RELIABLE COOLING OF HIGH-POWER LASER DIODE ARRAYS

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Abstract

Northrop Grumman / Cutting Edge Optronics has developed a line of microchannel-cooled laser diode arrays in which the coolant is electrically isolated from the current path. As a result, these arrays do not require the use of deionized water. The thermal performance of these arrays is presented and, in one case, shown to far exceed the performance of standard copper microchannel-cooled packages. This sets them apart from other non-DI microchannel coolers currently on the market which typically have worse thermal performance than copper MCCs.

These newly-developed coolers are compatible with other technologies developed by NGCEO that enable long lifetimes under harsh operating conditions. In particular, these arrays can be assembled using hard-solder technology that enables power-cycled and high-current operation. The soldering technology also generates arrays that are easily lensed and satisfy a wide range of direct diode needs, including welding, marking, and complex line generation applications.

These microchannel-cooled arrays represent an important next step in the solid state laser industry. They allow for much simpler (non-deionized) cooling systems while maintaining excellent thermal performance and lifetime.

Introduction

Recent advances in semiconductor technology have led to the creation of laser diode bars capable of producing hundreds of watts of CW output power. These devices typically operate with electrical-to-optical efficiencies in the range of 50-75%. As a result a tremendous amount of waste heat is generated, with heat fluxes on the order of 1 kW/cm^2 common in the industry today. As device technology continues to improve and optical output powers continue to increase, additional waste heat will need to be removed by laser diode packages.

The most common method of removing large amounts of waste heat in a laser diode package is by using microchannel-cooled packaging technologies. This method allows for cooling fluid to pass very near to the laser diode bar, with typical distances from the laser diode bar to the cooling fluid of approximately 200 μm. Most commercially-available microchannel coolers are made from multiple layers of copper. The laser diode bar is often soldered directly to the copper cooler. It is also common to solder the bar to a CTE-matched heatsink, and then solder the resulting subassembly to a copper MCC. This configuration allows hard solder to be more easily used.

While this approach provides excellent thermal performance, there are several drawbacks. The use of metallic microchannel coolers causes the electrical path to come in direct contact with the coolant. This requires the use of deionized water in order to ensure that no electricity flows through the coolant lines. Typically, water with a resistivity on the order of 0.5 MOhm*cm is used to cool microchannels in laser diode arrays.

The use of deionized water in microchannel-cooled laser diode arrays has led to a number of well-documented failure mechanisms, most notably the erosion and corrosion of the microchannel coolers [1]. Minimization of the corrosion failure mechanism requires a great deal of attention be paid to the entire cooling system [2]. In particular, it requires that the chiller be equipped with a means of controlling the pH and resistivity of the water. The use of certain common plumbing materials (i.e. brass) is also forbidden.

Erosion of copper microchannel coolers is also a significant problem. The thermal performance of a copper MCC can typically be improved by increasing the coolant flow rate. However, this increases the water speed through the cooler channels and speeds up the erosion process. Therefore two of the most critical factors in overall laser diode array lifetime – the thermal performance and robustness of the package –

have opposing relationships to increased device flow rate.

While these hurdles have been overcome in many applications, they present substantial barriers in others. The additional cost and size associated with chillers manufactured for deionized water applications makes their use cost prohibitive in many applications that could make use of small, microchannel-cooled arrays. In these applications the cost of the chiller can significantly outweigh the cost of the arrays. In addition, the complexity and maintenance needs of the cooling system place additional burdens on the end user of the laser system. This can be a roadblock to the success of the end user. Lastly, copper MCCs are fundamentally limited because the soft nature of copper makes the coolers susceptible to erosion.

Design

NGCEO has developed a new laser diode array package which possesses many of the benefits of copper MCCs but eliminates the drawbacks [3,4]. The new package is based on multi-layer ceramic technology. Both Low- and High-Temperature Cofired Ceramics (LTCC and HTCC, respectively) have been used by CEO to create MCCs. This technology has been used successfully in the electronics industry for many years. In particular, this technology has been used extensively in the manufacture of radio frequency devices, including many RF circuits in cell phones. This technology has also been used in a variety of microfluidic applications.

NGCEO has leveraged the conventional thick film processing and bonding techniques of the multi-layer ceramic industry to create multi-layer devices with water channels similar in nature to copper MCCs. A typical copper MCC has five layers. The LTCC designs proposed by NGCEO have between three and nine layers.

A simplified side-view schematic of one of these coolers is shown in Figure 1. Water flows through cooling channels in the ceramic body and impinges directly on the back of the heat spreader. These devices use electrically isolating submounts (AlN, BeO, or diamond) as heat spreaders in order to eliminate the need for deionized water and decrease the thermal resistance of the package. Since the coolant is in direct contact with the submount, the low thermal conductivity of the ceramic cooler body material does not adversely affect the thermal performance of the device.

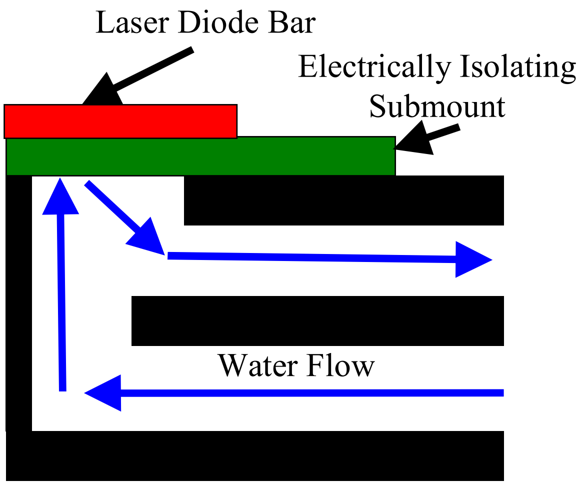

Figure 1. Side-view schematic of a ceramic MCC.

The design of the impingement cooling structure in the ceramic cooler can be optimized for any bar geometry through the use of computational fluid dynamics (CFD) software. An example of the array of cooling jets commonly used is shown in Figure 2. The blue color represents the interior of the ceramic structure that is filled by water during operation. This MCC contains an array of 27 jets arranged in nine rows of three jets each. An exhaust trench is located between each row of impingement jets.

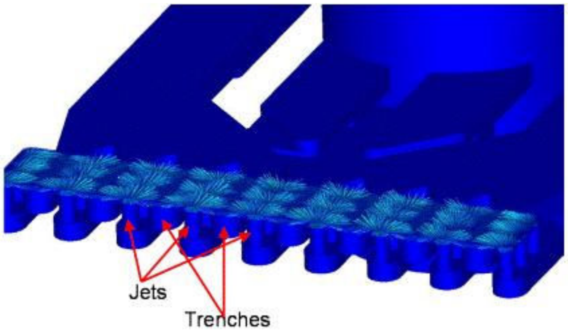

Figure 2. Internal structure of a ceramic MCC.

Design rules have been developed by the authors that enable maximum heat extraction at flow rates comparable to those used for copper MCCs, while simultaneously maximizing yield in the cooler manufacturing process. These design rules also allow the MCCs to be tailored for specific applications, such as when non-standard flow or pressure specifications exist.

A summary of the properties of the materials used in this package is given in Table 1. The materials used in these coolers offer several advantages over copper. First, all materials are significantly harder than copper which improves their erosion resistance. Second, the materials are closely CTE matched to GaAs and/or InP. This allows for the use of hard solders, such as AuSn, in the assembly process. The use of AuSn solder has been repeatedly shown to improve device lifetimes when compared to devices built with soft solder (e.g. indium).

Table 1. Hardness and thermal expansion data for materials used in ceramic MCCs. Copper is included as a reference.

Material	Use	Vickers Hardness (kgf/mm2) (typical)	CTE (ppm/K) (typical)
LTCC	Cooler Body	765	6
HTCC	Cooler Body	1500	8
AlN	Heat Spreader	1150	4-5
BeO	Heat Spreader	600	6-8
CVD Diamond	Heat Spreader	N/A	2
Copper	Standard Coolers	130	16

Thermal Performance

There are three main criteria that have to be evaluated when considering a new MCC. First, the thermal performance of the new package must be shown to be similar to (or better than) existing MCC designs. Second, the long-term erosion and corrosion performance of the package has to be evaluated. Third, practical considerations (such as form and fit) must be considered in order to understand whether or not the devices can be used as direct replacements in existing systems.

One statistic commonly used as a measure of thermal performance in laser diode packages is the thermal resistance, R_{th}. The thermal resistance is the increase in device temperature per incremental amount of waste heat that is generated:

$$R_{th} = \frac{dT}{dQ} \qquad (1)$$

The thermal resistance of laser diode arrays based on copper MCCs is in a range of 0.2-0.4 ^{o}C/W and is dependant on a number of factors, including the geometry of the laser diode bar and the coolant flow rate.

The modeled thermal resistance for diode arrays built with LTCC MCCs is shown in Figure 3. Data is presented for four different heat spreaders: AlN, BeO, and two grades of CVD diamond. This data is for a bar with a 1.2mm cavity length and ~ 54% fill factor and is representative of a bar typically used in 50-100 Watt CW applications. For flow rates commonly used in copper MCCs (0.05 - 0.1 GPM), the predicted performance of the samples with diamond heat spreaders exceeds that of the copper MCCs. In addition, the performance of samples with BeO heat spreaders is similar to that of copper MCCs.

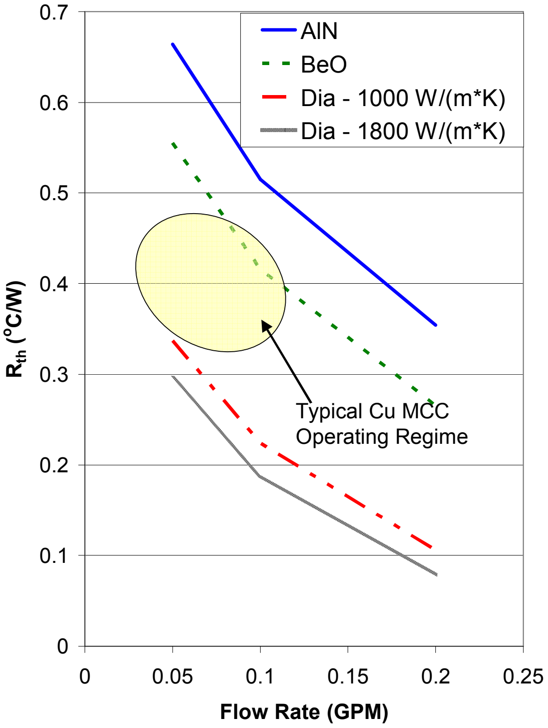

Figure 3. Modeled thermal resistance vs. flow rate for the LTCC MCCs with a variety of heat spreader materials.

Erosion Resistance

One of the primary drawbacks of the existing copper-based MCC technology is the fact that the coolers can erode when exposed to the high water speeds common to laser diode applications. NGCEO has conducted several erosion studies designed to understand the parameter space in which copper coolers can be operated reliably. The results of one such study are presented here to serve as a comparison to results obtained with the LTCC MCCs. A vertical stack of six copper MCCs was subjected to a flow rate of 0.2 GPM/cooler, which is approximately four times greater than the flow rate recommended by the manufacturer of the copper coolers. This was purely a test of the erosion properties of the coolers – no voltage or current was applied to the diode bars in the stack in order to eliminate the effects of galvanic corrosion.

At the conclusion of the erosion test, the top (mounting surface) layer of one of the coolers was removed and compared to an unused cooler. A picture of each cooler is shown in Figure 4. The water flow is such that it comes up through small holes near the front of the cooler (out of the page in Figure 4) and then away from the front of the cooler as indicated by the blue arrows. The zigzag pattern in the cooler is designed to promote turbulent flow and therefore improve the cooling properties of the MCC.

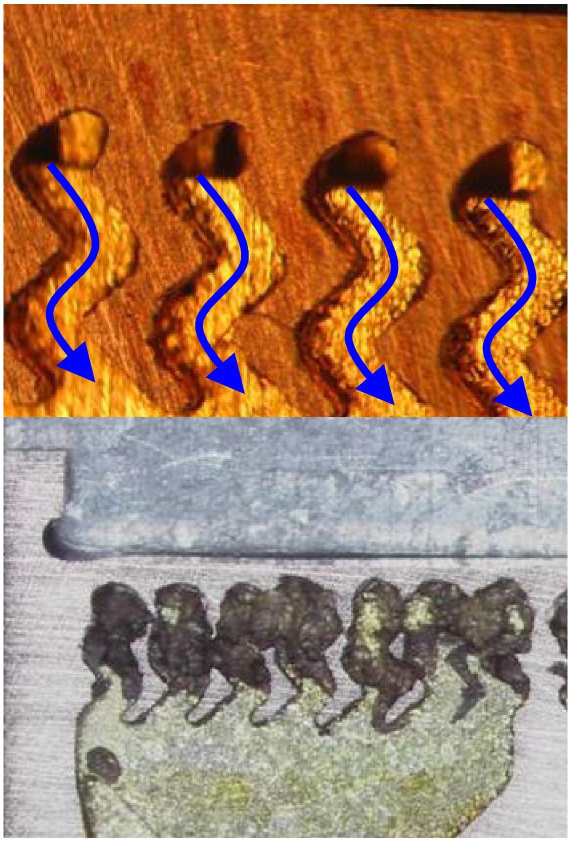

Figure 4. Examples of the internal structure of a copper MCC before (top) and after (bottom) a high-flow-rate test.

The effect of the high flow rate is clearly seen in the right hand side of Figure 4. Most of the structure that existed in the front of the cooler has been completely eroded by the water. The small holes in the front of the cooler that transport the water to the cooling layer have greatly expanded in size, and a significant portion of the zigzag pattern has been eroded away. This picture is representative of what has been observed in other tests conducted at high flow rates.

A similar test has been conducted with three ceramic coolers, one cooler with each of the thermal window materials (AlN, BeO, and CVD diamond). These coolers were packaged into single-bar MCC arrays and placed in a life test system. A flow rate of 0.25 GPM/cooler was set for the devices and the system was allowed to run without any pH or resistivity control. After approximately 550 hours, the sample with a BeO thermal window was removed from the system. The thermal window was removed and the internal channels of the cooler were examined under a microscope. The bottom of the thermal window was also examined to look for signs of erosion from the impinging water. The other two samples were tested for an a total run time of approximately 2500 hours, at which time the sample with the AlN thermal window was removed for a similar analysis. Photographs of the internal structure of these two samples, along with an unused cooler, are shown in Figure 5. (Note: The different color seen in the third image is a function of the microscope and camera settings. There was no change in the color of the device over the course of the test.)

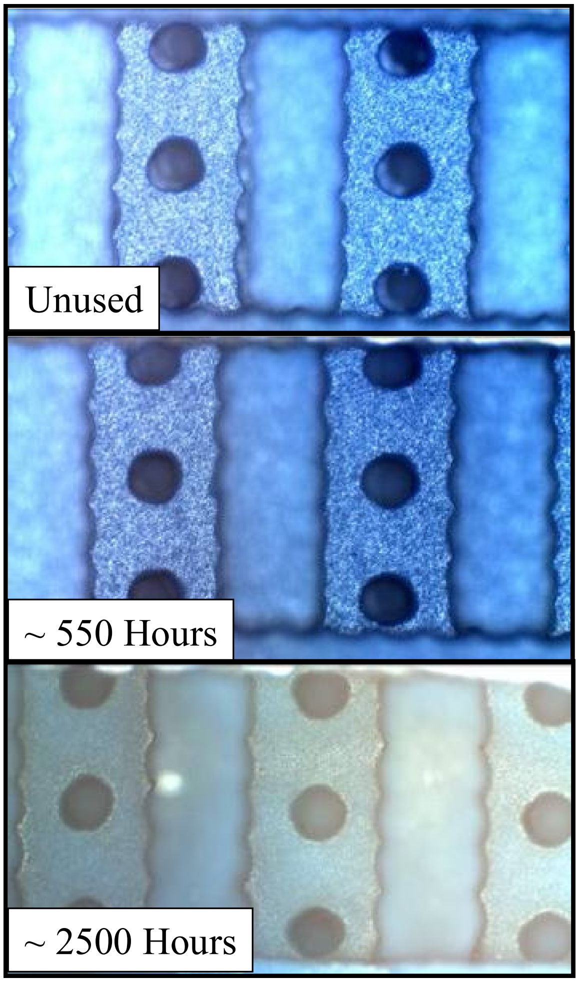

Figure 5. Internal structure of example LTCC MCCs at three different times during a high-flow-rate test: before the test (top), 550 hours (middle), 2500 hours (bottom).

The performance differences between the copper and ceramic coolers in high-flow conditions are striking. The ceramic coolers exhibit little (if any) erosion after 2500 hours at 0.25 GPM/cooler, whereas the copper coolers had eroded to the point of failure after 1000 hours at 0.2 GPM/cooler. Of equal importance is the erosion resistance of the thermal window materials. The BeO examined at 550 hours and the AlN examined at 2500 hours each showed very limited signs of erosion. This test demonstrates the robust nature of the ceramic microchannel coolers.

The resistance to erosion of the LTCC MCCs opens the door to a wide range of operating conditions. In applications where high flow rates are available, they can be used to improve the thermal performance of the devices with little negative impact on overall array lifetime.

Array Configuration

NGCEO has developed several different MCC designs based on multi-layer ceramic technology. One MCC is a direct form and fit replacement for existing copper MCCs produced by NGCEO. These MCCs can be stacked vertically and horizontally and result in arrays with the same bar-to-bar pitch as is standard for arrays based on copper MCCs. As a result, existing copper-based MCC arrays can be replaced with ceramic-based MCC arrays with no mechanical impact to the overall laser system. An example six-bar LTCC MCC array is shown in Figure 6.

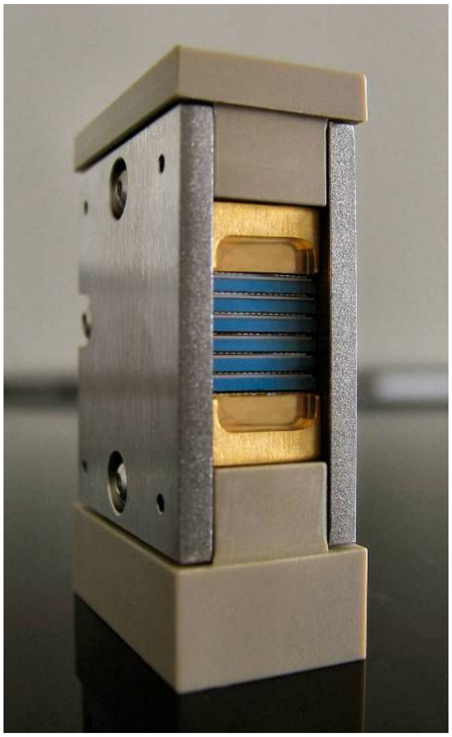

Figure 6. Six-bar array built from LTCC MCCs. This array is a form-and-fit replacement for a six-bar array built from copper MCCs.

One of the primary strengths of this approach is the high level of configurability that is possible with the ceramic MCCs. The manufacturing process for multilayer ceramic substrates is very mature. As a result there is little additional lead time associated with custom MCC designs. This enables NGCEO to design coolers which meet the exact specifications of each customer's application.

Conclusion

Northrop Grumman Cutting Edge Optronics has developed a new laser diode cooling technology using ceramic microchannel coolers. These coolers have many of the same strengths as the current state-of-the-art copper microchannel coolers, but they do not share the same weaknesses. Since the thermal and electrical paths are electrically isolated, standard filtered water can be used as a coolant (deionized water is not required). In addition, the robust nature of the ceramic materials used enables a much higher degree of erosion resistance.

The ceramic coolers can be produced in a wide range of sizes and shapes, which opens the door to novel solid-state laser pumping geometries. The design flexibility also enables the creation of direct replacements for many copper coolers and copper-based diode arrays currently on the market.

References

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Author

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