Characteristics and reliability of high-power InGaAs/AlGaAs laser diodes with decoupled confinement heterostructure

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ABSTRACT

In order to overcome catastrophic optical damage(COD), decoupled confinement heterostructure(DCH) featuring a broadened waveguide and thin carrier block layers have been developed. Due to decoupling of carrier and optical confinement, a DCH laser can be designed more flexibly than a conventional separated confinement heterostructure (SCH) laser, i.e., laser diodes can be designed with a variety of gain coupling factor $\Gamma_{\perp}$, quantum-well number N_w, keeping the beam divergence angle constant.

COD level of various DCH lasers with uncoated facet was examined in 50μsec pulse operation and following results were obtained; COD was normalized by equivalent vertical beam width $d/\Gamma_{\perp}$ (where d is thickness of quantum-well) and COD level of 980nm InGaAs quantum-well lasers was twice as high as that of 860nm GaAs quantum-well lasers, i.e., 100-110mW/μm for InGaAs-QW and 40-50mW/μm for GaAs-QW in the case of $d/\Gamma_{\perp}\sim 1$. So, COD level can be manage in DCH scheme.

Epitaxial structure has been optimized through the high-power performance of gain guided multi-mode lasers. The CW maximum power 6.3W was attained for 50μm aperture and 9.5W for 100μm aperture, which was limited by thermal saturation. Lifetest was carried out for 50μm aperture devices at the condition of 50°C-1.0W. All 14 devices were operating over 13,000hrs without failure. The median life was estimated to be more than one hundred thousand hours at 50°C.

Real index guided structure was fabricated with a multi-step MOVPE epitaxial growth. Stable fabrication could be possible even in a conventional process, since chemically active Al-content was greatly reduced at 980nm in DCH. The maximum CW output power was 1.3W, which was limited by thermal saturation. Single mode operation was extended up to 700mW. And 500mW kink-free output was reproducibly obtained in a self-aligned real index guide structure. Preliminary life tests showed the stable operation at 300mW-50°C and 300mW-70°C.

Keywords:High-power laser diodes, Catastrophic optical damage(COD), InGaAs/AlGaAs laser, Decoupled confinement heterostructure(DCH)

1.INTRODUCTION

High-power and high reliability laser diodes are required in various industrious fields such as DPSS, printing, medical treatment, material processing and telecommunication.

980nm laser diode is most inportant devices as a pump source in erbium-doped fiber amplifiers(EDFAs)[1] of optical transmission system applications, since it has low-noise figure than 1480nm pumping.

However so far it is generally believed that the reliability of high-power of 980nm laser diodes is not good as 1480nm laser

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because of the occurrence of catastrophic optical mirror damage (COMD)[8,9]. Namely nonradiative recombination and reabsorption of laser light via surface states on the normal facets induces facet heat-up, subsequent facet degradation and finally sudden failure in high-power operation[2,3].

To overcome this problem, a variety of laser structures, that is, window structure, facet passivation etc. has been developed. And we have proposed decoupled confinement heterostructure (DCH) in GaAs/AlGaAs quantum-well laser diodes[4].

In this paper, 980nm broad area and single mode InGaAs/AlGaAs lasers with DCH are reported. The authors think that those lasers have two effects. First, gain coupling factor $\Gamma_\perp$ is able to be reduced. So equivalent vertical beam width $d/\Gamma_\perp$ is enlarged. As a result, COD level is increased and reliability in high-power operation is enhanced. And simultaneously the decrease of $\Gamma_\perp$ suppressed hole burning effect. So in the case of single mode lasers, lateral mode is expected to be more stabilized for less $\Gamma_\perp$[5] and higher power single mode operation is anticipated. Second, reduction of Al content is possible in comparison with SCH. So DCH gets the advantage to low electric and low thermal resistance. This has an effect of supressing temperature rising of laser chip and improving energy efficiency. And it is faverable to broad area lasers which is operated on large current.

2.LASER STRUCTURES FLEXIBLY DESIGNED BY DCH

In Fig.1, a schematic DCH epitaxial profile is shown. DCH laser diode is characterized by broadened waveguide layers and thin carrier-block layers sandwiching active area. It is one of the features of DCH that very flexible design of optical intense distribution in the waveguide mode is possible. Due to decoupling between carrier and optical confinement, it expands freedom of designing laser diodes.

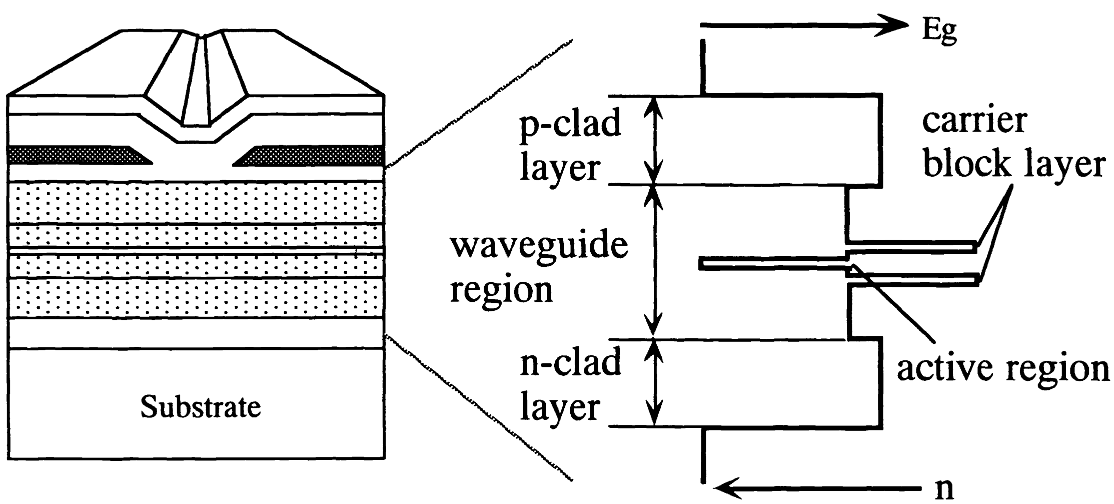

Fig.1 Cross sectional figure of laser diode and schematic epitaxial profile for DCH

For example laser diodes with a variety of $d/\Gamma_\perp$ can be designed keeping a vertical FFP angle constant. Here d is the width of qwantum well and $\Gamma_\perp$ is a gain coupling factor per quantum well. In Fig2, near field and far field patterns(NFP,FFP) of typical design are shown, which are calculated by multi-layer waveguide approximation[6,7]. In general, normalized frequency V in 3 layer slab waveguide approxmation is defined by $V=\pi W/\lambda(n_w^2-n_c^2)^{0.5}$. Here, W is the thickness of waveguide region in between cladding layers, λ is wavelength, n_w and n_c are reflective indices of waveguide and cladding layers. Those values are (a)$\sim\pi/2$ (b)$\sim\pi$, respectively. In Fig.2, it is seen that $d/\Gamma_\perp$ increases with normalized frequency V. And optical peak intensity of waveguide mode is reduced with the same FFP angle 20degrees. And existence of carrier-block layer affects NFP and $d/\Gamma_\perp$, but not FFP strongly. Generally it is necessary to make cavity length longer in order to maintain laser oscillation for less $\Gamma_\perp$. Therefore it is important to lessen internal loss as small as possible. So minimum $\Gamma_\perp$ is actually limitted by internal loss and net gain characteristics of quantum-well as a function of current density.

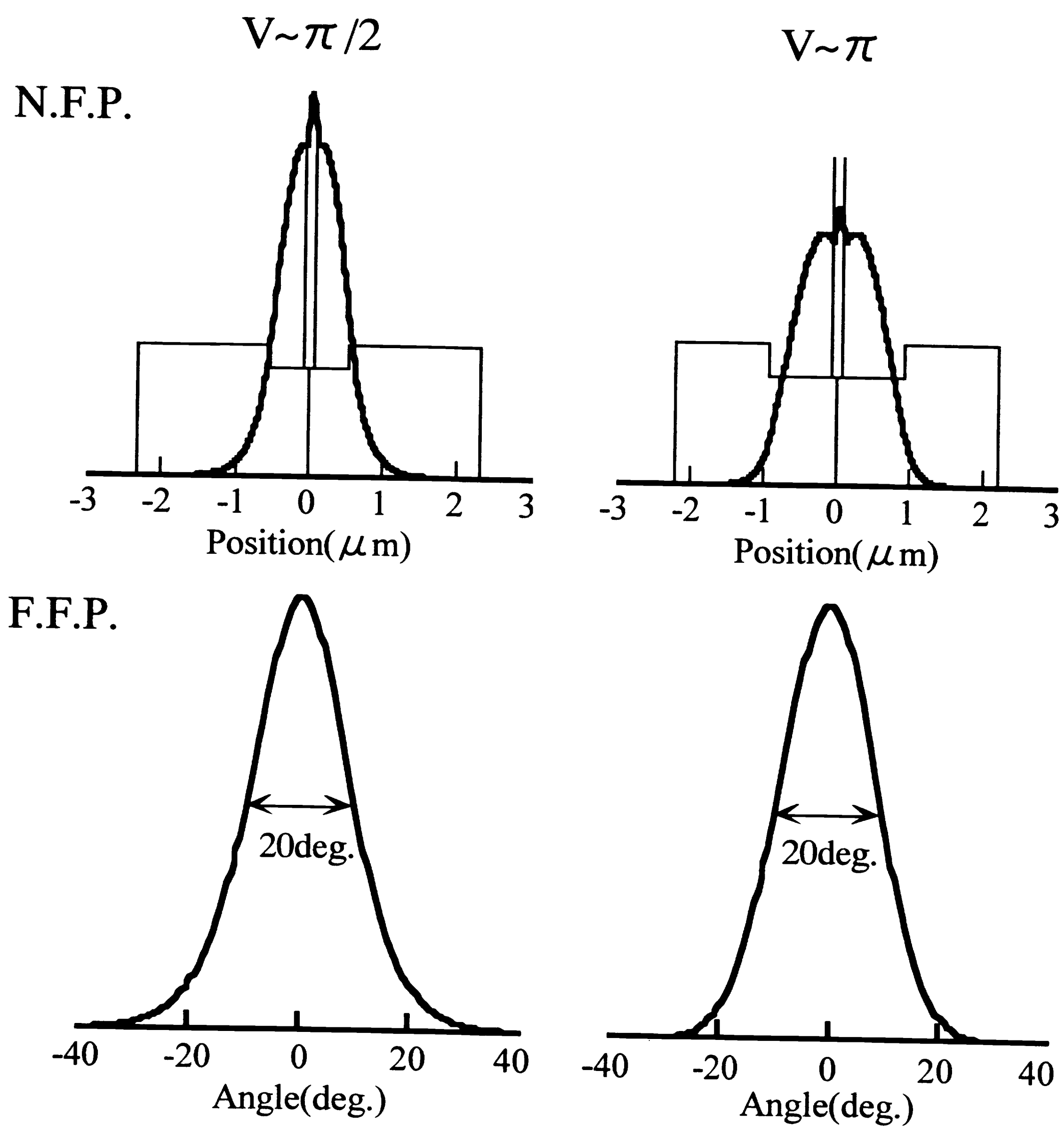

Fig.2 Calculated vertical NFP and FFP of two typical designs of DCH with $V\sim\pi/2$ and π
NFP is normalized by integral intensity. FFP is normalized by peak intensity.
Both designs have the same FWHM of FFP and quite different in NFP and $d/\Gamma_\perp$.

3. COD LEVEL OF GaAs-QW AND InGaAs-QW LASERS

COD level of InGaAs/AlGaAs qauntum-well laser diodes was compared with that of 860nm GaAs/AlGaAs quantum-well laser. In Fig.3, COD levels devided by lateral waveguide width of uncoated front facet lasers are shown as a function of $d/\Gamma_{\perp}$. The front facet of lasers was as cleaved and the rear facet was coated to be 95% reflectivity with dielectric multi films. The laser structure was ridge or self aligned structure(SAS) waveguide with lateral waveguide width of 4~10μm and cavity length of 1500μm. COD level was measured at the condition of 50μsec-Pulse operation at 25°C. As seen in Fig.3, COD level is normalized by $d/\Gamma_{\perp}$. It was found out that COD level of laser diodes with InGaAs/AlGaAs quantum-well was about twice as high as that of laser diodes with GaAs/AlGaAs quantum-well. For around $d/\Gamma_{\perp}$ 1μm, COD level of GaAs/AlGaAs quantum-well laser was ~50mW/μm and that of InGaAs/AlGaAs qauntum-well laser was ~110mW/μm.

In the case of high-power operation of laser diodes, life time of lasers are subject to sudden failure due to facet degradation ,that is,COMD and it is strongly dependent on power density[8,9]. In Fig4, time-to-COMD are shown as a function of radiated power density per 1μm lateral waveguide width on the occasion of operating 860nm ridge waveguided AlGaAs/GaAs laser diodes. In this case the lasers were coated to be 4% front with Al2O3 by conventional RF-sputter and 95% rear facet reflectivity as mentioned above. They were operated on auto power control (APC) at 20°C. It shows time-to-COMD decreased as operating power density increased. And it was indicated that time-to-COMD was hightened by enlargement of $d/\Gamma_{\perp}$. Measurement of time-to-COMD of InGaAs/AlGaAs quatum-well laser diodes is under investigation.

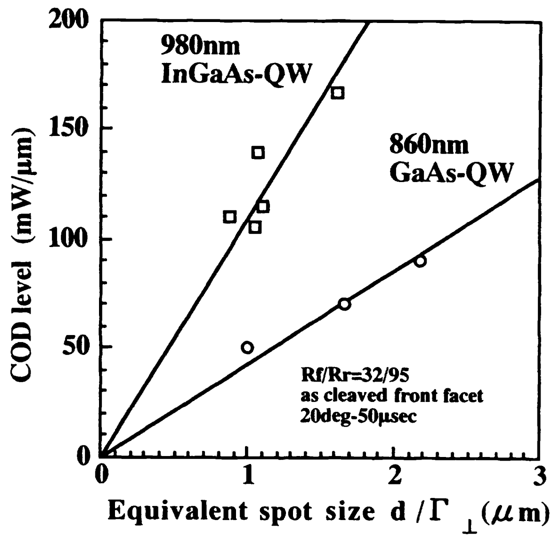

Fig.3 COD level as a function of $d/\Gamma_{\perp}$

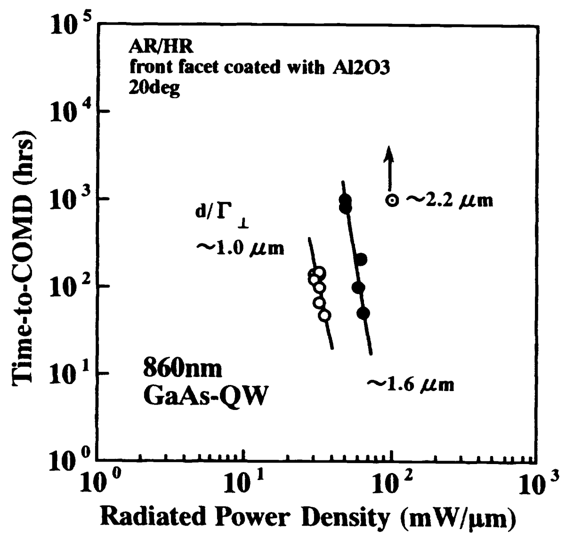

Fig.4 Time-to-COMD as a function of radiated power density

4.InGaAs/AlGaAs BROAD AREA LASERS

InGaAs/AlGaAs broad area gain guided laser diodes as shown in Fig.5 were fabricated. In vertical waveguid structure, V was approximately π. In the active layer, quntum-well composition was $In_{0.18}Ga_{0.82}As$ and quantum-well number was 2. The aperture size was 50μm or 100μm in this experiment. The front and rear facet reflectivities were 2% and 96%,respectively. The laser cavity length was 1500-2000μm. The laser diode chips were bonded junction down on CuW submount with AuSn solder or diamond submount with In solder.

Internal loss was estimated to be about 1.5cm^{-1} by the plot which showed reciprocal slope efficiency as a function of reciprocal mirror loss. This is one of the smallest values so far as the authers know. It is thought that this value owes modulation doping between waveguide and cladding layer. And it is also quite effective in reducing electrical resistivity. Even 50μm aperture device had maximum output power of over 8W in 50μsec pulse operation at 25°C.

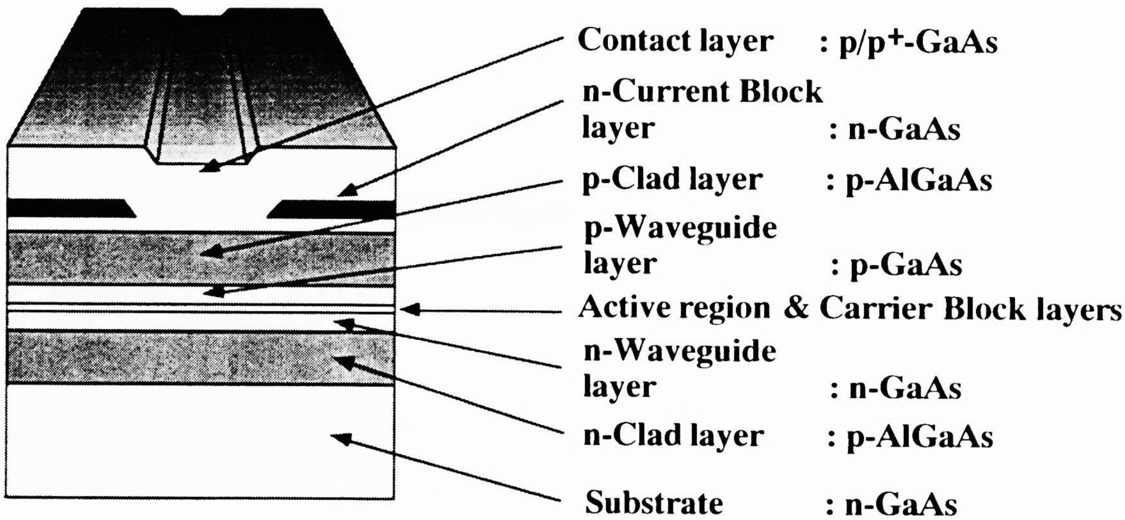

Fig.5 Cross sectional figure of InGaAs/AlGaAs broad area laser diodes

In Fig.6 and Fig.7, L-I characteristics of 50μm aperture and 100μm aperture devices in CW-operation are shown respectively. Only for these data, devices were bonded on diamond submounts with In solder. In the case of 50μm-aperture, the maximum output power was 6.3W at 20°C and conversion efficiency was ~55%. The maximum output power of 100μm-aperture device was 9.5W at 10°C. It was limitted by thermal saturation. And energy conversion efficiency of laser diode peaked ~56% at 2.5W for 100μm device.

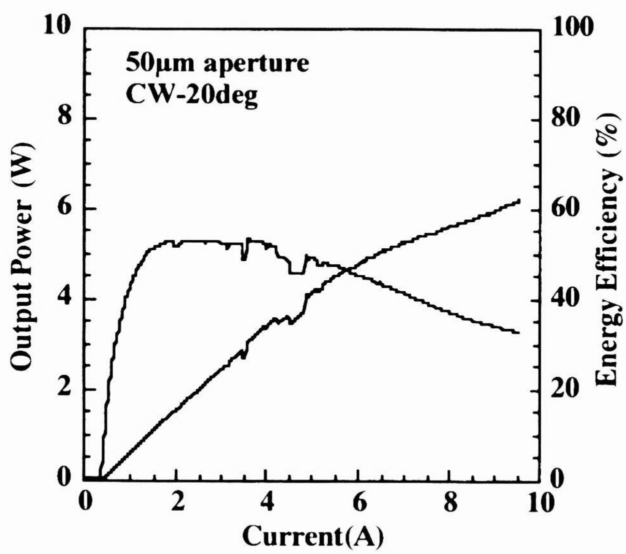

Fig.6 I-L characteristics of 50μm-Aperture device

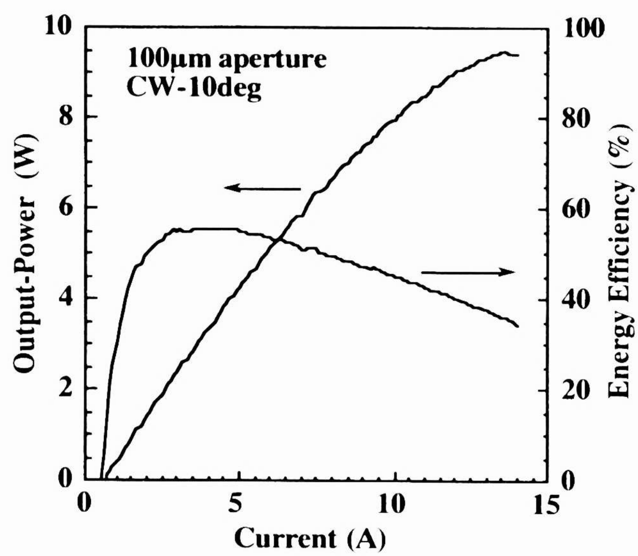

Fig.7 I-L characteristics of 100μm-Aperture device

The reliability of those lasers was investigated. Fig.8 shows the CW aging test results. Under the condition of 50°C-1.0W, all the 14 devices have been operating for over 13,000hrs without any failures. The estimated Mean Time Between Failure

(MTBF) in exponential model was about 200,000 hours at 60% confidence level under this condition. And the calculated median life (ML) in log-normal model was about one hundred thousand hours at End of Life (EOL) of 20% current increase.

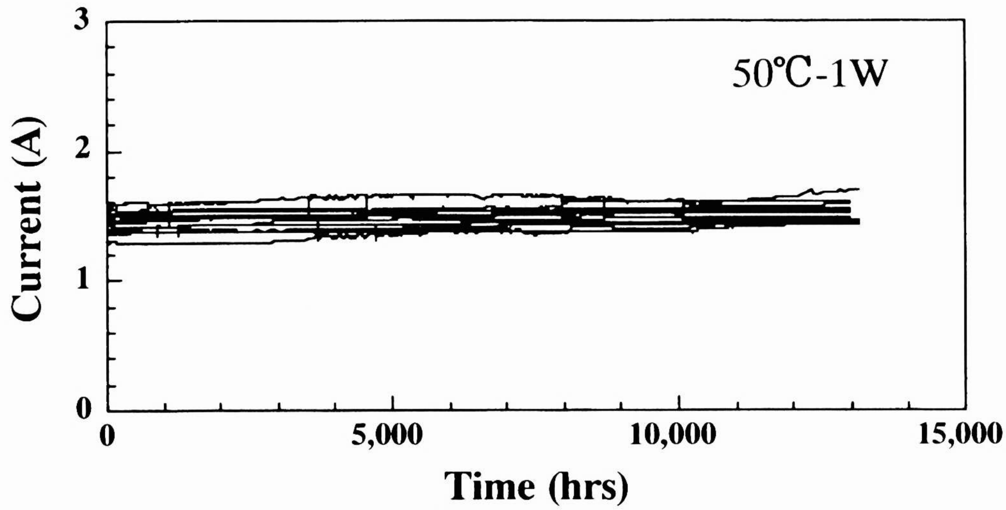

Fig.8 Reliability test result of 50μm aperture broad area laser diodes under the condition of 50deg-1W

5.InGaAs/AlGaAs INDEX GUIDED LASERS

By the process consisted of multi-step metalorganic vapor phase epitaxy(MOVPE), SAS waveguided laser diodes were fabricated as shown in Fig.9. The vertical waveguide structures were designed to make the beam divergence angle to be 27degree in FWHM. Lateral waveguide width was 4~6μm. The laser front facet was coated with Al2O3 and rear facet with dielectric multi films. The front and rear facet reflectivities were 2% and 96%, respectively. The laser cavity length was 1800μm. The lasers were mounted on Cu/W heatsinks junction p-side down.

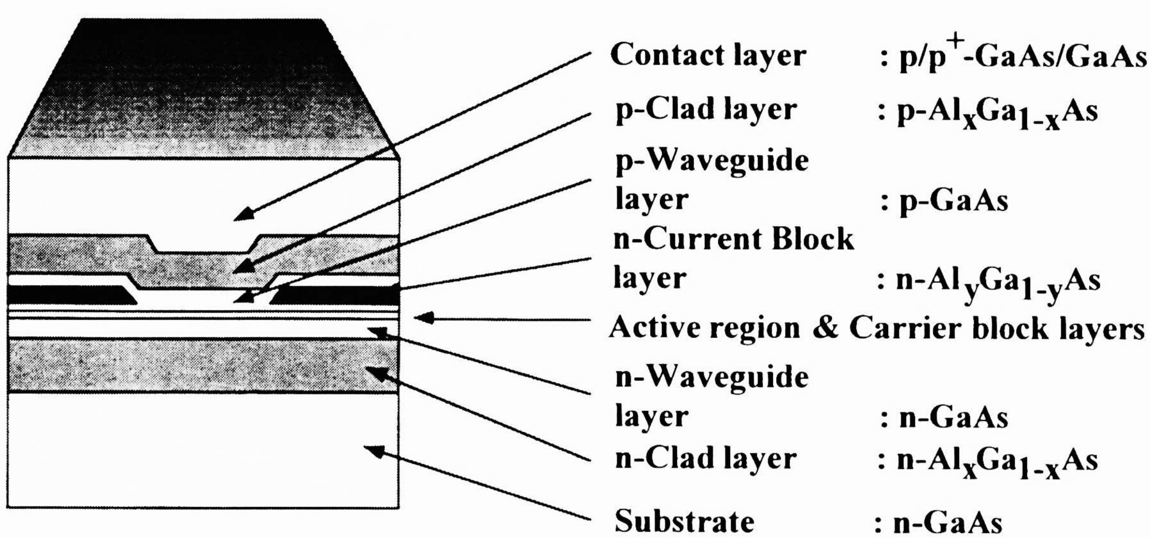

Fig.9 Cross sectional figure of InGaAs/AlGaAs SAS index guided laser diode

Typical L-I characteristics and energy efficiency at 25°C-CW operation are shown in Fig.10. Maximum output power was about 1.3W. Catastrophic degradation was not observed and light output was limited by thermal saturation. Threshold current and slope efficiency at 25°C were ~90mA and 0.90W/A,respectively. Energy efficiency of the laser diode peaked ~47% at output power nearly 300mW.

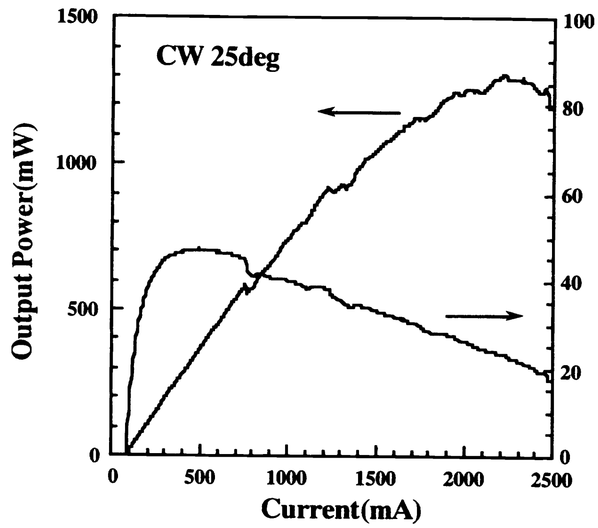

Fig.10 L-I characteristics of index guided DCH

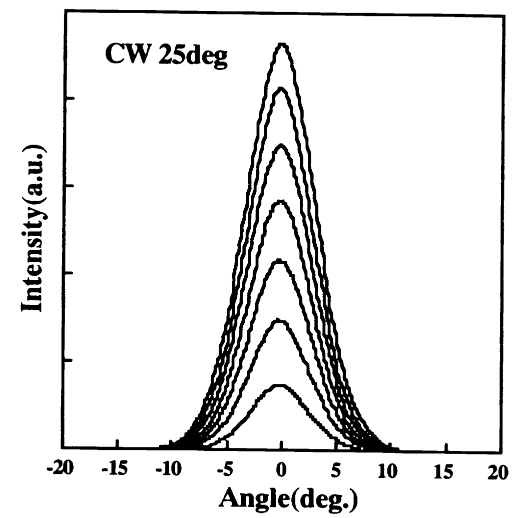

Fig.11 Lateral FFP of index guided DCH for 100-700mW

As shown in Fig.11, lateral single mode operation in some devices extended up to 700mW CW at 25°C. At the kink level, lateral far field single mode pattern was disturbed. Beam divergence angles of perpendicular and parallel far-field pattern to junction plane were about 27 and 7 degrees FWHM at 300mW, respectively.

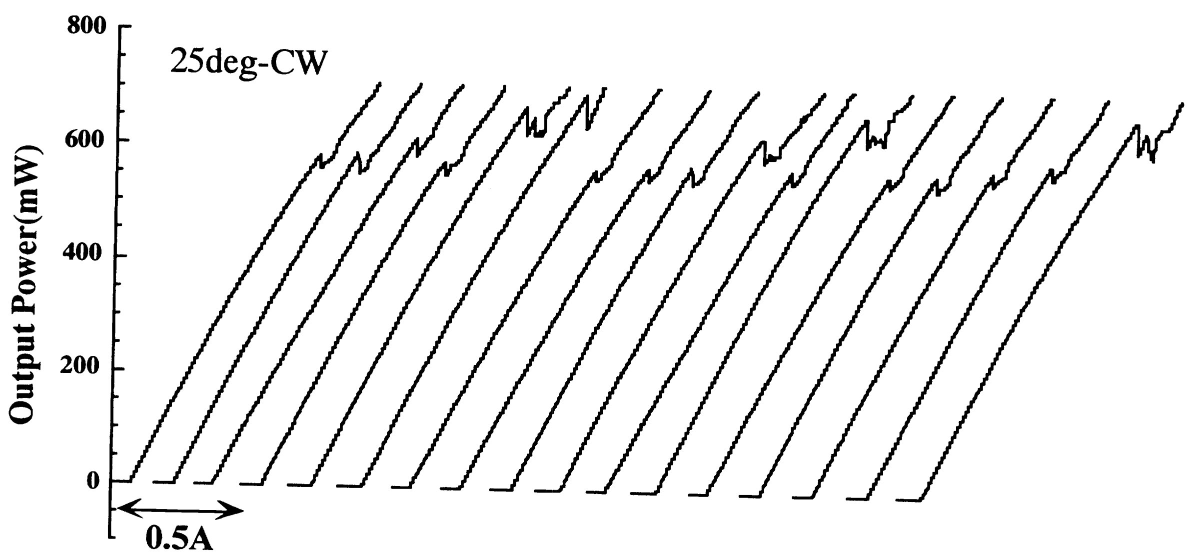

Fig.12 L-I characteristics of unselected 17 devices of fabricated SAS-index guided DCH-LD

In Fig.12, L-I characteristics up to 700mW of unselected 17 devices are shown. The high kink level over 500mW was kept reproducibly kept to high-power level of over 500mW. It indicates that very stable fabrication was realized due to the structure produced by simple process. And it is thought that the effect of lower $\Gamma_\perp$ led this good result to optical mode as stated above.

Fig.13 show temperature dependence of L-I characteristics in CW operation at the range of 20-80°C. The maximum power over 600mW was obtained at 70°C. And as seen in Fig.14, single spatial mode operation up to 400mW was kept even at high temperature 70°C.

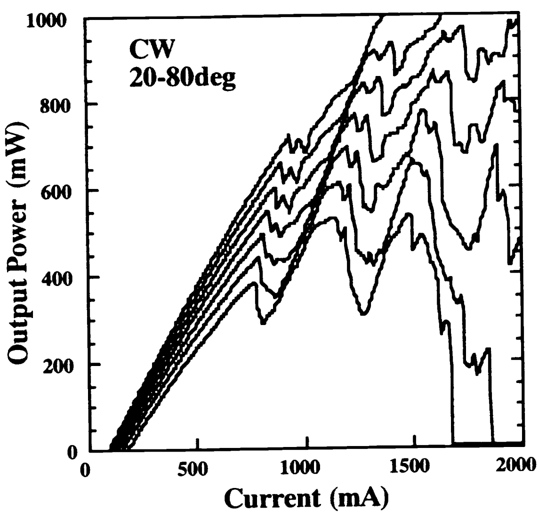

Fig.13 L-I characteristics in 20-80°C

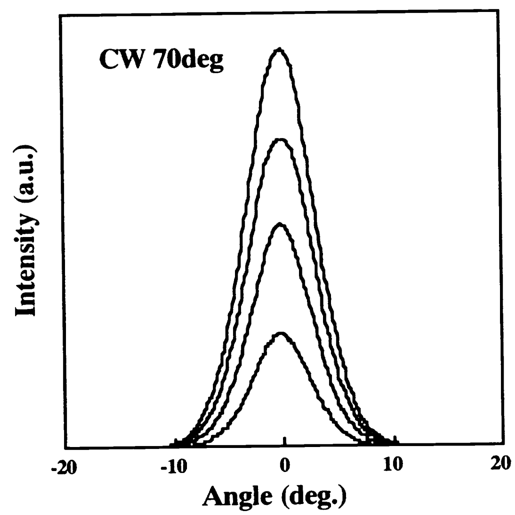

Fig.14 Lateral FFP in 100-400mW at 70°C

Fig.15 shows the preliminary CW aging test results. Under the condition of 50°C-300mW, they have been operating for near 4,000hrs. At 70°C, the several laser diodes have been operating for over 2,000hrs. Systematic life tests are going on.

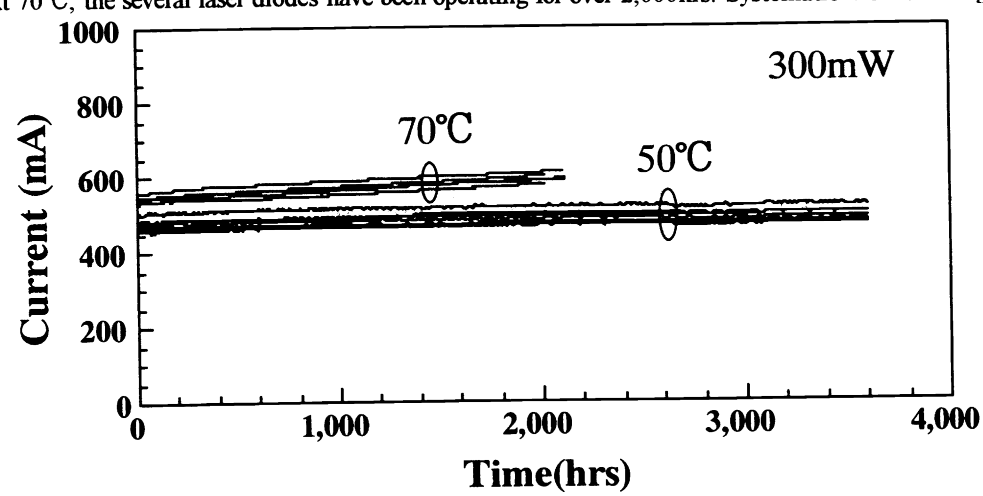

Fig.15 Preliminary CW aging test results

In addition, experimental single mode fiber (SMF)-coupling output power of over 300mW was obtained reproducibly at 25°C. It is thought that the result was reflected by not only high-power single mode operation but also better beam quality of DCH laser diode at high-power level.

6.SUMMARY

The excellent characteristics of the laser diodes with DCH structure in the InGaAs/AlGaAs material system were demonstrated. And we suggested possibility of high-power devices for pump source.

InGaAs/AlGaAs broad area laser diodes achieved high-power and high reliable operation of MTBF of two hundred thousand at 50°C. And index guided lasers of high-power single mode operation over 500mW were reproducibly obtained. Preliminary reliability test was shown at high-power operation of 300mW. The reliability tests along Bellcore's requirements are going to be executed.

Finally from now on, the high-power laser diodes used in EDFA or other usage will be advanced so far as information society makes progress. We shall go on challenging development of the highest power laser diodes.

7.ACKNOWLEDGEMENTS

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