High Efficiency kW-class QCW 88x nm Diode Laser Bars with Passive Cooling

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ABSTRACT

We present our recent efforts to improve power rating, efficiency, reliability, and cost of diode laser bars in the 88x nm wavelength band. QCW kW-class diode laser bars are grown by metal-organic chemical vapor deposition (MOCVD), and are cleaved, passivated, coated, and die bonded onto either standard copper CS-style heat sinks using indium solder, or onto expansion matched CuW CS heat sinks using AuSn solder. In an effort to realize high power operation, the high efficiency 880-nm epitaxial design has been optimized. Bars of varying fill factors, cavity lengths, and facet coating reflectivities are explored to improve the rated electrical to optical (E-O) efficiency up to approximately 70% under low duty cycle QCW operations. The enhanced E-O efficiency makes possible not only the passive cooling of the devices, but also reliable operation in the kW power range. We demonstrate that the semiconductor laser bars can survive over 100 million laser shots working in QCW mode. It is expected that the development of these passively cooled, highly efficient and highly reliable QCW kW-class diode laser bars will enable commercial applications.

Keywords: High power diode lasers, Quasi-CW, kW-class laser, solid state lasers, high efficiency, reliability

1. INTRODUCTION

High-power diode laser bars are deployed as high-efficiency energy sources in a variety of industrial, medical, and military applications. The demand is application driven and has been growing for past few decades thanks to improvements in power rating, efficiency, reliability, and production costs [1]. In applications where quasi-continuous wave (QCW) operation mode is allowed with sufficiency short pulse length and repetition rate, a laser package has much lower effective thermal resistance than that operating continuous wave (CW). In such low-duty cycle QCW cases, a laser bar can have much higher peak power without the excessive heating that degrades E-O efficiency and reliability. This enables passive cooling, which is particularly important for compact, portable, and low-cost system level requirements and to reduce $/W.

nLIGHT offers lasers with high efficiency and reliability in the 870-980nm wavelength band. These products are enabled by high-quality metal-organic chemical vapor deposition (MOCVD) growth and wafers are processed using industry-standard broad area diode laser fabrication techniques. As an example, Fig. 1a shows the power and efficiency vs. drive current of 885nm cm bar arrays bonded to microchannel-cooled heat sink format. These particular devices are operated in CW mode, and achieve >200W power with ~70% conversion efficiency (measured at 5°C base) [2]. Fig. 1b shows the results from a CW lifetest of nLIGHT's commercial 885nm laser bars. These devices were operated at 110W, 40°C for 5644 hours (at which point the lifetest was suspended), totaling over 100,000 raw device hours failure free operation [3].

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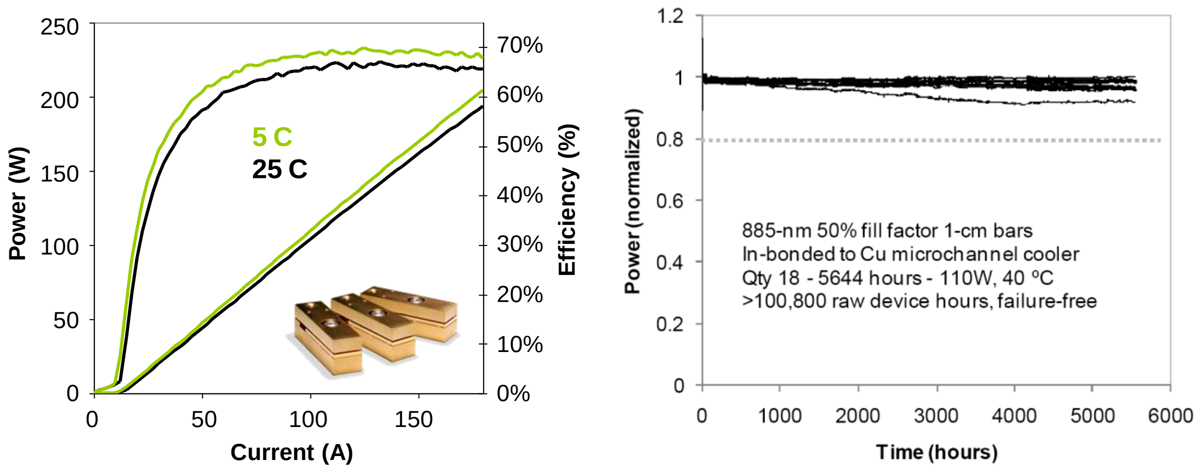


(a) (b)

Fig. 1: (a) CW power and efficiency vs. current for an 885nm, 60% fill factor laser bar. (b) Reliability assessment in microchannel active cooling format.

In this paper, we report on our continuing development activities towards kW-class QCW diode laser bars at the 870-890nm wavelength band with passive cooling packages using industry standard CS packages. This work was motivated by the requirement of much higher peak powers (above 1 kW/cm bar) as an enabling technology of laser inertial fusion energy (LIFE) [4]. In this application, QCW bars are operated at relatively low temperature and short pulse length/low duty factor to directly pump the upper neodymium (Nd) laser level at 872 nm [5].

2. DESIGN AND FABRICATION

2.1 Epitaxy

All epitaxial materials emitting at 870-890nm band are grown by MOCVD. The device epitaxial structure, composition, and doping level are adjusted to achieve the balance between the two optimized parameters of high power and high efficiency.

2.2 Device Layout

After epitaxy, the following device layout parameters were investigated for the optimized rated power, efficiency and reliability:

- Cavity length (CL): 1.5mm and 3.0mm;
- Bar width (BW): 3mm and 10mm;
- Fill factor (FF): 50% (100um/emitter and 200um/pitch) and 80% (120um/emitter and 150um/pitch).

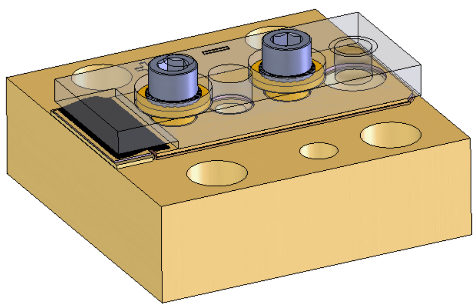
In this paper the diode laser bars with different configurations are marked as CL×BW×FF hereafter for simplification. Three mini bar configurations (1.5mm×3mm×50%, 1.5mm×3mm×80%, and 3.0mm×3mm×80%) and three bar configurations (1.5mm×10mm×50%, 1.5mm×10mm×80%, and 3.0mm×10mm×80%) are evaluated in this study.

2.3 Facet Coating

nLIGHT's nXLT technology is applied to these QCW bars to protect the facet from catastrophic optical mirror damage (COMD) [6]. Facets reflectivity is adjusted for different CL devices for performance optimization.

2.4 Packaging

The QCW bars are either directly bonded onto CS copper blocks using indium solder, or bonded onto expansion matched CuW inserts first using AuSn hard solder and then attached onto CS copper blocks using PbSn solder. Fig. 2 shows one of the CS packages fabricated in this study. It is worth noting that this configuration was studied specifically for rapid assessment of the device performance; in high-power applications, these devices would typically be bonded in a dense hard-soldered multibar stack configuration (such as a G-array).



(a)

(b)

Fig. 2: (a) CAD model of the CS package. (b) One of the CS packages bonded using AuSn/CuW insert and then PbSn attach.

2.5 Testing

The characterization (include LIV, spectrum, and spectral map, etc.) are tested up to 300A for the selected samples and the test conditions including 200 µs pulse width and 14 Hz repetition rate (0.28% duty cycle) with 10°C CS base temperature. The burn-in test is at 150 A for 24 hours (equals to 1.2 M laser shots) following the same QCW switching mode with the characterization tests. Preliminary accelerated life testing was performed at 150 A, at an accelerated 200Hz repetition rate and 20°C base temperature in order to collect ~100 million laser shots in six days. The testing details for the characterization, burn-in, and life tests are summarized in Table I.

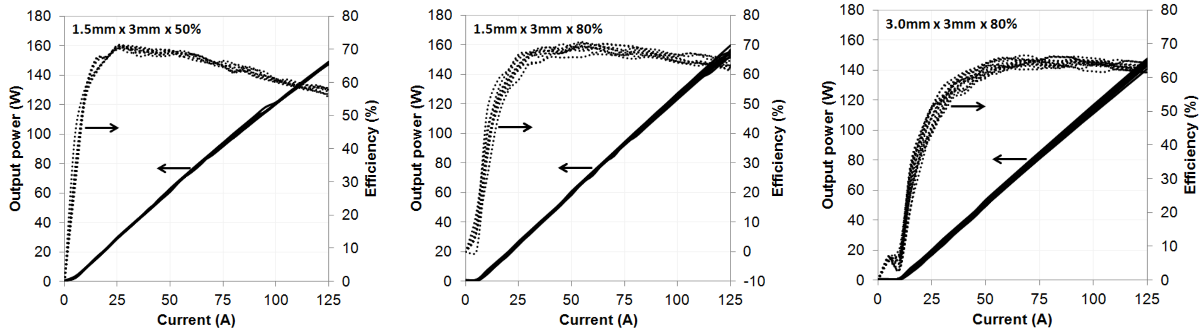
Table I: Testing conditions of characterization tests, burn-in tests, and accelerated life test in this study.

Tests	Characterization	Burn-in test	Accelerated life test
Operation current	Up to 300 A	150 A	150 A
Pulse width	200 µs	200 µs	200 µs
Repetition rate	14 Hz	14 Hz	200 Hz
Duty cycle	0.28%	0.28%	4%
CS base temperature	10-40°C	10°C	20°C
Duration of tests	N/A	24 hours (1.2M shots)	6 days (100M shots)

3. PERFORMANCE AND RELIABILITY

3.1 Performance

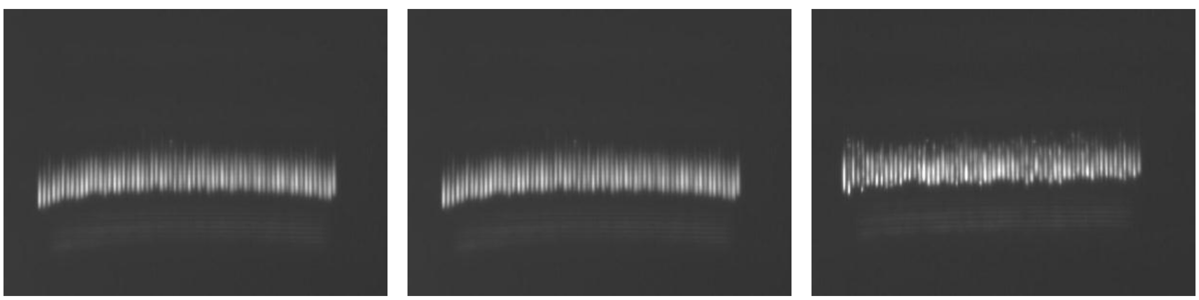
Fig. 3 depicts the power and efficiency of the 3mm mini bars after the burn-in test up to 125A. It is found that all three mini bar configurations (1.5mm×3mm×50%, 1.5mm×3mm×80%, and 3.0mm×3mm×80%) offer consistent testing results with ~70% peak power conversion efficiency and 1.3W/A slope efficiency.



(a) (b) (c)

Fig. 3: Power and efficiency curves of mini bars. (a) 1.5mm×3mm×50%, (b) 1.5mm×3mm×80%, and (c) 3.0mm×3mm×80%.

Fig. 4 shows spectral maps of the 10mm bars all at an operation current of 125 A after the burn-in test. In the spectral map, the *x*-axis (horizontal) is aligned with the bar lateral direction, i.e., the physical positions of each emitter, while the *y*-axis (vertical) is the wavelength distribution for each individual emitters. As shown in Fig. 4, it is found that the larger the laser active region, the narrower the spectral width at the operation current. This is because of the lower thermal resistance of the laser bars with larger active region.



(a) (b) (c)

Fig. 4: Spectral map of 10mm bars at 125A. (a) 1.5mm×10mm×50%, (b) 1.5mm×10mm×80%, and (c) 3.0mm×10mm×80%.

Fig. 5 depicts the increase of the full width half maximum (WFHM) spectral width with operation current for all three mini bar configurations. Again, the laser bars with larger the active region offer narrower emitting spectrum due to the reduction of the thermal resistance.

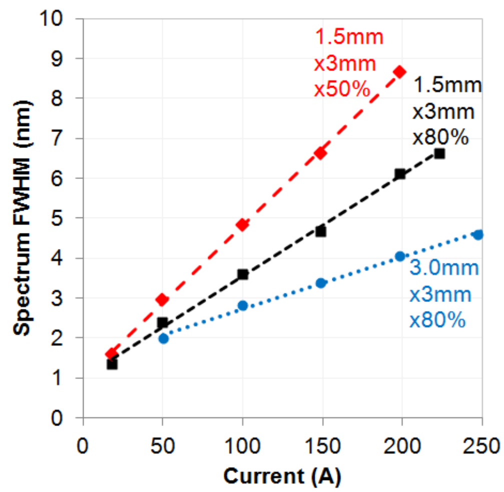


Fig. 5: Spectral width of 3mm mini bars versus operation currents.

3.2 Maximum Power Limitation

It is found that bulk catastrophic optical damage (BCOD), instead of COMD or thermal rollover, is the main limitation of the maximum output power of the laser bars under the targeted QCW operation conditions. This is as depicted in Fig. 6. As shown, the 1.5mm×3mm×50% mini bars have a BCOD level ~200W, while the 1.5mm×3mm×80% mini bars have a BCOD level ~280W. BCOD-free operation of the 3mm cavity length devices is observed to ~370W (limited by testing capabilities).

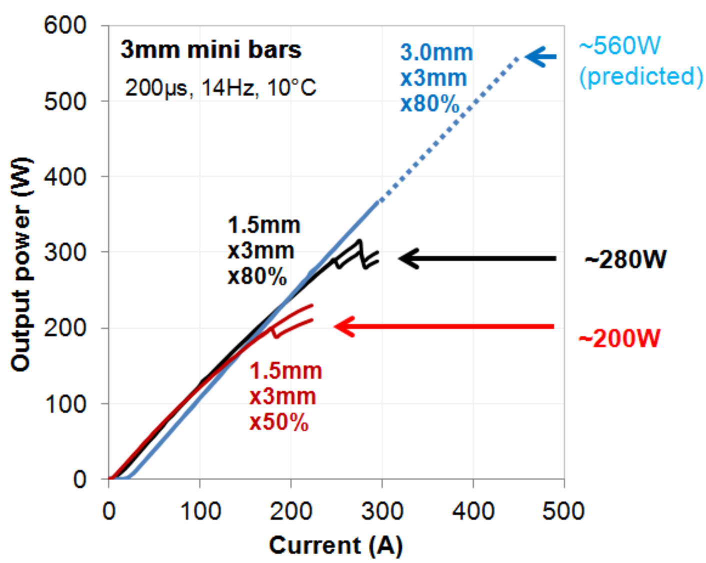


Fig. 6: Power versus current curves to reveal the bulk catastrophic optical damages (BCOD) from 3mm mini bars.

By scaling both fill factor and cavity length, the QCW operation power can be effectively increased without significant detriment to the operating efficiency. Based on prior assessment and comparison of single emitter devices, the 3.0mm×3mm×80% are predicted to fail to BCOD at a power level of ~560W – roughly 1.9 kW from a cm bar.

3.3 Life Test

Accelerated life test at 20°C CS base and 200 Hz repetition rate are used to demonstrate the 100M laser shot reliability. 45 mini bars—15 from each of the three mini bar configurations: 1.5mm×3mm×50%, 1.5mm×3mm×80%, and 3.0mm×3mm×80%—are life tested. After life test, only one emitter in one 1.5mm×3mm×50% mini bar died, as shown in Fig. 7. This corresponds to an 8% power degradation in that particular device. All other devices which were tested showed no degradation. This corresponds to a failure probability of <0.2% at the emitter level.

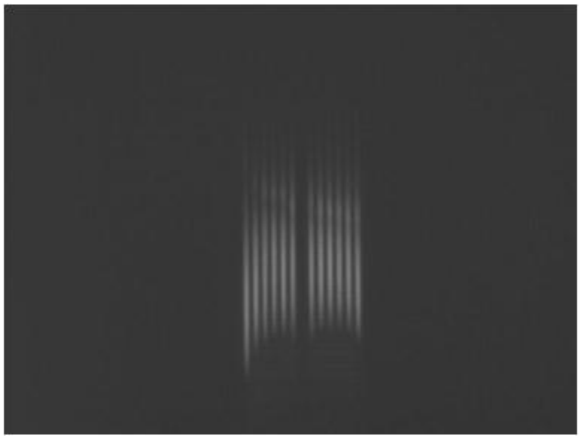


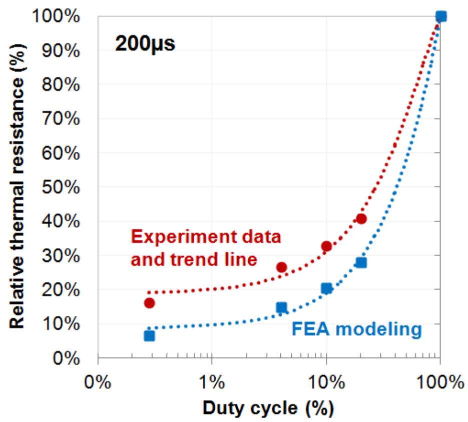
Fig. 7: Spectral map of the 1.5mm×3mm×50% mini bar with one died emitter (middle) after the life test.

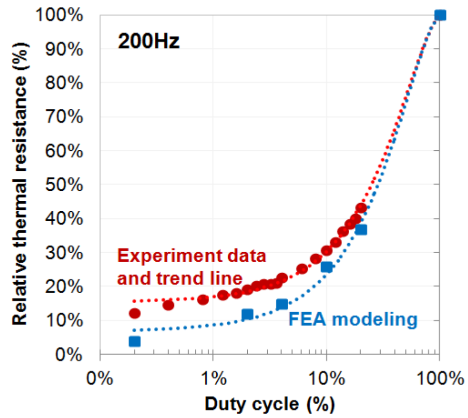
4. DISCUSSION

Both experimental data and thermal modeling based on finite elemental analysis (FEA) were used to predict the thermal behavior of the QCW bars operating in the passive cooling mode in the CS block packages. A phenomenological model based on the steady-state solutions of the diode laser rate equations [7] is used to describe performance of the QCW bars. In the phenomenological modeling, parameters such as transparent current and internal optical loss are adjusted to align the modeling results to the experimental results, and the modeling results are extrapolated to predict the performance of the QCW bars into the kilowatt power range.

4.1 Finite Elemental Thermal Analysis

Fig. 8 plots the effective thermal resistance in the QCW mode at (a) a fixed laser pulse length of 200µs and (b) a fixed repetition rate of 200Hz, respectively. In the plots, the experimentally measured data are plotted as red circles and the FEA modeling data are plotted as blue squares. Both of the data sets are normalized by their CW values, respectively, and trend lines are also added. It is interesting to see at both sufficient short pulse length and low repetition rate, the ratios of the QCW thermal resistance versus that of the CW thermal resistance are all saturated in a level of below 20%. In the low duty cycle range, the saturation level of the QCW experimental results is higher than that of the FEA modeling results. This is because that the current has limited ramp up and down speeds in the QCW experiment, so the below threshold losses becomes more evident in such operation mode. While in the FEA modeling, the ideal current square pulses are assumed. In reality, quality enhancement in current pulses can improve the QCW operation efficiency such that the experiment trend can match closer to that of the FEA modeling predicted in Fig. 8.



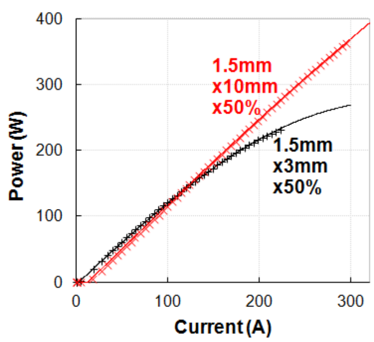


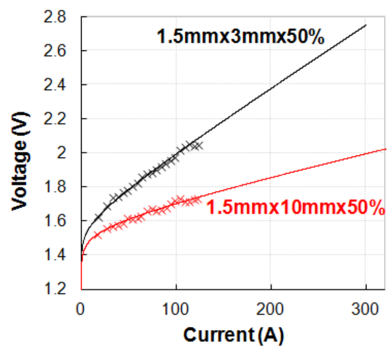
(a) (b)

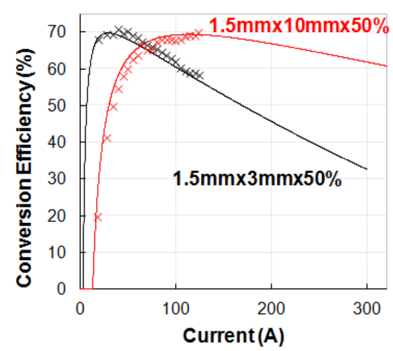
Fig. 8: Relative thermal resistance of QCW/CW versus duty cycles (a) at a fixed pulse width of 200µs and (b) at a fixed repetition rate of 200Hz.

4.2 Phenomenological Modeling

In the phenomenological modeling, the characteristics of a laser are described by the parameters in the diode laser rate equations. All three mini bar and three 10mm bar configurations are modeled for this purpose. As an example, Fig. 9 illustrates measured power, voltage and efficiency versus current for the 1.5mm×3mm×50% mini bars and the 1.5mm×10mm×50% bars. While the solid lines represent the modeling results which are shown to be in close alignment with the experiment data (discrete crosses).







(a) (b) (c)

Fig. 9: (a) The laser power, (b) voltage, and (c) E-O conversion efficiency experimental data (discrete ×) and the phenomenological modeling curves for the 1.5mm×3mm×50% mini bars and the 1.5mm×10mm×50% bars, respectively.

Next, modeling data are extrapolated the performance for 1.5mm×10mm×80% and 3.0mm×10mm×80% bars of the same laser epitaxy design shown in Fig. 10. BCOD levels of the two bar configurations are also marked in the same plot. As shown in Fig. 10, the 1.5mm×10mm×80% bars (shown in red) have a BCOD level below 1kW/cm bar; while the 3.0mm×10mm×80% bars (shown in blue) have a BCOD level ~1.9kW/cm bar. This is the same BCOD level as predicted from the 3mm mini bar data. So the elongated 3.0mm cavity length makes 1kW/cm bar possible. The E-O conversion efficiency is ~68% at the power rating of 1 kW/cm bar.

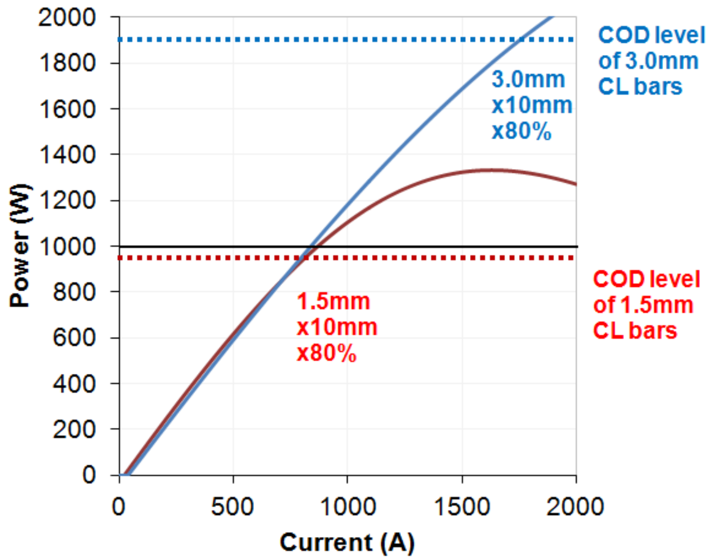


Fig. 10: Power versus current curves for 10mm bars.

5. SUMMARY

In summary, kW-class QCW 88xnm diode laser bars are fabricated in CS passive cooling packages. Bar performance with different cavity lengths, bar width, and fill factors was discussed. 3.0mm cavity length makes 1kW/cm bar possible to operate at ~68% efficiency without any predicted catastrophic optical damage. Development of QCW bars with even higher QCW power rating is ongoing.

6. REFERENCE

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