High-power AlGaInAs/GaAs microstack laser bars

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ABSTRACT

The maximum useful optical power of laser bars is limited due to thermal and lifetime constraints to typical values of 50 W/cm cw or 120 W/cm qcw. A promising new approach is the so-called microstack laser in which several laseractive areas are integrated vertically in the same monolithic structure. In order to drive these structures in series with high efficiency low-resistance tunnel-junctions have to be realized. By optimizing the MOVPE growth process tunnel-junctions with a specific differential resistivity of 2.5×10^{-4} Ωcm^2 could be obtained, which are suitable for the monolithic interconnection of laser structures.

We realized microstack lasers with two and three active zones for the 800 nm and 900 nm band in the InGaAlAs/GaAs-system using conventional LOC-SCH-structures. Compared to reference lasers with only one laser active structure a slight increase in threshold current can be observed, which is attributed to an increased current spreading due to the highly conducting tunnel junction. The I/V-characteristics show turn-on voltages corresponding to the number of active layers and there is no significant additional potential barrier due to the tunnel-junctions detectable. The differential efficiency scales with the number of laser junctions. AR/HR coated lasers with two or three junctions show efficiencies at 800 nm of 2.2 W/A and 3.1 W/A respectively. Mounted 1 cm-laserbars with an asymmetrically coated double microstack-structure have been operated up to 95 W cw and 240 W qcw with 20% duty cycle. Due to the high slope efficiency (2.1 W/A) and the low series resistance the wallplug efficiency exceeds 50 %. qcw-lifetests at 210 W with 20 % duty-cycle showed only small degradation up to 5 Gshot.

Keywords: semiconductor laser arrays, InGaAlAs, micro-stack, tunnel junction, high power, qcw operation

1. INTRODUCTION

Solid state laser pumping is an important application for high power semiconductor lasers. The higher electro-optical conversion efficiency (50%), and narrower spectral emission (2-5 nm) of laser diodes allow for more efficient pumping compared to flash lamps, and consequently lead to superior thermal and optical properties of the solid state laser. Also, their long lifetime which today exceeds 20 to 50 kh reduces operating and maintenance cost. The higher capital cost however, related to the need to solder and assemble many diode bars, has yet impeded their widespread use. Over the last few years the cost of semiconductor pumping power could be reduced significantly to 50-10 $/W, mainly by an improvement of the semiconductor bar performance reaching 80W to 120W qcw, and 40 to 60W cw.

Yet a further performance increase and thus price reduction, especially for pulsed and qcw operation, is conceivable using a promising approach proposed almost 20 years ago[1] which we dubbed "microstack lasers". It consists in vertically integrating multiple active laser junctions in one structure using degenerately doped tunnel junctions to electrically connect the intermediate reverse junctions[2]. By stacking 2 to 4 emitters in this way, the output power of semiconductor lasers could theoretically be increased by a factor of 2 to 4 as the reliable output power is mainly limited by the power density at the laser facets. Modern growth technology can provide the necessary 10 to 20 μm thick high quality epitaxial layers. The limiting factors rather originate from the additional electrical and thermal resistance, and from current spreading towards the deeper junctions.

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2. MICROSTACK-LASER

2. 1. Principle of microstack-lasers

The basic structure of a triple microstack laser is shown in fig. 1. Each independent laser consists of a conventional LOC-SCH (large optical-cavity separate-confinement hetero) -structure with an InGaAlAs-double quantum well as active layer which can be designed for an emission wavelength from 780 to 1000 nm. Due to a relatively large separation in the order of several micrometers the transverse optical field do not overlap, so that the lasers are optically decoupled and operate individually. Due to the fact that here is also no overlap between the transverse modes and the tunnel junctions, there is no drawback in efficiency due to free carrier absorption in the highly doped layers.

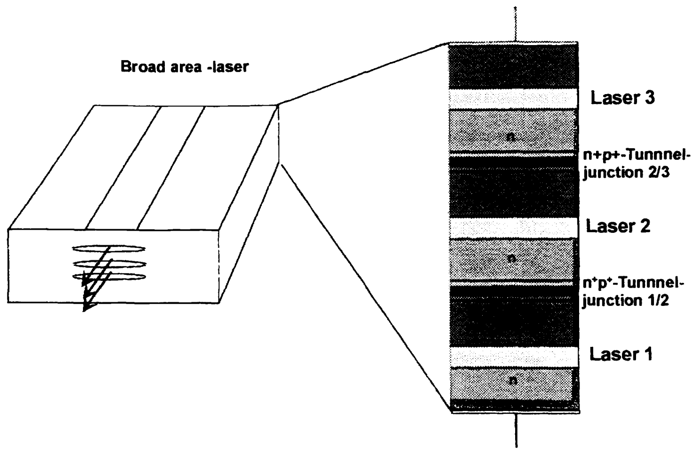

Fig. 1.: Principle of a triple microstack laser

2. 2. GaAs-tunnel juctions

The overall efficiency of lasers is determined by the electrooptic conversion efficiency (internal efficiency and absorption losses) and by the electrical losses inside (or within) the structure. Therefore special attention has to be payed to the optimization of the tunnel junction which connects the lasers in series. A typical I/V-curve of an MOVPE grown GaAs-tunnel-junction is shown in fig. 2.

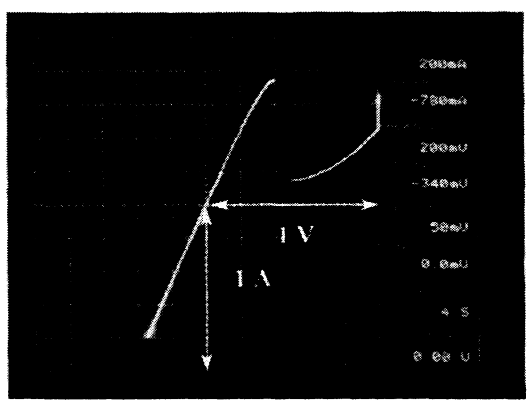

Fig. 2.: I/V-characteristic of a MOVPE grown GaAs-tunnel-junction (size 400*400 μm^2)

By optimizing the MOVPE growth process the doping concentration can be increased to high values so that tunnel-junctions with a specific differential resistivity of 2.5×10^{-4} Ωcm^2 including the contribution of the contacts of the test samples could

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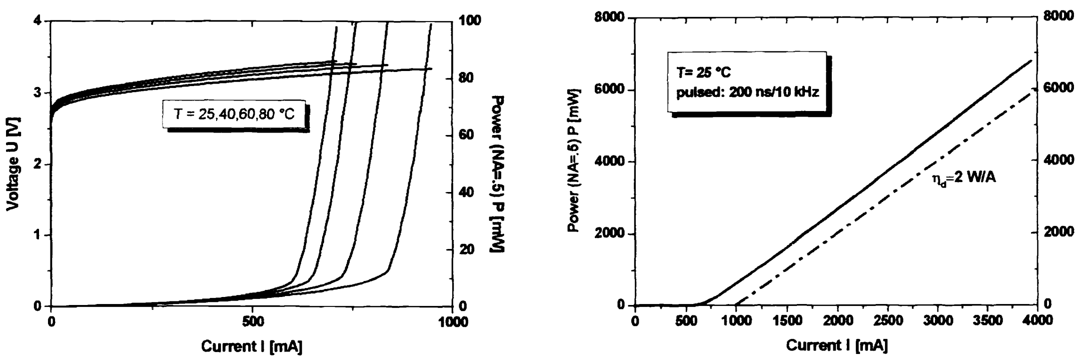
be obtained. This resistivity value is low enough to use the tunnel junctions for the monolithic interconnection of the laser-structures with low electrical losses.

2. 3. Single broad-area emitters

2. 3. 1. Electrooptical performance

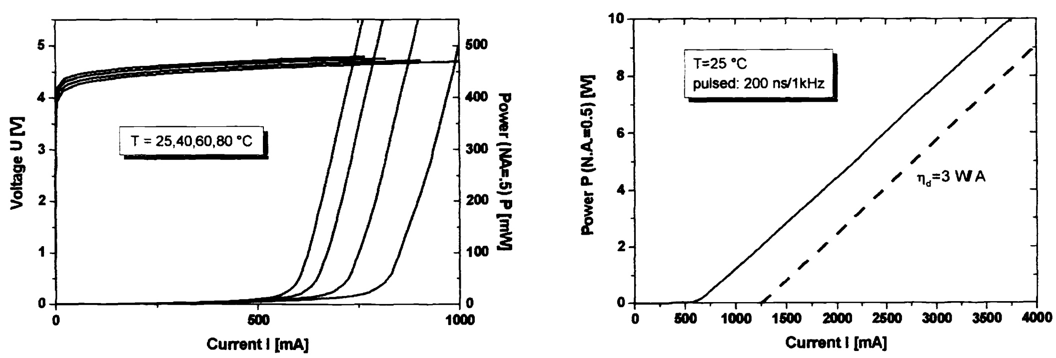
Double and triple micro stack structures for 808 nm and 905 nm operation have been grown by MOCVD. From these wafers we processed, cleaved and coated cw and qcw bars using our standard processing technology. Single chips with one array out of a bar have been prepared and tested in pulsed operation. The results for double- and triple-microstack lasers at 808 nm are shown in the following figures 3, 4.



a) b)

Fig. 3: Pulsed characteristics of an asymmetrically coated 200 x 900 μm² double micro-stack laser:
a) Temperature dependant P/I- and I/V-characteristics,
b) High power operation characteristics.

The threshold current at room temperature is 670 mA and the T_0-value is 170 K. In high power operation (fig. 3b) a power of 7 W at 4 A and a differential efficiency of 2.2 W/A have been measured. Compared to reference lasers with only one laser-structure a slight increase in threshold current can be observed, which may be attributed to an increased current spreading.



a) b)

Fig. 4: Pulsed characteristics of an asymmetrically coated 200 x 900 μm² triple micro-stack laser:
a) Temperature dependant P/I- and I/V-characteristics,
b) High power operation characteristics.

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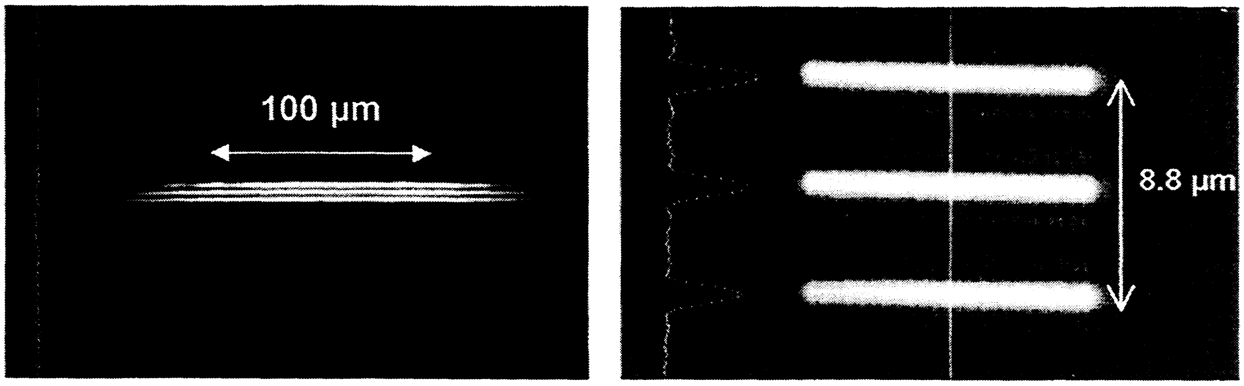
In fig. 4a,b the corresponding characteristics of a triple microstack laser are shown. This laser has a slope efficiency of 3.1 W/A per facet. The I/V-characteristics of all lasers show turn-on voltages corresponding to the number of active layers and there is no visible additional potential barrier due to the tunnel-junctions.

2. 3. 2. Emission properties

The emission properties of 100 µm wide broad area laser without further current confinement has been studied. In fig. 5 a the nearfield of a triple microstack laser is shown under medium magnification. Due to the current spreading in the highly conducting tunnel-junctions it is significantly broader than the 100 µm wide current injecting contact.



a) b)

Fig. 5.: Near-field pattern of a 100µm wide triple stack test-laser at 1.7 A
a) medium magnification
b) high magnification

Under high magnification (fig. 5 b) it is clearly seen that the three lasers are optically decoupled. The slight imbalance in the vertical power distribution comes from the different effective width of the stacked lasers.

The lateral and transversal farfield patterns in fig. 6 show the usual distributions from broad area lasers. There are no interference pattern in the transversal farfield visible, proofing again that there is no coherence between the neighbouring lasers.

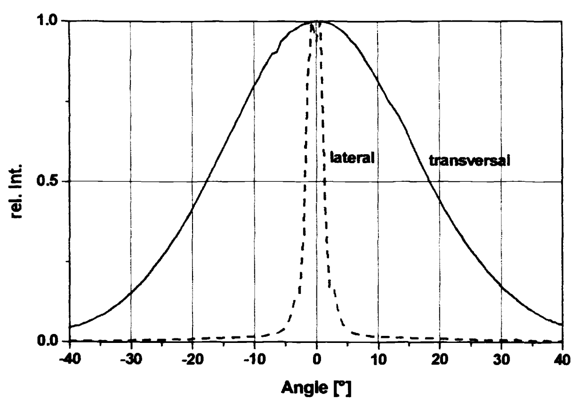


Fig. 6.: Lateral and transversal farfield patterns of a triple microstack laser

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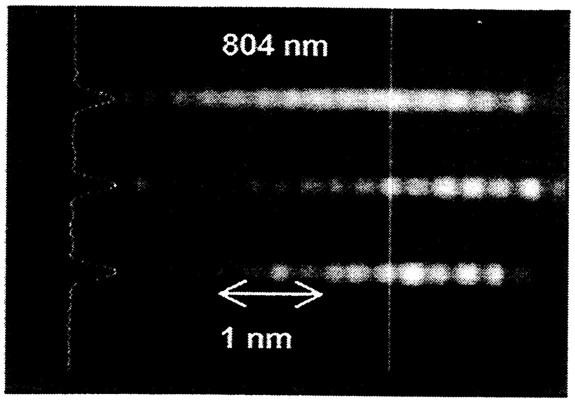
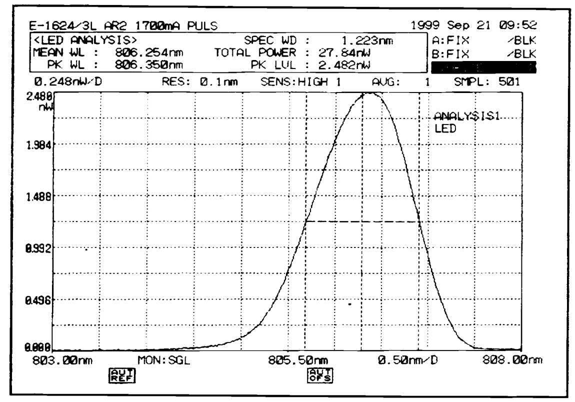
2. 3. 3. Spectral properties

The spectral properties of the test lasers under pulsed operation (1 μs/10 kHz) are shown in the pictures 7 a,b. The spectrally resolved nearfield of a very small lateral area of the whole lasing stripe shows a nearly perfect wavelength match of the three independent lasers. Due to the excellent reproducibility of the layer composition of the active layers the spatially integrated spectrum of the whole triple laser shows a very small half width of only 1.22 nm, which makes this laser attractive for long lasersbars commonly used for laser pumping, too.





a) b)

Fig. 7.: Spectral properties for a 100 μm wide laser at 1700 mA :
- a) spectrally resolved nearfield
- b) spatially integrated spectrum

3. SINGLE ELEMENT PULSE LASERS

For the operation in the 900 nm band double and triple microstack lasers with a specially designed transversal structure for low divergence angles have been developed. Single element broad area lasers with AR/HR-coating have been mounted junction up and tested under short pulse operation .

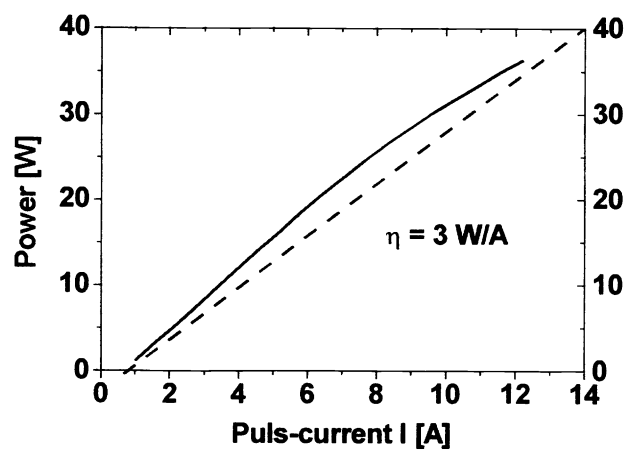


Fig. 8.: P/I-characteristic of a 900 nm-broad area triple microstack laser (200*600 μm^2) under short pulse operation (1 μs/10 kHz)

The threshold current under pulsed operation at room temperature is around 700 mA and the slope efficiency is above 3 W/A. The slight bending of the P/I-curve comes from the thermal heating at high drive levels. The transversal farfield pattern has a FWHM of 23°. Under operation with short pulses (20 ns) even higher peak powers over 80 W can be obtained. Several double and triple microstack lasers were mounted in a LED-like 5mm plastic package and an aging test was

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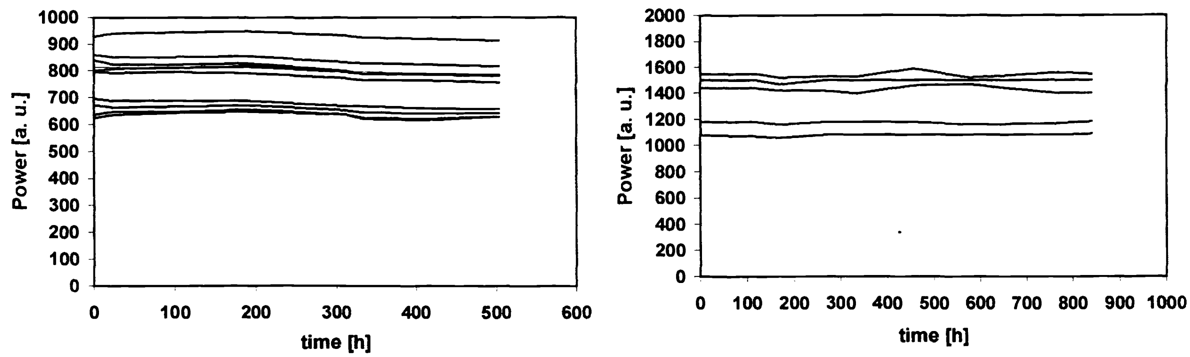
performed in pulsed operation (90 ns / 10 kHz) at 85 °C. The operating current is 21 A and the corresponding power levels are 32-36 W and 48-54 W respectively.



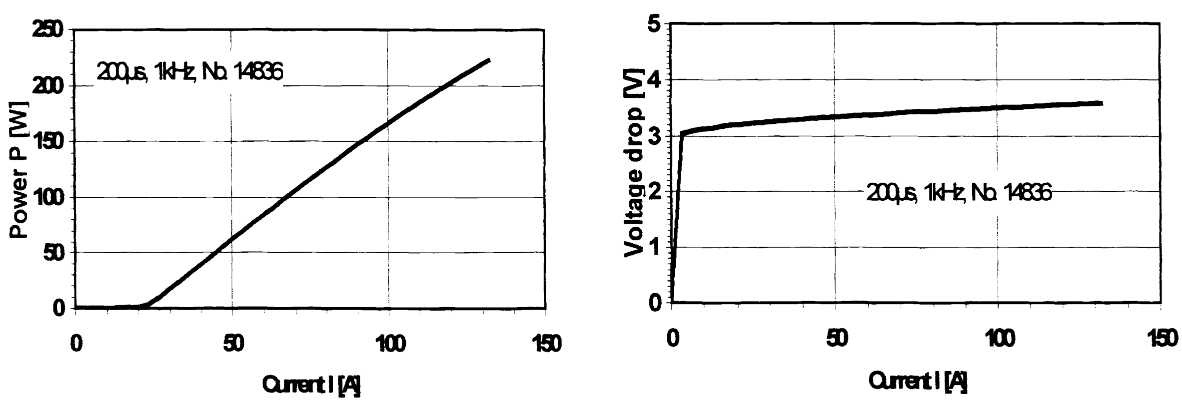
a) b)

Fig. 9: Aging characteristics of single microstack lasers operating in pulsed mode (I = 21 A 90 ns / 10 kHz) at elevated temperature (T = 85 °C)
a) double microstack laser (power level 32-36 W)
b) triple microstack laser (power level 48-54 W)

Even at this high power and temperature level there is only a small degradation visible over a time of 500 h and 900 h. These data make this laser an ideal candidate for range finding and illumination applications.

4. LASER BAR PERFORMANCE

Qcw bars with the double stack structure and 80% fill factor were mounted on mini-channel coolers and cooled with water at 20°C. They operate successfully up to a peak power of 240W (at 132A current) with 20% duty cycle (200µs pulse duration, 1kHz repetition rate). Typical electro-optical characteristics are shown in Figure 10. Threshold currents between 20 and 22 A, and slope efficiencies between 2.1 and 2.3 W/A are observed on the first bar structures.



a) b)

Fig. 10: Electro-optical characteristics of a qcw bar operated at 20% duty cycle:
a) P/I-characteristics
b) I/V-characteristics

At 20% duty cycle the conversion efficiency reaches 44% at 100W, and 48% at 200W peak output power. As expected, the turn-on voltage of the double stack bars is about 3.1 V, and the series resistance is 4 to 5 mΩ, compared to typically 2 to 3 mΩ for standard bars.

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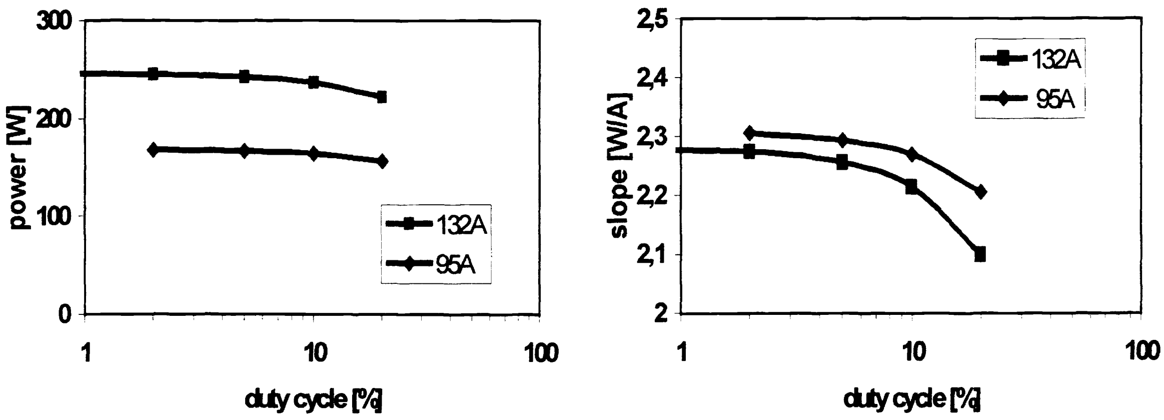
With an increasing duty factor the average thermal load on the heat sink increases and consequently the junction temperature rises. Fig. 11a shows the peak output power for fixed operation currents (95A, and 132A, corresponding to power levels of 150 to 170W, and 220 to 250W, respectively) and duty factors of up to 20%. According to these measurements the double stack bar appears suitable for duty factors as high as 20%. In this case the average thermal load



a) b)

Fig. 11: Impact of increasing duty factor on a double stack bar operated at fixed currents of 95A and 132A:
a) Peak output power
b) Slope efficiency

reaches about 50W and the output power drops by less than 10%. The drop seems to originate mainly from a thermally induced decrease of the slope efficiency (cf. Fig. 10b).

5. DEGRADATION MEASUREMENTS

In a lifetime test three bars are operated at power levels of 150W, 175W, and 200W. The duty factor is 20% (200 µs pulse duration, 1kHz repetition rate), and the respective currents are 90A, 101A, and 117A. Figure 12 shows the result of a 1500h test, corresponding to more than 5 Gshots. The degradation rates observed at 150W, 175W, and 200W were -2.5%, -2.7%, and –8.4% per 1000h, respectively. The corresponding extrapolated lifetimes (end of life criterion –20% output power) are >1300 h or 4.5 Gshots at 175 W and 200 W, and 8000 h or 29 Gshots at 150W.

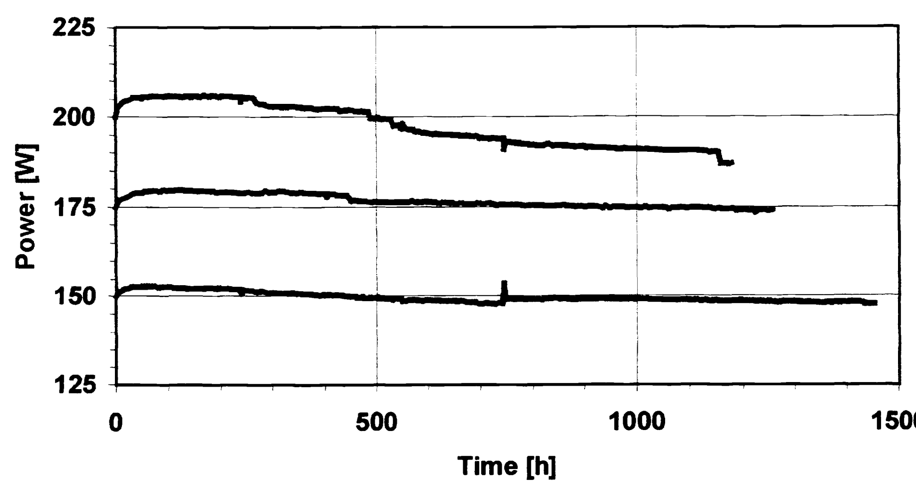


Fig. 12: Lifetime test of three actively cooled double stack qcw bars operated at 150W, 175W, and 200W (200µs, 1kHz).

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6. CONCLUSIONS

We have successfully fabricated monolithically integrated laser structures with two and three active laser junctions connected by low resistance tunnel junctions. 1 cm wide laser bars were manufactured using standard processes and mounted on actively cooled copper heat sinks. Performance tests showed turn-on voltages of 3V and slope efficiencies higher than 2W/A while thresholds around 21 A and spectral width around 5nm are comparable to standard structures. Bars were successfully operated up to 250W peak power at low duty factor, and up to 220W at a duty factor of 20%. Initial degradation tests at a duty factor of 20% (200µs, 1kHz) running over 1500 h indicate lifetimes of 8 kh (30Gshot) at 150W, and over 1000 h (4Gshot) at 175 W and 200 W.

This study on double stack structures proves that it is possible to increase the output power of diode laser arrays further by a factor 1.5 to 2, up to 170 to 220W peak power, depending on duty factor and required lifetime. The achievable average power is limited by the higher thermal load due to the thicker epitaxial structure and the limited thermal resistance of the heat-sink. The principal application for the microstack approach are therefore in qcw pumping solid state lasers up to 20-30% duty factor. Single broad area lasers can reach peak powers in the range of 100 W in short pulse operation. Due to their high power and reliability these lasers are especially suitable for range finding and illumination applications.

ACKNOWLEDGEMENTS

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