Reliable QCW diode laser arrays for operation with high duty cycles

Heiko Kissel*, Wilhelm Fassbendera, Jens Lotza, Kim Alegria b, Tobias Koenning b, Dean Stapleton b, Steve Patterson b, and Jens Biesenbach a

a DILAS Diodenlaser GmbH, Galileo-Galilei-Str. 10, D-55219 Mainz, Germany; 

b DILAS Diode Laser, Inc., 9070 S. Rita Road, Suite #1500, Tucson, AZ 85747, USA

ABSTRACT

We present performance and reliability data of high-brightness QCW arrays with a custom, compact and robust design for an operation with high duty cycles. The presented designs are based on single diodes consisting of a 1cm laser bar that is AuSn soldered between two CuW submounts. Arrays of up to 15 diodes as well as one single diode are connected to ceramic base plates on different heat sinks. The available optical output power is shown to be strongly depending 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. Operation at increased heat sink temperatures up to 45°C is possible without active water cooling or conduction cooling with the help of Peltier elements. Using an array of 15 bars at 980 nm with 20% fill factor and 2 mm cavity on standard ceramics, we can reach an optical output power of 1150 W at 45°C base plate temperature operating the array with 15 Hz and 15% duty cycle. Novel materials allow for more efficient operation and higher optical output powers.

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 in pulse energy, pulse duration and beam quality. 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) takes a few percent, thus strongly reducing the heating and all 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].

DILAS Diodenlaser GmbH has manufactured QCW laser diode arrays (LDAs) for short pulses of 1 ms 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 together with the compact design of usual QCW arrays [4,5]. For this purpose, we have developed a custom, compact and robust LDA design with large flexibility regarding the 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 1cm laser bar that is AuSn soldered between two CuW submounts. Arrays of up to 15 laser bars are connected to custom sized ceramic base plates on different heat sinks. The available optical output power is shown to be strongly depending 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. Operation at increased heat sink temperatures up to 45°C is possible without active water cooling or conduction cooling using Peltier elements.

*h.kissel@dilas.de; phone +49-6131-9226-227; fax +49-6131-9226-255; www.dilas.com

Updated 1 March 2012
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 cooling via backside cooled ceramic plates. The small elements shown in red color on both sides of the LDA are NTCs (Negative Temperature Coefficient Thermistors) for temperature monitoring during operation. 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.

Figure 1. Schematic drawing of a QCW LDA containing 15 laser bars on a custom ceramic base plate mounted on a copper block. The photographic inset on the right side shows the original size of one identically packaged 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 and a thermal as well as mechanical decoupling of the 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 spreaded to 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 cares for a minimum contribution of packaging to the electrical resistance reducing the waste heat from poorer transition resistances in 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 in a second step to a base plate.
- 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) 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.

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.

The 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 especially interesting for portable and mobile applications demanding a minimum of cooling. We have called LDAs with the above described general design C-stacks.

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 up to the absence of water or thermo-electrical cooling. Stack with multiple wavelengths due to customer’s requirements are also possible.

3. STACK PERFORMANCE

In the following, we present performance and reliability data of C-stacks with one to 15 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 powers. 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 ceramic materials. The smile size (peak to valley) of all sandwiched laser bars mentioned in sections 3.1-3.3 is less than 1.0 µm.

3.1 LDAs with 15 laser bars

In this section, we consider the performance of conduction-cooled LDAs containing 15 laser bars with 20% fill factor and a cavity length of 2000 µm emitting at 980 nm mounted on a custom designed AlN ceramic base plate. Figure 2 shows two versions with a slight difference in the heat sink. Version A on the left side has an additional ceramic plate below the copper heat sink for better mechanical stability of the stack in the first development stage compared to version B on the right side. The copper coated ceramic plates are soldered to the copper heat sinks. After an optimization of this soldering step, the ceramic plate below the heat sink in stack version A could be removed leading to an improved thermal resistance of the LDA (see Table 1).

![Figure 2. Two versions of LDAs with 15 laser bars. Version A on the left side has an additional ceramic plate below the massive copper heat sink compared to version B on the right side. Geometrical sizes: 39.8 x 28.7 x 8.1 mm³ (including the laser bars).](image-url)
1% to 25% corresponding to a pulse width extension from 400 µs to 10 ms let the optical output power drop by 6.5% at a driving current of 60 A. The optical spectra taken at 55 A are shown in Fig. 3(b). An increase of the duty cycle leads to an increase of the average output power and heat load. The observed redshift with increasing duty cycle is a measure for the rising junction temperature of the laser bars; it increases by about 32°C comparing spectra for duty cycles of 1% and 25%. Nevertheless, the LIV curve for a duty cycle of 25% corresponding to a pulse width of 10 ms remains linear up to 60 A or 807 W, respectively, illustrating the potential of the LDA for an operation at higher base plate temperatures.

Figure 3. (a) Optical output power vs. forward current for a LDA of version B containing 980 nm laser bars with 20% fill factor and a cavity length of 2000 µm. (b) Optical spectra at 55 A. The measurements were carried out with a repetition rate of 25 Hz for different duty cycles at a ground temperature of 20°C.

A comparison of the power-current characteristics and of the emission spectra for a repetition rate of 15 Hz and a duty cycle of 15 % at base plate temperatures of 20°C and 45°C is shown in Fig. 4(a). At a driving current of 90 A, the optical output power drops from 1252 W to 1155 W while the power conversion efficiency stays above 55%. The redshift of the spectra shown in Fig. 4(b) corresponds to the expected band-gap narrowing for the temperature difference of 25°C.

Figure 4. (a) Temperature dependence of the power-current characteristics between 20°C (blue lines) and 45°C (red lines) for a LDA of version B containing 980 nm laser bars with 20% fill factor and a cavity length of 2000 µm. (b) Optical spectra at 90 A. The measurements were carried out with a repetition rate of 15 Hz and a duty cycle of 15% corresponding to a pulse width of 10 ms.

A further improvement of the stack performance becomes possible when using alternative ceramic materials with higher thermal conductivities compared to standard AlN. Figure 5(a) shows the power-current characteristics for a LDA of a modified version B using a ceramic base plate with a better thermal conductivity (factor 1.8 compared to the LDA in Figs. 3 and 4) at a ground temperature of 45°C, again for a repetition rate of 15 Hz and a duty cycle of 15% corresponding to a pulse width of 10 ms. As you can see, the optical output power as well as the power conversion efficiency of the improved stack design at 45°C is comparable to the performance of the standard stack design with AlN ceramic at 20°C [see Fig. 4(a)] showing an optical output power of 1250 W at 90 A.

Figure 5(b) shows the temperature distribution in the modified LDA of version B for the given operation conditions (I=90 A, 15 Hz, 15% duty cycle) at a backplate temperature of 45°C received from a finite element analysis. The temperature difference between the backplate and the hottest points in the middle of the laser bar front facets is 24.03°C.
Figure 5. (a) Power-current characteristics for a LDA of a modified version B (using a ceramic base plate with a higher thermal conductivity compared to the LDA in Figs. 3 and 4) containing 980 nm laser bars with 20% fill factor and a cavity length of 2000 µm measured at a ground temperature of 45°C with a repetition rate of 15 Hz and a duty cycle of 15% corresponding to a pulse width of 10 ms. (b) Finite element analysis of the LDA for the given operation conditions (I=90 A). The shown temperature range spans from 45°C (blue color) to 69°C (red color).

Table 3 summarizes the results of the finite element analysis for the three stack designs mentioned above. The thermal improvements from stack version A to the modified version B using an alternative ceramic material with improved thermal conductivity is about 8.8°C in the junction temperature of the lasers bars.

Table 3. Results of finite element analysis for a backplate temperature of 45°C for a driving current of 90 A with 15 Hz and 15% duty cycle. T₁ gives the maximum temperature at the rear facets of the laser bars and T₂ is the maximum temperature at the front facets of the laser bars.

<table>
<thead>
<tr>
<th>Stack version</th>
<th>Thermal conductivity of base plate [W/(m×K)]</th>
<th>T₁ [°C]</th>
<th>T₂ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>180</td>
<td>63.81</td>
<td>77.78</td>
</tr>
<tr>
<td>B</td>
<td>180</td>
<td>60.52</td>
<td>75.13</td>
</tr>
<tr>
<td>B̃mod</td>
<td>325</td>
<td>58.07</td>
<td>69.03</td>
</tr>
</tbody>
</table>

The data presented in Sec. 3.1. show, that the considered C-stacks containing 15 laser bars can be driven with minimal cooling and at elevated temperatures. Together with its robust and compact design and with the possibility of an easy beam shaping due to the low fill factor of the used laser bars, it is very interesting for pumping applications in the defense area.

3.2 LDAs with 8 laser bars

In this section, we consider the performance of LDAs containing eight laser bars with fill factors of 50% and more and with a cavity length of 1500 µm mounted on another custom designed AlN ceramic base plate. Figure 6 shows an LDA of eight laser bars with a macro-channel cooler between two ceramic plates. In this photographic picture, the laser bars are equipped with micro-lenses for fast-axis collimation. The left 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 100 ms (e.g. hair removal) from compact QCW stacks.

Figure 7 shows the power-current characteristics for a water-cooled LDA containing eight 808 nm laser bars with 50% fill factor and a cavity length of 1500 µm at a water temperature of 25°C. In Fig. 7(a), the LDA is operated with a repetition rate of 3 Hz and 15% duty cycle corresponding to a pulse width of 50 ms. At this operation conditions, we have reached an optical output power of 890 W at a driving current of 120 A; there is only a slight deviation from the linear dependence of the output power on current.
For some applications like hair removal, longer pulses are required. Figure 7(b) shows the electro-optical performance for an operation with a repetition rate of 2 Hz and 20% duty cycle corresponding to a pulse width of 100 ms. For these pulse conditions our stacks reaches an optical output power of 580 W at a driving current of 85 A; again there is only a slight deviation from the linear dependence of the output power on current.

With this stack design, larger optical output powers can be reached in the 9xx nm wavelength range with more efficient and less temperature sensitive diode laser structures compared to the presented results for C-stacks with 808 nm laser bars. The limitation regarding the achievable optical output power and pulse length (or duty cycle as well) of QCW stack
designs is not only determined by critical optical damage (COD), but mainly by a maximum allowed junction temperature of the applied laser bars.

The result of an ongoing reliability test carried out in constant current mode on a water-cooled LDA containing eight 808 nm laser bars with 50% fill factor and a cavity length of 1500 µm at a heat sink temperature of 25°C is shown in Fig. 8. The LDA is operated with a repetition rate of 2 Hz and 20% duty cycle corresponding to a pulse width of 100 ms or an energy density of the LDA emission of 42 J/cm². After 2000 hours of operation, we detected a power degradation of 5%. The main power loss occurred in the time interval between 0 and 800 hours giving rise to a life time expectation of more than 8000 hours of operation – more than usually expected for medical or cosmetic diode laser applications.

Another possible application for water-free, conduction-cooled C-stacks containing eight laser bars is pumping of solid-state lasers generating high-energy ultrashort pulses at moderate repetition rates, e.g. for future inertial-confined-fusion facilities. Due to longer upper-state lifetimes in ytterbium doped host materials, pump pulse lengths of about 1 ms are required. For this particular demand, the macro-channel cooler in the stacks (as shown in Fig. 6) is replaced by a massive copper block for conduction-cooling. Selected electro-optical data of this stack geometry are depicted in the following (see Figs. 9 and 10).

Figure 9. (a) Power-current characteristics for a conduction-cooled LDA containing eight 940 nm laser bars with 80% fill factor and a cavity length of 1500 µm. (b) Optical spectra taken at 300 A. The measurements were carried out at a ground plate temperature of 20°C with a repetition rate of 10 Hz and a duty cycle of 1% corresponding to a pulse width of 1 ms.

The power-current characteristics for a conduction-cooled LDA containing eight 940 nm laser bars with 80% fill factor and a cavity length of 1500 µm is shown in Fig. 9(a). The measurement was carried out at a ground plate temperature of 20°C with a repetition rate of 10 Hz and a duty cycle of 1% corresponding to a pulse width of 1 ms fitting the above mentioned pulse requirements for the pumping of Yb³⁺:CaF₂. The stack achieved an optical output power of 3500 W at a...
driving current of 390 A, which corresponds to more than 435 W per bar. The achievable output power decreases with increasing duty cycles as shown in Fig. 10(a). The redshift of the emission wavelength at a driving current of 300 A for an increase of the duty cycle from 1% to 2.5% is shown in Fig. 9(b); it corresponds to an increase of the junction temperature of about 13°C.

The result of an ongoing reliability test carried out in constant current mode on a conduction-cooled LDA containing eight 940 nm laser bars with 80% fill factor and a cavity length of 1500 µm at a heat sink temperature of 20°C is shown in Fig. 10(b). The LDA is operated with a repetition rate of 10 Hz and 1% duty cycle corresponding to a pulse width of 1 ms. The test power was chosen to be 2400 W or 300W per bar regarding customer’s requirements. After 1000 hours of operation we could not detect any power degradation proving reliable operation of the stacks at this power level and pulse conditions.

3.3 Single laser bar design

In this section, we consider the performance of a C-stack like conduction-cooled design containing only one single laser bar [as shown in Fig. 11(a)] with fill factors of 75% and more and a cavity length of 1500 µm emitting at 940 nm.

Figure 11. (a) Conduction-cooled LDA with one single laser bar. Geometrical sizes: 14.0 × 10.6 × 5.5 mm³ (including the laser bars). (b) Power-current characteristics for a conduction-cooled LDA containing one 940 nm laser bar with 75% fill factor and a cavity length of 1500 µm measured at a ground plate temperature of 20°C with a repetition rate of 50 Hz and a duty cycle of 0.25% corresponding to a pulse width of 50 µs.

Figure 11(b) shows the power-current characteristics for a conduction-cooled LDA containing one 940 nm laser bar with 75% fill factor and a cavity length of 1500 µm. The measurement was carried out at a ground plate temperature of 20°C with a repetition rate of 50 Hz and a duty cycle of 0.25% corresponding to a pulse width of 50 µs without additional
cooling. A possible application is laser ignition of several highly flammable substances. At I=640 A, an output power of 710 W was achieved. Up to this power level, no events of COD were observed.

Other potential applications of these devices demanding larger pulse widths in the range of 1 to 5 ms are diode laser pumps for range finding or gated imaging systems. Figure 12(a) shows the power-current characteristics for a conduction-cooled LDA containing one 940 nm laser bar with 80% fill factor and a cavity length of 1500 µm. The measurement was carried out at a ground plate temperature of 20°C with a repetition rate of 10 Hz and a duty cycle of 1% corresponding to a pulse width of 1 ms. The achieved optical output power at a driving current of 330 A was 400 W with a power conversion efficiency of 63.4%. In the broad output power range between 135 and 250 W, the power conversion efficiency is even larger than 68%.

![Figure 13](image)

Figure 13. Ongoing reliability test carried out in constant current mode at I=400 A on a conduction-cooled LDA containing one 940 nm laser bar with 75% fill factor and a cavity length of 1500 µm at a heat sink temperature of 20°C. The LDA is operated with a repetition rate of 5 Hz.

Figure 13 depicts an ongoing reliability test carried out in constant current mode at I=400 A or 420 W, respectively, on a conduction-cooled LDA containing one 940 nm laser bar with 75% fill factor and a cavity length of 1500 µm at a heat sink temperature of 20°C. The LDA is operated with a repetition rate of 5 Hz. After 400 hours of operation with 1% duty cycle corresponding to a pulse width of 2 ms, the test is continued with a duty cycle of 2% corresponding to a pulse width of 4 ms. Within the recent test duration we could not detect any power degradation at the applied pulse conditions.

4. 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 with high duty cycles. These so-called C-stacks are based on single diodes consisting of a 1 cm 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 fitting to the demand of various applications. The available optical output power was shown to be strongly depending 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 15 laser bars with 20% fill factor and a cavity length of 2000 µm emitting at 980 nm we have demonstrated an output power of 1150 W (15 Hz, 15% duty cycle, 10 ms) at a base plate temperature of 45°C. First tests using alternative ceramic materials with better thermal conductivity have shown potential to a power enhancement of about 10%. It was shown, that these C-stacks can be driven with minimal cooling and at elevated temperatures. 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.

LDAs containing 8 laser bars with 50% fill factor and a cavity length of 1500 µm emitting at 808 nm were mounted on potential-free macro-channel coolers allowing the usage of tap water and an operation with duty cycles of up to 20% or pulse lengths of up to 100 ms (e.g. hair removal). They have demonstrated an optical output power of 580 W (2 Hz, 20% duty cycle, 100 ms) at a base plate temperature of 25°C. An ongoing reliability test at an LDA emission of 42 J/cm² gives rise to a life time expectation 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).

In a C-stack like conduction-cooled design containing only one single laser bar with fill factors of 75% and 80% and a cavity length of 1500 µm emitting at 940 nm, an output power of 700 W (50 Hz, 0.25% duty cycle, 50 µs) at a base plate...
A temperature of 20°C was shown. For higher duty cycles with pulse lengths up to 10 ms, reliable devices with a power levels of 400W are available.

The investigated C-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.

Operation at increased heat sink temperatures up to 45°C is possible without active water cooling or conduction cooling with the help of Peltier elements. Using an array of 15 bars at 980 nm with 20% fill factor and 2 mm cavity on standard ceramics, we can reach an optical output power of 1150 W at 45°C base plate temperature without additional cooling operating the array with 15Hz and 15% duty cycle. Novel materials allow for more efficient operation and higher optical output powers.

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 especially interesting for portable and mobile applications demanding a minimum of cooling.

The work on the C-stack design with respect to materials, processes and structures is continued, and even better results can be expected in the near future.

5. ACKNOWLEDGEMENTS
The authors acknowledge the technical support of Michael Stoiber, Iris Scholl and Peter Groß.

REFERENCES