Enhanced fiber coupled laser power and brightness for defense applications through tailored diode and thermal design

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ABSTRACT

Advances in both diode laser design and packaging technology, particularly thermal management, are needed to enhance the brightness of fiber coupled diode lasers while maintaining the small size and light weight required for defense applications. The principles of design for high efficiency fiber coupling are briefly covered. Examples are provided of fielded and demonstrated 100 and 200 micron diameter fiber coupled packages ranging in output from a few hundred to kW-class units in fibers, to include sub-kg/kW capabilities.

The demand for high-power and high-brightness fiber coupled diode laser devices is mainly driven by applications for solid-state and fiber laser pumping. The ongoing power scaling of fiber lasers requires scalable fiber-coupled diode laser devices with increased power and brightness.

A modular diode laser concept combining high power, high brightness, wavelength stabilization and low weight, which is considerable concern in the SWaP trades needed to field defense systems, has been developed. In particular the defense technology requires robust but lightweight high-power diode laser sources in combination with high brightness.

The heart of the concept is a specially tailored diode laser bar, with the epitaxial and lateral structures designed such that only standard fast- and slow-axis collimator lenses in combination with appropriate focusing optics are required to couple the beam into a fiber with a core diameter of 200 µm and a numerical aperture (NA) of 0.22. The spectral quality, which is an important issue especially for fiber laser pump sources, is ensured by means of Volume Holographic Gratings (VHG) for wavelength stabilization.

This paper presents a detailed characterization of different diode laser sources based on the scalable modular concept. The optical output power is scaled from 180 W coupled into a 100 µm NA 0.22 fiber up to 800W coupled into a 400 µm NA 0.22 fiber. In addition we present a lightweight laser unit with an output power of more than 300 W for a 200 µm NA 0.22 fiber with a weight vs. power ratio of only 0.9 kg/kW.

Keywords: High power diode laser, high brightness, fiber coupled, lightweight defense technology, fiber laser pump source

1 INTRODUCTION

The development of high-power and high-brightness fiber coupled diode laser devices in the defense space is primarily pushed by the need to pump high brightness fiber lasers with high brightness fiber-coupled diode lasers, compact in size and light in weight. Typical requirements are 300W to 1kW from a 200µm fiber, with a strong preference toward a weight-to-power ratio of 1kg/kW.

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In addition to these technical requirements economic aspects become more and more important in order to reduce the costs per watt per unit brightness per unit lifetime. The basic design concept of a scalable diode laser system has to take into account the requisite technical issues without losing sight of a cost structure that makes the unit(s) fieldable. As a result DILAS has consistently pursued the development of tailored minibars (T-bar), which is the heart of the modular concept\(^1\)\(^2\). Design is performed in such a way as to enable automation of the production steps providing a smooth transition from laboratory development to low cost, repeatable, manufacturing.

2 GENERAL DESIGN ASPECTS OF MODULAR DIODE LASER CONCEPT

In this section we present some general design aspects of the modular diode laser concept which enables combining high power, high brightness, wavelength stabilization and optionally low weight.

2.1 Basic laser unit

The diode laser engine for Dilas’ high brightness, low weight fiber coupled modules is a tailored minibar, whose pitch, emitter size and number of emitters is chosen such that a desired beam quality in slow-axis direction can be realized without using sophisticated beam shaping optics. The goal is to use only fast-axis collimator (FAC) and slow-axis collimator (SAC) lenses for collimation in both axes followed by only one additional focusing optic for efficient coupling into a fiber with 200 \(\mu\)m core and a numerical aperture of 0.22.

Compared to standard 10 mm wide bars the T-bar has a reduced number of emitters arranged with a large pitch resulting in a low fill factor. The advantage of such a low fill factor bar is a reduced thermal crosstalk between the emitters. The lateral structure of the T-bar is defined by 5 emitters with an emitter width of 100 \(\mu\)m spaced by a pitch of 1 mm. The left part of Fig. 1 shows a thermal simulation of a standard bar with 10 mm width in comparison to the T-bar. The simulation shows that for the standard bar neighbouring emitters are strongly thermally coupled, each emitter coupling to at least the two nearest neighbors on either side. For the low fill factor T-bar the thermal crosstalk is significantly reduced which increases potential output power per emitter at comparable emitter temperature or greatly enhanced reliability by operating at comparable power but greatly reduced emitter temperature. In addition, for the low fill factor bar, collimation by slow axis collimating (SAC)-lenses is more efficient with regard to beam quality.

![Mini-Bar 5 emitters](image1)

![Standard-Bar 25 emitters](image2)

**Fig. 1:** Thermal simulation of a standard bar with 10 mm width and 25 emitters (upper left diagram) in comparison to a minibar with reduced number of emitters (lower left diagram). Measurement of the beam characteristics for the baseplate with resulting beam quality of 16.4 mm x mrad \((M^2=53)\) in slow-axis direction and 6.6 mm x mrad \((M^2=21)\) in fast-axis direction, respectively (right diagram).

The next step of the modular concept is to arrange seven tailored minibars on one baseplate in combination with FAC and SAC for each bar. In addition mirrors are implemented on the baseplate to build an optical stack. All optical components are mounted using automated processes to ensure very high reproducibility and an efficient production process. As a result, pointing errors are minimized enhancing fiber coupling or wavelength stabilization. Wavelength stabilization is done using single volume holographic grating for the whole baseplate, e.g. 35 emitters are locked by a single grating. Another important design aspect is that the cooling strategy allows the use of industrial water for the bottom-cooled baseplate.
The baseplate with seven minibars is characterized by an output power of about 260 W at a current of 40 A and an overall beam quality of better than 20 mm x mrad enabling efficient coupling into a 200 µm NA 0.22 fiber. The right part of Fig. 1 shows a measurement of the beam quality for the baseplate. The resulting beam qualities are 16.4 mm x mrad ($M^2 = 53$) for the slow-axis direction and 6.6 mm x mrad ($M^2 = 21$) for the fast-axis direction, respectively.

The central wavelength of the base plate is 976 nm with a spectral width of about 4 nm (90 % power content). Optionally – again by using one common VHG for the whole base plate - the central wavelength can be fixed and the spectral width can be reduced down to 0.5 nm (90 % power content). Furthermore it is worth noting that the laser light of the base plate is linearly polarized.

### 2.2 Modular Laser Concept

The basic idea of the modular laser concept is to use the standard laser unit described in the previous section as a building block for a variety of lasers with different output powers and beam qualities. According to the modular design principle the baseplates can be easily combined to scale output power, which is realized optically by spatial and/or polarization multiplexing. The advantage of a common baseplate as a basic building block for the modular system is that the baseplate can be produced in high volume. The production process for the baseplate is highly automated which leads to a cost-efficient and reliable building block with high repeatability regarding optical properties.

The modular concept is schematically shown in Fig. 2. Starting with a one-plate unit with 200 W output power for a 200 µm fiber (NA 0.22) we end up with a laser system consisting of 8 baseplates resulting in 1.7 kW output power for a 400 µm fiber (NA 0.22) at one single wavelength.

![Fig. 2: Schematic drawing of modular diode laser concept based on one common baseplate.](image)

### 2.3 Explanation of diode laser brightness

This section is provided as explanatory reference concerning diode laser brightness and the efficient coupling of diode lasers into optical fiber. Shown in Fig. 3 is a rendering of the slow axis divergence of a diode laser. At drive current $I_1$, the diode displays a given SA divergence and couples efficiently into the fiber. At drive current $I_2$ the divergence increases, resulting in a spot size at the fiber that does not efficiently couple into the fiber. Figure 4 illustrates what happens when a lens is used to reduce the spot size at the fiber—the reduced spot size comes at the expense of increased NA, which will also compromise fiber coupling efficiency for too large a NA. This property of the beam, the beam parameter product, the product of the spot size with the beam divergence, is an invariant. It cannot be improved without active means. Hence, it is not possible to engineer a fiber coupled module whose brightness exceeds that of the ensemble of high power diode lasers that comprise its engine. The T-bar provides such an engine. The remainder of the construct, from the sub-mounts, to the thermal pathways, to the optical train,
serves to preserve the brightness in transferring the optical power from the facet of the diode to the exit facet of the optical fiber. The modular concept herein described well serves that function.

Fig 3: The top down view of the diode and its slow axis. At current $I_1$, the diode slow-axis divergence still permits efficient fiber coupling. At some current the divergence increases to such a degree that the spot size at the fiber overfills the core.

Fig 4: A lens pair (telescope) may be used to reduce the spot size at the fiber. The nature of the beam parameter makes it such that this cannot be accomplished without an increase in NA, thereby also reducing the fiber coupling efficiency.

It is worth noting at this stage that fiber coupled unit output power and lifetime were typically limited by the catastrophic optical damage of the diode's facet (see Fig. 5-Left). Presently, the module output power is typically limited by fiber failure (see Fig. 5-Center and Right)-the diode itself makes more power than can be efficiently coupled into the fiber core.

Fig 5: Left: An LIV plot showing the COD point of the diode; Center: A burned fiber; Right: A fiber fracture.

### 3 RESULTS

In this section a detailed characterization of different laser units is presented, which have been realized using the modular concept described in the previous section.

#### 3.1 Laser unit with one baseplate for 200 µm (NA 0.22) and 100 µm (NA 0.22) fiber

A laser unit with a single baseplate was designed with regard to compactness, costs and overall efficiency. The overall size of the module is about 130 x 65 x 39 mm$^3$ with a weight of below 1 kg. Experimental results are shown in Fig. 6. An optical output power of 230 W with a 200 µm NA 0.22 fiber at a current of 40 A has been demonstrated. The corresponding electrical-to-optical efficiency is more than 52 % (Fig. 3-Left).
The right part of Fig. 6 shows the results of the wavelength stabilized version. The maximum output power was 200 W at a current of 42 A. The central wavelength is fixed at 976.7 nm with a line width of 0.5 nm (90 % power content). The corresponding spectrum is shown in the lower right part of the right diagram.

![Fig. 6: Output power and efficiency of the one-plate unit for a 200 µm NA 0.22 fiber without VHG (left diagram) and with VHG for wavelength stabilization (right diagram). Data are shown as function of current at a temperature of 25°C. The stabilized spectrum for the version with VHG is shown in the lower right part of the right diagram.]

As mentioned in the previous section one important feature of the T-bar is the linear polarization of the diode output. Polarization beam combining can be applied to improve beam quality by a factor of 2 and make it possible to couple the beam into a fiber with core diameter of 100 µm and a numerical aperture of 0.22. The dimension and the weight of the housing remain unchanged when compared to the 200 µm version. Measurement data of the 100 µm unit is shown in Fig. 7. The maximum output power was 180 W at a current of 40 A with a corresponding electro-optical efficiency of 41 % (Fig. 4-Left). The results were achieved with a mode stripped SMA-fiber with antireflection coating on one end. The right part of Fig. 7 shows a measurement of the beam caustic to identify beam quality in both directions. The resulting beam qualities are 8.8 mm x mrad (M^2 = 29) for the slow-axis direction and 6.4 mm x mrad (M^2 = 21) for the fast-axis direction, respectively. The astigmatism is less than 10 µm.

![Fig. 7: Output power and efficiency of 100 µm NA 0.22 unit as function of current at a baseplate temperature of 25°C (left part). Measurement of the beam characteristics with a resulting beam quality of 8.8 mm x mrad (M^2=29) in the slow-axis and 6.4 mm x mrad (M^2=21) in fast-axis, respectively (right).]

### 3.2 Laser unit with two baseplates

In this subsection we describe the first level of power scaling, which is realized by combining two baseplates to one common laser unit. The beams can be combined by polarization multiplexing or by arranging the beams spatially on top of each other in the fast-axis direction by means of an optical stack, respectively. The targeted output power for the two-plate unit is 300 W out of a 200 µm fiber with numerical aperture of 0.22.
The principal setup of the laser unit is shown in Fig. 8. After beam combining by polarization combining, beam sizes have to be adapted for efficient fiber coupling using a single, common spherical focusing optic. The mechanical design of the laser unit results in an outer dimension of 250 x 195 x 67 mm³ with a weight of 4.4 kg.

Fig. 8: Mechanical design of the two-plate unit. Mechanical dimensions are 250 x 195 x 67 mm³ with a weight of 4.4 kg.

The experimental results for the two-plate unit are shown in Fig. 6 for a 200 µm fiber with NA 0.22. The left part of Fig. 9 shows the output power and electro-optical efficiency. The maximum output power is 380 W at a current of 40 A with an electro-optical efficiency of 42 %. The targeted output power of 300 W is achieved at a current of 30 A with an efficiency of 46 %. The corresponding spectrum is shown at right in Fig. 9 for a current of 40 A. The central wavelength is 976.4 nm and the spectral width is 4.9 nm (90 % power content).

Fig. 9: Output power and efficiency curve of a unit with two base plates designed for a 200 µm NA 0.22 fiber as function of current at a temperature of 25°C (left part). The corresponding spectrum is measured at a current of 40 A (right part).

3.3 Laser unit with four baseplates

Further power scaling is achieved by increasing the number of baseplates per laser unit. The next level is a unit that consists of four baseplates with 7 bars per plate. In each case two plates are stacked optically by means of several folding mirrors. Afterwards the two resulting beams are combined by polarization coupling to enhance the brightness. The overall brightness of the four-plate unit still allows efficient fiber coupling into a 200 µm fiber with NA 0.22. Experimental results for such a unit at a central wavelength of 976 nm have also already been presented recently1. An output power 775 W of optical output power at a current of 40.5 A for a 200 µm fiber with NA 0.22 has been demonstrated. The spectral line width of the laser unit was 5.1 nm (90 % power content). As mentioned before wavelength stabilization is possible by using only one common VHG per baseplate. The output power of the four-plate unit with VHG was 690 W at a current of 40 A with a central wavelength of 976.8 nm and a spectral width of only 0.7 nm (90 % power content)1.

In the meantime the mechanical design of the laser unit has been optimized to make it suitable for further power scaling by adding even more baseplates. In addition the beam shaping optics has been modified with regard to numerical aperture. For some defense applications a numerical aperture below 0.22 is needed, so an optical design
for an optional numerical aperture of 0.12 has been added. Of course, this is at the expense of retaining the fiber diameter because the overall beam parameter product must remain unchanged.

Fig. 10 shows the experimental results for the four-plate unit at a wavelength of 976 nm with a low numerical aperture of 0.12. Output power of 840 W at a current of 40 A out of a 400 µm fiber with a numerical aperture of 0.12 has been achieved. The corresponding electro-optical efficiency is 47 % at 40 A. The right part of Fig. 10 shows the mechanical layout with dimensions of 285 x 280 x 100 mm³ and a weight of 9.7 kg.

![Fig. 10: Output power and electro-optical efficiency of a unit with four baseplates as function of current at a temperature of 25°C (left part). The fiber is a 400 µm fiber with numerical aperture of 0.12 and the central wavelength of the laser unit is 976 nm. Mechanical dimensions are 285 x 280 x 100 mm³ with a weight of 9.7 kg (right part).](image)

4 LIGHTWEIGHT VERSION

Defense applications require small, lightweight packages, without loss of power or efficiency, to enable the fielding of fiber lasers on fixed wing, rotary wing and unmanned platforms. While industrial applications normally target robustness, compactness and cost-efficiency, the weight of laser units becomes important in applications where the unit must be mounted to on a robot arm, for instance. In this section the properties of a laser system that has been especially optimized for low weight is described.

4.1 Design of lightweight laser unit

The laser unit for the lightweight version is also based on the scalable modular concept described in the previous sections. Significant weight reduction has been achieved by adapting the baseplate and by changing the material of the housing. The cooling structure has been optimized to reduce material and weight. It is important to mention that the cooling concept is still based on industrial water. Further incremental weight reduction is achieved using alternative material such as magnesium alloy in parts of the housing. The specific weight is 35% less when compared to the standard aluminum and even 80% less when compared to copper. The design of the laser unit is shown in Fig. 11. The weight of the units is just 278 g with outer dimensions of 87 x 65 x 45 mm³.
The experimental results of the lightweight unit are shown in Fig. 12. The left part shows output power and efficiency as a function of current at a temperature of 20°C. A 200 µm SMA-fiber (NA 0.22) with mode stripper and antireflection coating on (only) the end facet has been used. The maximum output power was 308 W at a current of 50.5 A with a corresponding electro-optical efficiency of 47%. An output power of 200 W is achieved at a current of 29.7 A with an electro-optical efficiency as high as 56%. At right in Fig. 12 is shown the spectral characteristics measured at a current of 49 A. The central wavelength is 975.7 nm with a line width of 4.7 nm (90% power content).

One approach to quantify the performance of a lightweight laser unit is to describe the output power in relation to the weight. Taking into account the output power of 308 W and the weight of 278 g the resulting weight vs. power ratio is only 0.9 kg/kW.

**SUMMARY AND CONCLUSION**

In conclusion, a modular diode laser concept for building highly efficient fiber coupled diode laser units with a variety of different output powers and beam qualities has been presented. The salient idea in the concept is to use a standardized building block for all laser units, one that is itself lightweight, efficient making use of high brightness T-bars as the chip engine, while also enabling automated and cost-efficient production with very high repeatability of optical properties.

In detail various defense laser units starting from a one-plate unit with an output power of up to 230 W for a 200 µm NA 0.22 fiber and ending with an eight-plate unit with an output power of 800 W coupled into a 400 µm NA 0.22 fiber have been presented. The linear polarization of the base plate allowed polarization beam combining for enhancing the brightness, which resulted in a one-plate unit with up to 180 W for a 100 µm NA 0.22 fiber.
For all laser units wavelength stabilization is possible by inserting one common volume holographic grating per baseplate (5 T-bars or 35 emitters). As examples, this has been shown for the one-plate and four-plate versions with a reduction of the spectral bandwidth to 0.5 nm (one-plate) and 0.7 nm (four-plate), respectively, each at 90% power enclosure.

In addition detailed data for a laser unit that has been optimized with regard to low weight has been presented. Based on the same modular concept we have achieved an output power of 308 W for a 200 μm SMA-fiber with NA 0.22. The mechanical dimensions of the compact laser unit were 87 x 65 x 45 mm³ with a low weight of only 278 g leading to a weight vs. power ratio of merely 0.9 kg/kW.

It is important to notice that all results presented in this paper have been realized with one single wavelength at 976 nm. Base plates are now available at different wavelengths allowing further scaling of the output power by additional wavelength multiplexing. This will enable the building of laser units with multi-kW power in combination with beam qualities of 20 - 30 mm x mrad in the near future.

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