

Alternative cooling solutions for high power optoelectronic

Michael Leers*, Hans Schmidt**, Philipp Imgrund**

*Fraunhofer Institut for Lasertechnology

Steinbachstr. 15, 52074 Aachen, Germany

michael.leers@ilt.fraunhofer.de, phone: +49 241 8906 343,

**Fraunhofer Institute for Manufacturing Technology and Applied Materials Research Wiener Straße 12
28359 Bremen Germany

Abstract

The market for high power diode lasers is still growing very fast (more than 10% a year). New applications are developed permanent and the range besides telecommunication, automobile and medical industries is rising rapidly. Because of the bright facilities of high power diode lasers plenty of niche applications also benefit from the high efficiency of the semiconductors.

The interests in the R&D departments of diode laser industries have changed in the last years. Not the maximum of the emitted optical power out of the array is the main focus of the investigations anymore. The lifetime of the package is the critical value of the high power diode laser bars. A lot of R&D projects are focused on this issue. Common packages use a copper heat sink and Indium soft solder for mounting the laser bar. In the field of high power applications (> 100 W optical output power) water cooled heat sinks are necessary. In combination with the needed deionized water and high flow rates (0.5 l/min) corrosion is hard to prevent. Therefore, new cooling techniques are needed. In the last 12 months a lot of new solutions to increase the lifetime of the high power diode laser packages have been developed.

Basically the new solutions are divided into two groups. One is using new high performance materials, especially diamond composites. Their thermal conductivity is announced with up to 600 W/mK depending on the suppliers. This heat spreading material has a thermal conductivity which is up to 50% better than pure copper and will replace water cooled heat sinks.

The other is using new materials combinations for their active cooled heat sink instead of copper. New heat sink designs are possible because of new fabrication techniques like selected laser melting or μ -metal injection molding.

from the front facet (edge emitting device). Common laser bars have a filling factor of 30% and a pitch of 500 μm . As shown in Figure 1 the height of the epitaxial layer is 3-5 μm only. Due to this the heat sink has to be very precise and requirements for the surface and edge quality are very high. Typically, the front and top of the heat sink are ultraprecision machined, e.g. by diamond milling, to provide a mounting area with very high flatness and low roughness, as well as a very precise front edge. Typical specification values are less than 1 μm for the flatness, $R_a < 50\text{nm}$ for the roughness, and a radius of less than 1 μm for the front edge. Finally, the heat sinks are covered with a nickel and gold plating to provide corrosion protection and a solderable surface. The thickness of the solder on the heat sink is in the range of 4-7 μm . In general the laser bars are mounted p-side (epi-side) down. Due to this the solder layer thickness has to be very precise and the laser bar has to be mounted with a small overhang ($\sim 5\mu\text{m}$) with respect to the edge of the heat sink to avoid solder on the front facet (fig.2).

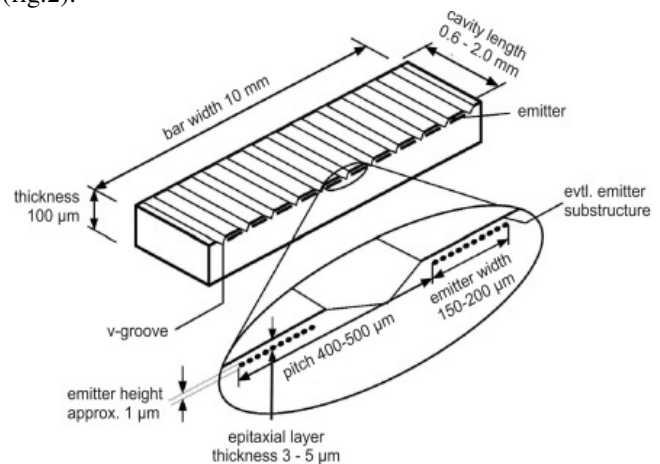


Figure 1: Structure of a laser bar with common dimensions (p-side up)

1. Introduction

Most high-power diode lasers are build from so-called laser bars. A laser bar integrates a linear array of laser emitters on a single chip. In the near infrared wavelength range (600-1100nm) gallium arsenide (GaAs) provides an optical gain by stimulated emission. The resonator is formed by the cleaved end facets of the chip. Additional coatings provide high reflectivity ($\sim 95\%$) on the backside and low reflectivity ($\sim 5\%$) on the front side of the laser bar. The laser radiation is emitted

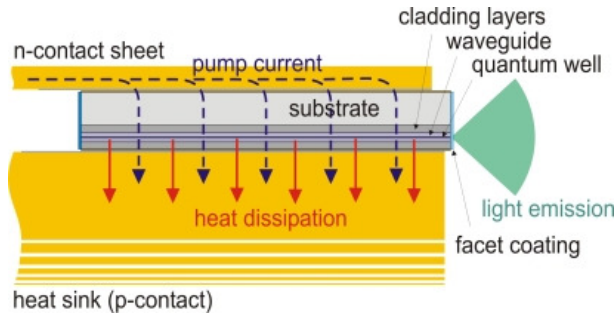


Figure 2: p-side down mounting with an “overhang” of 5μm to avoid solder contamination of the facet

State of the art heat sinks for high average power applications are the so called micro-channel heat sinks that provide very efficient cooling by a grid of fine cooling channels located below the mounting surface of the laser bar. For lower power requirements (<30W output power), conductively cooled heat sinks are sufficient

Independent of the heat sink type, the restriction to copper as the heat sink material bears two main disadvantages:

1. The coefficients of thermal expansion (CTE) of GaAs laser bars and the copper heat sink differ strongly. The CTE of copper is 16.8 ppm/K, whereas it is approximately 6.7 ppm/K for GaAs-based laser bars.
2. In combination with water-cooling, a number of corrosion mechanisms, as well as erosion caused by high water flow velocities, limit the lifetime of copper micro-channel heat sinks.

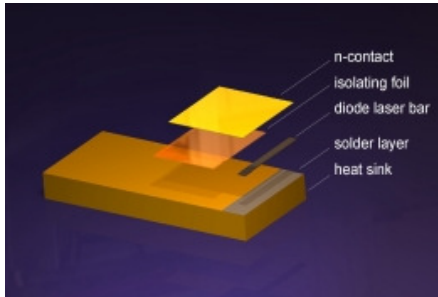


Figure 3: Assembly of a diode laser

While the application of appropriate protective coatings can optimize the second issue, as well as an appropriate point of operation leads to a reduction of turbulence and dead water areas, the expansion mismatch is inherent to using copper as a heatsink base material and cannot be avoided. To limit the induced stress in the laser bar an expansion matched packaging is necessary.

This paper will give an overview of cooling approaches for high-power diode laser bars. It will present possibilities to increase the lifetime of the heat sinks by expansion matching and optimization of the fluid behavior and to improve the thermal resistance by using novel high performance materials.

Thermal resistance

As a measure of the thermal performance of diode laser packages, commonly the total thermal resistance R_{th} is used. It is defined as

$$R_{th} = \frac{\Delta T}{P_{therm}}$$

where P_{therm} is the thermal power dissipated by the laser bar at a given operating point and ΔT is defined as the temperature difference between the hottest points of the laser bar and a reference temperature measured at the bottom side of the heat sink or – in case of water cooled heat sink – the cooling water temperature at the inlet into the heat sink. In a laser diode heat is mainly generated in the active zone, the light generating and guiding region in the waveguide of the laser emitters. The hottest point is located in the waveguide at the front facet of the laser diode.

The thermal power of the laser bar can be obtained from its characteristic curves, that is,

$$P_{therm}(I) = U(I) \cdot I - P_{opt}(I)$$

where $P_{opt}(I)$ is the optical output power and $U(I)$ is the operating voltage as a function of the driving current I . Since the emission wavelength of the laser bar depends on the temperature of the pn junction, the operating temperature can be calculated from the emission wavelength at the specific operating point:

$$R_{th} = \frac{\Delta T}{P_{therm}} = \left(\frac{\Delta \lambda}{\Delta T} \right)^{-1} \cdot \frac{\Delta \lambda}{P_{therm}}$$

The thermal wavelength drift factor $\Delta \lambda / \Delta T$ is a parameter that has to be determined for each laser bar in advance of the thermal resistance measurement, and $\Delta \lambda / P_{therm}$ is the slope in the wavelength – lost power diagram (Fig. 4).

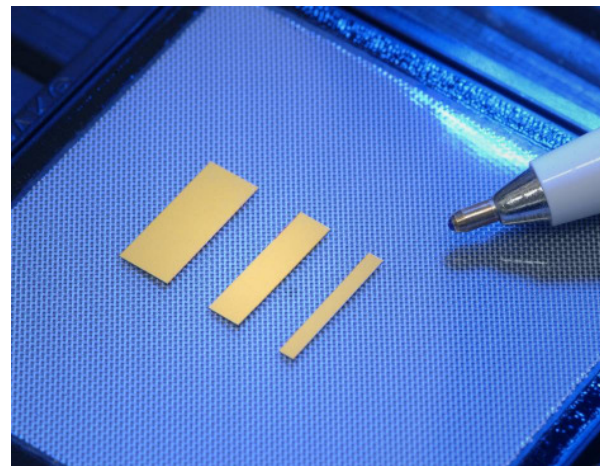


Figure 4: Laser bars with three different resonator lengths (1.2 mm, 2.5 mm and 4 mm) are used for the thermal resistance investigations.

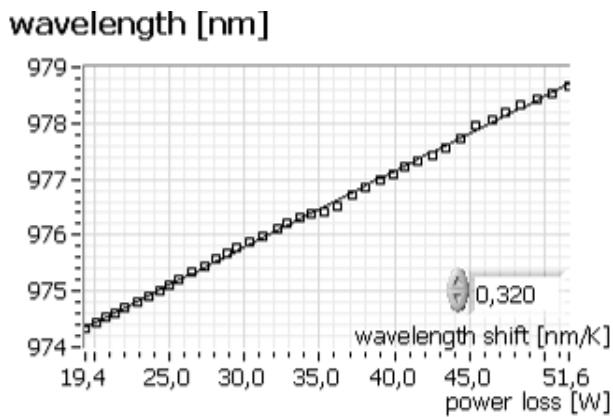
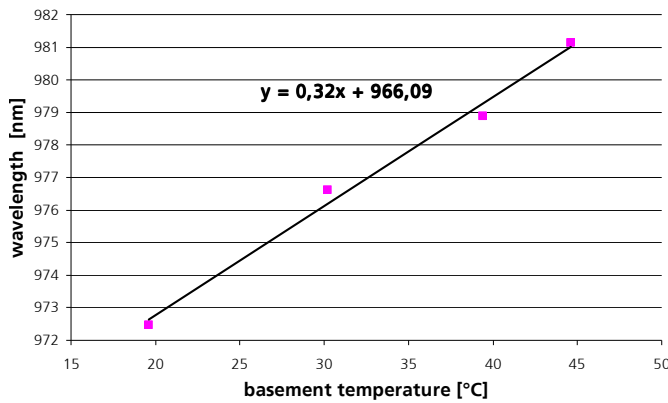


Fig. 5: Top: Results of a short-pulse measurement to obtain the thermal wavelength drift factor. Below: wavelength vs. lost power diagram

For an interpretation of the thermal resistance values, it is important to consider its dependence on the heat generation area. Using the same heat sink, but a larger laser bar with the same power loss, the thermal resistance will be lower because the heat flow is spread out over a larger contact area. A significant difference can still be seen when laser bars with different filling factors are used. Due to the three-dimensional heat flow inside the heat sink, no simple equation can be given in order to compare the thermal behavior of different heat sinks packaged with different laser bar geometries.

2. Conductively cooled heat sinks

For applications with less than 50 W thermally dissipated power per laser bar conductively cooled heat sinks are preferred. Pure copper heat sinks with their high thermal conductivity achieve a good thermal performance, but the CTE mismatch limits the lifetime of the mounted laser bar. The conventional expansion-matched solution uses WCu or AlN submounts requiring an additional mounting step and degrading the thermal performance (fig.4).

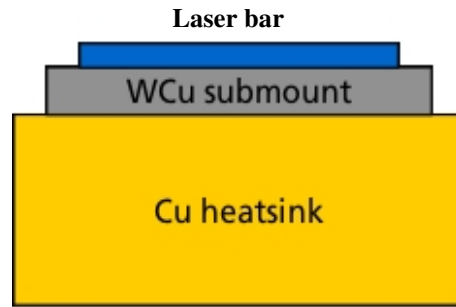


Figure 4: Scheme of an expansion matched heat sink with WCu submount

In contrast, Fraunhofer ILT has developed conductively cooled heat sinks with integrated expansion matching.

In a first approach copper heat sinks with inserted molybdenum layers were designed and fabricated (fig.5). Compared to standard copper heat sinks, with this approach, a coefficient of thermal expansion (CTE) of <9 ppm/K and a thermal resistance of <1 K/W have been realized.

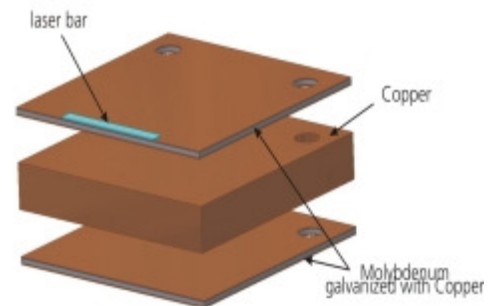


Figure 6: Diode laser mounted on a conductively cooled expansion-matched heat sink "Bright LC"

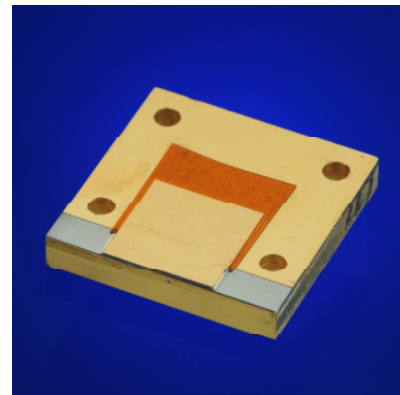


Figure 7: Diode laser mounted on a conductively cooled expansion-matched heat sink "Bright LC"

In order to simultaneously reduce both CTE and thermal resistance, new so-called high performance materials were explored as well. Primarily, these are diamond composite

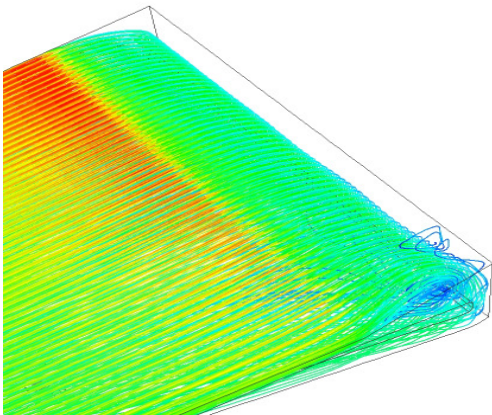
materials, such as Silver Diamond, Copper Diamond and Silicon Carbide Diamond (ScD). First heat sink samples have been designed and fabricated based on ScD material. By adding properly dimensioned top and bottom copper layers a CTE of 7-8 ppm/K and a thermal resistance of 0.7 K/W have been achieved. This heat sink provides an expansion-matched and thermally equivalent or even better alternative to standard pure copper heat sinks.

3. Water-cooled heat sinks

For high power applications (> 100W output power) water cooled heat sinks are used. Due to the high thermal power density, which has to be dissipated, an internal cooling structure with a high wall heat transfer coefficient (> 80,000 W/m²K) is needed to realize an efficient cooling performance. The thermal resistance of common copper heat sinks with micro channels is around 0.3K/W. For this, a flow rate of 0.5 l/min at a pressure drop of 1 bar is required. Along with the aggressive deionized cooling water the risk of erosion and corrosion effects inside the heat sinks is very high. Especially copper micro-channel heat sinks have a shortened lifetime because of these effects. To solve these problems new materials instead of copper would be a possibility, as well as special plating inside the heat sinks or the reduction of turbulences by a CFD improved channel design. Another solution is the use of macro channels instead of micro channels. The wall heat transfer coefficient of the macro channels decreases, the flow rate of 0.5l/min is realized at a lower pressure drop and a thermal resistance of 0.5K/W can be realized. Due to this erosion effects are reduced.

3.1. Macro-channel heat sinks

In many applications laser bars are operated in a medium power regime: conductive cooling is not sufficient anymore, but the full cooling performance of micro-channel heat sinks is not yet required. In these cases macro-channel heat sinks are a suitable cooling concept. However, especially the cooling performance of macro-channel heat sinks is very sensitive to the proper cooling channel design. Therefore, fluid simulations (CFD) are performed to optimize the cooling channel geometry, depending on the point of operation in terms of flow rate and pressure.



For a thermal power of 50-60 W per laser bar macro-channel heat sinks are a practical, compact and easy to fabricate solution.

3.2. Micro-channel heat sinks

Micro-channel heat sinks are the state of the art solution for maximum cooling performance in a very compact design. However, erosion and corrosion effects limit the lifetime especially of copper-based micro-channel heat sinks.

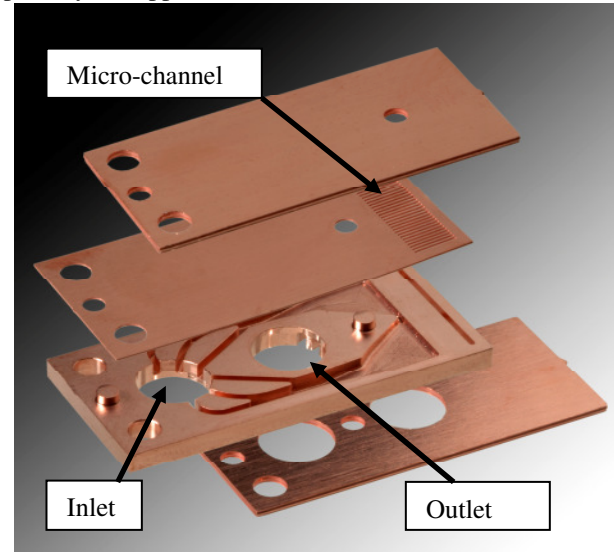


Figure 93: Assembly of a micro-channel heat sink.

Micro-channels have a typical dimension of 200x300μm²(fig. 13). During operation 0.5l/min is flowing through the cooling structure at a pressure drop between inlet and outlet of 1bar.

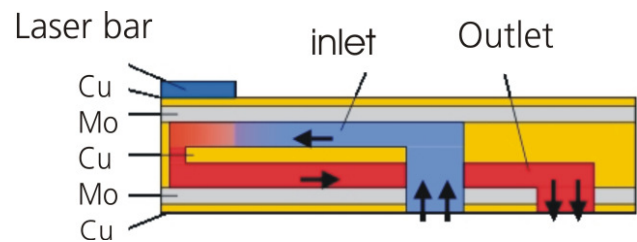


Figure 10: Assembly of an expansion matched micro-channel heat sink

In order to produce the inner structure of a micro-channel heat sink, typical outer dimension 12x1.5x25mm³, the heat sink is made out of several layers, which are finally joined together. The area of interest is the hot spot located underneath the laser bar where the micro-channels are placed. The main function of the micro-channel is to increase the contact surface between copper and water for a better waste heat dissipation. For cooling deionised water is used to avoid the effects of a galvanic cell.

Due to the aggressive deionised water the cooling fluid causes a number of corrosion mechanisms and limits the lifetime of copper micro-channel heat sinks. The application of

appropriate protective coatings can reduce corrosion. However, erosion effects can damage protective coatings, and at these defect areas corrosion may even be accelerated by electro-chemical mechanisms.

Especially erosion can be effectively reduced by an optimized cooling channel design. The Fraunhofer ILT is at a leading edge of investigation to study the water flow in the heat sinks with Particle Image Velocimetry (PIV) and uses CFD simulations to optimise the channel geometry for minimum erosion and maximum cooling performance.

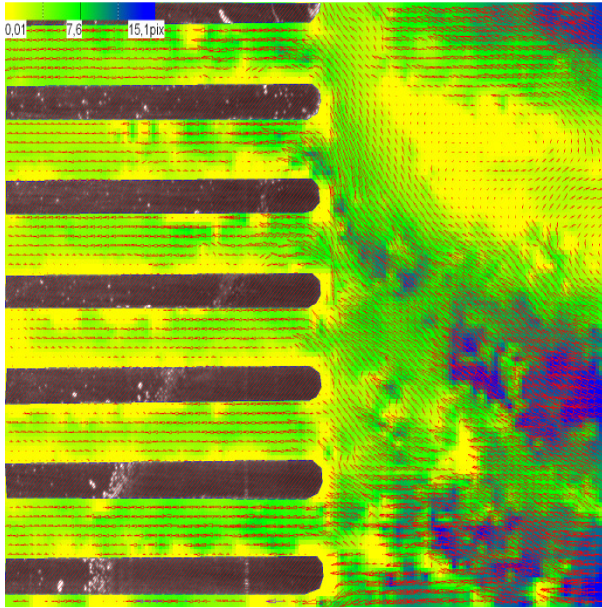


Figure 11: Visualized water flow in a micro-channel heat sink by PIV

PIV as a contact-free optical measurement technique analyzes the fluid dynamics in an acrylic glass heat sink model. The water flow is visualized by mixing small particles into the cooling fluid that are illuminated by a laser in short time intervals. From these stroboscopic pictures the local velocity and orientation of the water flow is calculated. This allows the detection of turbulences and dead water areas in the micro-channel heat sink. Even boundary layer flows can be visualized with PIV. Together with the CFD simulations this allows to optimize the design for a more effective usage of the micro-channels. Constructive changes in the heat sink design can easily be checked using CFD. After fabricating the new design PIV is used again to verify the studies.

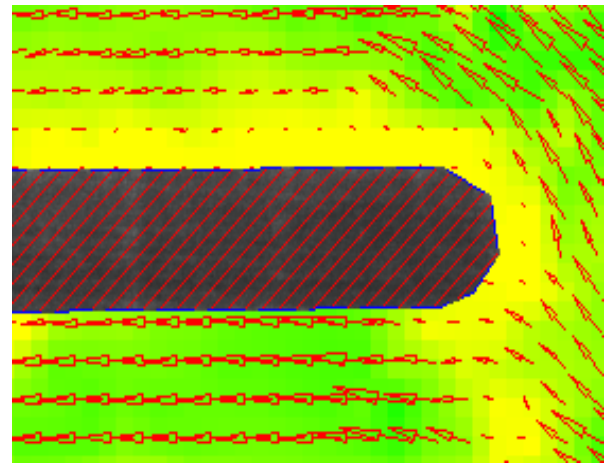


Figure 12: Visualized water flow in a micro-channel heat sink at the beginning of the cooling structure with PIV

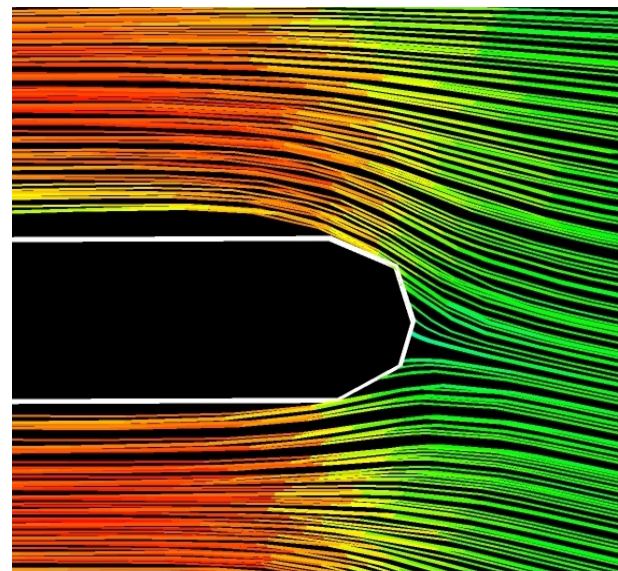


Figure 13: Visualized water flow in a micro-channel heat sink at the beginning of the cooling structure with CFD

Micro-channel heat sinks are mainly available made out of copper. Expansion matched solutions prefer the additionally mounted, WCu or AlN submount on standard micro-channel heat sinks. Compared to pure copper heat sinks the thermal resistance of such a package is increased to at 0.45K/W. Nowadays solutions without submounts are already on the market. For first example heat sinks with a copper/molybdenum/copper sandwich structure have been developed at the Fraunhofer ILT. Thermal simulations in advance were needed to define the layer thickness of the different materials. To avoid a bi-metal effect the design is constructed symmetrically.

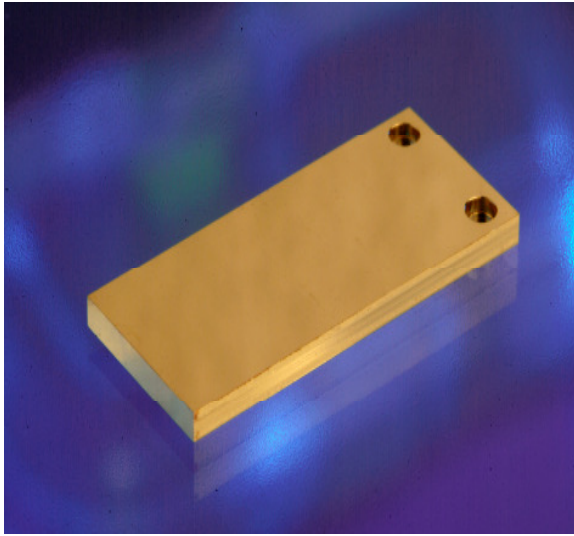


Figure 14: Expansion-matched micro-channel heat sink based on Cu/Mo

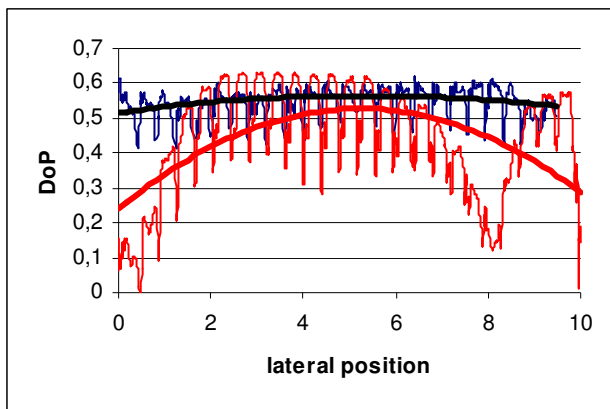


Figure 15: Comparison of DoP results of laser bars mounted with indium solder on an expansion matched heat sink (above) and a standard copper heat sink (below)

ILasCo heat sink

An alternative, highly efficient cooling solution for high power diode laser bars is the new ILasCo heat sink developed by Electrovac Curamik (Fig. 14). This heat sink is expansion matched because of its top and bottom layer made from direct copper bonded (DCB) Cu/AlN sandwich structures. The copper and the AlN layer have a specifically selected thickness resulting in a CTE of approx. 7 ppm/K which is close to the expansion coefficient of GaAs laser bars. The core of the heat sink is made out of AlN. Thus the cooling water circuit is electrically isolated from the laser bar, which allows the use of non-deionized water for cooling. Erosion and corrosion effects in the micro channels can be neglected due to the ceramic core. In the current version, the external dimensions are significantly larger compared to conventional copper micro-channel heat sinks: The ILasCo heat sink has a

width of 22 mm and a depth of 39 mm. After machining the thickness is approx. 3 mm. The top and bottom copper layers of the DCB sandwich structures have thickness of 300 μm .

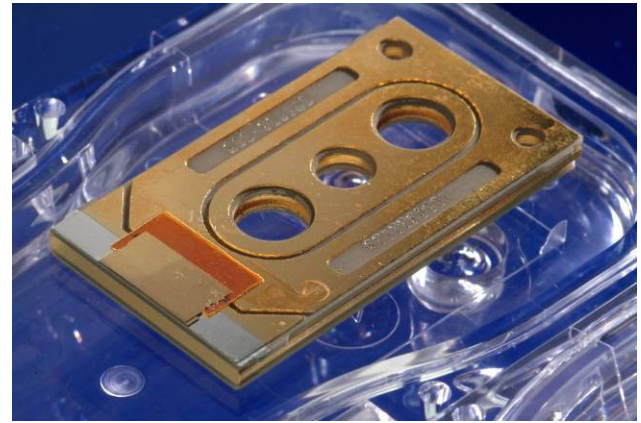


Fig. 16: Expansion matched and isolated heat sink ILasCo

As the ILasCo heat sink is a completely new concept and design of an actively cooled heat sink, a series of measurements and thermal simulations were necessary to reliably assess the thermal efficiency of these heat sinks. The main focus lies on the inner ceramic part, which allows the use of non-deionized cooling water. At the same time it serves to extend adjustment of the heat sink along with DCB construction on the upper and lower side of the heat sink. The flow simulations show a homogeneous cooling water flow through all micro channels. Dead water areas are not visible in the immediate vicinity of the laser bar.

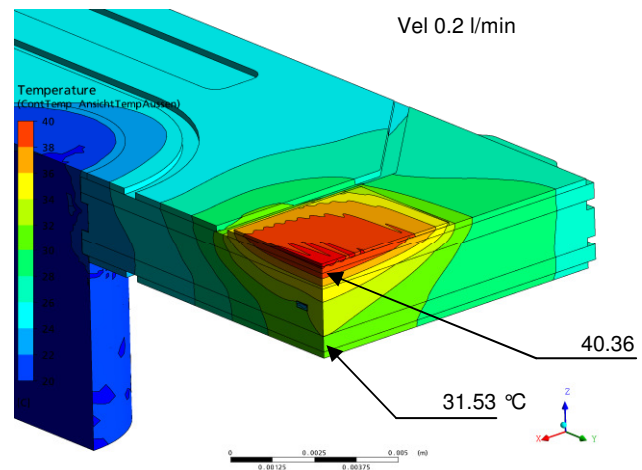


Fig. 17: Results of the CFD simulation for the ILasCo heat sink with a flow rate of 0.2 l/min and a laser bar with 4 mm resonator length. The cooling water temperature is 22 °C.

Since the thermal model for the ILasCo heat sink includes also a fluidic model of the cooling water flow in the heat sink it is possible to calculate also the dependence of the thermal resistance on the flow rate. For this purpose the flow rate in the model is varied between 0.2 l/min and 0.5 l/min. Temperature distributions resulting from these calculations are

shown in Fig. 15 and Fig. 16, comparing flow rates of 0.2 l/min and 0.5 l/min, respectively.

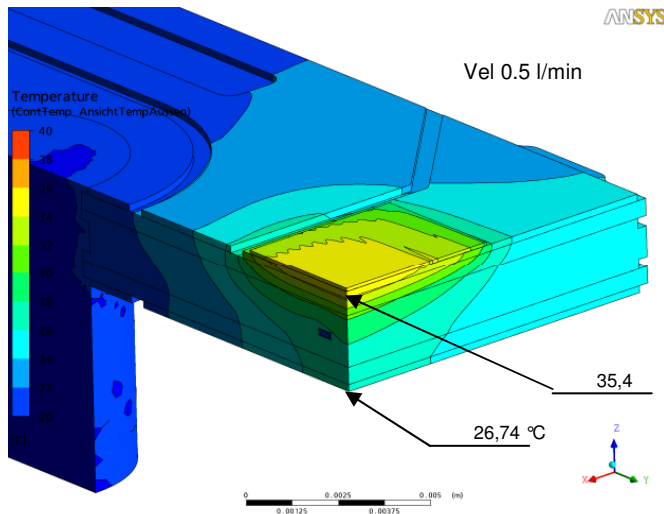


Fig. 18: Results of the CFD simulation for the ILasCo heat sink with a flow rate of 0.5 l/min and a laser bar with 4 mm resonator length. The cooling water temperature is 22 °C.

The cooling structure of the ILasCo heat sink is designed for laser bars with a resonator length of up to 4 mm. This is visible by the low thermal resistance of the package for bars with the long resonator length. At a flow rate of 0.5 l/min, the thermal resistance decreases by nearly 50% when increasing the resonator length from 1.2 mm to 4 mm. Also, the influence of the flow rate on the thermal resistance is significant, as illustrated in Fig. 17: For a 2.5mm bar, the thermal resistance is reduced by 15% when increasing the flow rate from 0.2 l/min to 0.5 l/min. Even more significant is the influence of the flow rate for the 4 mm bars: Here, the reduction of the thermal resistance is even 30%, showing the benefits of the internal cooling structure optimized for long laser bars.

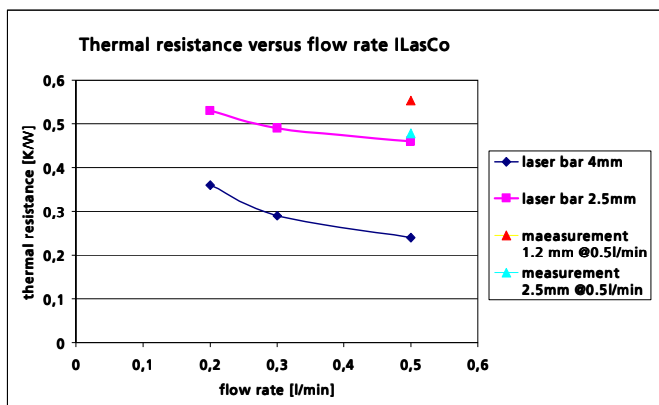


Fig. 19: Dependence of the thermal resistance on the flow rate for the ILasCo heat sink

The simulated value for a 2.5 mm laser bar at a flow rate of 0.5 l/min is confirmed by the measurement of a mounted laser

bar. Additionally, a 1.2 mm laser bar is mounted. For this resonator length a thermal resistance of 0.55 K/W is measured

4. Micro metal-injection-molding

A new approach is to manufacture heat sinks by micro metal-injection-moulding (μ -MIM), which allows an economic mass-production of complex micro near net shape parts. A large number of different metals and alloys are suitable for μ -MIM. Especially for mass production (>1000 parts) μ -MIM is a low cost process, which reduces part costs considerably. The main goal is to use the opportunities μ -MIM offers. That means to produce complex parts, which have an adjusted CTE in this case to GaAs. Therefore a material is needed, which combines good thermal conductivity behaviour with a low CTE. Tungsten and molybdenum combine a moderate thermal conductivity with a low CTE and in combination with copper have shown sufficient properties for application as submounts.

In the past there have been many approaches to produce copper-tungsten or copper-molybdenum parts by metal-injection-moulding [4]. The challenge was to obtain dense parts after sintering. The material systems WCu or MoCu are both pseudo alloys with no or very small miscibility of both components [5]. That means the attractive force between copper and tungsten/molybdenum is very small, which leads to several problems during sintering. Often the achieved density was less than 95% of theoretical density. It had been shown that the initial homogeneity of the copper and tungsten (molybdenum) plays a decisive role for the final density of the parts.

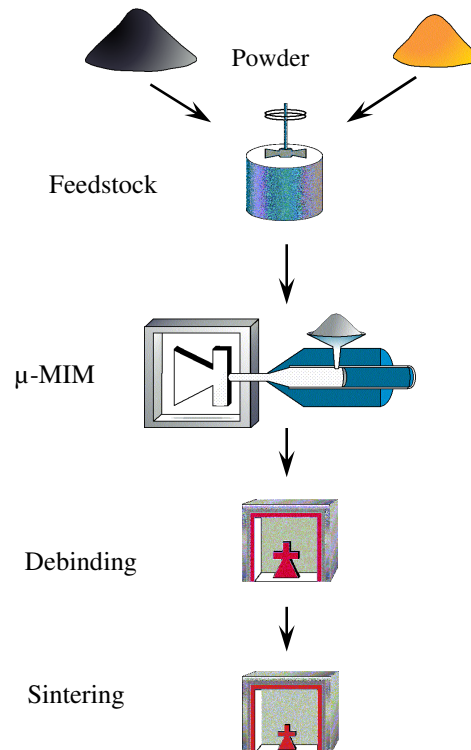


Fig. 20: μ -MIM process descriptions

The description of the experimental work is oriented on the (μ -)MIM process scheme: Blending of metal powders and feedstock processing, injection moulding, debinding and

sintering. The metal powders are in comparison to the conventional MIM process very fine with mean particle diameters smaller than $5\mu\text{m}$. Hence the process is modified concerning binder ratio, debinding rates, sintering rates and temperature [6,7].

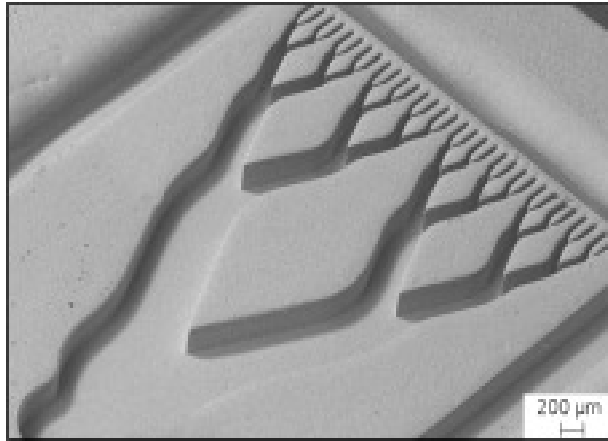


Fig. 21 Meander structure fabricated by μ -MIM

5. Conclusions and Outlook

Laser bars are being increasingly more efficient, they can reach higher optical output powers and efficiency for all the increase, the resulting thermal power loss even more. This can be realized by reducing the thermal resistance of the package consisting of laser bar, solder layer and heat sink. The decisive influencing factors are the type of cooling (water cooled or conductive heat sink), the employed heat sink material, the flow rate in case of active heat sinks, as well as the fill-factor and the resonator length of the laser bars.

Water-cooled heat sinks for high power applications need a reduction of the corrosion and erosion effects inside the water channels, along with the CTE matching for a longer lifetime. Especially erosion effects can be avoided by a closer look at the fluid behavior in the micro-channels. CFD simulations and particle image velocimetry (PIV) are analysis methods to find critical areas such as dead water zones or turbulence fields. After elimination of these problems the lifetime will be extended. As part of this work, a new expansion-matched heat sink with a ceramic core (ILasCo) has been investigated. The core is made out of AlN which allows the usage of non deionized water. Because of this the cooling circuit is electrically isolated. Erosion and corrosion effects in the micro channels can be neglected due to the ceramic core.

MoCu and WCu are promising materials for the production of active cooled heat sinks and can be net shape manufactured using the (μ)-Metal-Injection-Moulding process. The new approach using very fine powders supports the densification process caused by the good initial homogeneity. Also the results concerning the accuracy as well as the physical properties were satisfying. Furthermore no additional elements

were necessary to reach nearly full density at least for the mixtures with approx. 30vol.% copper.

For a successful implementation of WCu or MoCu heat sinks for high power laser diodes some work has to be done. The corrosion resistance of WCu and MoCu under process conditions has to be examined and a cheap joining process for WCu/MoCu parts has to be developed as there is no possibility of producing a heat sink with an internal structure by μ -MIM without joining.

Acknowledgments

The authors gratefully acknowledge support from the German Federal Ministry of Economics and Technology

Keywords

High-power diode lasers, expansion matching, micro-channel heat sink, macro-channel heat sink, conductively cooled heat sinks, particle image velocimetry, μ -MIM

References

1. Leers, M. et al, "Expansion-matched passively cooled heatsinks with low thermal resistance for high-power diode laser bars", Proceedings of SPIE, Volume 6104 pp. 20-29, 2006.
2. Westphalen, T. "Untersuchungen von Hochleistungs-Diodenlaserbarren mittels Einzelemittler aufgelöster Charakterisierung", Diploma thesis at the chair of TOS RWTH-Aachen, 2006
3. Tomm, J. "Quantum-Well Laser Array Packaging", McGraw-Hill Professional, 2006
4. Johnson, J.L.; German, R.M.: "Chemically activated liquid phase sintering of tungsten copper", Int. J. Powder Metall., 30, 1994, 1, pp 91-102
5. E. Kny: "Properties and Uses of the Pseudobinary Alloys of Cu with Refractory Metals", Proceedings of the 12th Int. Plansee Seminar, 1989, pp 763-772
6. T. Hartwig, T.-V. Duong: Miniaturisation of MIM, Proc. EuroPM 2000 - 2nd European Symposium on Powder Injection Moulding, München 2000, pp 229-234
7. T. Hartwig, A. Rota, V. Duong: Micro Powder Metallurgy for Micropart Production, Proc. 6th Int. Conf. on Micro Electro, Opto, Mechanical Systems and Components, Potsdam, Editoren H. Reichl, E. Obermeier, VDE Verlag GmbH, Berlin 1998, pp 539 – 544