High-brightness and high-efficiency fiber-coupled module for fiber laser pump with advanced laser diode

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ABSTRACT

High-brightness and high-efficiency fiber-coupled pump module has been developed with newly designed laser diodes and improved spatial optical system. High-power operation was realized by widening laser stripe width. The optical system of the module consists of only spatial multiplexing, not using polarization or wavelength multiplexing technique. Therefore it has advantages that no power loss at a polarization beam combiner or gratings, low material costs of optics, and high excitation efficiency by single wavelength excitation for a fiber laser. The peak power conversion efficiency of the module is 65.6% at 120 W output power, and its efficiency maintains more than 60% up to 220 W at 19 A driving current, and the maximum output power is 252 W at 23 A, at 25 degrees C heat sink temperature. The fiber outside diameter of the module is conventional 125 μm. Center wavelength of the laser is 915 nm.

Keywords: Laser diode module, high-brightness, high-efficiency, spatial multiplexing, single emitter, fiber-coupled

1. INTRODUCTION

The market growth of fiber lasers has been continued to be strong [1]. In kilowatt-class high-power fiber lasers for processing such as cutting or welding, the trend of more high power, high efficiency, and low cost is still ongoing. In order to improve these performance of fiber lasers, improvement of the characteristics of pump laser modules plays a very important role. Hence the development of the pump laser modules has been actively done by some companies [2, 3, 4].

A pump laser module for the fiber laser generally employs multi-single emitters from the competitive edge of its high-reliability and high-efficiency. We have designed the laser stripe width wider for the approach of high-brightness, high-efficiency, and low-cost of the pump modules [5]. Although the high-power operation and the high-efficiency in the high current region can be achieved by widening the stripe width, the design has a trade-off of beam-parameter-products (BPPs = half stripe width times half beam divergence angle) degradation in the horizontal direction. In Fujikura, all optical components are made by ourselves such as a pump combiner, a fiber grating, and a rare-earth doped fiber in addition to the pump module, so the total optimization of the pump laser BPPs and the fiber laser efficiency can be done. In this work we have developed the fiber-coupled pump laser module for the next generation high-power fiber laser unit. In the new module, the LD stripe width was designed to be 20% larger than before, and the operating current and output power were also increased by 20%. Although the core diameter and core delta were enlarged to adjust the new LD, the brightness was almost maintained by the improvement of spatial optical system. The fiber outside diameters is conventional 125 μm. The optical system of the developed LD module is constructed without polarization and wavelength multiplexing techniques because we tried to maximize the power while considering the efficiency is most important, so we didn't use the additive optics. Since there is no polarization multiplexing loss or external resonator loss for wavelength locking, the overall light extraction efficiency from LDs to the optical fiber is very high. Note, however, that in order to couple many beams to the fiber only by spatial multiplexing, the high assembling accuracy of optical elements is required. We accomplished this task by realizing an ideal beam layout by increasing the beam adjustment axis using two mirrors. As a result, we achieved high electrical-power conversion efficiency of 65.5% at 120 W at the peak, and 60% at 220 W. Cost performance is also excellent because there is no cost of Polarization Beam Combiner (PBC) or Volume Bragg Grating (VBG). In this paper, we discuss the design concept of high-power laser diodes by widening the stripe width and the spatial optical system of the module, and finally show the newly developed module's performance.

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2. MODULE DESIGN

2.1 Design concept of stripe width

Generally it is possible to increase the output power of the laser diode by widening the stripe width, because 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. And optical power density at the front facet of the diode decreases, then the catastrophic optical damage level increases. These features bring higher power operation with high reliability. These properties can be estimated by calculating mean-time-to-failure (MTTF) represented by the following formula.

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

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 BPPs become larger as widening stripe width. When comparing with the same operating current, the beam divergence angle of the LD with wide stripe width reduces reflecting of suppression of junction temperature, and the BPP deterioration is slight. However, NA of the slow axis of the laser has current dependency, and it becomes larger as the current becomes higher. Therefore, the concept of high-power operation offers essentially rising BPPs. So we need to design the optimum laser stripe width, NA, and output power of the pump modules as discussed below.

Considering the approach to increase the power of the pump module, there are two ways; one is to increase the power of each emitter, the other is to increase the number of emitters per one module. But both ways lead to increased laser NA. About the spatial optical system of the module, beams are stacked in the fast axis direction at a sub-millimeter pitch while they are not stacked in slow axis, and they are focused by f ~ 10-30 mm lens into the fiber as shown in Figure 1. The BPPs of the module is described as the following expression [6].

$$BPP_{LDM} = \sqrt{\left(BPP_{fast}\right)^2 + (BPP_{slow})^2} \tag{2}$$

The optical fiber is generally circle, when the BPP_{fast} = BPP_{slow} (that is square in angle space), the maximum brightness can be obtained. The BPP_{slow} is equal to BPPs of laser diode slow axis itself. Therefore, the number of beams to be stacked is limited by the BPP_{slow}. After all, the maximum power of the pump module is obtained by widening stripe width to BPP of the output fiber, and increasing the number of beam stacks to BPP_{slow}.

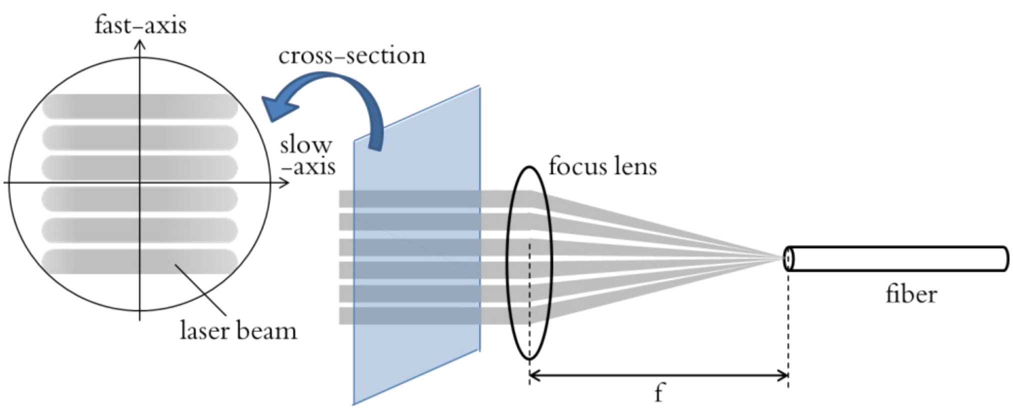

Figure 1. Beam focusing on fiber in the pump LD module.

Limitation of BPP of the pump module output fiber is determined by the fiber laser system. We have all optical components for fiber lasers in house such as an pump combiner, a fiber grating, and a rare-earth doped fiber in addition to the pump module, so the total optimization can be done.

The stripe width of the new LD was widened by 20%, and the operating current and output power were increased by 20%. The output fiber core diameter and core delta were enlarged for optimization, but the outside diameter remaining 125 μm.

Moreover, since this design concept is to increase the output power of each emitter and reduce the number of modules, it greatly contributes to cost reduction of the fiber laser.

In addition to the increasing operation power due to stripe width widening, significant increase in peak efficiency is also achieved by improving the light confinement factor in the vertical direction of the LD at the same time. But this will not be discussed in detail in this paper. The LDs were designed and manufactured by Fujikura group company OPTOENERGY Inc.

2.2 Spatial optical design

Polarization or wavelength multiplexing is useful as a beam combining technique for high-brightness pump modules. Since the pointing vector of the laser can be completely overlapped using the difference of the physical response to the polarization or wavelength, the number of beams to be stacked spatially can be reduced and condensed at a low NA (see Figure 1). However, the polarization and wavelength multiplexing are disadvantageous for efficiency and cost for the following reasons. First, in polarization multiplexing, since the light emitted from the LD is not perfectly linearly polarized, its polarization ratio becomes optical loss. And, the reflectance and the transmittance of the dielectric multilayer film in the PBC can not be 100%, and a loss of several percent occurs. Furthermore, the polarization rotation by the waveplate deviates from 90 degrees depending on the laser wavelength, which also becomes reflection and transmission loss at PBC. Regarding cost, PBC is very expensive compared to mirrors and lenses. Next, in wavelength multiplexing, when it is used as a pump laser, a dense wavelength multiplexing is required because absorption spectrum of ytterbium doped fiber is sharp. For this purpose wavelength locking is required, but the coupling loss of feedback light to the LD active layer and the diffraction loss at the external resonator mirror exist to some extent. In addition, VBG and diffraction grating are very expensive like PBC. From the above, if the high-brightness is realized by only spatial multiplexing, not using polarization or wavelength multiplexing, significant high-efficiency and low-cost can be achieved by reducing the optical loss and optical material cost. This technical challenge is how to stack a dozen of beams to compact size with low optical loss.

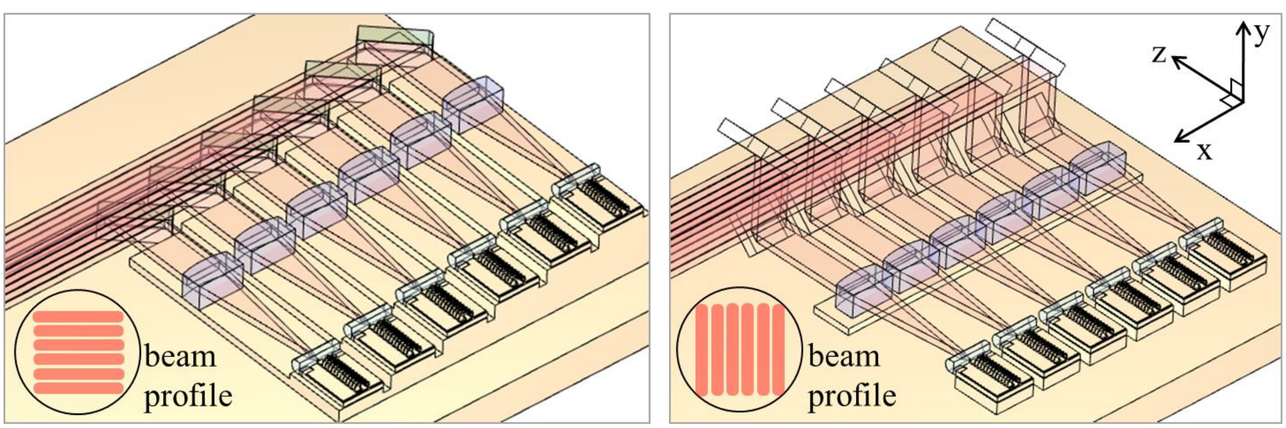

Figure 2. Package structure of general pump module (left). Laser diodes mounted on stair-like base and beams are stacked in y direction by each one-mirror. Developed module structure (right). Laser diodes mounted on a flat base. Beams are rotated 90 degrees and stacked in x direction by each two-mirror.

A layout of a general pump LD module is configured as shown in Figure 2 (left). A Chip-on-Sub-mount (CoS) is mounted on a stepped housing, collimated beam is formed by Fast Axis Collimator (FAC) and Slow Axis Collimator (SAC), the beam is reflected by one mirror and stacked in the y direction [7]. When the mounting position of CoS, FAC, and SAC are shifted from the design center, the beam propagation angle rotates or the beam position shifts in parallel. Then this beam angle or position deviation is corrected by the mirror. However, it is impossible to be completely corrected by one mirror alignment. Due to this beam shifts, an optical loss of beam stacking or a fiber coupling loss may occur.

We solved this problem by using two independent mirrors. As shown in Figure 2 (right), the beam is raised in the y direction with the first mirror and folded back in the x direction by the second mirror. The beam is rotated 90 degrees and stacked in the z direction. And by using two independent mirrors, it is possible to adjust the angle and position of the beam arbitrarily. Therefore, it is possible to correct all of them that mounting positional deviation, dimensional tolerance, fabrication process variation in x, y, θx, θy directions of the CoS, FAC, and SAC. We have realized low NA and high coupling efficiency by this optical system and we can achieve high brightness only by spatial multiplexing, without polarization or wavelength multiplexing. As for cost, since we use two mirrors, the material cost of the mirror itself doubles. But the price of mirror is low enough, so there is not much cost increase. On the other hand, optics such as wave plate and PBC for polarization multiplexing, VBG and dichroic mirror or diffraction grating for wavelength multiplexing are several tens of times the price, so it is far cheaper not to use these.

3. PERFORMANCE OF THE MODULE

Optical power and electrical-optical power conversion efficiency (PCE) of the developed module as the function of current are shown in Figure 3. Heatsink temperature is 25 degrees C, and operation mode is CW. The peak PCE is 65.6% at 120 W (at 10 A), and maintains more than 60% up to 220 W (at 19 A). This high-efficiency indicates that the optical loss inside the module is very small. Maximum output power is 252 W and PCE is 55% at 23 A.

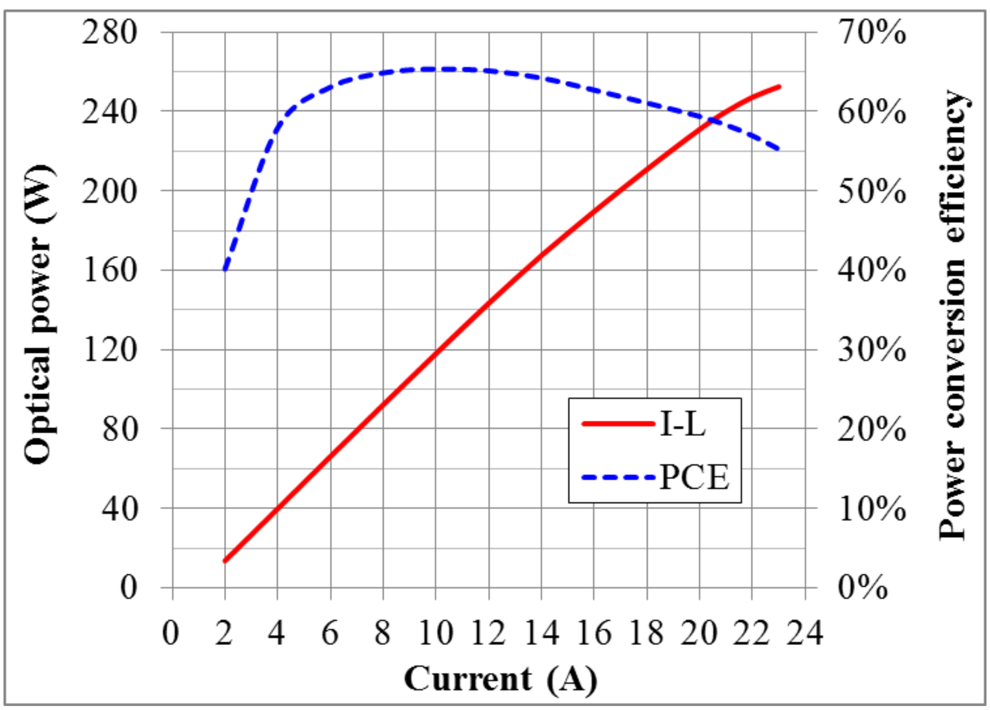

Figure 3. Optical output power and electrical-optical power conversion efficiency characteristics of the developed module.

To demonstrate the improvement of the performance of the developed module, we show the comparison of optical power and PCE with conventional module in Figure 4. Since the stripe width of new LD has been increased by 1.2 times as compared with the conventional one, the linearity of I-L curve is kept up to the 1.2 times higher current side, and the power scaling has been established. An improvement of more than 10% of the peak efficiency is a result of improving the light extraction efficiency of the module and also tuning the light confinement factor in the vertical direction of the LDs. PCE in high current range, the developed module drops more gently reflecting the I-L characteristics. Although the core diameter and core delta are widened adjust to the new LDs, the brightness is almost maintained by the improvement of the spatial optical system. The fiber outside diameters are both 125 μm. And, their package platforms are common, so outside dimensions do not change. However, heat dissipation is improved by changing the materials of the internal heat spread sub-mount and fiber-mount, then reliability of that parts in high power operation are secured.

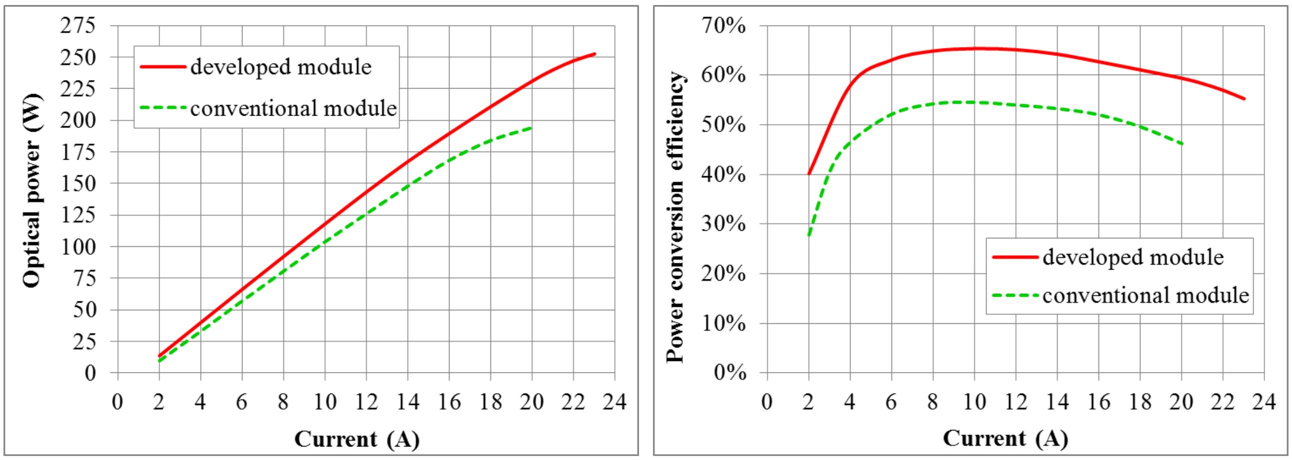

Figure 4. Comparison of developed module and conventional module of optical power (left), and power conversion efficiency (right).

4. CONCLUSION

High-brightness, high-efficiency, low cost fiber coupled laser diode module has been developed. Newly designed wide stripe LDs were employed and spatial optical system has been improved by using two-mirror alignment technology. It was not included an unnecessary optics like PBC or VBG, because it was maximized the output power by giving the highest priority to efficiency and cost. The electrical-optical conversion efficiency is 65.6% at the peak at 120 W output power, 60% at 220 W from 125 μm fiber. These modules are significantly useful for the pump of kilo-watt class general-purpose fiber lasers or direct diode lasers because of its high-performance of power, efficiency, and cost. By necessary, farther high-brightness can be realized by using polarization or wavelength multiplexing in addition to the developed base technology of the spatial optical system, although they sacrifice some efficiency and cost per watt. These ultra-high-power pump modules for high-end fiber laser model will be unveiled in the near future.

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