Scalable high-power and high-brightness fiber coupled diode laser devices

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ABSTRACT

The demand for high-power and high-brightness fiber coupled diode laser devices is mainly driven by applications for solid-state laser pumping and materials processing. The ongoing power scaling of fiber lasers requires scalable fiber-coupled diode laser devices with increased power and brightness. For applications in materials processing multi-kW output power with beam quality of about 30 mm x mrad is needed.

We have developed a modular diode laser concept combining high power, high brightness, wavelength stabilization and optionally low weight, which becomes more and more important for a multitude of applications. In particular the defense technology requires robust but lightweight high-power diode laser sources in combination with high brightness.

Heart of the concept is a specially tailored diode laser bar, whose epitaxial and lateral structure is 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.

In this paper we present 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 1.7 kW 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, lightweight, fiber coupling, defense technology, fiber laser pump source, materials processing

1 INTRODUCTION

The development of high-power and high-brightness fiber coupled diode laser devices is primarily pushed by two fields of application, namely solid-state laser pumping and materials processing. The demand for diode laser sources in the solid-state laser pumping area is mainly dominated by the further increasing market for fiber laser systems. A typical brightness requirement for fiber laser pump sources is 200 W with a beam quality of about 20 mm x mrad. In materials processing the main goal is an output power of about 4 kW in combination with a beam quality of at least 30 mm x mrad, which is needed to replace inefficient lamp pumped solid-state lasers. Laser systems based on high-power diode laser devices can benefit from high wall-plug efficiency, high optical power, reliability, high robustness against environmental conditions, small footprint and potentially low weight.

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In addition to these technical requirements economic aspects become more and more important in order to reduce the costs per laser unit. The basic design concept of a scalable diode laser system has to take account for the technical issues as well as for economic aspects. As a result DILAS consistently pursued the development of tailored minibars, which is the heart of the modular concept. The second main design aspect of the modular concept is the possibility of automation of production steps to allow for a stable and cost-efficient production process.

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 basic subunit 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 µm core and a numerical aperture of 0.22.

Compared to standard 10 mm wide bars the minibar 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 tailored minibar is defined by 5 emitters with an emitter width of 100 µm spaced by a pitch of 1000 µm. The left part of Fig. 1 shows a thermal simulation of a standard bar with 10 mm width in comparison to the minibar. The simulation shows that for the standard bar neighboured emitters are thermally affected by each other. For the low fill factor bar the thermal crosstalk is significantly reduced which increases potential output power per emitter and reliability. In addition for a low fill factor bar collimation by SAC-lenses is more efficient with regard to beam quality.

![Thermal Simulation](image)

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 automatically to ensure very high reproducibility and an efficient production process. As a result pointing errors are minimized which is important for beam quality with regard to fiber coupling or wavelength stabilization, which is possible by using only one volume holographic grating for the whole baseplate. 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.
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 - 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 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)

### 3 RESULTS

In this section we will present a detailed characterization of different laser units, which have been realized based on 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

Results for a laser unit with one baseplate have already been presented recently. The laser unit with one baseplate was designed with regard to compactness, costs and overall efficiency. The overall size of the module is about 130 x 65 x 39 mm³ with a low weight of below 1 kg. Experimental results are shown in Fig. 3. We have demonstrated an optical
output power of 230 W with a 200 µm NA 0.22 fiber at a current of 40 A. The corresponding electrical to optical efficiency is more than 52 % (left part of Fig. 3).

The right part of Fig. 3 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 linewidth of 0.5 nm (90 % power content). The corresponding spectrum is shown in the lower right part of the right diagram.

As mentioned in the previous section one important feature of the baseplate is that the laser beam is linearly polarized. Therefore 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 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 are shown in Fig. 4. The maximum output power was 180 W at a current of 40 A with a corresponding electro-optical efficiency of 41 % (left part of Fig. 4). The results were achieved with a mode stripped SMA-fiber with antireflection coating on one end. The right part of Fig. 4 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. 3: 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.](image)

![Fig. 4: Output power and efficiency of 100 µm NA 0.22 unit as function of current at a temperature of 25°C (left part). Measurement of the beam caustic with resulting beam quality of 8.8 mm x mrad ($M^2=29$) in slow-axis and 6.4 mm x mrad ($M^2=21$) in fast-axis, respectively (right part).](image)
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 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. 5. After beam combining by polarization coupling beam sizes have to be adapted for efficient fiber coupling with one 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. 5: Mechanical design of the two-plate unit. Mechanical dimensions are 250 x 195 x 67 mm³ with a weight of 4.4 kg.](image)

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. 6 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 in the right part of Fig. 6 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. 6: 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).](image)

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 recently. We
have demonstrated 775 W of optical output power at a current of 40.5 A for a 200 µm fiber with NA 0.22. The spectral linewidth 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). 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 many industrial applications a numerical aperture below 0.22 is needed, so we have added an optical design for an optional numerical aperture of 0.12. Of course, this is at the cost of the fiber diameter because the overall beam parameter product remains unchanged.

Fig. 7 shows the experimental results for the four-plate unit at a wavelength of 976 nm with a low numerical aperture of 0.12. We have achieved 840 W at a current of 40 A out of a 400 µm fiber with a numerical aperture of 0.12. The corresponding electro-optical efficiency is 47% at 40 A. The right part of Fig. 7 shows the mechanical layout with dimensions of 285 x 280 x 100 mm³ and a weight of 9.7 kg.

3.4 Laser system with eight baseplates

The laser system that has been described in the previous section has the potential to achieve 1 kW output power for a 200 µm fiber with NA 0.22 by simply increasing the power per emitter which is expected in the near future. However, for some applications in materials processing even more output power is required but not necessarily with the high brilliance of 22 mm x mrad which is needed for efficient coupling into a 200 µm fiber with NA 0.22. It is often sufficient to have a beam quality of about 30 mm x mrad, which is comparable to lamp-pumped solid-state lasers.

The modular concept allows scaling of output power by further increasing the number of baseplates from four to eight. However, the doubled number of baseplates is at the cost of the overall beam quality, which does not allow efficient coupling into a 200 µm fiber (NA 0.22) for the eight-plate version. The experimental results of a laser unit with eight baseplates are shown in Fig. 8. The left diagram shows the output power as a function of current for a 300 µm fiber and a 400 µm fiber, each with NA 0.22. We achieved 1500 W for the eight-plate unit with a 300 µm NA 0.22 fiber at a current of 40 A. For a 400 µm NA 0.22 fiber a maximum output power of 1700 W was achieved at a current of 42 A. The electro-optical efficiency and the spectral characteristics of the eight-plate unit are comparable to the four-plate unit.

The mechanical layout is shown in the right part of Fig. 8. By comparing the design with the four-plate version (Fig. 7) the modular concept is obvious. The mechanical dimensions for the eight-plate version are 480 x 310 x 100 mm³ and the weight is 13 kg.
Fig. 8: Output power of a unit with eight base plates as function of current at a temperature of 25°C (left part) for a 400 µm fiber and a 300 µm fiber, each with NA 0.22. The central wavelength is 976 nm. Mechanical dimensions are 480 x 310 x 100 mm³ and the weight is 13 kg (right part).

4 LIGHTWEIGHT VERSION

For industrial applications the main design focus is on robustness, compactness and cost-efficiency and not necessarily on the weight of a laser system. The weight of laser units becomes important e.g. for applications where the laser unit has to be mounted to a robot arm. For applications in the defense range lightweight laser systems are also very important with regard to portable laser systems. In this section we describe the properties of a laser system that has been especially optimized for low weight.

4.1 Design of lightweight laser unit

The laser unit for the lightweight version is also based on the scalable modular concept which has been described in the previous sections. Significant weight reduction has been achieved by adapting the baseplate and by changing the material of the housing. Regarding the baseplate 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. Regarding the housing we have used an alternative material with low weight which is based on a magnesium alloy. The specific weight is 35% less when compared to aluminum and even 80% less when compared to copper. The design of the laser unit is shown in Fig. 9. We could reduce the weight down to 278 g with outer dimensions of 87 x 65 x 45 mm³.

Fig. 9: Design of the lightweight laser unit with mechanical dimensions of 87 x 65 x 45 mm³ and a weight of only 278 g. A one-euro coin with a diameter of 23.25 mm is shown as comparison of sizes.
The experimental results of the lightweight unit are shown in Fig. 10. The left part shows output power and efficiency as a function of current at a temperature of 20°C. We have used a 200 µm SMA-fiber (NA 0.22) with mode stripper and antireflection coating on the end facet. 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 %. The right part of Fig. 10 shows the spectral characteristics measured at a current of 49 A. The central wavelength is 975.7 nm with a linewidth 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.

Fig. 10: Output power and efficiency curve of the lightweight unit as function of current at a temperature of 20°C for a 200 µm SMA-fiber with NA 0.22 (left part). The corresponding spectrum is measured at a current of 49 A (right part).

**SUMMARY AND CONCLUSION**

In conclusion, we have presented a modular diode laser concept for building highly efficient fiber coupled diode laser units with a variety of different output powers and beam qualities. The main idea of the concept is to use a basic building block for all laser units, which enables automated and cost-efficient production with very high repeatability of optical properties.

In detail we have presented different 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 1.7 kW coupled into a 400 µm NA 0.22 fiber. 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. Exemplarily this has been shown for the one-plate and four-plate version with a reduction of the spectral bandwidth down to 0.5 nm (one-plate) and 0.7 nm (four-plate), respectively.

In addition we have presented detailed data for a laser unit that has been optimized with regard to low weight. 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. In the meantime base plates are available at different wavelengths allowing to further scale 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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