Nanoscale Coating for Microchannel Cooler Protection in High Powered Laser Diodes

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Abstract

High powered laser diodes are used in many applications that require stable optical output, such as materials processing, medical and military applications, and solid-state laser pumping [1,2]. Due to the low electrical to optical efficiencies of 25-35%, significant waste heat is generated which increases the junction temperature and alters the wavelength of the emitted beam. The industry standard for rejecting this waste heat is single-phase, copper microchannel cooler (MCC) using high-purity de-ionized water (DIW) coolant. However, the high-purity DIW coolant is pumped through the copper MCCs in presence of leakage current at high velocity, which causes erosion-corrosion damage to the micron sized heat transfer surface areas, and reduces the thermal performance of the cooler. Since the corrosion of copper is highly dependent on the pH and dissolved oxygen (DO) content of the DIW coolant, strict control on water conditioning system is employed. This strict control scheme leads to additional equipment, costs and reliability concerns.

Extension of the cooler lifetime by protecting the MCCs against erosion-corrosion can be achieved by applying a uniform, pin-hole free and conformal coating to the internal features of the MCCs. However, many coating and plating techniques, such as nickel and gold plating, cannot meet these requirements. Thus, a vapor phase deposition technique that uniformly applies a nanometer thin, conformal, inert, hard, coating to the high-aspect ratio internal features of the MCC was developed to protect the copper MCC against erosion-corrosion in high powered laser diode applications. Corrosion rate measurements of baseline uncoated and coated copper samples exhibited a one to two order of magnitude reduction in corrosion rate when exposed to DIW with a pH of 6.0 – 9.0 and a DO concentration ranging from 0.5 ppm to 10.0 ppm. This study shows that the strict controls required to maintain the pH and DO can be severely relaxed by applying the coating resulting in reduced operational costs and increased reliability. Furthermore, evaluations of the coating thickness deposited throughout the microchannel region of the MCC demonstrate the uniform and conformal application of the coating in the high aspect ratio features. Lastly, thermal and hydraulic performance evaluations of coated MCCs revealed that the application does not impede the thermal or hydraulic performance of the MCC, thereby enabling lifetime extension without adding pumping power requirements.

Keywords

Laser diode, thermal management, nanoscale, corrosion, erosion, microchannel coolers

Nomenclature

R_{th}	Thermal Resistance [K/W]
T_H	Heater Temperature [°C]
T_{out}	Outlet Temperature [°C]
T_{in}	Inlet Temperature [°C]
$\dot{m}$	Mass Flow Rate [kg/s]
C_p	Specific heat capacity [J/gK]
COP	Coefficient of Performance [dimensionless]
ρ	Density [kg/m^3]
ΔP	Differential Pressure [Pa]

1. Introduction

High powered laser diodes have output power in the range of 50-100 W in continuous wave mode (CW) [1] and have electric to photonic efficiencies of 25-35% [2]. Thus, high powered laser diodes generate significant amounts of waste heat. Compounded with their small footprint, high powered laser diodes can generate heat fluxes on the order of 100s of W/cm^2 [2]. If the waste heat is not removed, the junction temperature of the laser diode increases and shifts the output wavelength by 1 nm for every 3 K change in junction temperature. Thus, applications that require high powered laser diodes with stable optical output, such as materials processing, medical and military applications, and solid-state laser pumping, require efficient rejection of this waste heat [1,2]. In order to remove this waste heat and maintain stable optical output, laser diode bars are die bonded to copper microchannel coolers (MCCs) and arranged in stacks, as presented in Figure 1 [3].

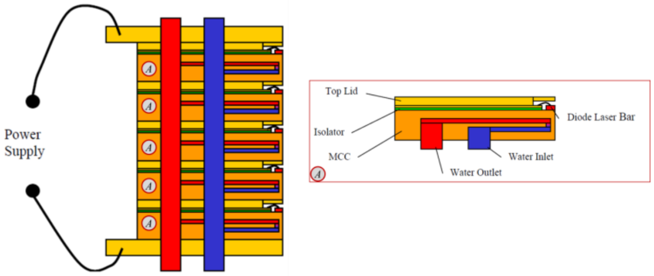


Figure 1. High powered laser diode stack demonstrating laser diode bar die bonded directly to the MCC with parallel cooling path and series electrical connections.

As shown in Figure 1, the high powered laser diodes are bonded directly to the MCCs and each cooler is electrically connected in series. Thus, the coolant for the stack must have high electrical resistivity to reduce leakage currents. As a result, high-purity, de-ionized water (DIW) with a resistivity of 0.3 MΩ·cm is used as a coolant. The MCCs are designed with micron sized heat transfer features directly underneath the bonded laser diode to improve heat transfer and maintain stable laser diode junction temperatures. However, the DIW coolant is pumped through these MCCs at linear velocities of approximately 4 m/s, which causes erosion-corrosion, also known as flow assisted corrosion, of the MCC features [4]. Furthermore, the corrosion rate of copper is accelerated by one order of magnitude when the pH of the coolant water decreases from pH 8 to 6. If not controlled, the corrosion damage to the micron sized copper heat transfer features can be damaged, thereby reducing the thermal performance of the cooler and raising laser diode junction temperatures. As a result, the output wavelength of the emitted light shifts and when it reaches values unacceptable to the application, the cooler must be replaced. These costly replacements typically occur every 10,000 hours, requiring frequent system downtime. In this paper, results on corrosion protection from vapor based deposition coating is presented that alleviates the necessity on strict controls to maintain the DI water quality and reduces the corrosion rate by an order of magnitude.

2. Coating Application Technique

The current standard to reduce the rate of erosion-corrosion is application of nickel and gold plating to protect the internal features of copper MCC heat transfer surface areas. This gold plating is known to be non-conformal and prone to have pin-hole features that act as precursors to corrosion. In addition, the trend of reducing laser diode footprint while maintaining component power leads to high waste heat flux that require ultra-fine microchannel feature sizes to maintain laser diode junction temperature. Hence, in these state-of-the-art MCCs nickel and gold plating techniques cannot be employed as they block the microchannel features.

To prolong the lifetime of copper MCCs, a vapor phase deposition technique that deposits a hard, inert coating on the internal features was developed. This vapor phase deposition technique results in a nanometer thin, uniform coating on the complex, high aspect ratio internal surfaces of the MCC [5]. The hard and inert coating is designed to protect the underlying copper from erosion and corrosion, respectively. Additionally, the nanometer-scale thin coating does not add thermal or hydraulic resistance, thereby maintaining thermal and hydraulic performance of the MCC.

This coating is applied in a coating deposition chamber where vapor phase reactants are dosed into the reactor volume. Deposition within the internal microchannel features is achieved by holding the vapor phase reactants in the chamber for the amount of time required for the reactant to diffuse into these features. Ultimately, this method enables a uniform application of the coating on the internal surfaces that protects the MCC from erosion-corrosion, thereby reducing degradation of the heat transfer surfaces and extending the lifetime of the MCC.

3. Copper Corrosion Evaluations

3.1 Experimental setup

Due to the high purity DIW required to electrically isolate the microchannel cooler and reduce leakage current, the rate of corrosion of the copper MCC internal features increases. This corrosion rate is dependent on the pH and dissolved oxygen (DO) concentration of the high purity DIW coolant [4]. To evaluate the improved passivation of the inert coating, the corrosion rate of baseline uncoated copper and coated copper flat plate samples was evaluated by electrochemical impedance spectroscopy (EIS) [6] at pH ranging from 6.0-9.0 in 0.5 increments and DO ranging from 0.5-10.0 in 0.5 increments in simulated laser diode thermal management operating conditions outlined in Table 1. In order to control the coolant properties within the specifications listed in Table 1, a custom made flow cell that also served as an electrochemical cell to perform in-situ EIS measurements was developed and is presented in Figure 2.

Table 1. Corrosion Rate Evaluation Test Conditions

Test Parameter	Value
Coolant	De-ionized water (DIW)
Coolant pH	6.0 – 9.0
Coolant Resistivity	0.3 MΩ·cm
Dissolved Oxygen Content	0.5-10.0 ppm
Temperature	25 ºC

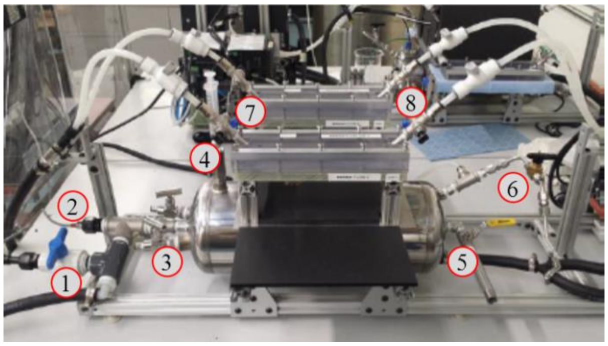


Figure 2. Test apparatus for evaluating the corrosion rate of uncoated and coated copper samples with (1) dissolved oxygen probe (2) DIW resistivity probe (3) oxygen and nitrogen sparging lines (4) pH solution injection port (5) DIW pH testing tap (6) gas release vent (7) electrochemical cell inlet with thermocouple and (8) electrochemical cell outlet.

The DO of the DIW coolant was controlled by sparging nitrogen or oxygen into the coolant reservoir tank and was monitored by a DO meter. To achieve stable DO concentration below 1 ppm, a deoxygenating contacting membrane was used, as shown in Figure 3.

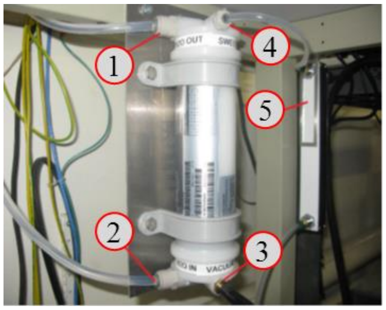


Figure 3. Deoxygenating contact membrane for achieving DO concentrations of less than 1.0 ppm. (1) DIW outlet (2) DIW inlet (3) nitrogen sweep gas inlet (4) vacuum pump outlet (5) nitrogen sweep gas flow meter.

The pH of the DIW coolant was maintained by injecting 0.1 M sodium hydroxide (NaOH) or 0.1 M hydrochloric acid (HCl) solutions into the reservoir tank to raise or lower the pH to the specified condition, respectively. The resistivity of the DIW coolant was controlled by pumping the DIW through a de-ionizing filter bed (not shown). Lastly, the DIW was pumped through a chiller (not shown) to maintain the temperature under all conditions evaluated at 25 °C. Under this mechanism, all DIW properties relevant to simulating laser diode thermal management conditions were controlled within the specifications listed in Table 1.

3.2 Coating passivation results

The corrosion rate of the baseline uncoated and coated copper samples were evaluated by EIS and a copper release map (*i.e.* contour plot of corrosion rate against pH and DO) is presented in Figure 4. For comparative purposes, the copper release maps of the baseline uncoated and coated copper samples are shown on an equivalent scale. As shown in Figure 4, the corrosion rate of the baseline uncoated copper sample exhibited a dependence on the pH and DO concentration of the DIW coolant and varied by approximately one order of magnitude across the range of conditions tested. However, the corrosion rate of the coated copper sample was found to be consistent across all pH and DO concentrations tested. Furthermore, the corrosion rate of the coated copper sample was approximately one to two orders of magnitude lower than the uncoated copper baseline sample.

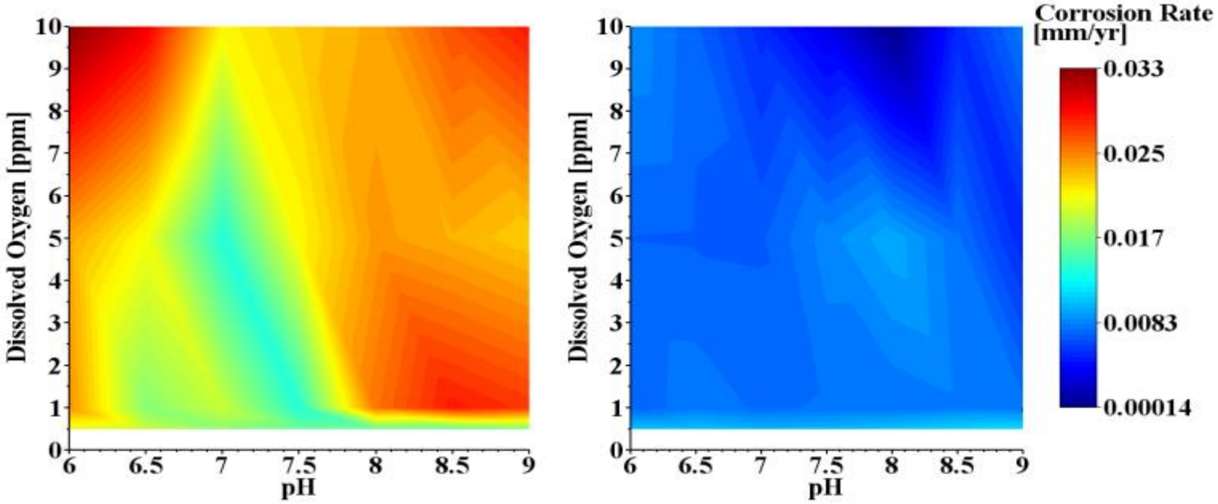


Figure 4. *(Left)* Copper release map of the baseline uncoated copper sample and *(Right)* coated copper sample demonstrating that the corrosion rate of uncoated copper is highly dependent on the pH and DO of the DIW coolant while the corrosion rate of the coated copper sample maintains a uniform corrosion rate across all DIW conditions evaluated. Thus, the coating not only reduces the corrosion rate by one to two orders of magnitude compared to the uncoated baseline sample, it also reduces the strict DIW control requirements.

Thus, these results clearly indicate that the corrosion of copper MCCs is sensitive to the DIW coolant conditions requiring strict control of the pH and DO in laser diode thermal management applications to maximize MCC lifetime. The application of the nanometer thin coating significantly reduces the dependence of the corrosion rate on the pH and DO concentration of the DIW coolant. Furthermore, a water conditioning system failure event results in a large shift in DIW coolant pH or DO. Such an event could lead to increase of the corrosion rate of the uncoated copper MCC internal features by an order of magnitude. Under this same event, the coated MCC will maintain the reduced corrosion rate, thereby minimizing corrosion degradation of the MCC heat transfer surface areas and thereby improving the reliability of the operation. After performing proper life testing studies, the coating provides a potential situation to completely eliminate the water conditioning system, which would be beneficial in systems requiring light-weight and infrequent monitoring.

4. MCC Coating Uniformity Evaluation

4.1 Experimental setup

Once the erosion-corrosion resistance of the coating was demonstrated, it was applied to several commercially available copper MCCs. After the coating was performed, these MCCs were cross-sectioned to expose the interior of the MCC and evaluate the thickness of the coating deposited on the high-aspect ratio internal features. Electrical discharge machining (EDM) was used to remove the top surface of the MCC, exposing the internal features without damaging the underlying structure. An image of a cross-sectioned copper MCC is shown in Figure 6.

Due to the nanometer scale of the applied coating, mechanical or abrasive methods of exposing a cross-section of the coating for thickness measurements are not appropriate and would damage the coating. Instead, a small (~15μm wide) cross-section was cut out of the surface of interest using a focused ion beam (FIB) technique. In this technique, a finely focused Ga+ beam is impinged on the sample surface, causing ions from the surface to be sputter removed. In this way, a cross-section of the coating can be exposed without damaging the coating for accurate thickness measurements. An image of a FIB cross section is shown in Figure 5.

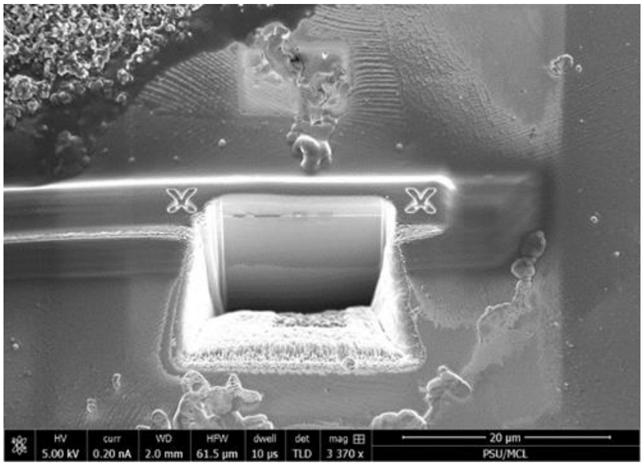
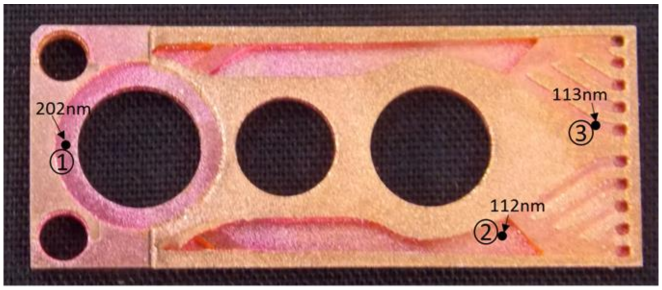


Figure 5. SEM image of FIB-cut cross section exposing coating



● = Approximate FIB/SEM locations

Figure 6. Exposed interior features of commercially available copper MCC. Approximate locations of three FIB/SEM thickness measurements and average coating thicknesses are shown.

4.2 Results

FIB cuts were made at three different locations on a coated copper MCC. At each location a thickness measurement was performed by SEM imaging. Figure 6 shows the approximate location of the three FIB/SEM measurements. The first is on the exterior of the MCC, in the seat for an O-ring, which is also a location in which erosion-corrosion may occur. The second is near the entrance of the microchannel features, while the third is in the microchannel features.

The average measured thickness in the first location was 202 nm. The average measured thickness in the second location was 112 nm. Finally, the average measured thickness in the third location in the microchannel region was 113 nm. SEM images of the coating cross-section are given in Figure 7 through Figure 9, respectively. These measurements confirm that the vapor phase deposition process is successful at applying a coating in the high aspect ratio internal features of the MCC with a thickness adequate for erosion-corrosion protection.

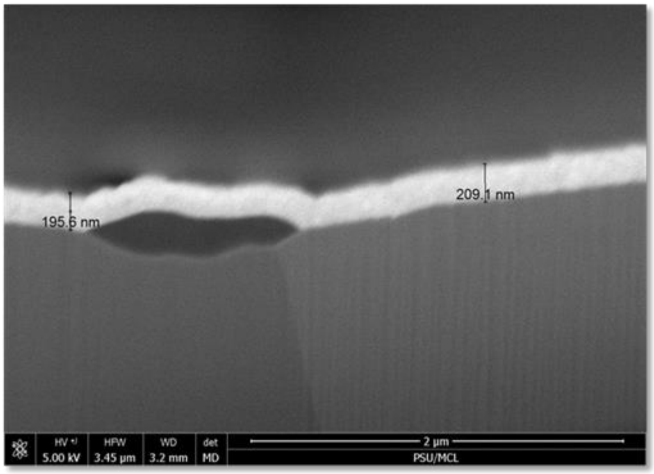


Figure 7. SEM image thickness measurement in O-ring inset (Point 1 in Figure 6).

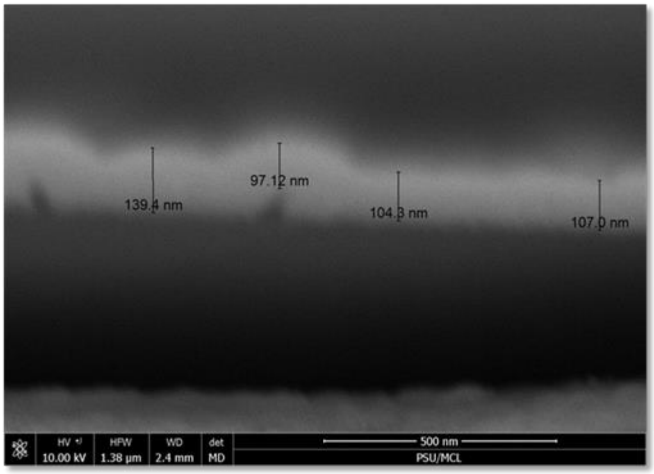


Figure 8. SEM image of coating thickness measurements near mouth of microchannel (Point 2 in Figure 6).

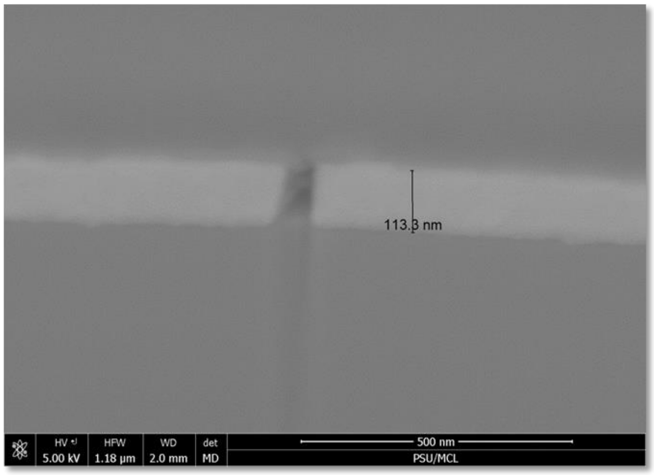


Figure 9. SEM image of coating thickness measurement in microchannel (Point 3 in Figure 6).

5. MCC Performance Testing

5.1 Experimental setup

In order to evaluate the long-term reliability of baseline uncoated and coated MCCs, an experimental apparatus was developed and built to expose the MCCs to high-velocity DIW, matching the conditions of laser diode thermal management.

The test apparatus consists of a pumped loop that provides two test cells with high-velocity DIW. Each test cell consists of a set of four copper MCCs that have been assembled into a stack, similar to Figure 1, such that the DIW coolant flows through the four in parallel. One test cell is assembled from baseline uncoated MCCs, while the second is assembled from coated MCCs. A schematic of the test apparatus is given in Figure 10, while a photograph is given in Figure 11.

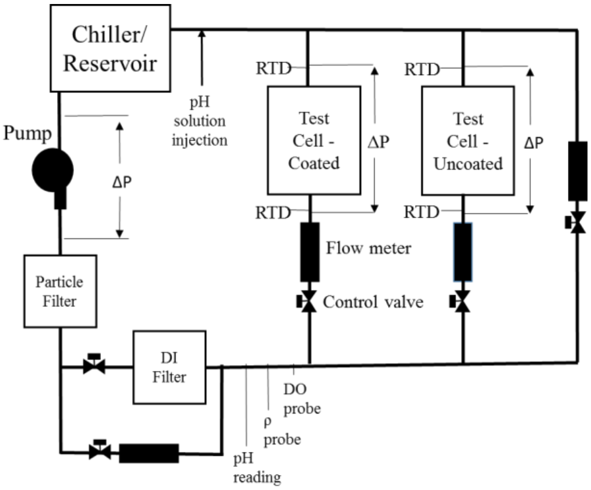


Figure 10. Schematic of long term MCC reliability test apparatus

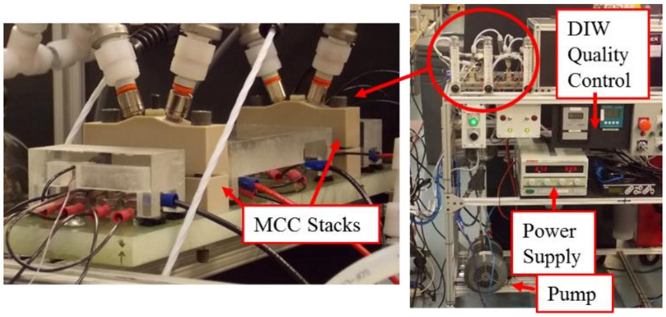


Figure 11. Long term MCC reliability test apparatus.

To mimic the waste heat loads of the laser diodes, resistive chip heaters were bonded to the surface of the MCCs in the footprint of a laser diode. These heaters were wired in parallel so that the power applied to each MCC was the same. The resistive heaters were soldered to the surface of the MCC using a low melt temperature Sn solder, in order to minimize the thermal contact resistance between the heaters and the MCCs. Insulative inserts were fabricated to go between the individual MCCs in the stack. A manifold for DIW inlet and outlet was also design and fabricated. The location of the resistive heaters and an assembled MCC stack is shown in Figure 12.

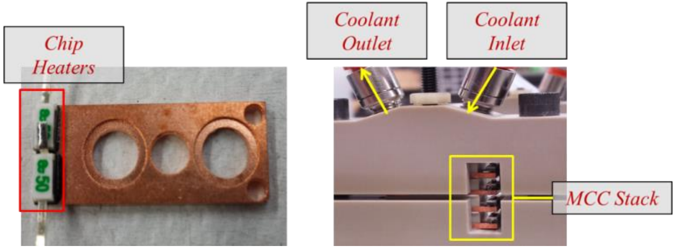


Figure 12. Resistive chip heaters bonded to surface of copper MCC to simulate laser diode waste heat load (left). Four copper MCCs integrated into a stack for long term reliability testing (right).

As shown in the schematic in Figure 10, the long term reliability test apparatus also includes DIW quality control equipment for maintaining the resistivity, pH, and DO content of the DIW coolant. The testing conditions that are maintained in the long term reliability test are given in Table 2.

Table 2: Long term MCC reliability testing conditions

Operating Condition	Value
Coolant	De-ionized water (DIW)
Coolant resistivity	0.3 MΩ·cm ± 0.05 MΩ·cm
Coolant dissolved oxygen (DO)	10 ppm ± 5 ppm
Coolant pH	6 ± 1
Flow Rate per Stack	0.5 GPM
Coolant Inlet Temperature	18 ºC ± 2 °C
Heater Power Supply Voltage	90 VDC
Heater Power Supply Current	6.8 Amps
Heater Power Per Stack (Per Cooler)	324 W (81 W)

The test apparatus is instrumented to continuously measure several important parameters. These parameters include the DIW inlet and outlet temperature for each MCC stack, the DIW pressure drop across each MCC stack, and the DIW flow rate through each stack. Additionally, thermocouples are placed on the surface of each resistive heater to measure the heater temperature of each MCC in both stacks. A significant change in any of these measurements indicates a change in the hydraulic diameter of the microchannel features in the MCCs. This indicates that erosion/corrosion is occurring and constitutes a failure of that MCC. The target duration of the life test is 10,000 hours or until failure of the MCC was observed, whichever comes first. The preliminary results only for the first 720 hours, out of the ongoing 10,000 hour life test, are presented in this paper.

5.2 MCC performance testing results

The addition of a nanometer thin coating was hypothesized to add negligible thermal resistance and have a negligible effect on the hydraulic diameter of the MCCs, thereby maintaining the thermal and hydraulic performance of the MCC while protecting the MCC from corrosion and erosion damage. In order to evaluate this hypothesis, baseline uncoated and coated copper MCCs were evaluated in the test apparatus presented in Figure 11 before and after 720 hours of exposure to simulated laser diode thermal management operating conditions. At each time increment the differential pressure, thermal resistance, and coefficient of performance (COP) of the MCC stack were measured at DIW coolant volumetric flow rates ranging from 0.2 GPM to 0.5 GPM in 0.1 GPM increments under a heat load of 225 W per MCC stack (56.25 W per cooler).

The thermal resistance of the MCC stack was calculated from Equation 1, where R_{th} is the thermal resistance, T_H is the average temperature of the heaters soldered to the MCC surfaces, T_{out} is the outlet DIW coolant temperature, T_{in} is the inlet DIW coolant temperature, $\dot{m}$ is the mass flow rate of the DIW coolant, and C_p is the specific heat capacity of the DIW coolant. Additionally, the COP of the cooler is a metric that balances the heat removal power with the pumping power required for the stack and was calculated from Equation 2, where ρ is the density of the DIW coolant and ΔP is the differential pressure across the MCC stack.

$$R_{th} = \frac{T_H - (\frac{T_{out} + T_{in}}{2})}{\dot{m}C_p(T_{out} - T_{in})} \qquad \text{Equation 1}$$

$$COP = \frac{\rho C_p(T_{out} - T_{in})}{\Delta P} \qquad \text{Equation 2}$$

The results of the measurement of the key performance metrics are presented in Figure 13 through Figure 15, respectively.

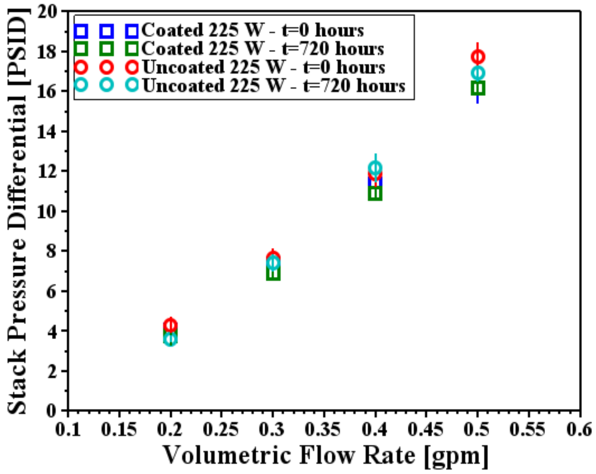


Figure 13. Differential pressure of the baseline uncoated and coated MCC stack before and after 720 hours of life testing indicating that the coating did not hinder the hydraulic performance of the MCC and that no degradation of the microchannel features was observed.

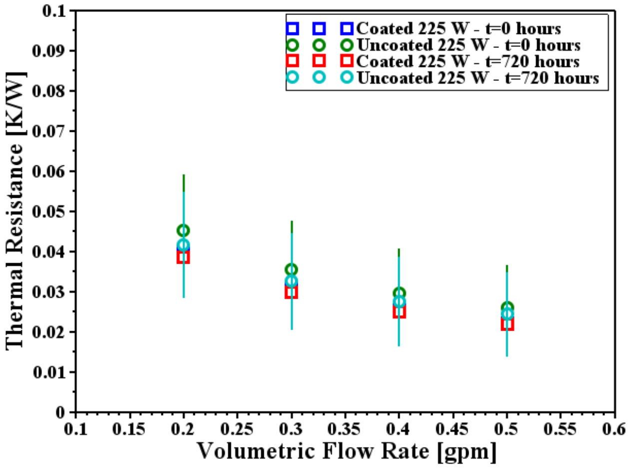


Figure 14. Thermal resistance of the baseline uncoated and coated MCC stack before and after 720 hours of life testing indicating equivalent thermal performance of the coated and uncoated MCC stack.

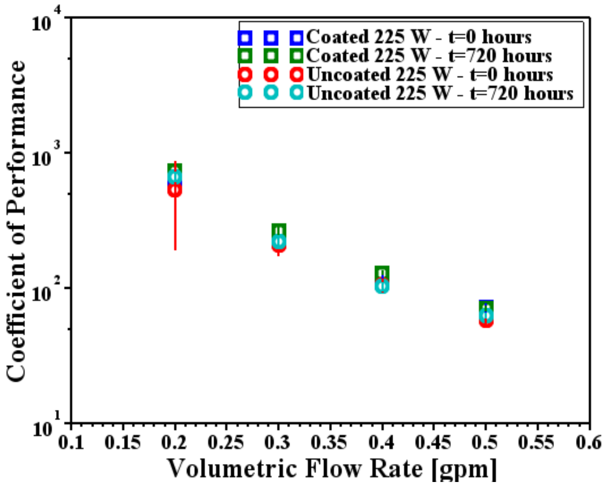


Figure 15. Semi-log plot of the coefficient of performance of the uncoated baseline and coated MCC stack before and after 720 hours of life testing indicating equivalent thermal and hydraulic performance of the coated and uncoated MCC stacks.

The differential pressure of the MCC stack is inversely proportional to the hydraulic diameter of the MCC features. Thus, clogging or reduction of the hydraulic diameter due to the coating would produce an increase in differential pressure while expansion of the hydraulic diameter due to degradation of the microchannel walls would result in a decrease in differential pressure at a given volumetric flow rate. As shown in Figure 13, the initial differential pressure of the baseline uncoated MCC stack and coated MCC stack were equivalent indicating the application of the coating did not reduce the hydraulic diameter of the microchannel features, thereby maintaining flow performance of the MCC. Moreover, after 720 hours of exposure to simulated laser diode thermal management operating conditions, the differential pressure of the uncoated baseline and coated MCCs were equivalent to their respective initial values indicating degradation of the microchannel features due to erosion-corrosion was not observed.

Furthermore, as shown in Figure 14, the coated MCC stack exhibited a smaller thermal resistance with lower standard deviation than the uncoated MCC stack due to deviations in the flow distribution through the baseline uncoated MCCs through the parallel flow path. Thus, a larger deviation and higher average in the heater temperature was observed. Additionally, the thermal resistance of the respective coolers did not change before and after the 720 hour life test evaluation indicating that no degradation of the heat transfer surfaces due to erosion-corrosion was observed. Moreover, the COP of the uncoated baseline and coated MCC were equivalent before and after the 720 hour evaluation. Therefore, the application of the coating did not impede the thermal or hydraulic performance of the MCC. However, the lifetime of the coolers under test is approximately 10,000 hours and degradation of the MCC is not expected to be observable after 720 hours of testing. For this reason, the life test evaluation will be continued until failure of the MCC stack is observed or 10,000 hours of exposure to simulated laser diode thermal management conditions is achieved.

6. Conclusions

High powered laser diodes have been emerging in many applications, such as military, material processing, and medical fields. However, in order to maintain the laser diode junction temperature, and therefore the optical properties, the high powered laser diodes are die-bonded to the surface of copper MCCs, which also serve as electrodes for energizing the laser diode. In order to reject the waste heat generated by the laser diode and reduce leakage currents, high purity DIW is pumped through the copper MCC at high velocity. This results in erosion-corrosion of the features within the MCC, which degrades the heat transfer surface areas resulting in reduced thermal performance of the MCC. Ultimately, the rejection of waste heat is reduced, increasing the laser diode junction temperature, requiring costly replacement and maintenance. In order to extend the lifetime of the MCC, a vapor phase deposition technique was used to deposit a hard, inert, nanometer thin coating that significantly reduces the erosion-corrosion of the MCC features, thereby maintaining thermal performance. This coating has demonstrated to reduce the corrosion rate of copper by one to two orders of magnitude over a DIW coolant pH range of 6.0 to 9.0 and dissolved oxygen concentration of 0.5 ppm to 10.0 ppm. Furthermore, through FIB/SEM measurements, this coating technique demonstrated uniform deposition throughout the complex, high aspect ratio features of the MCCs. Lastly, thermal and hydraulic testing of the MCCs demonstrated that the coating does not impede the thermal or hydraulic performance of the MCC, thus providing added protection from erosion-corrosion that extends the lifetime of the MCC stack and reduces costly replacement and maintenance intervals without requiring added pumping power for the DIW coolant.

7. Acknowledgements

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8. References

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