High Power Laser Diode Module for Fiber Laser Pumping Source

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High power laser diode modules are essential devices for fiber laser systems because properties of the modules directly affect the performance of the fiber laser systems. We have realized high power and high reliable laser diode modules by combining assemble technology developed for optical communication devices and high power laser diode chips developed by OPTOENERGY Inc.

1. Introduction

Fiber laser systems of various power ranges from several watts to over kilo-watt are widely used all over the world as light sources for marking or metal processing. High power laser diode modules are essential devices for these fiber laser systems because properties of the modules directly affect the performance of the fiber laser systems. We have realized high power and highly-reliable laser diode modules by combining assemble technology developed for optical communication devices and high power laser diode chips developed by OPTOENERGY Inc.

2. High-power laser diode

2.1 Device structure

Figure 1 shows the schematic structure of 900 nm range high power multi mode laser diode (LD) based on InGaAs/AlGaAs materials. Laser structure consisting of an active layer, a waveguide layer and a cladding layer is formed on GaAs single crystal substrate by epitaxial growth technique. Light emitting width of LD defined by lateral current confinement structure is set to be 100 µm in order to match the core diameter of an optical fiber for efficient optical coupling. Laser mirror facets with flatness of atomic layer level are formed by using cleavage technique. Laser facets are anti-reflection (AR) coated on front side and high-reflection (HR) coated on rear side. The laser light is mainly emitted from the front AR-coated facet. The maximum operable power of these LDs are, in general, limited by the catastrophic optical damage (COD) on laser mirror generated when the optical density exceeds the material limit 1) 2) 3) 4) 5) 6).

Therefore, it is essential to manage the COD power level in order to ensure high reliability and high output power operation. The process chain of COD mechanism is schematically shown in Fig. 2. Dielectric film coating on laser facets are applied for the purpose of not only for facet reflectivity control but also for protecting the semiconductor surface from oxidation. If

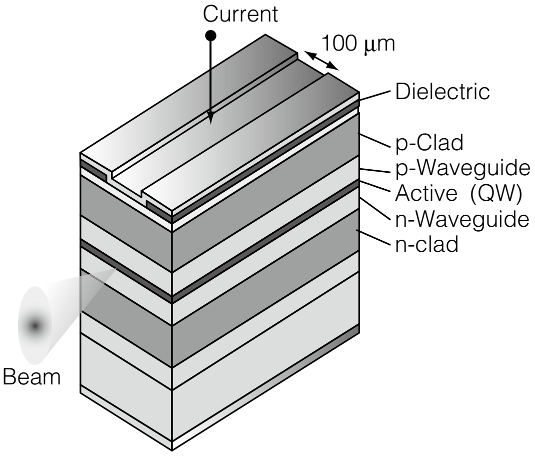

Fig. 1. Schematic structure of multimode semiconductor laser diode chip.

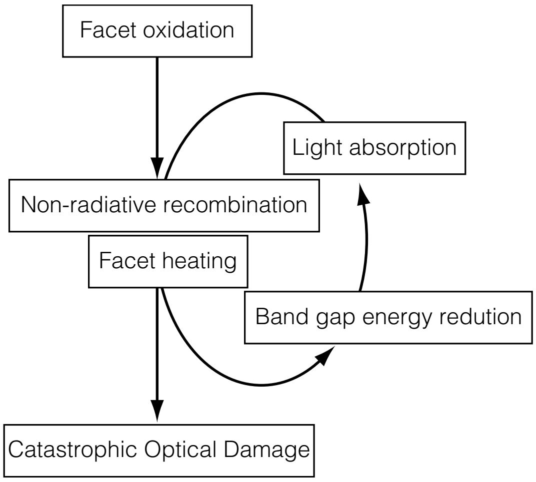

Fig. 2. Degradation process of LD facet mirror.

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Panel 1. Abbreviations, Acronyms, and Terms.

GaAs—Gallium Arsenide
InGaAs—Indium Gallium Arsenide
AlGaAs—Aluminum Gallium Arsenide
CoS—Chip on Submount
DCH—Decoupled Confinement Heterostructure
CW—Continuous Wave
WPE—Wall Plug Efficiency
LD—Laser Diode
COD—Catastrophic Optical Damage
MTTF—Mean Time To Failure

special consideration is not paid for the laser facet formation process, high-density of surface states are generated in the laser facet due to the oxidation of the semiconductor surface [7] [8]. Such surface states cause non-radiative carrier recombination generated by light absorption in laser facet region and that induced local heating on a laser output facet. The local heating on the laser facet further causes band gap shrinkage followed by optical absorption increase. Then such a positive feedback loop of facet heating mechanism eventually result in catastrophic damage of laser facets. This process chain is so called COD. Therefore, key point to prevent the COD and to improve the reliability at high output power operation is suppressing the local heating on laser facets in every conceivable way, such as laser facet passivation to prevent surface state generation [9], minimization of light absorption [10] [11] [12], and light density reduction at laser facet [1].

OPTOENERGY realized high reliability of these lasers with long-term stable operation at high output power by applying unique LD design called decoupled confinement heterostructure (DCH) [13]. Figure 3 shows band-gap diagram, and corresponding carrier distribution and optical mode profile for DCH and conventional separate confinement heterostructure (SCH). The advantage of DCH is that it can reduce the optical density at the active layer without any penalty in carrier confinement. This is an essential condition to achieve high COD level, as well as high power and high temperature operation. Therefore, DCH is a promising structure for high power and high reliability LDs.

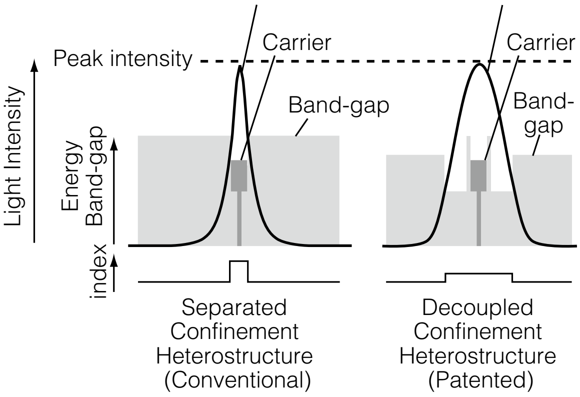

Fig. 3. Comparison of conventional structure and DCH concept.

LDs are bonded on submounts using AuSn eutectic solder with epi-side down configuration (called Chip-on-Submount: CoS) as shown in Fig.4. The submount is high thermal conductivity type with thermal expansion coefficient matched to the GaAs substrate. Figure 5 shows light output versus current (I-L) characteristics measured for CoS LD under CW and pulsed driving conditions. In the case of CW driving condition, COD is not observed because the light output is limited by power saturation due to heating of the LD chip. For accurate evaluation of COD level, therefore,

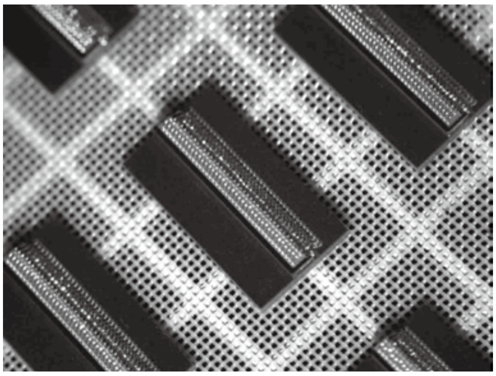

Fig. 4. LD chip on submount (CoS).

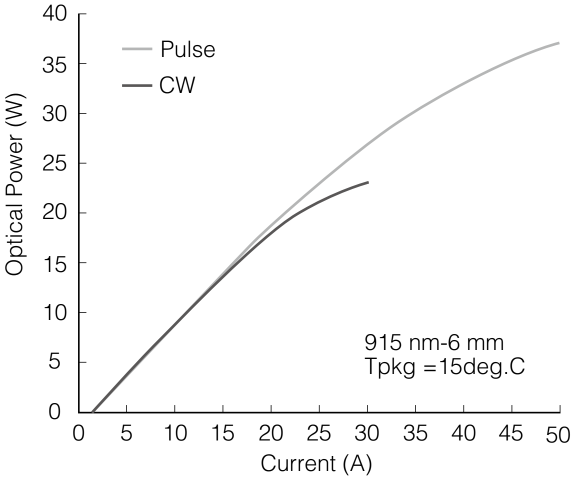

Fig. 5. Comparison of I-L characteristics between CW and pulse operation for 6 mm-CoS under package temperature Tpkg of 15deg.C.

pulsed operation of LD is necessary in order to avoid the thermal influence. The light output power under pulsed operation reached 38 W at 50 A driving current without COD. This result proved the advantage of DCH structure for highly reliable COD free operation.

2.2 *Electro optical properties*

Long cavity design is widely used as a simple solution to increase LD practical output. However, there is a trade-off relationship between practical output power and wall plug efficiency (WPE) in terms of cavity length. Therefore, there is an optimal laser cavity design dependent on laser applications. For this reason, we chose two different cavity length of 4 mm and 6 mm. 4mm cavity LDs are suitable for WPE preferred application because they have a feature of high WPE with low operation current. On the other hand, 6 mm cavity LD is suitable for power preferred application because of superiority in high power operation due to efficient heat dissipation. Light output power and WPE characteristics measured for 4 mm and 6 mm-cavity LDs are shown in Fig. 6 and Fig. 7, respectively. Typical value of laser characteristics are listed in Table 1. Practical output power in 4 mm-LDs is 13 W, while that in 6mm-LDs reaches to 15 W. Practical output powers of these LDs are at the level of world top-class among single emitter lasers with 100 μm wide stripe. WPEs measured at room temperature are as high as 60 % at 13 W for 4 mm-LDs and 55 % at 15 W for 6 mm-LDs, respectively.

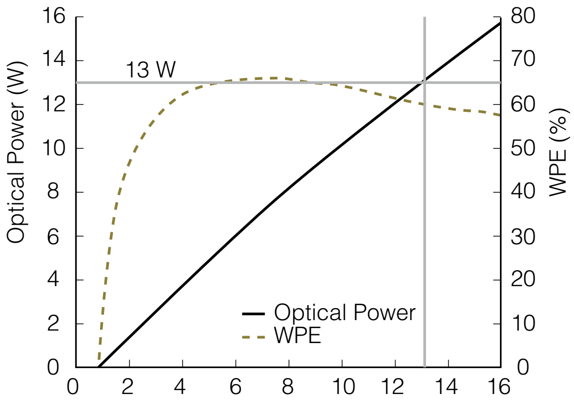

Fig. 6. Characteristics of 4 mm-CoS.

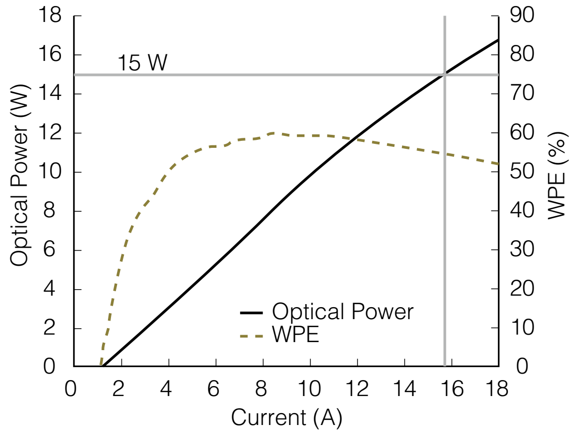

Fig. 7.Characteristics of 6 mm-CoS.

Light beam divergence properties of LDs is also an important characteristics similar to the light output power because it directly influences fiber coupling efficiency. The beam divergence properties measured for vertical and horizontal directions are shown in Fig.8. For vertical direction, single transversal mode with Gaussian profile and constant divergence angle 27° (FWHM) are obtained without any driving current dependency. On the other hand, horizontal transversal mode shows multi mode oscillation and have the injection current dependency. This is due to so-called thermal lens effect caused by the refractive index increase at the center area of waveguide through partial temperature increase.

Table 1. Properties of 4 mm-CoS and 6 mm-CoS.

Parameter	Unit	Laser characteristics	
Cavity length	mm	4	6
CW output power	W	13	15
Power conversion efficiency	%	60	55
Horizontal beam divergence @95% power	°	<11	<11

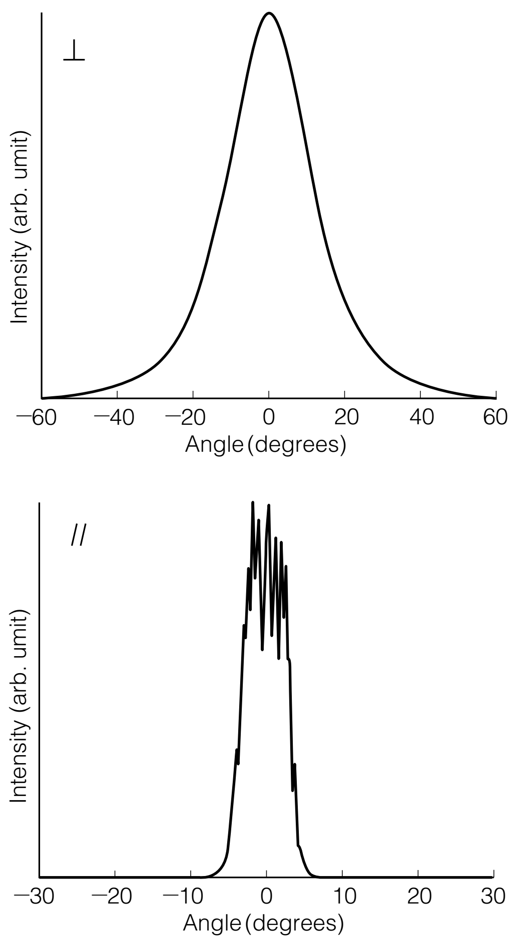

Fig.8. Typical beam divergence pattern of 4mm-CoS measured in perpendicular (⊥) and horizontal (//) directions.

This thermal lens effect tends to be suppressed in long cavity length LDs such as 6 mm than 4 mm under the same driving current condition, because of reduced junction temperature.

Therefore, horizontal beam divergence angle at practical output power of 15 W in 6 mm-LD is achieved to be 11°, that is almost the same divergence angle of the 4 mm-LD at 13 W output condition. These results show that the both type of LDs have sufficiently small beam divergence angles, which guarantee high coupling efficiency to an optical fiber.

2.3 Long-term reliability of LD

In order to validate LD reliability for long term and high power operation, multi–cell accelerated aging tests were carried out for five different output power levels and junction temperatures. More than 800,000 device hours have been accumulated by using 150 devices with long-term aging data up to 6,500 hours at maximum, in order to estimate random failure rates for 6 mm and 4 mm-LDs. Light output versus aging time characteristics at the highest acceleration conditions for 4 mm and 6 mm-LDs are shown in Fig. 9 and Fig. 10, respectively.

Only one device failed at 1,600 hours in 6 mm-LDs aging test due to COD of the front facet. However for other tested devices, apparent degradation has not been observed up to 6,500 hours aging time. From these multi-cell accelerated aging test results, we estimated mean time to failure (MTTF) for the condition of rated optical power and submount temperature of 25 deg.C. Estimated MTTF values are summarized in Table 2.

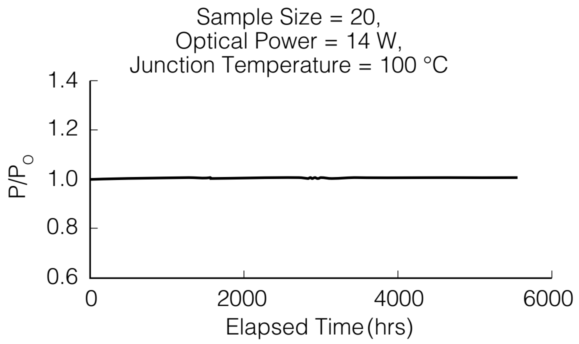

Fig.9. Power variation trend of accelerated aging test for 4 mm-CoS.

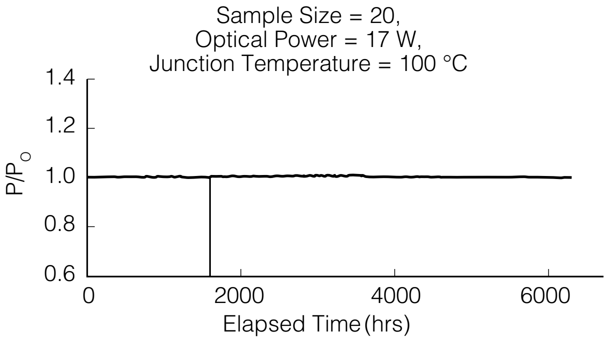

Fig.10. Power variation trend of accelerated aging test for 6 mm-CoS.

MTTF of random failure mode for 4mm-LDs is estimated to be 560,000 hours for 13 W operation condition and that for 6 mm-LDs is 630,000 hours for 15 W operation condition, respectively. These MTTF values are the world top-level to the best of author's knowledge.

3. Laser diode module

3.1 Properties of laser diode module

We have developed two types of LD modules; one is a single-chip LD module which uses one LD chip inside the module, the other is a multi-chip LD module which uses several number of LD chips inside the module. Appearances of the single-chip LD module and the multi-chip LD module are shown in Fig.11 and

Table 2. Calculated results of MTTF for random failure mode under submount temperature of 25 deg.C.

LD Type	Po (W)	Tj (°C)	MTTF@CL60 % (hrs)
4 mm-CoS	11	65	2,250,000
	12	70	1,190,000
	13	80	560,000
6 mm-CoS	13	65	1,890,000
	14	70	1,070,000
	15	75	630,000

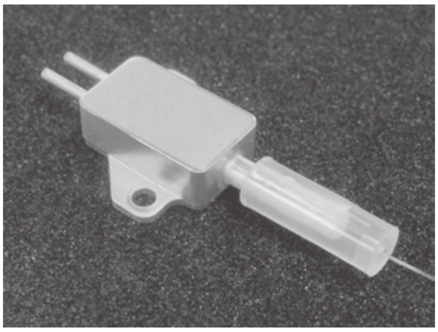

Fig.11. Appearance of single-chip LD module.

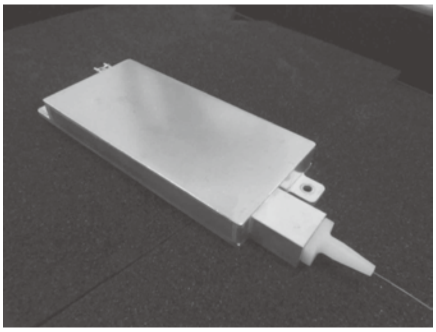

Fig.12. Appearance of multi-chip LD module.

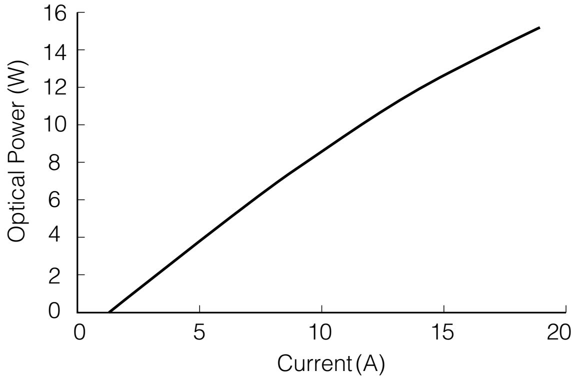

Fig.13. Characteristics of single-chip LD module.

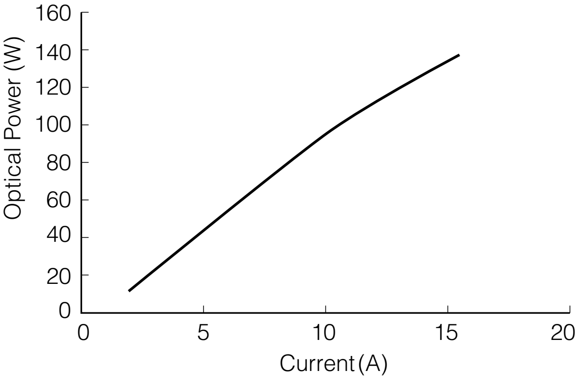

Fig.14. Characteristics of multi-chip LD module.

Fig. 12, respectively. Figuress 13 and 14 show optical output power properties from these LD modules. Table 3 shows basic properties of the single-chip LD module and the multi-chip LD module. We chose longer LD chip which has 6mm cavity length for the single-chip LD module because of higher power with a single chip. As a result, over 13 W operation optical power is achieved. On the other hand, we have employed shorter LD chips which have 4 mm cavity length because higher efficiency in the power consumption is required for the multi-chip LD module. The multi-chip LD achieved over 110 W optical power and 50 % wall plug efficiency.

3.2 Reliability of the laser diode modules

Both single and multi-chip LD modules passed strict reliability test based on optical communication systems. In addition, these modules have the same life time to the LD chip. These properties indicate that we do not apply any damage to the LD chips during fabrication process of these modules.

4. Conclusion

We have developed two types of LD module using LD chips developed by OPTOENERGY. One is the single-chip and the other is the multi-chip LD module. These LD modules are widely used for our fiber laser systems and contribute to achieve high-power and high-reliability systems.

Table 3. Properties of single-chip LD module and multi-chip LD module

Parameter	Unit	Characteristics	
Number of diode chips	-	single	multi
Output power	W	13	110
Power conversion efficiency	%	45	50
Operation current	A	16	12

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