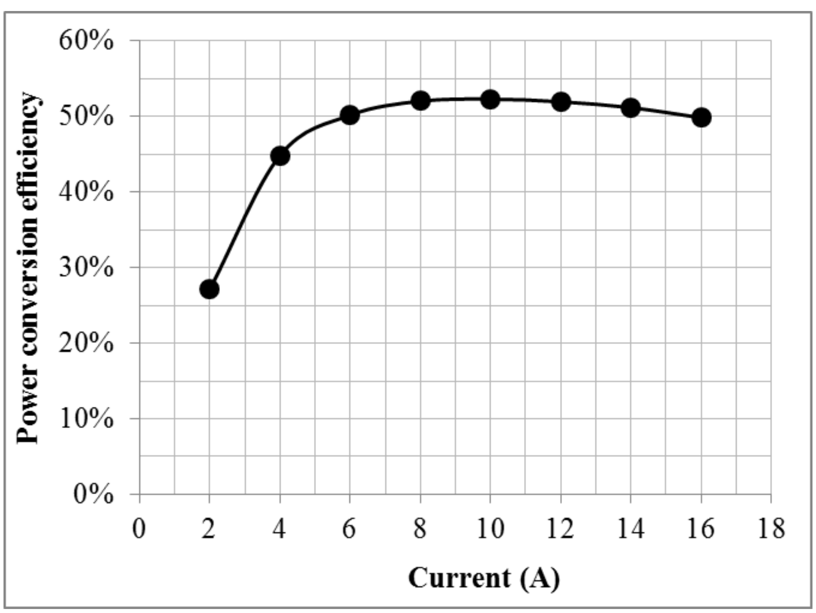

Figure 4. Power conversion efficiency of the module.

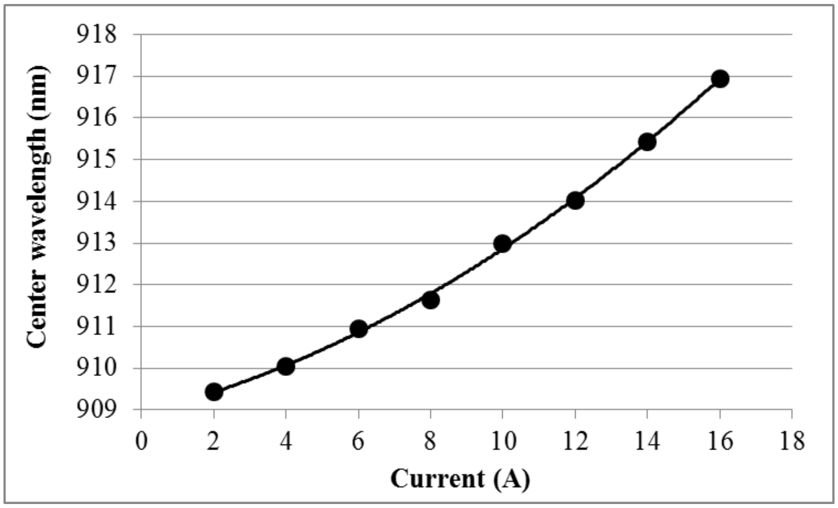

Figure 5. Center wavelength shift of the module.

Figure 6 shows temperature dependences of L-I and power conversion efficiency on current. The characteristic temperature of threshold current T_0 of the module was 182 K, and that of slope efficiency T_1 was 1000 K obtained respectively, that were almost similar value of laser diode chip's. That indicates the coupling efficiency of the module is stable at 15-45 degrees C range.

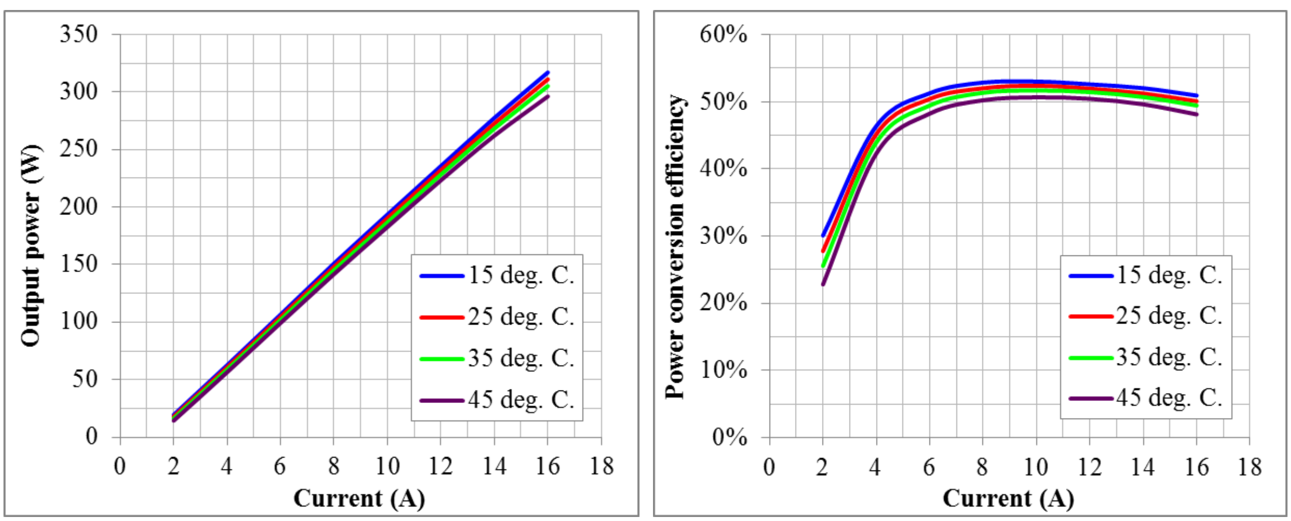

Figure 6. Temperature dependence of output power (left) and power conversion efficiency (right) of the module.

3.2 Reliability

To verify the reliability of developed high-brightness modules, we ran accelerated test by using several number of modules that include 158 chips inside. The test condition is 16.5 A driving current, 35 degrees C at heatsink temperature. No change has been observed up to 1500 hours as shown in Figure 7. This results indicate that there are no effect to the reliability to the laser diode chip by packaging process even COD level nor DLD level.

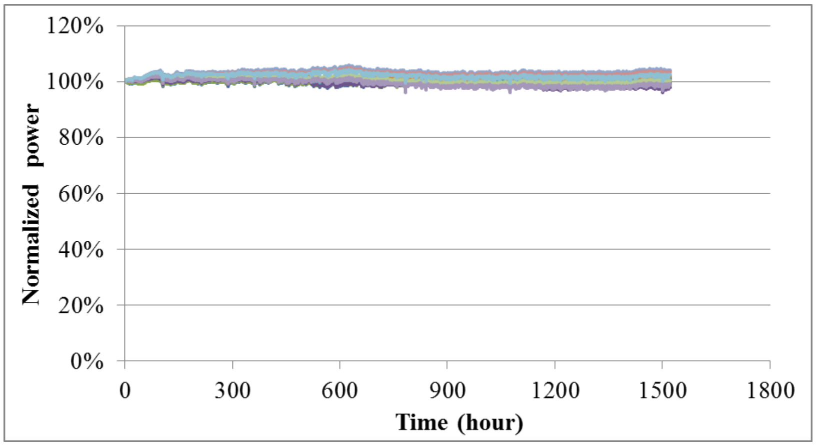

Figure 7. Accelerated test result of the modules. 16.5 A, Heatsink temperature=35 degrees C.

4. CONCLUSION

High-power, high-brightness modules have been developed. The laser diodes design, the spatial optical design, the package(thermal) design are comprehensively optimized. Over 300 W output power was obtained with 100 μm core NA 0.22 fiber, and the power conversion efficiency reached to 50% at 300 W, which is commercially available level. These ultra-high-brightness pump modules contribute further to cost reduction and compactness of kilowatt fiber laser systems. In addition, increasing a power of pump modules directly increase a power of a fiber laser, it would be expected to make over 10 kW systems.

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