Lifetime testing of Laser Diode Coolers

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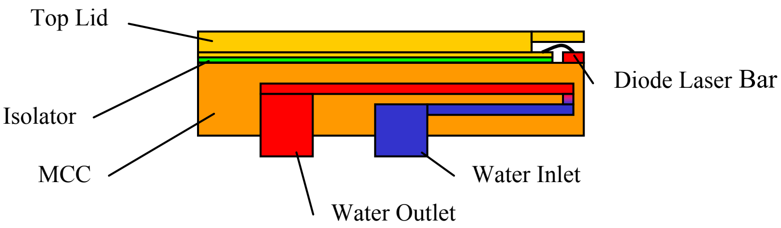
Abstract

The purpose of this paper is to report life-testing results of a copper micro-channel cooler [MCC] for high power diode laser [HPDL] bars. The testing is being done on MCC's with 3 different internal designs at three different flow rates, ranging from 0.2 l/min. to 0.5 l/min. Water conductivity is kept constant at 5 micro-Siemens/cm, and the water temperature is maintained at 25C. The MCC's do not have a voltage applied to them. The test is ongoing, but results up to 15,000 hours will be reported. Preliminary results indicate that lifetimes over 20k hours can be achieved with proper control of conductivity, and that flow rate and internal structure are secondary considerations compared to water quality.

Keywords: diode laser, micro channel cooler, life time test, active cooling, liquid cooling.

1 INTRODUCTION

High power laser diodes are made of semiconducting materials which produce very high heat loads. Optical efficiencies of these diodes are very highly temperature dependent, so precise temperature control is necessary. Conventional cooling systems for high-power diode arrays typically use liquid cooled approaches to maintain the diode temperature near room temperature. The so called micro-channel-coolers [MCC's] are mini-heat exchangers made of copper, with channels of a few hundred microns in size. The Diode Laser, with a typical dimension of 10mm x2 mm and a typical output power of 80 W is mounted p-side down on the front edge of the MCC [Picture 1]. The MCC's are typically stacked in vertical [Picture 2] or horizontal stacks. The electrical circuit is built just by mounting the MCC with an isolator and a top lid, where the wire bonds for the n-contact are mounted. This means that the system for the laser diodes is a series setup. Cooling water is supplied by the inlet and outlet holes of the MCC. The cooling system for a vertical stack is a parallel setup, where each inlet hole is connected to each other, just being sealed with an O-ring. The difficulty is that tap water would short the electrical path through the laser diode (i.e. one electrical path would be through the water). Each laser diode has a typical voltage drop of 1.7 Volts. For that reason de-ionized [DI] water is used, so the ability of the water to conduct current is almost reduced to zero. [1, 2].



Picture 1: principle mounted diode laser bar on MCC

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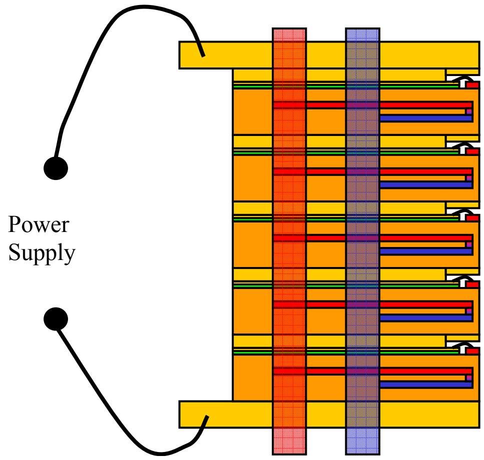


Picture 2: typically setup for a 5 diode lasers vertically MCC stack

2 COPPER CORROSION

The corrosion of a metallic material implies the reaction of a material with its environment causing a measurable change in the material and properties possibly leading to corrosion damage (DIN standard 509000; ISO standard). This is usually an electrochemical process but it may be related to a chemical or physical process. When analyzing the possible types of corrosion damage, the system should be regarded as a whole. In this way, not only damage to the material has to be considered, for instance by uniform or localized attack, but also undesired changes in the medium such as contaminants like heavy metal ions (and their catalytic effects on electrode processes) or complex ligands (which influence the chemical equilibrium). By viewing corrosion from a material/medium point of view the varied possible combinations arising from the large number of materials and media can be clearly categorized.

The following is concerned primarily with, in our opinion, typical corrosion phenomena in copper-based micro channel water coolers. Please note that we will not focus on the different kinds of corrosion processes, e.g. area corrosion, erosion corrosion, pitting corrosion, bio corrosion and galvanic corrosion, as the principal reactions and processes as well as the resulting consequences are more or less the same. For further and more detailed information please check the relevant literature [3-9].

The chemical element copper (Cu = cuprum) belongs to the so called Ib metals -together with silver and gold, which are usually known as noble under ambient conditions. The electrode potential of copper, however, is +0.52 V in Cu^{+-} solution and +0.34 in Cu^{2+}-solution, which is relatively low. Therefore, copper is noble in water only under non oxidative conditions, i.e. in the absence of oxygen. In the presence of atmospheric oxygen following anodic cell reactions proceed:

equation 1 $Cu \rightarrow Cu^{+} + e^{-}$

The Cu^{+} oxide will be oxidized by oxygen forming Cu^{2+}:

equation 2 $Cu^{2} \rightarrow Cu^{2+} + e^{-}$

The corresponding cathodic cell reaction is the following:

equation 3 $O_2 + 2\,H_2O + 4\,e^{-} \rightarrow 4\,OH^{-}$

The Cu^{2+} ion itself can act as well as an oxidant:

equation 4 $Cu^{2+} + e^- \rightarrow Cu^+$

Please note, the respective cell reactions take place everywhere on the tubing walls of the micro-channels, depending on the local potential differences. The latter may be caused by non-homogeneities e.g. of the surface oxide distribution, gradients of the dissolved oxygen or the flow rates, and of course by external applied potentials.

Finally, a transformation via the hydroxide forms the corresponding water- insoluble hydroxide and oxide respectively. A possible reaction scheme might be the following

equation 5 $2\,Cu^+ + 2\,OH^- \rightarrow (2\,Cu(OH)) \rightarrow Cu_2O + H_2O$

equation 6 $Cu_2O + 1/2\,O_2 + 2H_2O \rightarrow Cu(OH)_2$

equation 7 $Cu^{2+} + 2\,OH^- \rightarrow Cu(OH)_2$

equation 8 $Cu(OH)_2 \rightarrow CuO + H_2O$

As one can see, a number of different species have to be considered already in this simple model. The species participating in the transformations of copper in aqueous solution in the presence of oxygen together with the typical color can be listed as follows

Solids:	Cu	copper	red
	Cu_2O	copper (I)-oxide	red
	CuO	copper (II)-oxide	black
	$Cu(OH)_2$	copper (II)-hydroxide	blue
In solution:	Cu^+	copper (I)-ion	colorless
	Cu^{2+}	copper (II)-ion	blue
	CuO_2^{2-}	cuprate	blue

Therefore, the dissolved copper will be deposited close to the dissolution place or somewhere else in the cooler under the terms of the thermodynamic principles. The deposited solid itself may cause a reduction of the flow-through diameters and therefore a higher pressure drop and/or a reduced flow rate. With respect to the thermodynamically possible transformations of these species at different pH and electrode potentials detailed information can be found in the so-called Pourbaix-diagrams [5].

According to these phenomena, one might think that copper, as a material, is not the best choice with respect to corrosion. But there is a mechanism going in the opposite direction, i.e. stabilizing the copper system, the so-called passivation. Here, the solid copper oxides/hydroxides cover the copper metal and, therefore, act as a barrier to further oxidation processes, i.e. the underlying copper metal is protected. Unfortunately, this passivation layer is not as erosion-resistant as the metallic copper. Therefore, at high flow rates the passivation layer may be removed and the bare metal gets into contact with the "electrolyte", the oxygen-containing water, and the formation of an oxide layer starts again. Over time the copper metal will be removed layer by layer. This mechanism of corrosion is called erosion-corrosion. The degradation of the passive layers usually starts at flow rates above 1-2 m/s, while using CuNi-alloys the stability of the material increases significantly. Because of this effect, it is clear that an optimized flow profile should enhance the life-time significantly.

Besides oxygen in the water, the dissolved atmospheric carbon dioxide complicates the system as it influences the pH on the one hand and reacts with the above listed species on the other hand forming the so called patina.
According to the following equation

equation 9 $CO_2 + H_2O \leftrightarrow HCO_3^- + H^+$

equation 10 $HCO_3^- + H_2O \leftrightarrow CO_3^{2-} + H^+$

carbon dioxide reacts with water forming, in addition to H^+, hydrogen carbonate and carbonate respectively, i.e. the pH decreases. Usually, the H^+ neutralizes the OH^- formed in equation 7. With decreasing CO_2 concentration (closed system) the pH (no neutralization) and the amount of solid insoluble species (cf. equation 7 and equation 8) would both increase, leading to a further reduction of the flow-through. Furthermore, the carbonate reacts with the copper oxides and hydroxides forming a basic carbonate, the so-called "patina", a green surface texture created by slow chemical alteration of copper. The most famous example is the Statue of Liberty, which gets its green colour from the natural patina formed on its copper surface and therefore protects the underlying copper for further corrosion. As is true for the pure oxide-passivation layers, the patina is not stable at flow rates above 1-2 m/s.

As already mentioned, corrosion is usually an electrochemical process implying the flow of electrons from an anode to a corresponding cathode. In the case of copper corrosion in aqueous oxygen-containing solutions the cell reactions can be described according to equation 1and equation 3. These reactions, and therefore corrosion, take place as long as the potential differences are higher than the equilibrium potential of the half-cell processes. The half-cell potentials are given by the Nernst-equation and are influenced by a large number of factors, e.g. concentration and temperature gradients as well as passivating coatings. In the case of an operating laser diode an external potential of 1.7 V has to be applied [Picture 1], which is much higher than the corresponding half-cell potential according to equation 1or equation 2. For that reason, water with a low conductivity, i.e. a high electric resistance, has to be used. According to Ohm's law

equation 11 $U = R \cdot I$

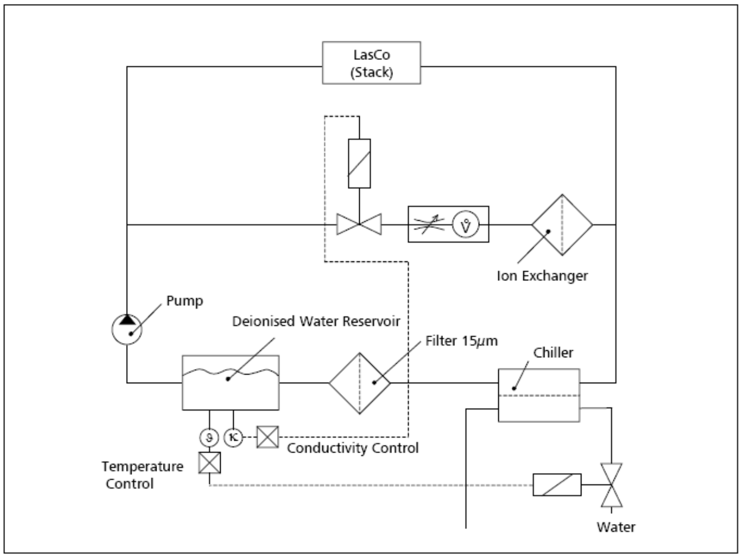
the potential drop (IR-drop) increases with increasing ohmic resistance, i.e. using water with a low conductivity minimises the corrosion phenomena due to the external applied potential. The o-ring seats are exposed to the highest external potential (shortest water distance). By virtue of the high IR-drop over the long distance to the micro-channels [Picture 2], it's perspicuous to assume that possible effects of an external applied potential can be excluded. On the other hand the use of low-conductivity water shifts the equilibrium according to equation 1 and therefore enhances the corrosion, i.e. it "extracts" the copper. For that reasons water with a conductivity of 1-5 µS/cm is well accepted as a good compromise between the need of a high electrical resistance and the prevention of copper extraction.

As we don't have the premises to build up laser diode stacks under real conditions, i.e. with mounted laser diode bars and applied potential, the results presented in this paper are restricted to the life-time investigation of the micro-channel structure. We examined three different microstructures CUR 3/1, 5/1 and 7/1 at different flow rates (0.2, 0.3 and 0.5 L/min) in a cooling water with a constant conductivity of 5 µS/cm. The cooling water was held constant at a temperature of 25 °C, to our knowledge the most common cooling temperature. Please note, that temperature effects due to the laser diode being working will not be considered in this study.

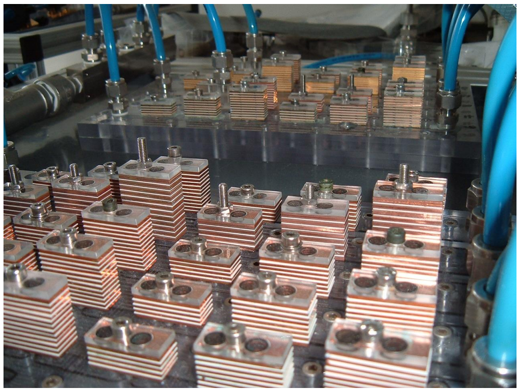
3 TEST RESULTS

Typical Setup of Cooling Circle Life time testing:

The cooling system consists of a single loop and a bypass line as in Figure 1. The single loop consists of the pump, the piping to the laser diode stacks, the stacks themselves with the associated fittings and fixtures, the return piping from the stacks, the chiller, then a filter (15 micron), and a de-ionized water reservoir. The bypass consists of a control valve and an ion-exchange bed. The complete cooling system must be treated as a CLOSED SYSTEM in terms of liquid or solid species.



Setup Conditions:



First filling of system was done with distilled water

Conductivity: 5µS/cm, automatically controlled by a mixed bed ion exchanger

Water Temp.: 25 °C

Flow rates: 0.2, 0.3 and 0.5 L/min realized by 5, 8 and 12 MCC stacks at a constant flow per line

Three different MCC designs: CUR 3/1, CUR 5/1 and CUR 7/1

Number of analyzed coolers: 80

Total under test: 300

Time Schedule:

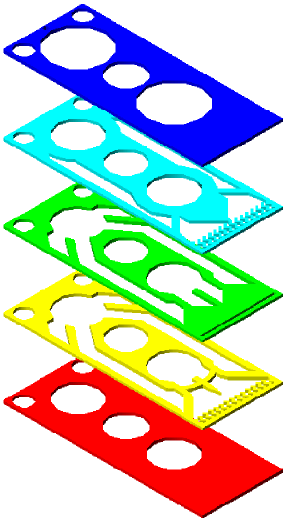
Test start: 10. November 2004

Report status: 15.000 hours

Actual status (31.12.06): 19.500 hours

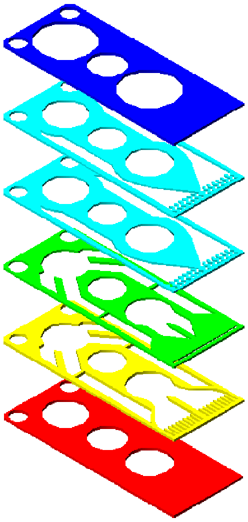
The three different MCC's are:

CUR 3/1



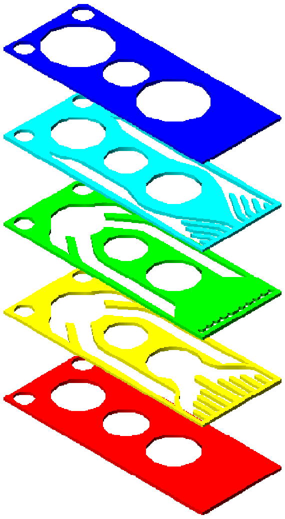
5 layers with Rth optimized "zig-zag" structure.

CUR 5/1



6 layers with "straight finger structure" in the inlet layer (yellow) and "zig-zag" in the outlet layer (light blue).

CUR 7/1

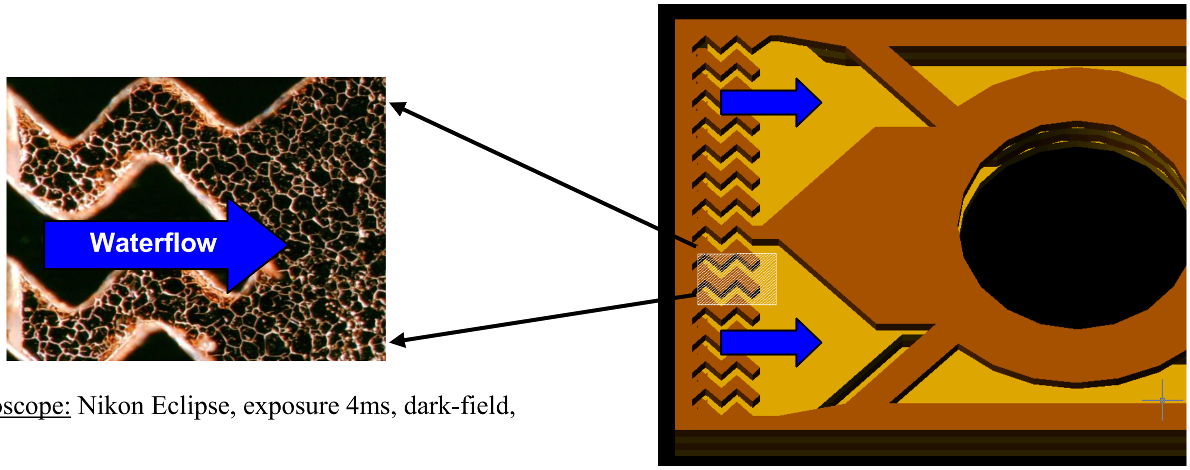


5 layers with flow optimized "finger structure"

RESULTS

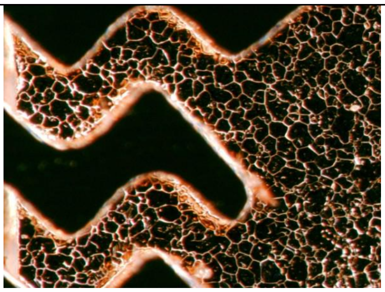
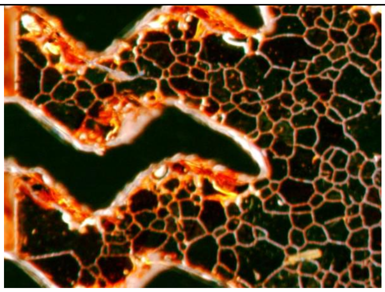
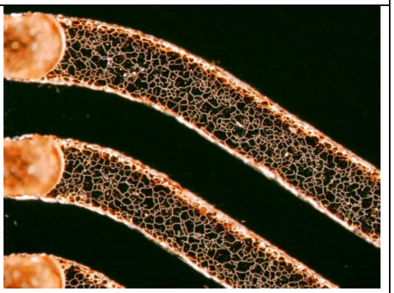
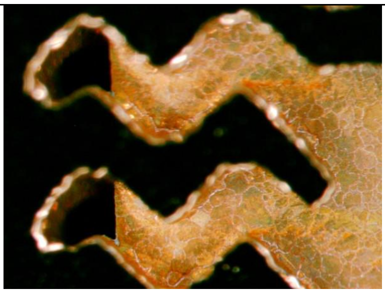
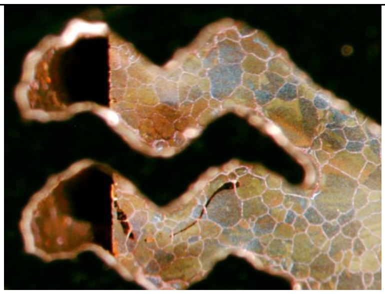
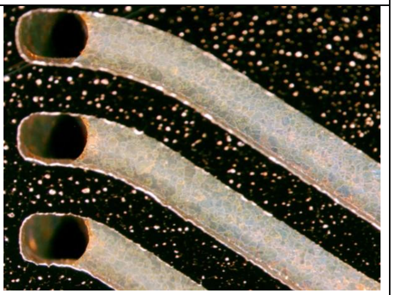
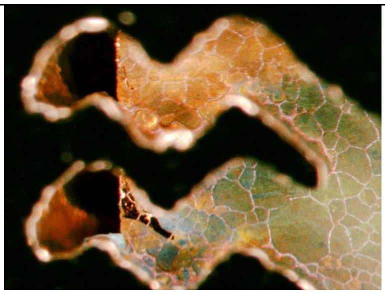
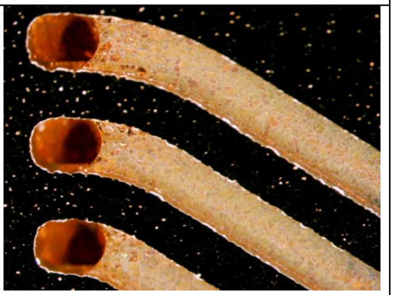
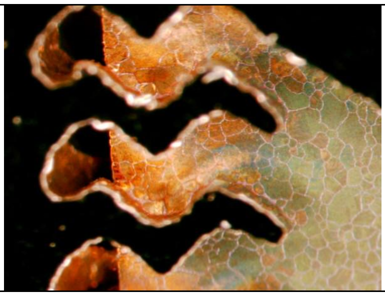
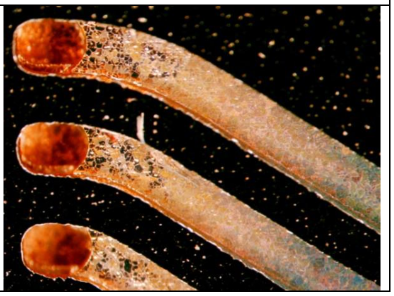
The following pictures show the outlet layer under the LD bar area for the different MCC (CUR 3/1, 5/1, 7/1) at different flow rates at different testing times (0 h, 5000 h, 15000 h).

The pictures are taken according to the following mechanism:

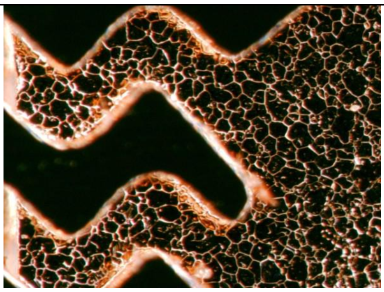
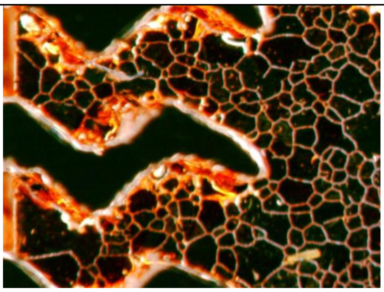
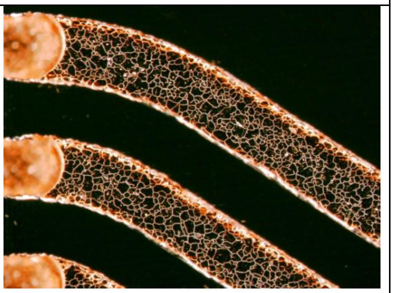
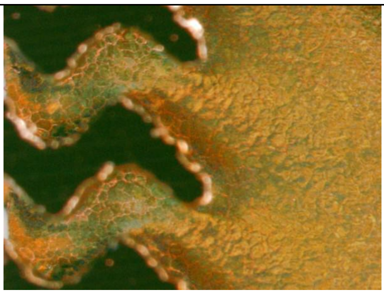
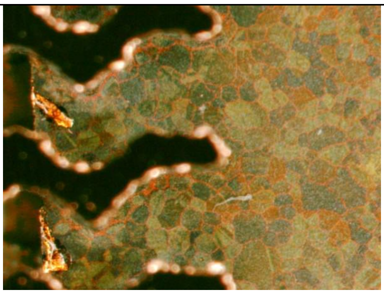
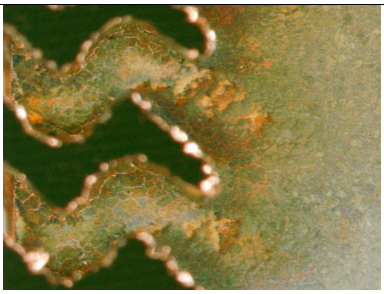
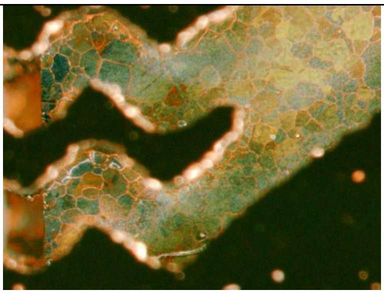
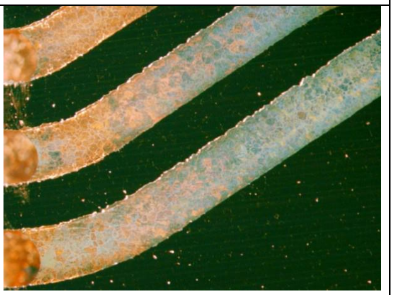
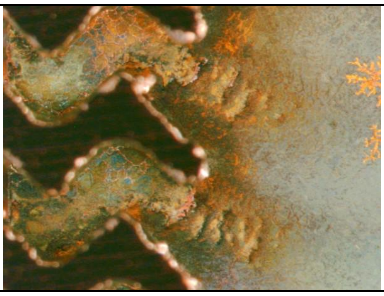
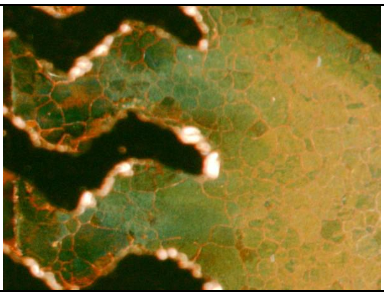
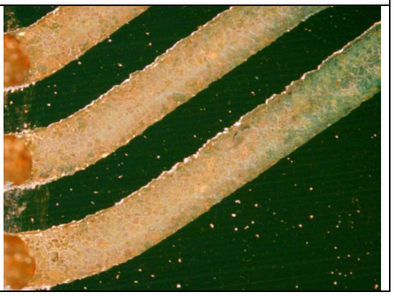


Microscope: Nikon Eclipse, exposure 4ms, dark-field,

Results after 5,000 h

	CUR 3/1	CUR 5/1	CUR 7/1
Reference at 0 h			
0.2 L/min			
0.3 L/min			
0.5 L/min			

Results after 15,000 h

	CUR 3/1	CUR 5/1	CUR 7/1
Reference at 0 h			
0.2 L/min			
0.3 L/min			
0.5 L/min			

4 DISCUSSION

From the pictures displayed above, we can see that with decreasing flow velocity and increasing time thicker oxide passivation layers form on the surface of the micro-channels. The formation of these passivation layers is well documented in the literature [3, 4]. In areas with narrowing channels that evoke flow velocity maxima, increased polished copper surfaces are to be observed.

In the detail, it can be seen that in the CUR 3/1 type cooler, there are deposits in the transition between the micro-channel region and the wider reflux channel. Based on the red color of the deposited grains (visible at a larger magnification, not shown here), it can be inferred that these deposits consist, for the most part, of Cu_2O, see chapter 2. According to the reaction scheme, equations 5-8, these deposits consist of copper that has been removed from areas with high flow velocity. These high flow velocity areas are typical for the CUR 3/1, which has the lowest thermal resistance. As expected, these deposits and the corresponding copper removal are highly pronounced at the highest flow rates of 0.5 L/min. Interestingly enough, there are no visible geometric variations in any of the micro-channel structures.

In the CUR 5/1 cooler type, in comparison with type CUR 3/1, no deposits in the transition between the micro-channel area and the wider reflux channel are visible. That can be explained with by the enlarged channel cross-section in the type CUR 5/1, which results in slower linear flow velocity. In the same way, there are no visible geometric variations in the micro-channel structure in CUR 5/1.

In the case of the MCC CUR 7/1 one can observe only changes in the formation of the coating. This is caused by the design of the flow-optimized "finger structure". Again, we can not observe any visible geometric variations in the micro-channel structure.

5 CONCLUSION

The results of these investigations must be understood in the context of what we did not include in this investigation for the sake of simplicity. There were no laser diode bars soldered to the coolers we tested, nor was there an electrical potential applied across these cooler stacks. As already mentioned, we believe that focusing on the micro channel structure significant effects of an applied potential can be neglected, but not excluded. Concerning the heat generated by the bars, one has to take some effect on the lifetime of the coolers into account.

In any case, our goal was to obtain a specific and credible answer to the question whether pure copper coolers are sufficiently reliable with the usual process parameters of flow, temperature, and conductivity, to be used with confidence for cooling laser diode bars for an acceptable life-time. The results represented here show that with the specified operating parameters no changes of the micro-channel structures are visible. These results appear to be indistinguishable between the three cooler designs up to 15000h. We believe that the cooling performance of each of the three designs is unchanged after a continuous period of operation of 15000 h. We assume that there will be no degradation of performance for the next 15000h.

In summary, if the water parameters are properly controlled, copper micro-channel coolers can have a long lifetime (20k+hours) over a range of flow velocities and cooler designs. (Conversely, uncontrolled water will cause catastrophic failure in a few hundred hours.)

6 LITERATURE

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