Water cooled, hard soldered kilowatt laser diode arrays operating at high duty cycle.

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ABSTRACT

High brightness laser diode arrays are increasingly found in defense applications either as efficient optical pumps or as direct energy sources. In many instances, duty cycles of 10-20% are required, together with precise optical collimation. System requirements are not always compatible with the use of microchannel based cooling, notwithstanding their remarkable efficiency. Simpler but effective solutions, which will not involve high fluid pressure drops as well as deionized water, are needed. The designer is faced with a number of challenges: effective heat removal, minimization of the built-in and operational stresses as well as precise and accurate fast axis collimation. In this article, we report on a novel laser diode array which includes an integral tap water cooling system. Robustness is achieved by all around hard solder bonding of passivated 940nm laser bars. Far field mapping of the beam, after accurate fast axis collimation will be presented. It will be shown that the design of water cooling channels, proper selection of package materials, careful design of fatigue sensitive parts and active collimation technique allow for long life time and reliability, while not compromising the laser diode array efficiency, optical power density, brightness and compactness. Main performance characteristics are 150W/bar peak optical power, 10% duty cycle and more than 50% wall plug efficiency with less than 1° fast axis divergence. Lifetime of 0.5 Gshots with less than 10% power degradation has been proved. Additionally, the devices have successfully survived harsh environmental conditions such as thermal cycling of the coolant temperature and mechanical shocks.

Keywords: laser diode array, high power, QCW, high duty cycle, built-in cooling, tap water, hard soldering, fast axis collimation

1. INTRODUCTION

Optical pumping of solid state lasers as well as directed energy applications require in many instances high-brightness laser diode arrays (LDA) operating at a duty cycle of 10-20%. Under such high duty cycle operation, passive (conductive) cooling is restricted, while micro-coolers using de-ionized cooling water can have a negative impact on the LDA reliability.

A variety of power density and brightness requirements can be addressed by conductive cooling. However, conductively cooled devices are limited to duty cycles not exceeding 4%, with a practical limit of 2%, and to pulse widths not exceeding 300 µs – 400 µs.

Microchannel cooling, on the other side, allows for high power LDA operation in CW mode due to its excellent heat extraction capacity. Similarly, hard pulse cooling requirements can also be addressed by the use of microchannel coolers. While offering excellent thermal performance, the use of microchannel coolers suffers from several drawbacks. Typically, microchannel coolers cause the electrical path to come in direct contact with the coolant. This requires the use of deionized water in order to suppress the flow of electricity through the coolant lines. Usually, water with a resistivity of the order of 0.5 MOhm•cm is used to cool microchannel LDA mounts. The de-ionized water leads to electrochemical corrosion of the microchannel coolers, their clogging with the
corrosion products and cooler leaks\(^1\), which, in turn, cause severe reliability issues. SCD’s LDAs cooled by non-de-ionized tap water\(^2\) eliminate the above failure mechanisms, albeit they still carry the special coolant requirements required by most microchannel cooler designs, i.e., water filtration for particles >10 \(\mu\)m - 15 \(\mu\)m, high coolant flow rate, large inlet-to-outlet coolant pressure drop and high cost of microchannel mounts.

The key building block of each LDA is a laser bar soldered to a heat spreader (HS) (Fig. 1). The submount’s heat sinking ability is largely determined by two critical cross-sections. The first cross-section is parallel to the laser bar \(p-n\) junction and having an area of \(L_c \times 1\,\text{cm}\), where \(L_c\) is the cavity length of a standard 1 cm laser bar. The second cross-section is perpendicular to the \(p-n\) junction and has an area of \(w \times 1\,\text{cm}\), where \(w\) is the HS width, the heat flowing laterally to an adjacent heatsink (whether conductively or actively cooled). Table 1 summarizes the estimated average heat fluxes through the two cross-sections for typical laser bar powers, HS widths and operating duty cycles, assuming a laser bar wall-plug efficiency of 50%.

<table>
<thead>
<tr>
<th>Duty cycle</th>
<th>Power (per bar)</th>
<th>Bar cavity length</th>
<th>HS width</th>
<th>Average heat flux, Section 1</th>
<th>Average heat flux, Section 2</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>(W) mm</td>
<td>(W/cm^2) mm</td>
<td>(W/cm^2) mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>80 (peak) 0.6</td>
<td>0.25</td>
<td>8</td>
<td>19</td>
<td>Passive</td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>80 (peak) 1.0</td>
<td>0.25</td>
<td>5</td>
<td>19</td>
<td>Passive</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>100 (peak) 1.0</td>
<td>0.25</td>
<td>20</td>
<td>80</td>
<td>Passive</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>120 (peak) 0.6</td>
<td>1.0</td>
<td>40</td>
<td>24</td>
<td>Passive</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>200 (peak) 1.2</td>
<td>1.0</td>
<td>33</td>
<td>40</td>
<td>Passive</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>150 (peak) 1.2</td>
<td>1.0</td>
<td>50</td>
<td>60</td>
<td>Passive</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>150 (peak) 1.2</td>
<td>1.5</td>
<td>62.5</td>
<td>50</td>
<td>Built-in</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>150 (peak) 1.2</td>
<td>1.5</td>
<td>125</td>
<td>100</td>
<td>Built-in</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>150 (peak) 1.2</td>
<td>1.5</td>
<td>188</td>
<td>150</td>
<td>Built-in</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>150 (peak) 1.2</td>
<td>1.5</td>
<td>250</td>
<td>200</td>
<td>Built-in</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>50 1.0</td>
<td>1.0</td>
<td>500</td>
<td>500</td>
<td>Microchannel</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>80 1.5</td>
<td>1.5</td>
<td>533</td>
<td>533</td>
<td>Microchannel</td>
<td></td>
</tr>
</tbody>
</table>
The typical heat fluxes both from the bar to adjacent HS (section 1) and from the HS to underneath heatsink (section 2) for low duty cycles regimes of 2%-5% can be effectively removed by conduction. However, for higher duty cycles, the conduction heat transfer is not effective, and active cooling is required.

In this work, we present the results of the development and characterization of a novel LDA package for operation at high duty cycles. The main features of the package are:

- Built-in cooling system
- No-filtration-needed tap-water coolant
- CTE-matched parts and all-hard-solder bonding, ensuring very high immunity to thermo-mechanical fatigue associated with prolonged pulse operation and/or harsh environmental thermal cycling
- High-power 940 nm facet-passivated bars emitting 150 W – 170 W of optical power with low degradation rates
- High brightness output enabled by high-precision fast-axis collimation
- Small footprint and compact design
- Easy installation and handling.

2. DESIGN AND MANUFACTURING

Package design

Our LDA stack incorporating ten 10 mm laser bars with collimating optics is shown in Fig. 2.

![Figure 2. Photograph of the collimated LDA stack](image)

The following issues, often requiring engineering trade-offs, were carefully addressed in the course of the LDA design and manufacturing:

- Reduction of packaging-induced strain
- Minimization of temperature rise
- Reduction of the coolant pressure drop
- Low cost manufacturability of all parts

Fig. 3 gives a cross-sectional schematic of the LDA stack. The base of the stack can be made from a non-conducting, non-metal material. As its contribution to cooling is negligible, the main considerations for the choice of base material were easy machining and low cost. The cooler assembly is made from a single block of CuW material and includes a pin-fin convection cooler and tabs for lens attachment. All bar-HS submounts are bonded together to form a rigid stack subassembly that we call the Robust Head (RH). The RH features non-conducting heat-spreaders at the bottom of the
subassembly, allowing bar-HS submounts to be electrically isolated from the cooler. In order to reduce the packaging-induced strain, we have selected HS and cooler materials that are CTE matched to GaAs bars. All bonding between these parts is performed using our AuSn hard solder technology.

![Cross-sectional view of the LDA stack.](image)

**Simulation**

During LDA operation, the waste heat generated by the laser bars is transferred to the adjacent HS by conduction, then the thermal path continues from the HS to the cooler, and finally from the cooler to the coolant by forced convection. The overall heat flow in the LDA system thus poses a multi-parametric three-dimensional problem involving a complex geometry. In order to simplify the thermal model, the simulation was performed in two stages: first for convective cooling and then for the conduction heat transfer in the RH.

When removing substantial heat fluxes by convection cooling from a compact device, pin fins are traditionally used. Usually, pin fins are of round shape. As the pin's radius and pin spacing approach 0.1 mm, the efficiency of convective cooling is improved because of the increased pin surface area. However, the manufacturing of round pins is rather expensive and a small pin spacing dictates the use of finely filtered coolant.

We have decided to analyze only square pins of 0.3 mm – 0.4 mm width with a spacing equal to the pin width. Multiple simulation runs were performed in order to establish an appropriate choice of cooler pin length and width. The cooler geometry used in coolant flow and heat transfer simulations is presented in Fig. 4.

The simulation key input data were:

- Coolant inlet temperature of 25°C;
- Coolant flow rate of 2 L/min;
- Cooler pin structure as shown in the inset of Fig. 4;
- Square pin shape with width $a = 0.3 \text{ mm} - 0.4 \text{ mm}$;
- Pin length, $L = 2-5 \text{ mm}$;
- Pin spacing, $b = a$;
- Heat load of $70-90 \text{ W/cm}^2$ on the top surface of the cooler.
The calculated difference between the maximum temperature of the cooler's top surface and coolant inlet temperature (temperature rise) as a function of pin length is shown in Fig. 5, whilst Fig. 6 plots the dependence of the coolant pressure drop. At a fixed coolant flow rate, the temperature difference in Fig. 5 is reduced with reducing pin length, since short pins intensify the convective heat transfer. At the same time, short pins cause a significant increase in the coolant pressure difference (Fig. 6). Pin widths of 0.4 mm – 0.5 mm were found to have little effect on both the maximum temperature rise and pressure drop.
The typical modeled temperature distribution over the top surface of the cooler is presented in Fig. 7.

The temperature distribution across the top surface of the cooler is fairly uniform to within 4°C – 5°C, which reduces the temperature-dependent lasing wavelength variation across the LDA stack.

The conductive heat transfer from the laser bar to the HS was simulated for bar – HS submounts (Fig. 1) within the context of the RH. The calculated maximum temperature rise (i.e., the difference between the maximum temperature of laser bar and the temperature of top surface of the cooler) is presented in Fig. 8 and Fig. 9. The temperature rise
drops by about 6°C as the bar cavity length increases from 0.6 mm to 1.5 mm at a fixed laser bar power of 150 W under 10% duty cycle operation (Fig. 8).

The influence of the HS width on the temperature rise for thick HS is relatively weak (Fig. 9): the temperature is reduced by only <2°C as the HS width is varied from 1.2 mm to 1.8 mm for a fixed laser cavity length of 1.2 mm when operated under the above conditions.

![Temperature rise vs bar length (HS width 1.5 mm)](image)

**Figure 8. Temperature rise for different bar length.**

![Temperature rise vs HS width (bar cavity length 1.2 mm)](image)

**Figure 9. Temperature rise as a function of HS width.**

Passivated laser bars at 940 nm.

SCD’s product-grade QCW 200 W 9xx nm bars were used to manufacture the simulated LDA stack. The bars have a cavity length of 1.2 mm and 80% filling factor with 50 emitters designed for optimal power efficiency at high current loads of 150 A – 200 A. The target wavelength of 940 nm was obtained by adjusting the indium content of the InGaAs active layer of the wafer structure. The aluminum concentration in the AlGaAs p-cladding layer was increased with a view to suppressing the carrier overflow and achieving a linear \( L-I \) curve under high duty-cycle operation.

One of the main limitations to the long-term reliability of Al-containing laser bars at 9xx nm wavelengths is the facet failure due to Catastrophic Optical Damage (COD). COD is initiated near the laser facet by the re-absorption of photons at non-radiative recombination centers formed by native oxides of Al, Ga and As as well as by lattice defects.
A special facet passivation process was developed, whereby the laser bar facets are treated prior to facet mirror coating, with the resulting bars exhibiting extended reliability under high-power operation.

Lens mounting

Our active alignment method and the equipment used were reported elsewhere\(^4\). Aspherical microlenses of 1.5 mm width are attached to each of the 10 bars in the LDA stack of a 1.75 mm pitch. During the alignment procedure, the lens is positioned in front of the laser bar with the whole LDA stack powered on. The precision alignment of the lens requires a translation stage with three directional degrees and two rotational degrees of freedom, along with a simultaneous collection and analysis of the far-field intensity distribution of the emitted radiation. Once an optimum alignment is achieved, optical-grade epoxy is applied affixing the lens to the support tabs. The automated micro-lens attachment procedure is highly reproducible and, combined with the use of high-quality collimation micro-lenses, allows to reduce the fast axis divergence to values as low as 10 mrad at >90% power with minimal loss.

3. STACK PERFORMANCE

The manufactured stacks were routinely tested at up to a 170 A operating current at 10% duty cycle, with a 500 μs pulse width and coolant flow rate of 2 L/min at an inlet temperature of 25°C. The typical performance of the collimated stack comprising 10 bars at 940 nm wavelength is presented in Fig 10. The LDA's wall-plug efficiency of >50% is maintained over a current range of 60 A – 170 A, reaching its maximum of 60% at 110 A. At 170 A, the LDA emits over 1.6 kW of QCW power. Notwithstanding the relatively low coolant flow rate of 0.2 L/min per bar and the high waste heat power of 150 W, no thermal rollover is observed indicating an excellent cooling capability of the LDA stack.

![Collimated stack: power and efficiency](image)

Figure 10. Total power output and wall-plug efficiency of the collimated LDA stack.

The spectral distribution of the collimated LDA stack is presented in Fig. 11. The spectrum width at half maximum is about 3 nm, with almost 100% of the optical power contained in a spectral window of 6 nm, which confirms good cooling uniformity over the entire emitting area of the stack.
The collimation quality of the LDA stack was measured with a ceramic slit of 35 mm × 2 mm located in the focal plane of the collecting lens. The slit dimensions correspond to the angle, $\alpha = 170$ mrad, of the slow axis divergence, and to the angle, $\beta = 10$ mrad, of the collimated fast axis divergence. The optical power was measured with a power meter positioned just behind the slit. With 91% of the total power traversing the slit, the stack brightness in a solid angle

$$\Omega = 4 \sin^{-1}(\sin \frac{\alpha}{2} \sin \frac{\beta}{2}),$$

exceeds 450 kW cm$^{-2}$sr$^{-1}$.

Reliability testing of high power lasers is frequently reported in the literature. However, there is scarce lifetest data on collimated stacks, as the reliability of these devices is affected by the prolonged exposure of coated micro-optics to a very high power density as well as by the residual retro-reflection into the laser bars.

Two collimated stacks were operated for 400 M shots in accelerated ageing regime: a constant operating current of 160 A and 10% duty cycle at a coolant inlet temperature of 45˚C (Fig. 12). The linear power degradation was < 2% over almost 400 M shots.

The non-accelerated lifetime at a nominal temperature of 25˚C can be estimated with the use of an Arrhenius-type acceleration factor, $AF$.:
\[ AF = \exp \left( \frac{E_a}{k} \left( \frac{1}{T_0} - \frac{1}{T} \right) \right), \]

where:
- \( E_a \) – activation energy,
- \( k = 8.63 \times 10^{-5} \text{ eV/°K} \) - Boltzman constant,
- \( T_0 \) - reference temperature in degrees of Kelvin,
- \( T \) - test temperature in degrees of Kelvin.

Taking a rather conservative \( E_a \) estimate of 0.4 eV \(^6\)\(^7\), a lifetime of >1 Gshot at 2 % power degradation and a coolant temperature of 25°C can be expected.

Environmental testing is employed to examine the ability of an LDA stack to preserve its electro-optical characteristics under exposure to thermal cycling, thermal shocks, mechanical vibration and mechanical shocks. Extreme environmental conditions are part of the testing protocol and serve to identify any latent LDA failures that may not transpire during LDA's initial operation and storage. For example, thermal cycling and thermal shock can expose, in two different mechanisms, CTE mismatch-related issues in the packaging design of the LDA. Such CTE issues cause internal stresses at the interface between the materials in the package resulting in irreversible damage either to the assembly (e.g., solder or glue) or critical parts (laser bar, heat sink, etc.).

Three stacks were extensively tested under harsh environmental conditions. The results of the collimated power measurements are presented in Fig. 13. The legend for the figure is as follows:

- Characterization #1 – initial characterization prior to the environmental test;
- Characterization #2 – after storage high temperature test from +33°C to +85°C;
- Characterization #3 – after storage low temperature test at -40°C;
- Characterization #4 – after vibration test from 20 Hz to 2000 Hz at 20g peak acceleration;
- Characterization #5 – after mechanical shock at 500g acceleration;
- Characterization #6 – after 45 thermal cycles at temperatures from -20°C to +45°C;
- Characterization #7 – after 200 thermal cycles temperatures from -10°C to +45°C.

All three stacks have successfully passed the above environmental tests, with only slight power variations well inside the measurement and reproducibility errors of the equipment used.

![Figure 13. Results of environmental testing.](image-url)
4. CONCLUSION

A reliable high-power QCW diode laser stack capable of operating at high duty cycles of up to 20% has been successfully developed, manufactured and tested. By employing an appropriate design of water cooling channels, careful choice of packaging materials, proper design of critical parts, and active optics alignment, we have demonstrated actively-cooled collimated laser diode arrays with extended lifetime and reliability, without compromising their efficiency, optical power density, brightness or compactness.

An optical power output of 1,600 W at 10% duty cycle, with close to 60% wall plug efficiency and <1° fast axis divergence, was demonstrated. An accelerated lifetime of >0.4 Gshots with <2 % degradation was experimentally proven at a 45°C coolant inlet temperature. A lifetime of >1 Gshots at 25°C coolant inlet temperature is expected.

The laser diode arrays were also successfully tested under harsh environmental conditions, including the thermal cycling of the coolant temperature between -20 °C and 45 °C and mechanical shocks at 500g acceleration. The results of both performance and reliability testing bear out the effectiveness and robustness of SCD's LDA stacks for high-power, high duty-cycle applications.

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