Reliable QCW diode laser arrays for operation with high duty cycles

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ABSTRACT

We present performance and reliability data of high-brightness QCW arrays and stacks with a custom, compact and robust design for an operation at high duty cycles. The presented designs are based on single diodes consisting of a 10mm laser bar which is AuSn soldered between two WCu submounts, as well as 10mm laser bars AuSn soldered to WCu submounts or Indium directly mounted to micro channel heat sinks. The available optical output strongly depends on the wavelength and fill factor of the laser bars as well as the duty cycle, the base plate temperature and the thermal performance to handle the thermal loss. Based on the applications requirements, conduction cooled stacks can be used in conjunction with thermo-electric coolers, water manifolds, or forced air cooling. For most demanding requirements at highest peak power and duty cycle, micro channel coolers with conditioned DI water offer the best cooling performance.

Keywords: QCW, laser diode arrays, hard soldering, reliability

1. INTRODUCTION

Quasi-continuous wave (QCW) laser bars and arrays have found a wide range of industrial, medical, scientific, space and military applications including range finding and target designation with a broad variety of pulse energies, pulse durations and beam qualities. The demand regarding optical output power, repetition rate and duty cycle strongly depends on the application.

Quasi-continuous-wave operation of a laser diode means that its pump source is switched on only for certain time intervals being short enough to reduce thermal effects significantly, but still long enough that the laser process is close to its steady state, i.e. the laser is optically in the state of continuous-wave operation. Usually the duty cycle (percentage of “on” time) is in the range of a few percent, thus strongly reducing the heating and any related thermal effects, such as thermal lensing [1] and damage due to overheating [2]. Therefore, QCW operation allows for the operation with higher output peak powers at the expense of a lower average power. Thus, the cooling arrangement of QCW arrays is usually designed for a small heat load, and the emitters can be more closely packed in order to obtain higher power densities resulting in QCW array sizes, i.e. volumes, being much smaller compared to usual stacks of micro-channel coolers or CS mounts [3].

Coherent/DILAS Diodenlaser GmbH has manufactured QCW laser diode arrays (LDAs) for short pulses of 1ms or less in many configurations for more than a decade. New applications require even higher duty cycles and pulse lengths, increased operating temperatures and less or no cooling combined with the compact design of usual QCW arrays [4,5]. For this purpose, we have developed a modular, compact and robust LDA design which can be easily adapted to a variety of applications in number of bars, the size and the material as well as the cooling concept of the ceramic base plates.

In this paper, we will report on performance and reliability data of three high-brightness QCW arrays based on single diodes consisting of a 10mm laser bar that is AuSn soldered to one or between two CuW submounts as well as Indium soldered bars to a micro channel heat sink. Arrays and stacks of up to 60 laser bars can be connected to custom sized modules in different designs, horizontally and vertically stacked, housed or unhoused in a variety of environmental protection classes. The available optical output power strongly depends on the wavelength and fill factor of the laser bars as well as the duty cycle, the base plate or coolant temperature and the thermal conductivity of the applied materials.

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2. GENERAL ARRAY DESIGN AND MANUFACTURING

A schematic drawing of the QCW LDA under consideration is shown in the left part of Fig. 1. The key feature of this design is a customized number of individual laser bars (marked with blue color) sandwiched between two thermal expansion matched submounts consisting, e.g., of copper tungsten (shown in orange color). They are arranged on an electrically insulating ceramic base plate (gray color) with a custom electrical contact structure (yellow color) using a low-melting solder. The custom size and shape of the ceramic base plate allows for an easy adaption to different active or passive cooling elements (brown color). An important benefit of this design is the improved thermal conductivity via the backside cooled ceramic plates. The small element shown in red color is an NTC (Negative Temperature Coefficient Thermistor) for temperature monitoring during operation. The black element is a Z-Diode to protect against reverse polarity. Both are optionally available and can be retrofitted. The photographic inset in the right part of Fig. 1 gives an impression of the original size of one identically packaged laser bar sandwich on another custom base plate consisting of the same materials.

Several items of this compact and robust array design allow for a reliable pulsed operation with high duty cycles and with increased base plate temperatures:

- The usage of laser bar sandwiches leads to an increased bar-to-bar pitch resulting in both thermal as well as mechanical decoupling of neighboring laser bars.
- The submounts act as heat spreaders, i.e. each laser bar is thermally connected to the ceramic base plate. The waste heat can be removed more efficiently because it is spread over a larger area resulting in decreased junction temperatures and, thus, allowing reliable laser operation at higher duty cycles in a broader temperature range.
- The individual contacting of each laser bar minimizes packaging related electrical resistance, thus reducing the waste heat induced at electrical contact areas compared to other stack geometries.
- Compared to very dense arrays without any submounts between the laser bars, each laser bar sandwich can be tested and selected before it is soldered to a base plate in a second step.
- The bars are soldered with AuSn in order to avoid thermo- [6] and electromigration [7] of soft solders like indium limiting the life time of QCW arrays.
- Each laser bar in the array is sandwiched between two thermal expansion matched submounts (e.g. copper tungsten) in order to reduce the packaging induced deformation stresses in the laser bar as well as its smile.
- The special array design allows for an easy and efficient optional beam shaping using fast-axis collimation (FAC) lenses for all bars as well as slow-axis collimation (SAC) lenses that are specifically designed for bars with low fill factor. In the latter case, fiber coupling becomes possible.
All ceramic materials used for base plates ensure high electrical insulation between the laser bar(s) and the body of the LDA up to 500 V, AC.

Due to the modularity of the LDA design, the technology is easily scalable and can be adapted to a variety of applications. It allows the use of ceramic materials with improved thermal conductivity and different heat sinks underneath the base plate based upon the customer’s needs. The improved thermal management and the robust, light weight design make these arrays particularly interesting for portable and mobile applications which are often limited in cooling capacity due to size and weight constraints. We have called LDAs with the above described general design C-stacks.

Coherent/DILAS Diodenlaser GmbH offers a broad variety of C-stacks for custom base plate sizes from 1 to 15 laser bars with cavity lengths up to 2.0 mm, with wavelengths between 766 and 1550 nm including multi-wavelength stacks, with a minimum bar-to-bar pitch of 1.7 mm and different cooling concepts including air and thermo-electrical cooling. Stacks with multiple wavelengths due to customer’s requirements are also possible.

3. GENERAL MICROCHANNEL-COOLER DESIGN AND MANUFACTURING

A schematic drawing of the microchannel-cooler is shown in the left part of Fig. 2. The key feature of this design is a microchannel-heatsink (marked with red color). The laser bar (marked with white color) is sandwiched between the microchannel-cooler (P-Side) and the N-Side terminal (black color) separated by an insulator (yellow color). Using a low-melting solder. An important benefit of this design is the liquid cooling via micro-channels close beneath the laser bar. The photo in the right part of Fig. 2 shows a similarly packaged laser bar with FAC micro optic.

![Figure 2. Schematic drawing of microchannel-cooler (left). Picture of actual laser bar on a similar micro channel cooler with-fast axis collimation lens.](image)

- The microchannel-cooler acts as heat spreader and P-terminal, i.e. the laser bar is in close proximity to the micro channels. The waste heat can be removed more efficiently because it is liquid-cooled resulting in decreased junction temperatures and, thus, allowing reliable laser operation at higher duty cycles in a broader temperature range.
- The individual contacting of each laser bar results in a minimum contribution of packaging to the electrical resistance, reducing the waste heat from poorer transition resistances compared to other stack geometries.
- Compared to other dense arrays, single micro-coolers can be tested, selected and easily exchanged.
- In order to avoid thermo- [6] and electromigration [7] of soft solders like indium limiting the life time of QCW arrays. The bars can also be soldered with AuSn via a WCu submount to the copper micro-cooler but increasing the minimum pitch in fast axis from 1,68mm up to 2,2mm.
- Similar to the passively cooled stack shown above, the special stack design allows for an easy and efficient optional beam shaping using fast-axis collimation (FAC) for all bars as well as slow-axis collimation (SAC) especially for bars with low fill factor. In the latter case, fiber coupling becomes possible.
- The so called E-Type devices can be easily stacked vertical without any additional connectors. Horizontal stacking for e.g. solid state laser pumping can also be realized by using standardized connectors.
4. COOLING CLASSIFICATION

4.1 C-Stack conductively cooled

Passively cooled modules lack any internal liquid cooled. They have a dedicated thermal interface and usually the baseplate surface where the module will be fixed has a specified temperature to achieve the required electro optical values. The thermal losses can be conveyed by air cooling, by a liquid (tab-water) cooled manifold, Peltier-elements or heat-pipes for example. They are usually used for low cost / low power applications, or in an environment where no liquids are allowed or available, or where only unconditioned water is available.

4.2 C-Stack actively cooled

Large cooling structures (macro channels) are used to flow coolant the back plane of the stack, allow the use tab water. The laser bar device, for example WCu sandwiched 10mm laser bar, is mounted to a metalized ceramic baseplate to provide the current path and isolate the devices among each other. The requirement to the coolant is low and will fulfilled by tab-water and a particle filter. This is suitable for higher power and duty cycle and requires a minimum controlling the flow.

4.3 E-Type actively cooled

The active cooling technique represents the most effective solution to dissipate a maximum of thermal loss. The laser bar is directly mounted in close proximity to the water channels with indium solder or AuSn soldered via a thermal expansion matched submount. Due to the electrical potential present on the heatsink, DI-water is required and both PH-value and flow rate need to be maintained within specified limits. A particle filter is required to protect the micro-channels from contamination.

5. APPLICATION AND CLASSIFICATION

Depending on the applications boundary conditions, e.g. power, pulse duration, cost, weight, ambient temperature, and the availability of liquid cooling, different heatsink-, cooling- and packaging-concepts are available. They can be combined with all available wavelengths and chip designs for different industrial, defense, medical, cosmetic or scientific demands. Regarding the demand and cooling concept, a variety of QCW conditions differing in frequency, duty-cycle and therefore pulse duration can be realized. The chart below provides an overview of the maximum optical power and pulse duration for various packaging types. The table below tries to give an impression how maximum power and pulse duration are impacting oneself and different heat sink and cooling concepts affecting this behavior.
Figure 5. Overview of QCW-Modules with different configurations, at different frequencies, wavelengths, and duty cycles comparing peak power versus pulse duration and applied cooling method.

6. STACK PERFORMANCE

In the following, we present performance and reliability data for stacks with one to 80 laser bars for different applications. Applying bars with an emitter pitch of 500 µm provides the opportunity for building small fiber coupled modules with high QCW output power. The available optical output power depends on the wavelength and fill factor of the laser bars as well as on the duty cycle, the base plate temperature and the thermal conductivity of the applied materials. The smile (peak to valley) of all sandwiched laser bars mentioned in this sections is less than 1.0 µm. The packaging processes for laser bars to heat sinks or micro channel coolers are fully- or semi-automated and therefore suited for high volume production.

6.1 Conductively cooled Laser Stack

Conductively cooled laser stacks as described in 4.1 are built in different standard and customized designs from 1 bar up to 15 bar modules. The pitch of 1.7mm provides the opportunity to add FAC and SAC micro optics for individual beam forming. The LI curve shown below is exemplary taken from a standard 1x8 laser bar module which has a total optical power of 8x550W=4.400W @ 10Hz, 1.2% duty-cycle, @ 20°C base plate temperature.
6.2 Indirect actively cooled LDAs with up to 12 laser bars

In this section, we present the performance of LDAs containing up to 12 laser bars with fill factors of 50% and more and with a cavity length of 1500 µm mounted onto a custom designed AlN ceramic base plate. Figure 6.2.1 shows an LDA of up to 12 laser bars with a macro-channel cooler between two ceramic plates. The right image shows the bottom view of the heat sink with large water in- and outlets. The main advantage of this design is an efficient and potential-free macro-channel cooler, allowing the usage of tap water. In the following, this design is considered for applications demanding pulse lengths of up to 400ms (e.g. hair removal) from compact QCW stacks.
Figure 6.2.1. LDAs of 8 laser bars with a macro-channel cooler between two ceramic plates. The left image shows the bottom view of the heat sink with large water in- and outlets. Geometrical sizes: $28.8 \times 13.8 \times 7.3 \text{ mm}^3$ (including the laser bars).

For some applications like hair removal, longer pulses are required. Figure 6.2.2 shows the electro-optical performance for various repetition rates and duty-cycles corresponding to a pulse width from 50ms up to 400ms. For these pulse conditions, modules achieve an optical output power per bar up to 110 W at a drive current of 120A. The table below shows clearly the influence of higher duty cycles and longer pulses reducing the maximum power.

![Graph showing comparison of maximum power at different operating conditions](image)

Figure 6.2.2. Comparison of the maximum power at different operating conditions with pulse lengths up to 400ms 1x8 module

10% 1Hz is a typical operating condition used for nuclear fusion. 500W maximum power per bar can be achieved in this very compact and robust standard package with FAC micro lenses for beam shaping. The lower maximum power at 400Hz 8% duty cycle is caused by the higher duty cycle. Although the pulse duration (0.2ms) is shorter, the module heats up more because of the overall shorter cool-down and longer on-times.
The thermal performance and behavior of the cooling concept and material is not only limiting the maximum power and pulse width of a module but also affect the wavelength shift over the operating current range. Increasing the current for higher optical power is moving the wavelength to the red, is a well-known behavior. For an indirect actively cooled module the wavelength increase is less than for a passively cooled module but larger compared to an actively cooled E-Type micro-cooler. For operating conditions shown above, the wavelength shift is around 1nm per 30A.
6.3 Actively cooled modules

Actively cooled modules with Indium soldered laser bars directly mounted to the heat-sink represent the design with the most efficient thermal management. This design is used for high power and high duty-cycle operation, for example nuclear fusion research programs. The lowest pitch of 1.68mm in fast axis and less than 12mm in slow axis, allows high power density as well as FAC and SAC beam shaping if necessary, although a high fill factor may limit the use of SAC lenses. Vertically or horizontally aligned modules in different standard and customized designs, housed and unhoused are available with up to 80 laser bars vertical stacked. Picture 6.3.1 shows the PI-curve and efficiency for a single device 630W @ 940nm, 400Hz, 8%, 0.2ms, 25°C, 7l/h.

![PI-curve and efficiency](image)

Figure 6.3.1. LI curve and efficiency of one micro-channel cooler with an directly Indium soldered 940nm laser bar at 400Hz, 8% duty cycle, 0.2ms.
Figure 6.3.2. Wave length shift at different current levels for one micro-channel cooler with an directly Indium soldered 940nm laser bar at 400Hz, 8% duty cycle and 0,2ms pulse width with an resulting $R_{th}=0.06K/W$ and a wave length shift of 1nm per 45A which is the lowest in this comparison.

Figure 6.3.3. High energy panel consisting of 8 stacks with 60 laser bars including micro optics for fast axis collimation. Each stack can be individually addressed with a diode laser controller. They are mounted to a common manifold but can optionally be individually supplied with coolant. The front side is NiAu plated for back reflection protection.

High energy panels in different customized designs for different applications are available and currently worldwide in use. For example panels with 10 stacks with 50 laser bars, each 500W @808nm, in summary 500 laser bars with a total optical power of 250KW per panel or more can be easily realized. For this example the emission size is $<120\text{mm (SA)} \times <93\text{mm (FA)}$, Wavelength tolerances $\pm 1.5\text{nm}$ can be achieved by selecting and adjusting the flow rate and or temperature for each stack or defined groups.
Figure 6.3.4 shows the influence of the distance between heat source and cooling interface as well as the material. The LI curve of the E-Type heat sink is steeper and achieves more power than the tab water operated indirect actively cooled C3 module. The main difference between these two modules is the use of WCu sub mounts for the C-type module, where the laser bar is AuSn soldered and the ceramic isolator with an thermal conductivity of around 170W/m/K, compared to the indium mounted E-type. Another difference is the distance to the cooling interface, which is much shorter for the E-type module, where the laser bars P-side is directly Indium soldered to the copper micro cooler close to the Cu cooling surface with a thermal conductivity of 394W/m/K.

7. SUMMARY AND OUTLOOK

We have presented performance and reliability data of high-brightness QCW arrays with a custom, compact and robust design for an operation at high duty cycles. These so-called C-stacks are based on single diodes consisting of a 10mm laser bar that is AuSn soldered between two CuW submounts. LDAs of up to 15 diodes were connected to ceramic base plates on different heat sinks, matching the demand of various applications. We have also shown 10mm laser bars AuSn soldered to WCu submount or Indium directly mounted to a Cu micro channel heat sink. The available optical output power was shown to be strongly dependent on the wavelength and fill factor of the laser bars as well as on the duty cycle, the base plate temperature and the thermal conductivity of the applied ceramic materials.

For a conduction-cooled LDA containing up to 15 laser bars with 80% fill factor and a cavity length of 1500 µm emitting at 980 nm we have demonstrated an output power of 550W per bar (10Hz, 1.2% duty cycle, 1.2ms) at a base plate temperature of 20°C and over 1000h burn-in, which is still running. It was shown, that these C-stacks can be operated with minimal cooling. Together with their robust and compact design and with the possibility of an easy beam shaping due to the low fill factor of the used laser bars, they are very interesting for pumping applications in the defense area.
Indirect actively cooled C-Stacks containing up to 12 laser bars with 50% fill factor and a cavity length of 1500 µm emitting at 808 nm were mounted onto potential-free macro-channel coolers allowing the usage of tap water and an operation with duty cycles of up to 55% or pulse lengths of up to 400 ms (e.g. hair removal). Optical output power of 870 W (2 Hz, 20% duty cycle, 100 ms) at a base plate temperature of 25°C has been demonstrated. Ongoing reliability tests at an LDA emission of 42 J/cm² suggest life time expectations of more than 8000 hours of operation. In a conduction-cooled version, a LDA containing 8 laser bars with 80% fill factor and a cavity length of 1500 µm emitting at 940 nm achieved more than 2500 W (10 Hz, 1% duty cycle, 1 ms).

Actively cooled E-Type heat sinks showed the best thermal performance of all investigated modules. We achieved 630W with a 940nm laser bar at 400Hz, 8% duty cycle, 0.2ms pulse width. Scalable for high power panels for nuclear fusion programs with multi KW power.

The investigated stacks allow for an easy and efficient beam shaping using fast-axis collimation (FAC) for all bars as well as slow-axis collimation (SAC) especially for bars with low fill factor. In the latter case, fiber coupling becomes possible.

The presented technology also offers scalability and modularity of the LDA designs allowing custom products with respect to user applications. It allows the use of ceramic materials with improved thermal conductivity and different heat sinks below the base plate based upon the customer’s needs. The improved thermal management and the robust, light weight design make these arrays particularly interesting for portable and mobile applications which can often only provide a minimum of cooling capacity.

The work on the C-stack design as well as E-Type heat sinks with respect to materials, FA and SA pitch, processes and structures is continued, and even better results can be expected in the near future.

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