980 nm Diode Laser Pump Modules Operating at High Temperature

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ABSTRACT

Existing thermal management technologies for diode laser pumps place a significant load on the size, weight and power consumption of High Power Solid State and Fiber Laser systems, thus making current laser systems very large, heavy, and inefficient in many important practical applications. This problem is being addressed by the team formed by Freedom Photonics and Teledyne Scientific through the development of novel high power laser chip array architectures that can operate with high efficiency when cooled with coolants at temperatures higher than 50 degrees Celsius and also the development of an advanced thermal management system for efficient heat extraction from the laser chip array. This paper will present experimental results for the optical, electrical and thermal characteristics of 980 nm diode laser pump modules operating effectively with liquid coolant at temperatures above 50 degrees Celsius, showing a very small change in performance as the operating temperature increases from 20 to 50 degrees Celsius. These pump modules can achieve output power of many Watts per array lasing element with an operating Wall-Plug-Efficiency (WPE) of >55% at elevated coolant temperatures. The paper will also discuss the technical approach that has enabled this high level of pump module performance and opportunities for further improvement.

Keywords: Diode Laser Pump, High Power Laser, High Efficiency Laser Diode, DPSSL, High Temperature Coolant, Micro-Jet Impingement Cooler

1. INTRODUCTION

High energy lasers are utilized in many military and commercial applications, such as directed energy weapon applications, laser welding and cutting applications, and medical applications, to name a few. These high energy solid-state lasers require diode laser pump arrays that are efficient, reliable, and low cost, size, weight, and power consumption (c-SWaP). It is also necessary that the diode pump array generate a high beam quality optical output. In the case of an aircraft-borne directed energy weapon, the diode pumps must operate over a wide temperature range (-40 °C to 60 °C). Cooling these pump lasers represents a significant challenge when considering a deployable 100kW+ high energy laser system.

In our work, we address these challenges of improving diode laser pumps through both laser chip design and thermal management design. Our objective is to mitigate the c-SWaP burden imposed on high average power (> 100 kW) solid-state lasers by the cooling system of high power semiconductor laser pumps. Our solution includes two essential and complementary goals. The first goal is to design, fabricate and demonstrate pump lasers at wavelengths near 1 µm with improved laser chip architectures that enable high junction temperature lasing while simultaneously maintaining high efficiency operation. The second goal is to design, fabricate and demonstrate a novel scalable cooling approach for the diode lasers that brings the coolant closer to the diode structure and thus reduces the thermal resistance significantly over existing technology. This reduced thermal resistance between device junction and coolant, in conjunction with chip operation at high junction temperature, will allow for pump operation at high heatsink temperatures, the laser chip being cooled effectively by liquids at a relatively high temperature.

In addition to achieving high temperature diode pump performance, the proposed new semiconductor laser chip architecture will offer excellent device reliability and beam quality, meeting the requirements for pumping slab or fiber lasers.

2. DESIGN AND FABRICATION

2.1 Laser Chip Design

Semiconductor lasers as pumps for solid-state systems have been studied for several years, spanning a large wavelength range (~780 nm to 2100 nm), with design advances achieving wall-plug-efficiencies in excess of 70% in some cases[1]; however, these high efficiencies were achieved in systems in which the lasers were cooled with DI water at a temperature less than 6 degrees Celsius. In modern high power diode lasers, optical absorption loss is dominated by free carriers in the active region, and engineering of the optical mode allows for improved efficiency by reducing total absorption losses in the structure[2].

We employ both rigorous finite-difference-time-domain simulations and phenomenological laser modeling tools to optimize our epitaxial structure and laser designs for high-efficiency performance at elevated operating temperatures. Example simulation results for a single emitter at various operating temperatures are given in Figure 1. As operating temperature rises, the conversion efficiency decreases, output power decreases, and junction temperature increases, as expected.

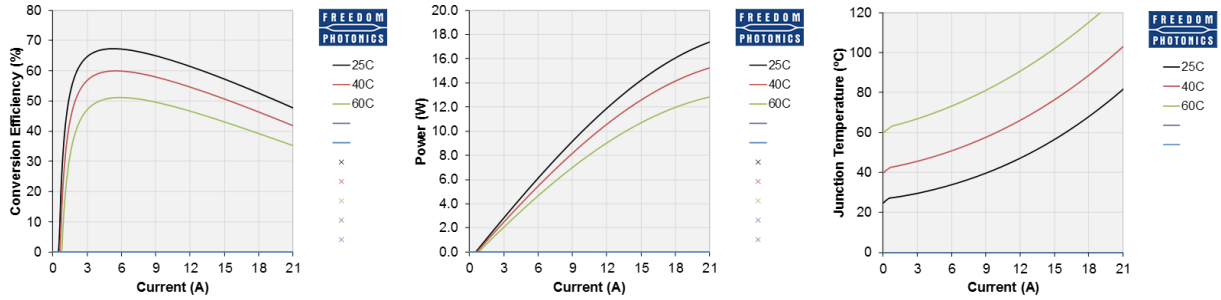

Figure 1 – Laser performance predictions, from phenomenological model based on rate-equation analysis. Plotted results show conversion efficiency (left), output power (center), and junction temperature (right) for a 4 mm x 100 µm single emitter operated at three different heat sink temperatures: 25 °C, 40 °C, and 60 °C.

2.2 Laser Chip Fabrication

Epitaxial layers were grown by MOCVD on GaAs wafers to form a P-I-N laser diode structure. Using these wafers, we fabricated devices at 980 nm in a 3x1 emitter array configuration. Arrays of various emitter widths and cavity lengths, with geometries chosen based on laser performance simulation results, were processed. Figure 2 shows a cross-sectional view schematic of one of the laser chip arrays. The emitter width is defined by trenches on both sides of the ridge that are dry-etched using an ICP etching tool. Ohmic contacts are deposited by E-beam evaporation on the P-side of each emitter, and the array is then metallized such that all three emitters are pumped through a single contact. The wafer substrate is thinned to 150 microns, and the wafer backside is metallized. Finally, the wafer is cleaved into bars, which are facet-coated with a high reflectivity (HR) coating at the back facet and a partial reflectivity (PR) coating at the front facet to define the laser mirrors.

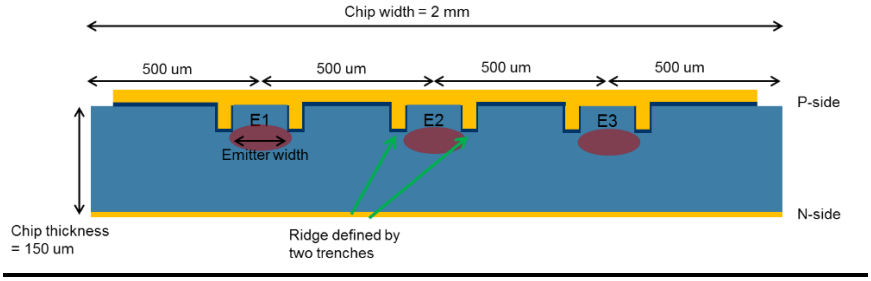

Figure 2 – Cross-sectional view schematic of laser chips fabricated (not to scale). Chips comprise three emitters of variable width. The three emitters are labeled “E1”, “E2”, and “E3.” The total chip width of the 3x1 array is 2 mm, and the wafer thickness is 150 microns.

2.3 Flip-chip mounting

After wafer fabrication, cleaving, and HR/PR coating, the laser chips are flip-chip mounted onto indium-coated sub-mounts. There are several challenges associated with this process, including the short time scale for indium oxidation and the need for high-purity indium. After significant process development, we arrived at a successful recipe for indium deposition and die-bonding that produced good electrical and thermal characteristics. In Figure 3, a flip-chip bonded laser array is shown. Many wirebonds are used to connect the backside of the laser chip to the top N-electrode of the sub-mount.

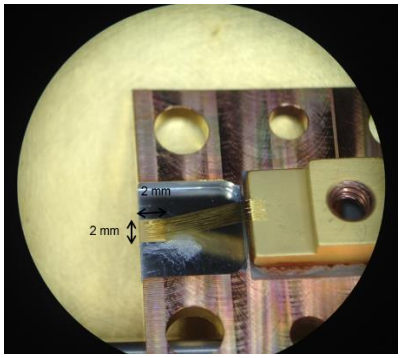

Figure 3 – Fabricated laser chip array, flip-chip bonded onto an indium-coated sub-mount. The dimensions of the chip are 2 mm by 2 mm.

2.4 Thermal Management Design and Fabrication

The design concept for our thermal management system for high power diode lasers is shown in Figure 4. The design includes using micro-jet impingement cooling in a micro-fluidic manifold to cool a two-dimensional stack of laser diode arrays. By bringing the coolant closer to the diode structure than standard micro-channel coolers, the thermal resistance between the emitter junction and the coolant is reduced significantly. This allows us to use a coolant at high temperature while maintaining high-efficiency laser operation, which is necessary for deployment in harsh conditions.

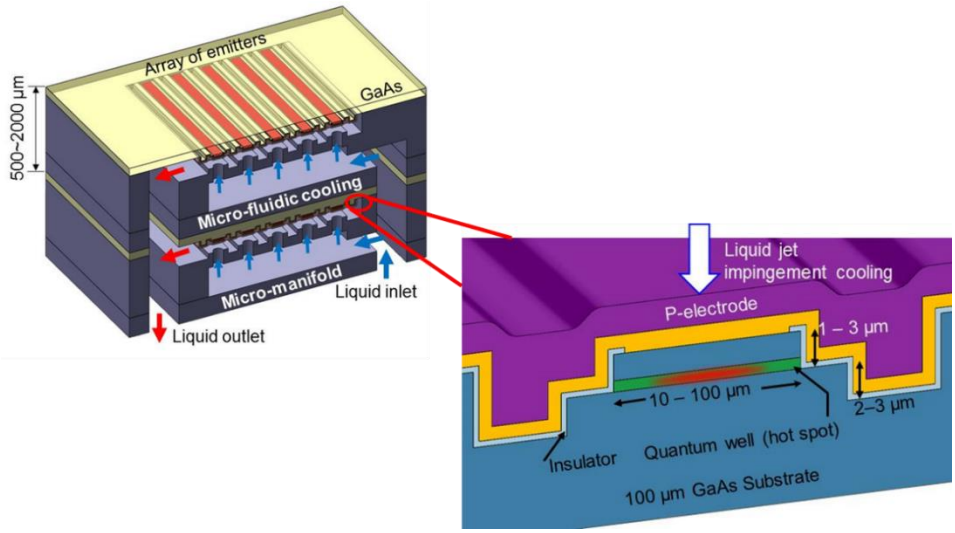

Figure 4 – Design concept of micro-jet impingement cooling system for high power diode lasers.

Micro-jet impingement cooling provides many advantages over standard micro-channel cooling technologies. Most micro-channel coolers are designed for DI water only. The channels are often very small, prone to clogging and corrosion. It is also necessary to flow DI water continuously to avoid biological growths within the system, and deionizers for the water are bulky and expensive, nullifying the c-SWaP reduction efforts of the system. The use of DI water also limits the device usefulness in environments where freezing is a concern. In contrast, our micro-jet

impingement system uses larger flow passages, which allows us to flow a viscous refrigerant: 50% water-propylene-glycol (WPG). This fluid has a wide operating temperature range and does not need a deionizer.

We have performed extensive thermal modeling to inform the design of the cooling system for the 3x1 emitter mini-bar demonstration. These simulations have explored different micro-jet impingement patterns and channel sizes. We have also compared performance predictions of different cooler types. We calculated the thermal resistance of a state-of-the-art micro-channel cooler flowing DI wafer, a micro-channel cooler flowing 50% WPG, and our micro-jet impingement cooler flowing 50% WPG. The results are displayed in Table 1. The simulation predicts that a micro-channel cooler will perform slightly worse with 50% WPG than with DI water. Furthermore, our micro-jet impingement cooler performs three times better than the micro-channel cooler design.

Table 1 – Comparison of simulated thermal resistance values of different cooler types.

Cooling Technology	Coolant	R_{jc} (°C/W) per Emitter
State-of-the-art Micro-channel Cooler	DI water	18.1
	50% WPG	23.6
Micro-jet impingement	**50% WPG**	**7.6**

This improvement in thermal resistance has significant implications for performance enhancement. For a given coolant temperature, the emitter junction temperature is lower in a system with lower thermal resistance. For many high energy laser applications, the coolest liquid available for laser cooling is at approximately 50 °C. It is therefore important to demonstrate high-efficiency laser performance at elevated coolant temperatures, which was a key focus of our work.

The thermal management test set was designed to facilitate ease of testing different laser arrays and different micro-jet impingement flow patterns. Figure 5 shows a schematic and a photograph of the test set, which is designed for testing a single laser mini-bar. The laser chip is mounted P-side down onto the P-electrode of the sub-assembly, and the backside of the chip is wirebonded to the N-electrode. This sub-assembly is attached to the orifice plate, which has an array of jet heads for micro-jet impingement cooling. This test set will be modified as we expand the technology to larger laser bars and two-dimensional arrays of laser bars.

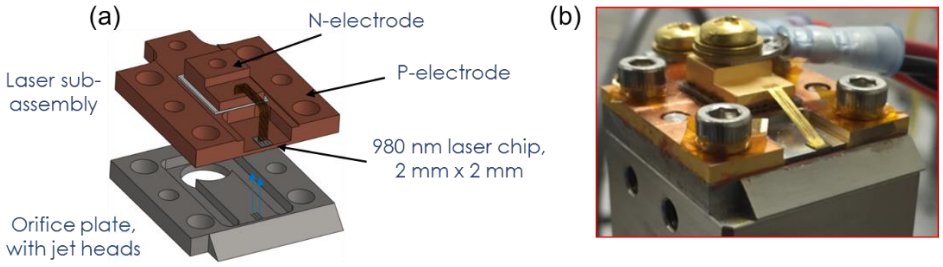

Figure 5 – Thermal management test set. (a) Schematic of laser sub-assembly and orifice plate with jet heads. (b) Photograph of installed test set, with a fabricated laser chip mounted on the laser sub-assembly.

3. RESULTS AND DISCUSSION

Using our high temperature micro-jet impingement cooling test set, we tested many laser chip at 980 nm, of various emitter widths and cavity lengths. The results highlighted below are from a chip with three emitters of 50 µm width and 2 mm cavity length. The chips are cooled with 50% WPG coolant at 50° C. Total coolant flowrate was maintained at 225 mL/min (75 mL/min per emitter), resulting in a typical cooler pressure drop of 4.6 PSI. The lasers were also tested at 40 °C and 22 °C, for comparison. Our results for wall-plug-efficiency (WPE) and output power are plotted in Figure 6, along with corresponding I-V curves and an example spectrum. We have demonstrated peak efficiency of 55% at 50° C coolant temperature. The total current at peak efficiency is 6 A (or 2 A per emitter) and the current density is 2000

A/cm^2. The experimental thermal resistance from emitter junction to coolant was calculated to be 8.2 °C/W. This is within 10% of our thermal simulation result of 7.6 °C/W, which gives us confidence in our thermal modelling approach.

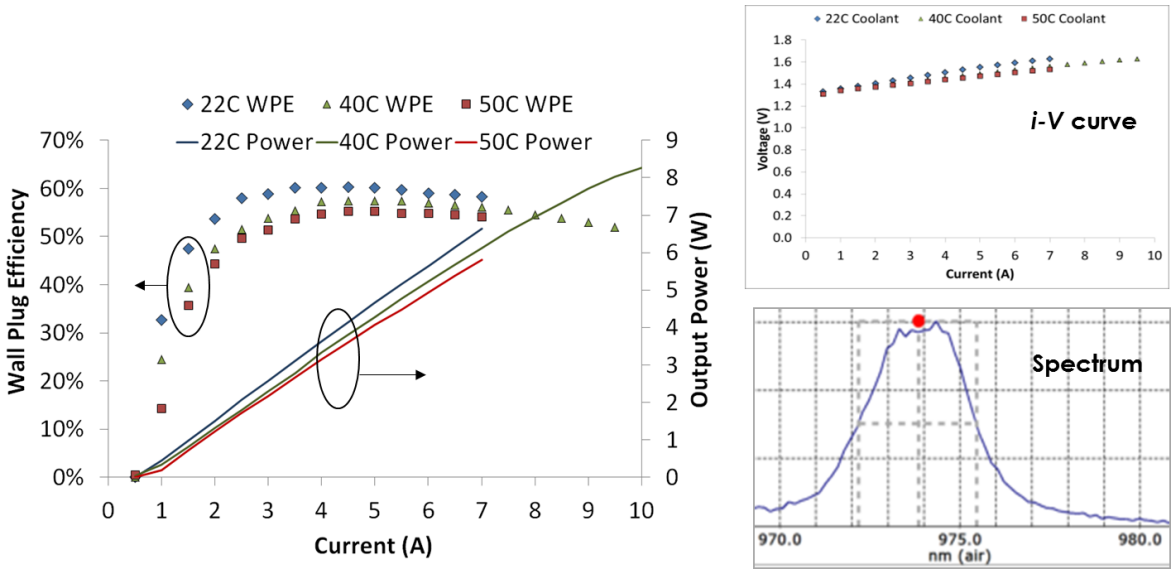

Figure 6 – Test results of a high-efficiency, three-emitter laser array chip. Left: Output power and wall-plug-efficiency of array chip, measured at three coolant temperatures: 22 °C, 40 °C, and 50 °C. Top right: IV curves for array chip, measured at the same three coolant temperatures. Bottom right: a representative optical spectrum from the array chip, with centroid wavelength of 974 nm.

Table 2 summarizes the results for WPE, junction temperature, and output power at three coolant temperatures (22 °C, 40 °C, and 50 °C) and for two conditions (peak WPE and at maximum tested power). These chips were tested under conservative conditions, so this does not represent the maximum power that these lasers are capable of achieving. The peak WPE drops approximately 0.18% for each degree Celsius of coolant temperature increase. Efficiency is reduced because of the reduction in the slope efficiency with temperature increase. The slope efficiency is 1.0 W/A at 22°C coolant, 0.97 W/A at 40°C coolant, and 0.92 W/A at 50°C coolant.

Table 2 – Summary of test results for 980 nm three-emitter laser chip.

	Coolant Temp. (°C)		
	22 °C	**40 °C**	**50 °C**
At Peak WPE:			
WPE	60%	57%	55%
Output Power	4.1 W	4.8 W	4.9 W
Junction Temp	29 °C	50 °C	61 °C
At Max. tested power:			
WPE	58%	51%	54%
Output Power	6.6 W	8.3 W	5.8 W
Junction Temp	35 °C	62 °C	63 °C

We also performed tests at three different coolant flowrates, with results shown in Figure 7. Our current experimental operating point is at a flowrate of 225 mL/min. By using half of that flowrate, or 113 mL/min (37 mL/min per emitter), the pressure drop is reduced by a factor of four, corresponding to an eight-fold reduction in pumping power. The penalty is a 13% higher thermal resistance, which results in 1°C higher emitter temperature (at peak WPE) and 1% lower WPE.

This penalty is minor and acceptable, given the large improvement in pressure drop. These results indicate the promise of using this thermal management system for larger laser array systems, in which the benefit of a low pressure drop is magnified.

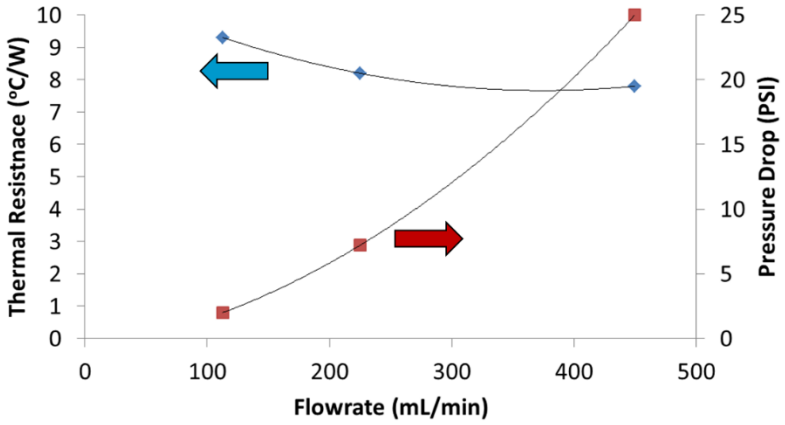

Figure 7 – Thermal resistance and pressure drop at three different flowrates. The test was performed with a 980 nm chip with three emitters, 2mm cavity length, and 10% fill factor. Coolant was 50% WPG at 50°C.

4. CONCLUSION

We have demonstrated state-of-the-art laser diode performance with an innovative thermal management architecture. Our micro-jet impingement cooling system provides very low thermal resistance between the emitter junction and the coolant. This allows us to achieve high-efficiency laser diode performance at elevated coolant temperatures, which improves the ruggedness and reliability of our diode laser pumps. This technology is scalable to larger two-dimensional diode arrays for pumping high energy lasers in a plethora of commercial and military applications.

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