400-W Peak CW Power per Bar from 1-cm GaAs Bars For Emission Wavelengths From 800-nm to 980-nm, 90-W at 660-nm

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Peak optical power from single 1-cm diode laser bars is advancing rapidly across all commercial wavelengths. Progress to date has allowed us to demonstrate > 400-W peak output from single 1-cm diode laser bars at emission wavelengths from 800-nm to 980-nm. The available range of emission wavelengths has also been increased, with 90-W bars shown at 660-nm. Peak power is seen to correlate closely to peak efficiency. Further advances in diode laser efficiency and low thermal resistance packaging technology continue to drive these powers higher. The most critical improvements have been the reduction in the diode laser operating voltage through optimization of hetero-barriers (leading to 73% efficient 100-W bars on copper micro-channel) and a reduction in packaging thermal resistance by optimizing micro-channel performance (leading to < 0.2-°C/W thermal resistance).

1. Introduction

Diode lasers provide the optical energy used in military, industrial and medical applications. As the reliable power level of diode lasers increases, the cost in $/W falls, enabling wider deployment and higher power systems. Also, higher peak powers enables diode lasers to access markets which were previously unavailable, such as direct materials processing. In particular, diode laser bars have long been used as the pump sources for solid-state crystals, providing uniform high pump power densities over a large area, as required for high power > 10-kW systems.

Here, we discuss our progress in advancing the peak output power of such diode laser bars. First, we review the peak power and efficiency achieved to date from 600-nm to 2000-nm. We then discuss the limitations to peak bar power, observing that in the 800-980-nm band, the major limitation to power is now the diode laser cooler itself. Next, we note that for a given cooler technology, the highest output power is achieved from the largest device area, as this most effectively spreads the heat. Finally, we show some recent reliability data on testing to higher powers per bar.

2. Overview of Peak Power Achievable per Bar

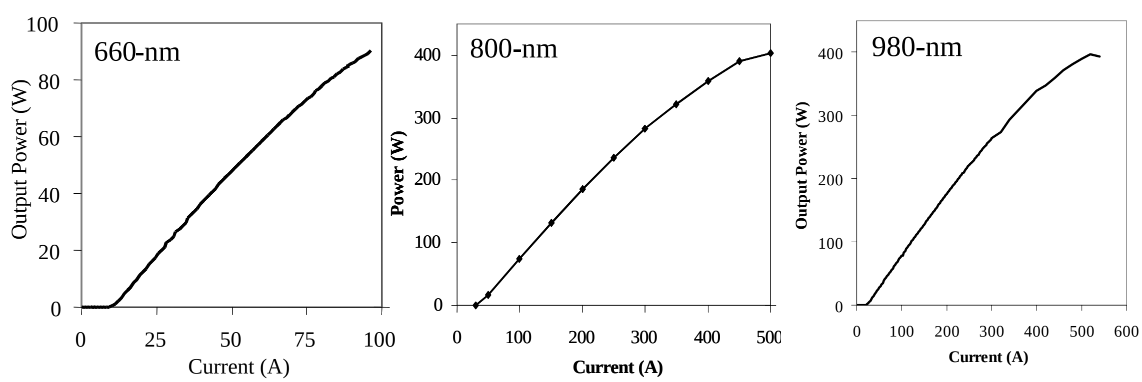

Figure 1: Peak power in excess of 400-W per bar is achieved from 800-nm to 980nm (center, right), with 90-W per bar demonstrated at 660-nm (left) [1].

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Figure 1 shows the peak output power of nLight bars mounted to a copper water-cooled micro-channel cooler, at a selection of wavelengths. From 800-nm to 980-nm, peak powers in excess of 400-W are demonstrated, for 3-mm cavity bars with 80% fill factor, operated at 5-C water and 0.5-lpm flow rate. At 660-nm, a peak power of 90-W is demonstrated, for a 1-mm cavity bars with 30% fill factor operated at 10-C water and 0.5-lpm flow rate, as discussed in [1].

The peak achievable power and the peak material power conversion efficiency vary with wavelength, summarized for nLight material in Figure 2. The peak power and peak efficiency curves are closely correlated – the highest efficiency devices deliver the highest peak power. Lessons learned under the SHEDs program have enabled such high peak output powers in the 9xx-nm wavelength band.

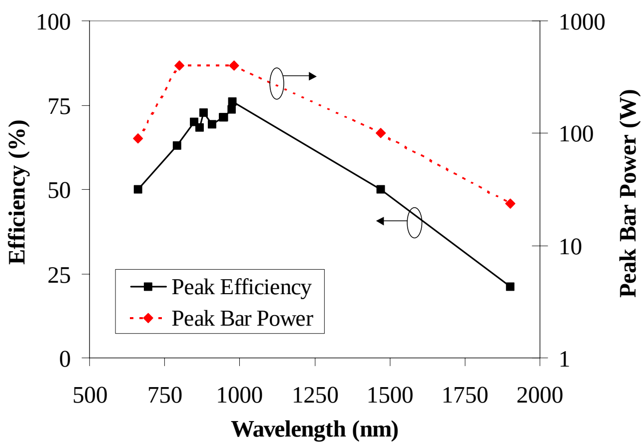

Figure 2: Overview of peak power and efficiency across wavelength [1].

3. The Micro-channel Cooler is now the Key Limitation to Peak Bar Powers

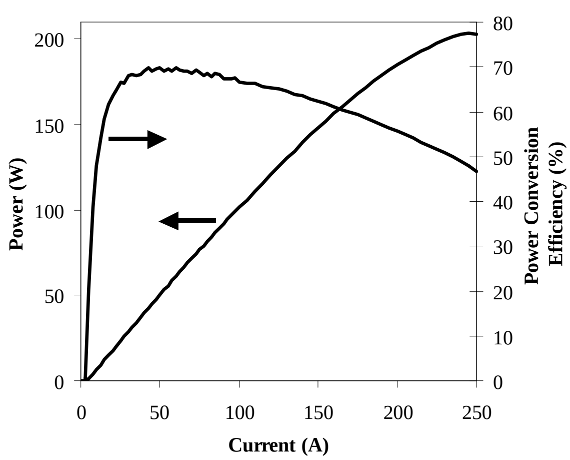

Figure 3: 20% fill factor facet passivated bars deliver extremely high power density (200-W rollover), equivalent to > 800-W from a high fill factor bar

Water-cooled micro-channel heat-sinks are high performance components that cool diode laser bars very effectively. However, the heat loads generated by very high power bars are large enough to be lead to early thermal rollover, even when a microchannel cooler is used. To illustrate, figure 3 shows the peak power of a 975-nm 20% fill factor, 1.5mm cavity length diode laser bar bonded to a micro-channel cooler, operating with 5C water at 0.5-lpm. The bar thermally rolls at 203-W. The expectation would be that increasing the fill factor of the bar to 80% would increase the peak power to > 800-W. Unfortunately, in a high fill factor bar, the heat loads become so high that such a bar thermally rolls over at significantly less than 400-W.

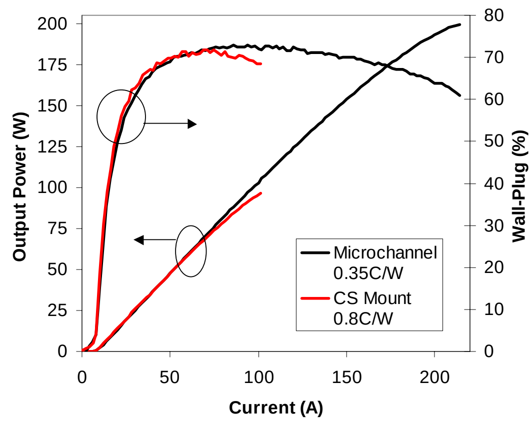

Figure 4: Peak power is degraded for high bar thermal resistance even for bars with very high power conversion efficiency [2].

If the diode laser efficiency could be increased sufficiently, the thermal resistance of the cooler would in principle become less significant. As an example, figure 4 shows how a high performance 73% efficient SHEDs bar (50% fill factor, 1-mm cavity length) is affected if the thermal resistance is degraded, for example by bonding it to a passively cooled CS mount. A bar design that previously rolled thermally at 200-W per bar on microchannel cooler is limited to < 100-W on a CS mount. In other words, even for diode lasers with state of the art efficiencies, the thermal resistance of the cooler strongly affects the peak achievable power.

4. Bar Design to Maximize Power for Given Cooler Performance

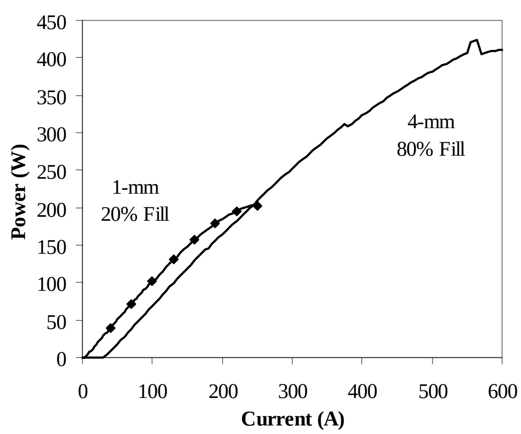

Figure 5: Increasing the physical size of the diode laser bar enables higher peak power, by spreading heat over a larger area.

For a fixed cooling power heat-sink, one approach to increasing peak power is to increase the physical size of the laser, for example increasing the cavity length. Heat generated in the diode laser is spread over a larger area and is more effectively removed. Unfortunately, longer cavity lengths lead to higher optical losses inside the diode laser and lower power conversion efficiency. However, thermal resistance scales simply by 1/Length, with power conversion efficiency falling much more slowly. For example, if the cavity length is doubled, the efficiency of a typical diode laser (with optical loss of ~ $1cm^{-1}$) will drop by ~10%, but the thermal resistance will drop by a factor of close to 2.

Longer cavity length presents additional practical difficulties - effectively bonding such a large surface area device is more challenging, and the defect density in a real wafer must be very low. However, when these challenges are resolved, extremely high powers and low thermal resistances can be achieved. For example, Figure 5 shows how increasing fill factor and cavity length increases peak output power of a 9xx-nm diode laser design to greater than 400-W. Very low thermal resistance is achieved for long cavity, high fill factor bars, with values as low as 0.12K/W achieved for 4-mm cavity, 80% fill factor, as shown in Figure 6. This performance is sustained up to a waste heat level of 600-W. The thermal resistance is measured by tracking the average bar wavelength as a function of the heat left behind in the cooler, as drive current is increased.

In all cases discussed here, bars are cooled only from a single side. Further increases in optical output power can be achieved by cooling the bar from both sides – running micro-channels across both the cathode and anode of the diode laser [3]. However, such double sided coolers are significantly thicker, degrading the overall power density achievable in a useable system – in the worst case, this can lead to no net benefit over two bars on separate coolers stacked on top of each other.

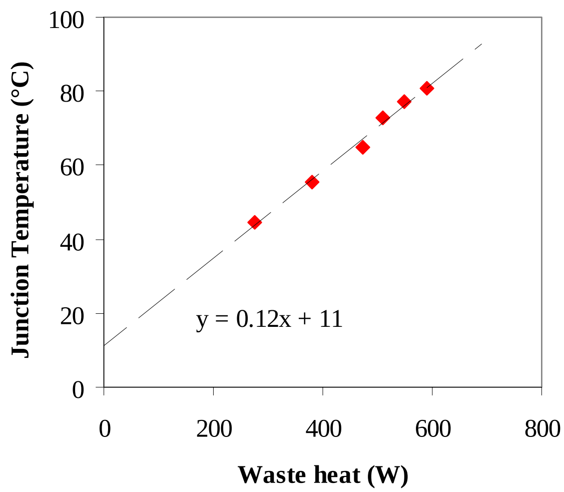

Figure 6: Large area diode laser bars can be effectively cooled to very high currents and waste heat levels.

5. Endurance Testing Result

To demonstrate the high power capability of a given diode laser design, one common approach is to perform step stress life-testing, driving the lasers to ever-higher power per bar. Results from initial step-stress testing for 3-mm cavity, 80% fill 800-nm laser bars are shown in Figure 7, with bars to date showing good performance to a power per bar of 185-W.

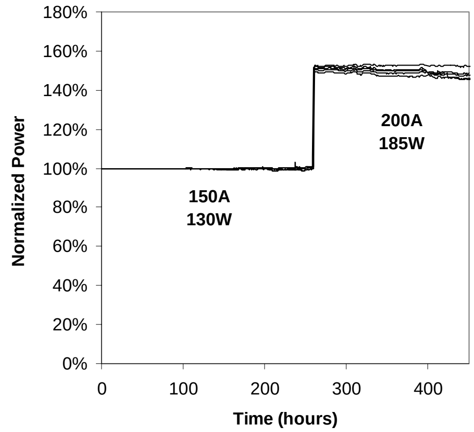

Figure 7: initial step-stress data on long cavity bars

6. Conclusions

The peak CW output power of semiconductor diode lasers continues to increase, reaching > 400-W in the 800-nm to 980-nm wavelength band. In this region, the performance of semiconductor components has now advanced to the point where the major limitation to peak achievable power is now the thermal resistance of the micro-channel cooler. Away from this region, the lower power conversion efficiency limits the peak achievable bar power.

7. References

[1] Paul Crump, Jun Wang, Steve Patterson, Damian Wise, Alex Basauri, Mark DeFranza, Sandrio Elim, Weimin Dong, Shiguo Zhang, Mike Bougher, Jason Patterson, Suhit Das, Mike Grimshaw, Jason Farmer, Mark DeVito and Rob Martinsen. “Diode Laser Efficiency Increases Enable > 400-W Peak Power from 1-cm Bars and Show Clear Path to Peak Powers in Excess of 1-kW” ", in Proceedings of Photonics West, High-Power Diode Laser Technology and Applications IV, Paper 10, Proc SPIE 6104, (2006)

[2] Paul Crump, Weimin Dong, Shiguo Zhang, Mike Grimshaw, Mark DeFranza, Sandrio Elim, Damian Wise, Guokui Kuang, Jun Wang, Suhit Das, Jason Farmer and Mark DeVito: “> 76% CW Wall-plug Efficiency at High Powers from 0.98-µm Emitting Laser Diodes” (2005) Paper #402, Proceedings ICALEO 2005, Miami, FL USA.

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8. Acknowledgements

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