A Corrosion and Erosion Protection Coating for Complex Microchannel Coolers used in High Power Laser Diodes

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ABSTRACT

With efficiencies in the range of 50-75%, significant amount of waste heat is generated during the operation of high power laser diodes. In order to maintain consistent optical performance, the temperature of the laser diode needs to be managed effectively. Single phase copper microchannel coolers (MCC) with high purity and low electrical conductivity de-ionized water (DIW) at high velocities are used to dissipate the heat. Though thermally beneficial, the high velocity, high purity DIW coolant exposes the copper MCC to erosion and corrosion damage [1]. This substantially decreases the thermal performance of MCC and requires costly replacement within a short duration. This paper presents the experimental validation of a new vapor deposition coating, developed by Advanced Cooling Technologies, Inc., (ACT) for enhanced protection of MCCs in high power laser diode systems. MCC samples with coating were exposed to accelerated erosion and corrosion testing in high velocity, high purity water that simulates laser diode operating conditions. Evaluation of thermal resistance, pressure drop, and optical properties of MCC stacks demonstrated significant improvements in erosion/corrosion protection provided by the coating without impeding the cooling performance of the MCCs. Hence, the coating will increase the lifetime of MCCs and reduce costly maintenance intervals.

KEY WORDS: laser diode thermal management, nanoscale coating, liquid cooling, erosion and corrosion testing, electrochemical impedance spectroscopy analysis

INTRODUCTION

High power laser diodes are used in applications requiring high-average optical power including materials processing, medical applications, and solid-state laser pumping [2, 3]. A typical laser diode unit is comprised of several separate laser diode bars. The output per bar may reach 50-100W in continuous wave (CW) mode, and 100-150W in quasi-continuous mode (QCW) [2]. Since the electrical-to-optical efficiency of a high power laser diode ranges from 50-75%, a significant amount of waste heat is produced during operation, with heat fluxes on the order of 1 kW/cm^2 [3]. Heat dissipation is currently a limiting factor, and will continue to be so as the next generation laser diodes are designed to meet the increasing optical output power demand.

Currently, the most efficient cooling method to remove the large amounts of waste heat is pumped single-phase coolant flowing through the microchannel coolers (MCCs).

In the laser diode stack, the bars are separated by MCCs that are fabricated using a combination of micro-machining, lithography, etching, and diffusion bonding [4]. Most commercially available MCCs are made with many thin sheets of photo-etched copper that are diffusion bonded together. Copper is used because of its excellent thermal conductivity and the microchannel is designed to increase the available heat transfer surface area. To minimize conduction resistance from the laser diode to the coolant stream, the wall thickness of the MCC is approximately 200 μm. [3]. Due to its excellent thermo-physical properties, de-ionized water (DIW) is pumped through the MCCs at high velocity to maximize heat transfer performance. Although this laser diode stack design with integrated MCCs is thermally advantageous, the use of copper allows the electrical path to come into direct contact with the coolant. When an electrical potential is applied to the copper, a very rapid electro-chemical reaction occurs between the copper and water that results in well-documented failure mechanisms including corrosion and erosion [2,5]. To minimize this reaction, the resistivity of coolant has to be kept high. It is normally recommended to use DIW with 0.1-0.5 MΩ/cm resistivity [1]. DIW with the optimum resistivity reduces the flow of electrons, and consequently the electrochemical reaction is only driven by leakage current [2]. This corrosive environment coupled with the need for high velocity coolant to dissipate large thermal loads, creates a corrosive-erosive environment shortening the life span of copper MCCs.

A typical cost effective approach used to prevent corrosion in copper MCCs involves application of very thin barrier coatings consisting of micrometer-sized nickel and gold films. Corrosion is primarily controlled by the gold thin film. To prevent copper diffusion into the gold and improve wear resistance, an intermediate layer of nickel is used. Although the nickel impedes copper diffusion, it does not completely prevent it [6]. Studies show that even at low temperatures, copper may diffuse across the nickel barrier [7, 8]. Additionally, microchannels with high aspect ratios tend to cause non-uniform electric fields during the metal plating process, and as a result, pinholes form in the gold/nickel film exposing bare copper.

A conformal coating that is electrically insulating for corrosion protection, hard for erosion protection, nanometer thin for low thermal resistance and well-established coating process for easy application on complex geometries was developed by Advanced Cooling Technologies, Inc. The coating utilizes a vapor phase deposition method, where precursor gases undergo chemical reactions on the exposed surface.

In this paper, the long term reliability of the coating on different MCCs under simulated operating conditions is investigated. Three MCC configurations varying from simple open fin geometry to complex geometries, with internal flow channels not available for direct observation, were tested for corrosion-erosion protection. The long term reliability testing indicates that the vapor phase deposition process enables precursor gases to reach the extents of high aspect ratio channel and uniformly coat the surface to protect against fast flowing corrosive fluids without impeding the heat transfer.

EXPERIMENTAL SETUP

In this section, the experimental setups and test protocols are presented. In order to compare the vapor based deposition coating with gold plating baseline, coated open fin MCCs, as shown in Figure 1A, were life tested in an erosion-corrosion flow loop. To evaluate whether the conformal coating can be deposited onto complex internal microchannels without adding significant thermal resistance and/or pressure drop, head to head coolers (H2H), as shown in Figure 1B, were evaluated in a flow cell before coating, after coating and after testing for 200 hours in simulated laser diode thermal management operating conditions. Finally, to evaluate the coating's contribution to the overall performance and reliability of laser diode applications, coated single bar coolers (SBC), as shown in Figure 1C, were evaluated for hydraulic performance before, during, and after a 1,000 hour life test in a laser diode bonded stack.

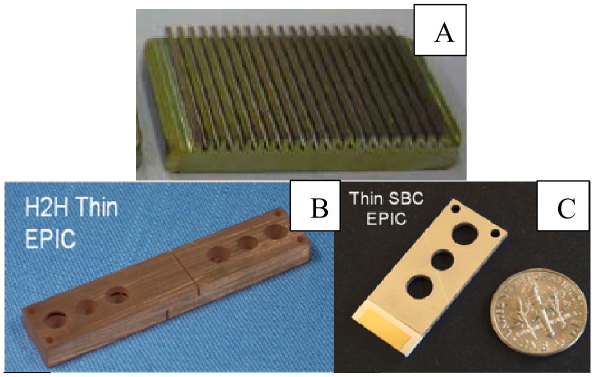


Figure 1: Images (A) open fin, (B) H2H and (C) SBC Coolers Used for Reliability Testing

Open Fin MCC Testing

The open fin MCCs provided by MicroCool have simpler geometry than the H2H and SBC coolers developed by Science Research Laboratory (SRL). Gold plating is applicable to the open fin MCCs. To confirm that the coating provides better protection than the industrial standard gold plating, coated and gold plated MCCs were both subjected to a 1,000 hour erosion-corrosion flow test, as shown in Figure 2.

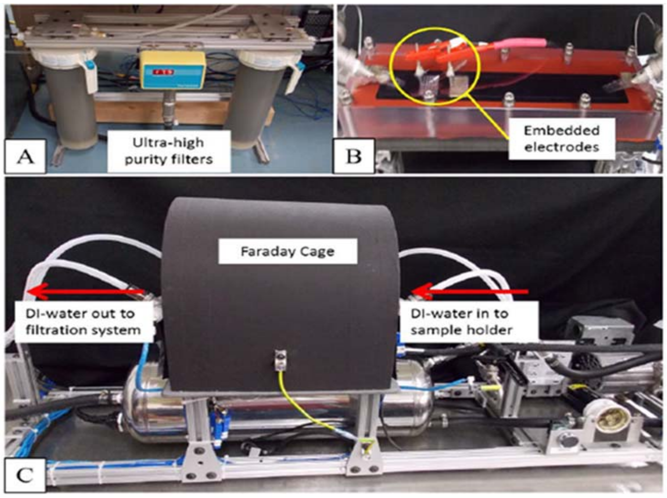


Figure 2: Erosion-Corrosion Flow Loop.

The erosion-corrosion flow loop includes filters and a resistivity meter to monitor and ensure high quality DIW is used throughout the test. In addition, electrode embedded tops and a Faraday cage are incorporated into the flow loop for evaluating the corrosion rate of the open fin MCCs by electrochemical impedance spectroscopy (EIS). High purity DIW with a water resistivity of $0.3\ M\Omega\cdot cm$ and a $pH = 6$ is used as the coolant. In typical laser diode systems where pH 8.2-8.6 water with low dissolved oxygen content is used, the copper release rate is $>2.5\ mg/m^2d$, whereas the copper release rate increases by an order of magnitude in pH 6-6.5 water [9, 10]. Therefore, the water pH used in the current setting accelerates the aging process by 10× than typical laser diode systems. Both samples were evaluated in a linear velocity of 3.8 m/s DIW for 1,000 hours. Corrosion rates of the samples were evaluated by the standard electrochemical impedance spectroscopy (EIS) [11-12].

H2H Cooler Testing

H2H and SBC are both high performance coolers with complex internal geometries to enhance the heat transfer for use in high power laser diode applications. The H2H coolers are essentially two identical SBC coolers with their active heat extraction areas joined during fabrication and enable the thermal resistance of the cooler to be evaluated. In order to compare the coating with gold plating on these coolers, several attempts to nickel plate the H2H coolers were carried out (*i.e.* nickel layer is the substrate of standard gold plating). These nickel plating processes resulted in formation of small particles that blocked the internal flow passages of the microchannels. Hence, gold plating is not applicable to these coolers. On the other hand, nanometer thin conformal coating was achieved on the coolers via its vapor deposition process. In order to evaluate the coating's impact on the coolers, thermal resistance and pressure loss of the coolers was measured before and after the coating as a function of cooler flow rate. To further evaluate the uniformity of the coating, the H2H coolers were tested in a corrosive-erosive DIW environment for 200 hours. After the test, the thermal resistance and pressure loss were measured again. The thermal resistance and pressure loss measurements and the 200 hour life test protocol are described as below.

The thermal resistance R_T in the H2H cooler design is evaluated by pumping two fluids of different temperatures through each side of the cooler. Heat is driven from one cooler to the other by flowing hot water (60-80 ºC) through one cooler and cold water (20 ºC) through the other, as shown in Figure 3. The temperature at the interface between the two coolers is the average of the hot cooler inlet water temperature and cold cooler inlet water temperature.

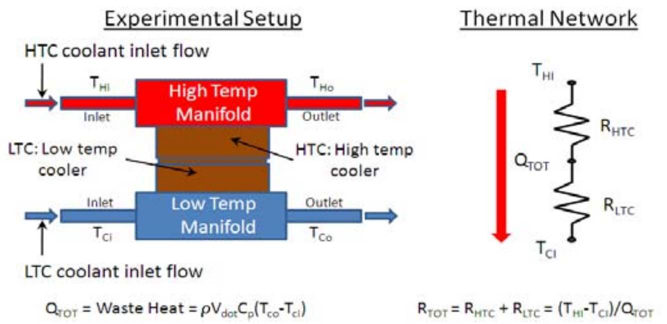


Figure 3: Test apparatus and representative thermal resistance network for determining the thermal resistance of H2H coolers.

As shown in Figure 3, R_{TOT} is the sum of the thermal resistances of the two coolers (R_{HTC} and R_{LTC}). Since both coolers are identical, the hot side and cold side thermal resistances are equal (*i.e.* $R_{HTC} = R_{LTC}$). Thus, $R_{HTC} = R_{LTC} = R_{TOT}/2$. The areal resistance, R_{th}, is obtained by multiplying R_{HTC} by A_{HX}, the heat exchange area.

The uncertainty in the H2H thermal resistance measurement was estimated to be ±2.5% based on the following considerations: 1) the H2H cooler configuration is treated as a counter-flow heat exchanger; 2) the temperature sensors (RTDs) were calibrated to 0.02K over the temperature range 0-80°C; 3) flow meter calibrations confirmed flow meter accuracy within 1%; 4) parasitic heat losses were minimized using thermal standoffs and foam insulation (*i.e.* ideally all heat leaving the hot side of the H2H heat exchanger is received by the cold side); 5) temperature dependence of the solids and fluids properties admitted; 6) lateral heat conduction at the interface between the hot and cold sides of the H2H device; 7) errors in measuring heat exchanger effectiveness, deriving conductance from effectiveness and determining the conductance of each side of the H2H device. All of these sources of error were considered to be independent, so the resulting overall uncertainty in determining R_T (±2.5%) is taken as the square-root of the sum of the individual errors squared. As noted in consideration 4), the heat lost from the coolant flowing through the hot side of the H2H device should be equal to the heat gained by the coolant flowing through the cold side. The experimental discrepancy between the heat lost by the hot side (Q_H) and the heat gained by the cold side (Q_C) is evaluated by the expression: $\zeta = (Q_H - Q_C)/(Q_H + Q_C)$, which is typically $-1.5\% < \zeta < +1.5\%$. This is consistent with the overall analytically estimated uncertainty (±2.5%) noted above.

The pressure loss ΔP is reported as the pressure difference between the inlet and outlet of the cold side. Although ΔP is measured for both the hot and cold sides, they are not equal since the viscosity of water is temperature dependent. The uncertainty in measured pressures was estimated to be ~2%. Pressure coefficient C_p $(= \Delta P/\dot{V}^2)$ is calculated based on the stack pressure loss, ΔP, and coolant flow rate through the stack, $\dot{V}$.

The accelerated life test was designed to simulate laser diode cooling conditions while accelerating the coolers' aging approximately 10× by reducing pH to increase copper release rates throughout the duration of the 200 hour test. The life test station as shown in Figure 4 incorporates pH and ion concentration (electrical conductivity) control. Dissolved oxygen content of the cooling water is monitored, but not controlled. Additionally, a 1 µm particulate filter is incorporated into the chiller of the pumped loop.

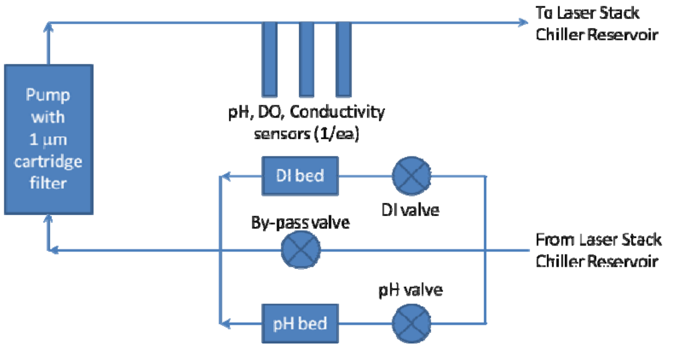


Figure 4: Schematic of the pumped loop water conditioning loop.

The deionization (DI), pH and by-pass valves are cycled based on control signals from monitors/controllers connected to the pH and conductivity sensors. The chiller reservoir is left open to ambient atmosphere allowing the dissolved oxygen concentration to become saturated with atmospheric oxygen. For the accelerated life tests, DI control is performed via a mixed bed cartridge and the pH control is performed via cation bed cartridge. The cooling water conditioning system maintains conductivity in the range of 2-4 µS/cm (0.25-0.5 MΩ·cm), dissolved oxygen levels in the 6-8 ppm (by weight) range, and pH = 6. A bias voltage of 2 VDC is being applied between coolers to simulate actual laser diode effects.

SBC Cooler Testing

After obtaining positive results from the H2H tests, the performance of the coating was demonstrated under actual laser diode cooling conditions using SBC coolers. The main difference between the SBC testing and the previous H2H testing is that the SBC test conditions include waste heat generated by the laser diodes. As shown in Figure 5, three laser diodes were directly bonded to the surface of SBC coolers to form the test stack, in which the top most cooler is a dummy cooler (*i.e.* no laser diode bonded to this cooler) to ensure that all coolers have equal heating load. This stack was then installed in the flow loop as described in Figure 4 and run for 1,000 hours under accelerated conditions which equivalents to 10,000 hours (6-6.5 pH, 2-3 µS/cm conductivity and ~7 ppm dissolved O_2). The ΔP versus flow rate characteristics of all SBCs were measured before the coatings were applied, after the coatings were applied and before laser diode bar attachment, and after the 1,000 hour laser diode life test. During the 1,000 hour life test the following properties were recorded: coolant flow rate, stack coolant inlet and outlet temperatures, coolant static pressure and differential pressure across the stack; and laser diode stack optical output power and optical output wavelength.

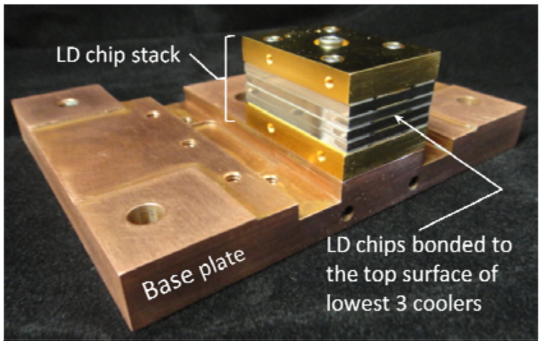


Figure 5: A stack of 3 laser diodes sandwiched between four coated SBC coolers.

RESULTS & DISCUSSIONS

Open Fin MCC Testing

In the open fin MCC testing, the goal was to compare the corrosion and erosion protection effect of the coating with the industry standard gold plating. Since corrosion is usually defined as degradation of the properties (such as thickness) of a material as a result of chemical reaction with the environment, corrosion rates in the unit of millimeters per year (mmpy) were measured for all test samples. These test samples included a coated copper MCC, a nickel/gold plated copper MCC (*i.e.* the gold baseline), and an uncoated copper MCC. The two coated samples were exposed to 0.3 MΩ·cm DIW with a pH = 6 for 1,000 hours at a linear velocity of 3.8 m/s. The uncoated MCC sample was measured at time 0. The time-evolved corrosion rates measured from the EIS analysis are presented in Figure 6.

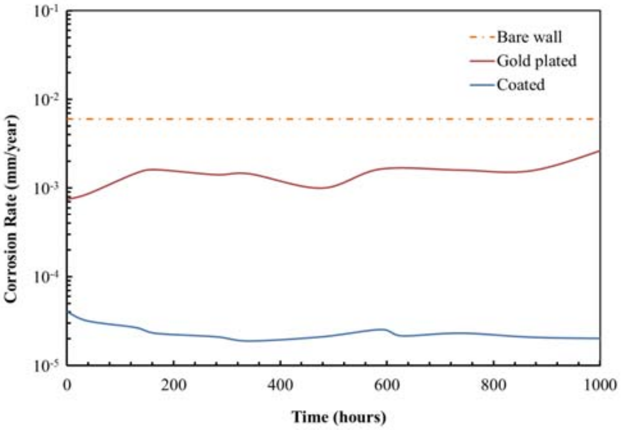


Figure 6: Time Evolved Corrosion Rates [in log scale]. Gold baseline MCCs and coated MCCs were tested in 3.8 m/s DIW with a water quality of 0.3 MΩ·cm and pH = 6 for 1,000 hours. The corrosion rate of an uncoated copper MCC was also plotted for reference.

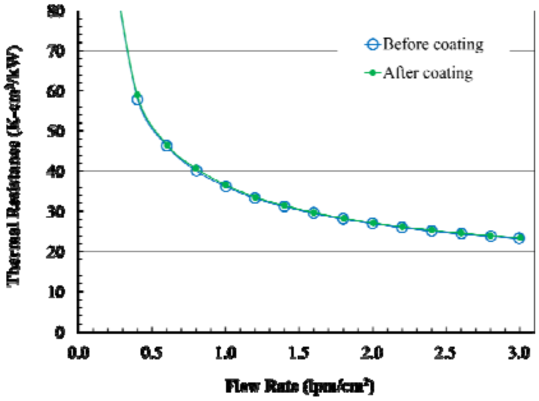
As shown in Figure 6, both the coated and the gold plated MCCs had a lower corrosion rate than the bare copper baseline demonstrating protection over corrosion and erosion. Among the two coatings, the coating demonstrated a much lower corrosion rate which was about 150× lower than the gold plating. The coating also showed little variation in corrosion rate over the testing period, whereas the corrosion rate of gold plating was gradually approaching that of the bare copper. It was also noted that the initial responses of both coatings to the flow were different. The gold baseline had a rapid increase in corrosion rate during the first 200 hours, meanwhile the corrosion rate of the sample barely changed. This phenomenon was related to the pin holes in the coatings. Bare copper underneath the coating was exposed to the DIW coolant and therefore was oxidized forming a passivation layer that reduced the corrosion rate. Pore resistance is an indication of the coating change due to the penetration of electrolyte into the micropores of the coating. For pin-hole free coatings, the pore resistance is very high. The initial pore resistance of the gold plated sample was measured about 200× lower than that of the coated sample, which indicated the gold plating was much more porous than the coating. The existence of the pin holes also left the sample under more severe erosion attack. Hence, the gold plating demonstrated a greater degradation rate than the coating.

Therefore, the coating exhibited greater resistance to both corrosion and erosion in comparison to the gold plating in the 1,000 hour MCC testing.

H2H Coolers Testing

The nanometer thin coating was suspected to have a negligible contribution to the thermal performance or the hydraulic performance of the flow channels in the H2H MCCs. In order to validate this hypothesis, experiments were performed to determine the effect of the coating on the thermal resistance and pressure loss.

Comparison of thermal resistance and pressure loss before and after coating for a representative sample H2H cooler is presented in Figure 7. The thermal resistance and pressure loss measurements of the coated and uncoated baseline H2H MCC are indistinguishable indicating that the coating did not hinder the thermal or flow performance of the coolers, thereby experimentally validating the aforementioned hypothesis.



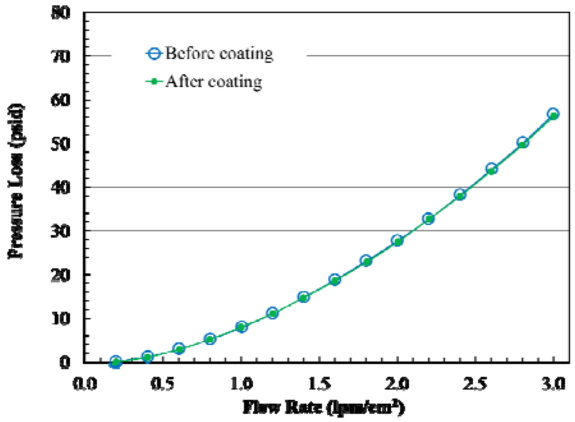


Figure 7: Thermal resistance (upper) and pressure loss (bottom) measurements of a representative H2H cooler before and after coating demonstrating that the coating does not hinder thermal or flow performance.

After demonstrating equivalent thermal and hydraulic performance, the coated and uncoated H2H coolers were subjected to flow which simulated accelerated laser diode cooling conditions. The pressure coefficients were recorded throughout the testing. The thermal resistance of the coolers was measured again after 200 hours

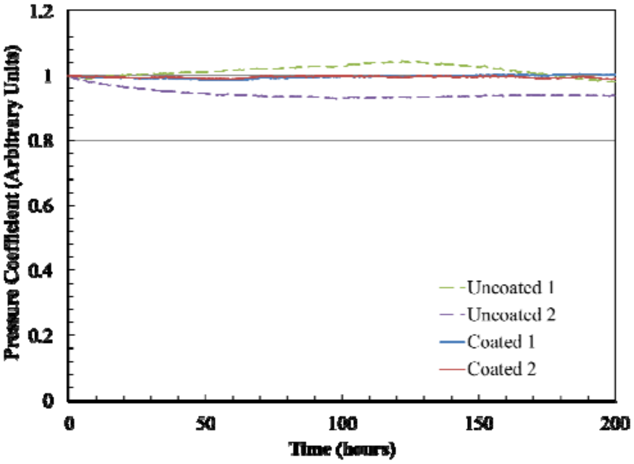


Figure 8: Pressure coefficients of coated and uncoated baseline H2H coolers throughout a 200 hour life test. Stable pressure coefficients of the coated coolers demonstrate protection from erosion/corrosion damage.

As shown in Figure 8, the pressure coefficients of the coated H2H coolers were stable around unity throughout the duration of the 200 hour test. However, the pressure coefficients for the uncoated H2H coolers either initially or eventually decreased. The increase in pressure coefficients was attributed to particulate matter blocking flow channels from erosion/corrosion damage upstream. The decrease in pressure coefficient was attributed to enlarging of the hydraulic diameter of the microchannels due to material loss caused by erosion/corrosion damage. These changes in pressure coefficients for the uncoated H2H coolers and the stable pressure coefficients of the coated H2H coolers demonstrated the erosion/corrosion protection of the coolers with the coating.

Figure 9 presents the thermal resistance versus flow rate profiles of the coated and uncoated H2H coolers measured after the 200 hour life test. The baseline H2H cooler demonstrated a significant 5.2% increase in thermal resistance at the highest flow rate, while the coating prevented degradation in thermal resistance during the life test. Given the uncertainty and repeatability of the thermal resistance measurements were within ±2.5%, the 5% change was outside experimental uncertainty. This increase in the thermal resistance of the uncoated cooler was a direct indication of corrosion due to the use of highly corrosive of low pH (pH = 6) DIW. The increasing thermal resistance of the cooler decreased the heat rejection capability of the cooler leading to increased laser diode temperatures and subsequent premature failures. Conversely, the minimal change in thermal resistance of the coated H2H coolers during the 200 hour life test exhibited protection from erosion/corrosion damage thereby increasing the life of the MCC and subsequently the laser diode.

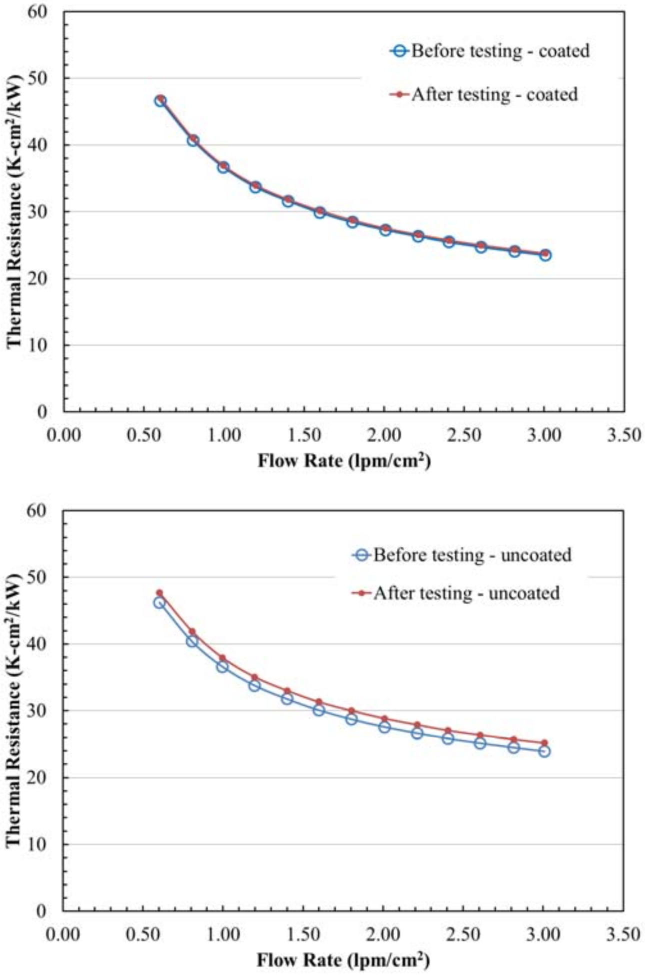


Figure 9: Thermal resistance of the coated (upper) and baseline H2H (bottom) cooler before and after 200 hour life test. The baseline H2H coolers demonstrated a 5% increase in thermal resistance while the coated H2H cooler demonstrated a negligible 1% increase.

The reliability and lifetime of the protective coating studied may be influenced by temperature, temperature differences and the compatibility of the coating material and heat sink material. Temperature and differences in temperature may degrade protective coatings via coefficient of thermal expansion (CTE) mismatch. Although there is a significant CTE mismatch between the protective coating and copper coolers (1:3 ratio), the coolers exposed to 80°C cooling water during H2H thermal resistance measurements showed no signs of coating degradation. During high power laser diode operation, where heat fluxes of 1-2 kW/cm^2 are present at the interface between the laser diode chip and cooler, wall temperatures in the microchannels of SRL's coolers are no greater than 20-40K above coolant inlet temperatures. As these temperatures are lower than those imposed during thermal resistance measurements, high power laser diode conditions are not expected to impact coating reliability. This experimental validation from the 200 hour life test serves as a proof-of-concept for the erosion-corrosion protection provided by the coating.

SBC Coolers Testing

To determine the long term performance of the coated MCCs in realistic laser diode systems, a 1,000 hour life test was conducted on SBC coolers that were bonded to active laser diodes. The 1,000 hour life test incorporated the high velocity, high purity de-ionized water coolant, corrosion enhancing electrical current, and heat dissipation from laser diode thereby accurately simulating laser diode operating conditions. Key performance metrics for the 1,000 hour life test were pressure loss, pressure coefficient and laser optical output power.

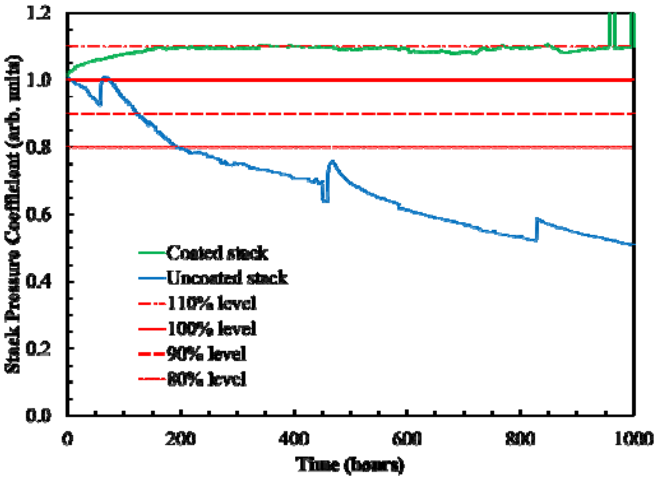


Figure 10: Pressure coefficients of the and baseline LD/SBC stacks demonstrating stable performance of the coated coolers.

Figure 10 presents the pressure coefficients of the laser diode stacks composed of coated coolers and baseline coolers, respectively. The pressure coefficients of the baseline decreased to 37.5% of its initial value after 600 hours of testing, which indicated severe erosion/corrosion of the microchannel coolers. Undulations and sharp spikes measured during the baseline test were attributed to system shutdowns and subsequent startups, which were well controlled (*i.e.*, the cooling flow was ramped up slowly, no water hammer). It was hypothesized that flow shutdowns and restarts dislodged material, which were probably corrosion products, thus led to temporarily blocking the microchannel passages and causing the pressure spikes. Unlike the baseline samples, the pressure coefficient of the coated coolers remained mostly stable with a 10% increase. The sharp increase in C_p at the end of the test was due to the failure of a flow meter. The stable flow performance of the coated stack demonstrated improved protection from erosion/corrosion damage, which will lead to longer cooler lifetime and reduced maintenance intervals. Moreover, the stable flow performance will provide reliable laser diode chip temperatures and optical power.

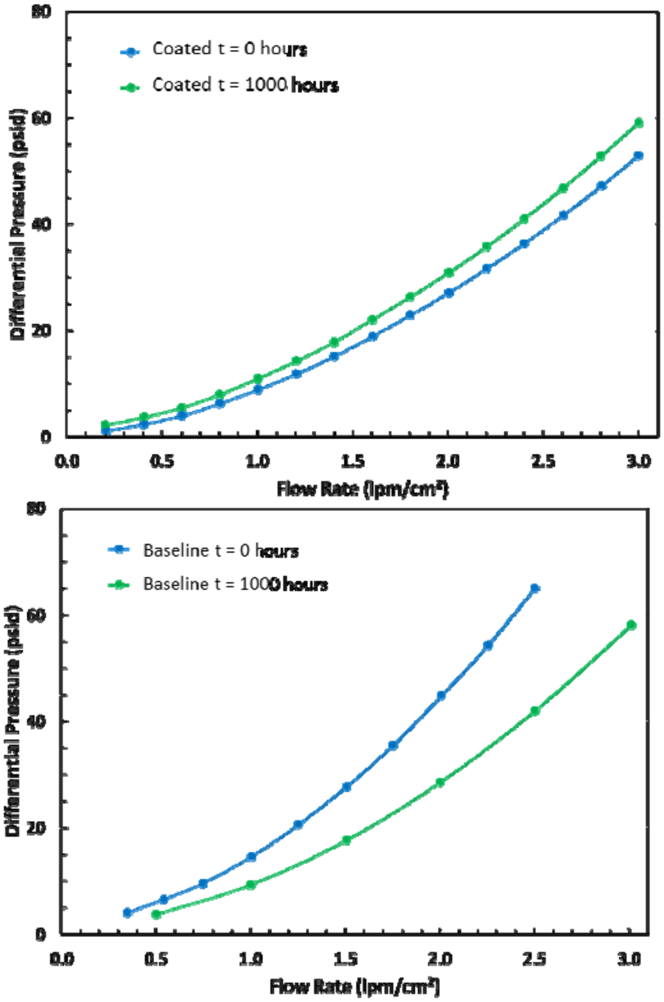


Figure 11: Initial and final pressure loss profiles of the coated (upper) and baseline (bottom) SBC coolers demonstrating enhanced protection of the coated cooler.

Figure 11 presents the pressure loss versus flow rate profiles of the coated and uncoated SBC coolers measured after the 1,000 hour life test. The baseline cooler shows a 35% decrease in pressure loss at the flow rate of 2.5 lpm/cm^2 after 1,000 hours of exposure to the erosive and corrosive coolant. Meanwhile, the coated cooler exhibited an 11% increase in pressure loss after 1,000 hours for the equivalent flow rate.

These changes in the pressure loss agreed with the changes in the pressure coefficients. Therefore, the coated cooler demonstrated significant improvements in stable operating conditions by reducing erosion/corrosion damage to the cooler.

In Figure 12, the wavelength and optical power output of the laser diode stacks evaluated throughout the 1,000 hour life test are displayed. The premature failure of the baseline laser diodes, which was unrelated to the thermal performance of the coolers, invalidated the baseline wavelength and optical output power data and thus the results are not presented. Nevertheless, the consistent wavelength and optical power output of the laser diodes with the coated MCC provides key evidence to the long term reliability of the coolers due to enhanced erosion/corrosion protection.

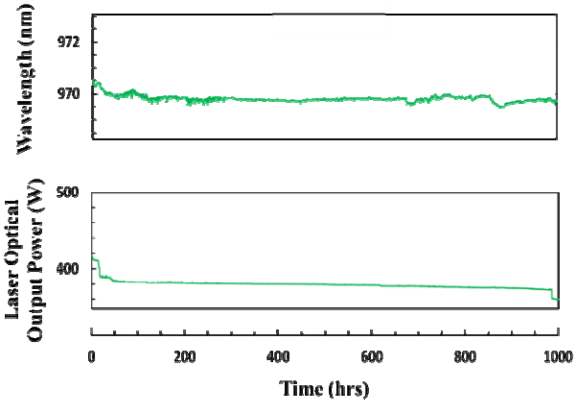


Figure 12: Wavelength (upper) and laser optical output power (bottom) of the coated SBC cooler stack demonstrating consistent optical performance provided by stable cooler performance.

A 1 K increase in laser diode junction temperature increases the output wavelength by 3 nm. Thus, the less than 0.5 nm change in wavelength throughout the duration of the 1,000 hour test with an acceleration factor of 10 indicates stable cooler performance due to enhanced erosion/corrosion protection.

CONCLUSIONS

In this paper, experimental validation of a novel vapor based deposition coating developed by Advanced Cooling Technologies, Inc., for enhanced protection of MCCs in laser diode systems is discussed. Three MCC configurations were studied for long term reliability by subjecting coated and uncoated baseline cooler stacks to simulated laser diode thermal management operating conditions. Corrosion rates of the coated open fin MCCs in 1,000 hour flow test demonstrated a two order of magnitude reduction in corrosion rate in comparison to the proven gold plating. In addition, the thermal resistance and pressure loss of coated and uncoated H2H coolers demonstrated that the coating did not hinder the thermal or flow performance of the MCC. Meanwhile the consistent thermal resistance and pressure coefficient of the H2H coolers measured before and after the 200 hour life test demonstrated the protection from the coating. In the 1,000 hour laser diodes bonded life test on SBC coolers, the coated coolers showed stable hydraulic and optical performance throughout the duration of the test while its uncoated counterpart suffered from severe pressure loss due to erosion/corrosion damage. Thus, the coated coolers exhibited consistent performance in long term life testing due to enhanced erosion/corrosion protection without impeding the thermal or hydraulic performance of the cooler. Furthermore, the enhanced protection of the coolers will lead to longer laser diode stack lifetimes and a reduction in costly maintenance intervals.

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