Advances in the power, brightness, weight and efficiency of fiber-coupled diode lasers for pumping and direct diode applications

Chris Ebert*, Tina Guiney, Joe Braker, Dean Stapleton, Kim Alegria, David Irwin


ABSTRACT

DILAS Diode Laser, Inc. continues to improve and optimize high-brightness fiber-laser pump modules. Highlights include a 330W module weighing in at 300 grams, achieving greater than 55% electrical-to-optical efficiency at the operating power from a 225µm/0.22NA fiber and a power-scaled version capable of >600 W, >50% efficiency and weighing in at less than 400 grams. The macro-channel coolers enabling these modules eliminate the need for micro-channels and deionized water and reduce pressure drop across the system. A road map to modules with >900W of output power will also be presented.

KEYWORDS: High-power diode laser, high-brightness, lightweight, fiber coupling, fiber laser pump source, materials processing, scalable, modular

1 INTRODUCTION

Beside the key parameters of output power, brightness and efficiency, which push developments in the major fields of solid-state laser pumping and material processing, the form factor, scalability and weight of the laser diode modules is becoming more and more important, particularly for directed energy applications. In addition to the possibility of a high degree of mobility for the laser system itself, the reduced size and weight enables a short beam path and reduced material consumption. We achieve these general advantages of the laser module design by the use of a reduced-footprint heat sink populated with four tailored mini diode bars. This base diode component enables performance due to its modular and scalable mechanical and optical design. Fiber coupled module power levels from 100W to 900 W out of a 225µm fiber with NA 0.22 at a single wavelength are achievable by combining an appropriate number of these building blocks. The automated production process of the building block element in combination with industrial water cooling, to avoid complex cooling water management, fits the economic needs of the market and reduces the costs per laser unit. DILAS has pursued the development of tailored minibars and modular laser module concepts for years, and these results represent the next step in a productive evolutionary process.1,2,3,4

* c.ebert@dilas-inc.com, tel. +1 (520) 539-6889; www.dilas.com
2 DESIGN ASPECTS OF THE MODULAR DIODE LASER CONCEPT
WITH EMPHASIS ON SIZE AND WEIGHT

This section covers the design aspects of laser modules built specifically for low weight and small footprint while preserving high power and high brightness. Optional wavelength stabilization with Volume Holographic Gratings (VHG) can be implemented as well.

2.1 The tailored minibar – the basic laser unit

The tailored minibar is the elementary subunit of the concept. The five emitter bar structure with a fill-factor of 10% and a pitch of 1000µm allows the collimation of the diode via simple fast-axis collimator (FAC) and slow-axis collimator (SAC) lenses. The resulting beam quality can be focused easily with one optical element directly into a 225µm core fiber with NA 0.22. With a beam parameter product (BPP) of about 22mm*mrad, the slow axis beam quality of one diode with appropriate micro optics fits within the fiber, whereas the fast axis has enough clearance in BPP for spatial combining of up to 16 bars.

2.2 The reduced footprint heat sink design – the subunit for the modular and scalable laser modules

For a modular concept, the goal is to arrange the optimal number of tailored minibars on one subunit as a building block that can be easily combined together to scale a laser module in power. Because of the beam quality in the fast axis and symmetry principles, i.e. for polarization and/or wavelength coupling, each subunit is populated with four tailored bars adjacent to each other in the horizontal dimension. Figure 1 shows a schematic drawing of this subunit. To reduce the length of the beam path and achieve a very compact mechanical design, the addition of subunits is in the vertical dimension - i.e. multiple subunits are stacked on top of each other. This stacking is pictured in Figure 2 and shows a stack consisting of four subunits with a diode array of 4 x 4 tailored bars, a total of 16 laser diode bars, each with 5 emitters. By utilizing polarization combination a laser module consisting of eight subunits, for a total of 32 tailored diode bars operating at a single wavelength, can be coupled into a 225µm core, NA 0.22 fiber.

The subunit is assembled with the FAC and SAC lenses in an automated process. The output power of one subunit at a current level of 50A is about 180W for the collimated beam. After mechanical stacking, the spatial combination of the beams in the fast and slow axes is done with mirrors via a semi-automated process to minimize pointing errors and ensure a high reproducibility, thereby achieving an optically stacked array. The final beam shaping to prepare the spatially combined beam for fiber coupling is done via cylindrical compression of the fast axis to match the divergence and beam size in the slow axis. Focusing of the beam is done with a single, aspherical lens to a 225µm core, NA 0.22 mode-stripped fiber.

The heat sink itself has to fulfill varied requirements. Beside the reduction of size and weight, the development focused on achieving vertical stacking, the use of conditioned tap water cooling and minimized thermal resistance. This results in a small, internally structured, copper heat sink with an overall weight of about 38g. The previous generation subunit as described in [1, 4] with seven tailored bars has a weight of about 585g. This is a near order of magnitude weight reduction per diode (ignoring for the moment that the heavier previous generation subunit has additional functionality relating to the structural support and sealing of the laser module itself).
2.3 Pulsed lifetesting

Furthermore, the combination of AuSn solder and CTE matched submounts permits hard-pulsing without the associated problems seen using In solder. Testing by DILAS shows <1% degradation in power and efficiency when tested for over 5M shots, with 0.5 sec on/off pulses. Negligible shift in wavelength or spectral width during the test is also observed. If any emitters or T-bars were degrading, the reduced efficiency would result in a red shift of the spectrum, which could be easily detected by comparing the spectrum before and after testing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pre-Test Data</th>
<th>Data @ 1550 hrs/ 5.5 M shots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current for 200W Operation</td>
<td>51.5 A</td>
<td>51.9 A</td>
</tr>
<tr>
<td>Overall Efficiency</td>
<td>60.8%</td>
<td>60.1%</td>
</tr>
<tr>
<td>Center Wavelength</td>
<td>975.6 nm</td>
<td>975.8 nm</td>
</tr>
<tr>
<td>Linewidth (FWHM)</td>
<td>3.7 nm</td>
<td>3.6 nm</td>
</tr>
</tbody>
</table>

Table 1: Diode performance of a macro cooler (with four tailored bars) before and after 5.5M shots at 0.5 sec on/0.5 sec off.

For industrial usage where weight and size are often not the primary driving factors, it is conceivable to have a multi-functional module capable of housing many subunits which can be populated with only the required number of subunits to achieve the desired power without changing the mechanics. Due to the small size and weight of the subunits they have a negligible effect on the overall weight and the footprint of the laser module. This standardized platform enables cost-efficient production and resides at the heart of DILAS’ modularized approach. For high-end applications, where a critical metric of a <1kg/kW weight-to-power ratio is specified, housings designed to hold only the required number of subunits are used.

3 RESULTS FOR LASER MODULES BASED ON THE REDUCED SIZE AND WEIGHT SUBUNIT AND MODULAR CONCEPT

In this section we will present the characterization of two different high-end laser units which have been realized with the subunit described in the previous section. These modules are particularly optimized for low weight providing an output power of 330W at a weight of 300g in one case, and more than 600W at a weight of less than 500g in the other, and both employing a 225µm core mode-stripped fiber with NA 0.22. The 300W unit is already in full production whereas the 600W unit is a prototype. Both units have a weight to power ratio of ≤1kg/kW.
3.1 The IS46.6 – a laser unit based on two subunits for 225 µm (NA 0.22) fiber coupling at 330W

The IS46.6 laser module consists of two of the previously described subunits. The mechanical arrangement of the subunits is in this case not vertically stacked. Instead, they are assembled on the outer sides of the main housing of the module and the beam path and fiber coupling optics are located between the subunits. In this way, the cooling capacity of the subunit is used for symmetric cooling of the main body and the area of fiber coupling, resulting in superior thermal performance of the module. The overall size of the unit is 98 x 45 x 44 mm³ at a weight of ~300g. The main body of the laser module is an aluminum alloy, whereas the cover parts are made of a magnesium alloy to yet further reduce the weight. (With an Al housing, the total weight is still only ~325g). The cooling concept guarantees reliability and stability by assuring cooling water only contacts components made of copper and PEEK. The automated production process of the laser module enables reproductibility and cost optimization. To date, several hundred modules have been delivered. Figure 3 shows a picture of the production module.

![Image of IS46.6 laser unit](image)

*Fig. 4: Picture of the IS46.6 light weight laser unit.*

As an illustrative example, we present the measurement results of a standard production laser module, with a mode-stripped fiber. The left side of Figure 5 shows the characteristic power vs. current curve and the electro-optical efficiency and the wavelength spectrum is displayed on the right. The peak output power of 333W is reached at 50A with an efficiency of 54%. The wavelength spectrum at 50A can also be seen.

![Output power and efficiency](image)

*Fig. 5: Output power and efficiency of an IS46.6 out of a mode-stripped 225 µm NA 0.22 fiber. The wavelength spectrum on the right side is measured at 50A and a cooling water temperature of 23°C.*

Optionally, the IS46.6 can be equipped with a monolithic Volume Holographic Grating (VHG) for wavelength stabilization. The line width of the wavelength spectrum is about 0.8nm at FW1/e². The corresponding graph is shown in Figure 7.

![Wavelength spectrum graph](image)
3.2 The IS53 – a laser module prototype based on four subunits for 225 µm (NA 0.22) fiber coupling at 600W

The IS53 prototype is based on four subunits. Instead of the symmetric mechanical concept of the IS46 (two subunits centered in the main body) the IS53 has four subunits in a vertically stacked arrangement as previously described and shown schematically in Figure 2. The fiber coupling area is now water cooled to carry the heavier heat load while the housing components are mainly made of coated magnesium alloy to reduce the overall weight significantly. To further dissipate the extra generated heat of the module, two additional water cooled elements cover the housing of the laser module. In summary, the light weight unit has a size of ~ 110 x 75 x 51 mm² at an overall weight of about 400g. The result is a weight-to-power ratio of just 0.63 kg/kW. Figure 8 shows a CAD model of the module, including fiber.

The output power of 625W is reached at a current level of 51.0 A. The wavelength spectrum, centered at 976.4 nm, has a width of 4.1 nm at FWHM. The power vs. current curve and voltage curve are shown in Figure 8, and the wavelength spectrum is shown in Figure 9.
Fig. 8: Output power and drive voltage of the IS 53 out of a 225 µm core NA 0.22 fiber.

Fig. 9: Wavelength spectrum of the IS53 module at 625W, with linewidth (FWHM) = 4.1 nm

3.3 Ocelot – a laser module prototype based on more subunits for 225 µm (NA 0.22) fiber

The next step in the roadmap is to utilize macrochannel coolers with T-bars bonded on both sides. This results in 8 T-bars from a cooler weighing only ~40 grams. Figure 10 shows an illustration of a double-sided cooler, with the T-bars on the opposite side visible in reflection.

Fig.10: Double-sided macro channel cooler with 8 T-bars – 4 on each side.
In order to assess the impact of any thermal cross-talk induced by double-sided operation, each side of the cooler (with 4 T-bars) was run independently. This is then compared to the results when running both sides (all 8 T-bars) simultaneously. Minimal degradation in electrical-optical efficiency (<1%) and total output power are seen, as illustrated in Figure 11, indicating adequate cooling of the double-sided cooler.

![Figure 11: Output power (sum) and Efficiency (average) of single-side operation (blue curves) and double-side operation (red curves).](image)

Due to the increased optical density of the double density coolers, it is possible to utilize three of these packaged together (for a total of 24 T-bar diodes) along with polarization multiplexing, and still maintain coupling into a 225µm/0.22 NA fiber. Total output power out of the fiber is targeted at 900W, with a package weight of 575 grams. Utilizing six of these pumps together should enable fiber amplifiers in the 4-5 kW range, while still maintaining a compact design. Furthermore, continued optimization should lead to a weight approaching 450 grams and possibly increased power levels.

![Figure 12: CAD model of Ocelot – fiber coupled module with from 900W output 225µm/ 0.22 NA fiber, weighing <600 grams.](image)

**SUMMARY AND CONCLUSION**

In conclusion, the presented scalable and modular diode laser concept for fiber coupled diode laser units, with emphasis on a reduced weight and size requirement, shows the potential of this small subunit approach to build diode lasers for the full spectrum of application fields. With weight-to-power ratios of less than 1 kg/kW for a whole laser module, including fiber, this concept is suitable for technologies with a high demand on mobility as well as for industrial usage due to the fact that the unit is based on a cost efficient assembling and production process. In detail, we have presented two laser units that meet stringent requirements on weight and size in combination with high brightness, high efficiency, and high-power. Shown were two subunit-based laser modules with an output power of...
330W at a weight of 300g already in series production and a four subunit-based prototype laser module with an increased output power of 625W at a weight of 400g. Both units are coupled into a standard mode stripped SMA-fiber with a core diameter of 225µm and NA of 0.22. The design of the modules allows the specifications to be relaxed to a level consistent with the use of industrial water while maintaining microchannel cooler-like thermal resistance. The subunit beam quality and opto-mechanical properties enable, in principle, more than one kW output power levels at a single wavelength by combining up to eight subunits in a very compact and weight reduced design. The option of wavelength stabilization and narrowing is illustratively shown for the two subunit-based laser module. The population of the subunit with diodes emitting at different wavelengths in the near future will extend the concept to the capability of wavelength multiplexing and a corresponding further scaling of the output power.

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