High-power, high-brightness and low-weight fiber coupled diode laser device

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ABSTRACT

New solid-state laser devices, especially fiber laser systems, require increasingly higher optical pump power provided by fiber-coupled diode laser modules. In particular for defense technology, robust but lightweight high-power diode laser sources with high brightness are needed.

We have developed a novel diode laser device combining high power, high brightness, wavelength stabilization and low weight, which becomes more and more important for a multitude of applications. Heart of the device is a specially tailored laser bar, which epitaxial and lateral structure is designed such that only standard fast- and slow-axis collimator lenses are required to couple the beam into a 200 µm fiber with numerical aperture of 0.22.

In this paper we present a detailed characterization of the new diode laser device with up to 775 W of optical power coupled into a 200 µm, NA 0.22 fiber. One important feature of the device is a lightweight design due to a special housing optimized for low weight. In addition we present results of a diode laser device with 675 W of optical output power and improved spectral quality, which is ensured over a wide range of temperature and current by means of volume holographic gratings for wavelength stabilization. For this device an overall efficiency of more than 42.5 % has been achieved.

Furthermore we present a compact diode laser source with 230 W of optical power coupled into a 200 µm, NA 0.22 fiber. This diode laser device is optimized with regard to highest efficiency and yields an overall electro-optical efficiency of more than 50 %.

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

1. INTRODUCTION

In the last few years high power solid state lasers, especially fiber lasers, have found a growing number of applications. As a consequence the demand for high power and high brightness fiber coupled diode laser modules as pump sources for these lasers has also been significantly increased. The main advantages of diode laser systems are high wall-plug efficiency, high optical power, reliability, high robustness against environmental conditions and small footprint combined with low weight.

However, efficient fiber coupling requires an adaption of the slow-axis beam quality, which is normally the limiting factor of a broad area diode laser bar, to the fiber requirements. Diode laser systems based on standard 10 mm broad area diode laser bars usually employ beam transformation systems to rearrange the highly asymmetric beam of the laser bar or laser stack. These beam transformation systems (prism arrays, lens arrays, fiber bundles etc.) are expensive and become inefficient with increasing complexity.

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To achieve the aim of increasing the brightness of fiber coupled diode lasers, DILAS consistently pursued the development of tailored minibars, which bring a couple of advantages compared to the traditional 10 mm broad diode laser bars. One basic benefit of these new bars is that the use of microoptics is limited to fast-axis collimator (FAC) and slow-axis collimator (SAC) lenses, respectively. Efficient fiber coupling into a 200 µm NA 0.22 fiber is possible without additional beam transformation optics. This leads to a simplified highly efficient optical system with an increased brightness \( B \) as defined in equation (1). The brightness of a diode laser beam is defined by the laser power \( P \) and the beam parameter product (BPP)\(^2\) in slow- and fast-axis direction:

\[
B = \frac{P}{\pi^2 \cdot BPP^2_{total}}; \quad BPP^2_{total} = BPP^2_{slow} + BPP^2_{fast}
\]

Another important approach for increasing the performance of diode laser systems, especially of pump sources, is to control peak wavelength and line width of the pump module. Wavelength control is possible by means of an external component like a volume holographic grating (VHG). The main advantages of spectrally stabilized diode laser modules are the reduced influence of temperature and current on the spectral properties of the module. As a consequence the requirements for the cooling system are reduced and the modules can be used under harsh environmental conditions. Wavelength control is also advantageous with regard to losses at dielectric coatings of mirrors and polarization couplers. Finally wavelength stabilization ensures stable and efficient pumping over the whole operating range and lifetime of the module.

In addition to the benefits mentioned above the requirements on the specification for the chip material are also reduced leading to a higher yield with regard to the selection of the chips on a wafer. However, it should be mentioned that all these properties depend on the locking range and that not all advantages can be fulfilled simultaneously\(^3\). The locking range is mainly determined by the reflectivity of the volume holographic grating, the reflectivity of the exit facet of the diode bar and the difference between the locking wavelength and the diode laser wavelength without VHG.

### 2. CHARACTERIZATION OF WAVELENGTH STABILIZED HIGH POWER DIODE LASER MODULES

In this section we present detailed experimental results of two newly developed wavelength stabilized high-power fiber coupled diode laser modules. Both, the 675 W and the 200 W version are designed to fit into a 200 µm mode-stripped fiber (NA 0.22) to fulfill highest requirements of modern diode based laser systems. In addition we will also present the results of the prototypes without wavelength stabilization.

#### 2.1. Design and performance of wavelength stabilized 675 W / 200 µm prototype

To fit the demands for compactness and high-brightness a compact and stable optical layout of the fiber coupled diode laser module is absolutely necessary. That means that the mechanical arrangement of the diodes as well as the optical path and the optical setup must be optimized to maintain the initial brightness of the diodes. Fig. 1 shows the optical layout of the 675 W module.

The diode bars are arranged in four blocks with 7 bars each leading to a total number of 28 diode bars for the whole module. Each of the 28 diodes is collimated with FAC and SAC-lenses. In each case two diode blocks are stacked spatially in fast-axis direction by means of several folding mirrors. The two resulting beams are finally polarization coupled to enhance the brightness of the module.

To realize a symmetric beam on the spherical focusing objective, the beam is expanded in the slow-axis direction with a cylindrical telescope. Last step of the optical setup is a set of spherical lenses to focus the beam into a 200 µm mode-stripped fiber with numerical aperture of 0.22. We have used a water cooled AR-coated QBH-fiber from Optoskand, which is well established in industrial applications.

\(^3\) defined as \( BPP = w_0 \cdot \theta \) (half beam waist diameter \( w_0 = d_0 / 2 \) times half far field divergence angle \( \theta \))
The first characterization step for the prototype module was to monitor the optical performance including electrical to optical efficiency and the spectrum without VHG elements. The left diagram of Fig. 2 shows the output power of the prototype with a 200 μm NA 0.22 fiber as a function of current and the corresponding electro-optical efficiency. The maximum output power was 775 W at an operating current of 40.5 A. The maximum of the electrical to optical efficiency curve is close to 48 % at 440 W output power and above 42 % for the whole operating range. The slope of the P-I curve is nearly linear up to 700 W and ongoing developments have the aim to expand linearity to higher current values. The spectral characteristics of the prototype are shown in the right diagram of Fig 2. The spectrum has a peak wavelength at 974 nm and the line width is 5.1 nm (90 % power included).

**Figure 2:** (left diagram) Current vs. power and efficiency curve of the prototype module without VHG at a temperature of 20°C. (right diagram) Spectrum of the module without wavelength stabilization. The peak wavelength is 974 nm and the line width is 5.1 nm for 90 % power included.
Next step was the implementation of the VHG for improving the spectral characteristics of the diode laser module. Therefore several volume holographic gratings with different reflectivity in the range of 3 - 15 % were tested. The determination of the VHG-reflectivity is always a trade-off between locking range under different operating conditions and power loss by the insertion of the VHG. It should be mentioned that the reflectivity of the diode laser bars has not been optimized with regard to the reflectivity of the VHG. To minimize costs and reduce the complexity of the optical setup for each diode block only one common VHG has been used. Figure 3 shows the experimental results of power and wavelength measurements for the wavelength stabilized diode laser device. The left diagram of Fig. 3 shows the output power of the wavelength-stabilized prototype with a 200 µm NA 0.22 fiber as a function of current and the corresponding electro-optical efficiency. The target power of 675 W was achieved at a current of 36.5 A with an overall electrical to optical efficiency of 42.5 %. Compared to the results above the output power is reduced by about 5 % caused by the losses of the VHGs. The maximum power was 690 W at a current of 37.4 A. The spectral data of the prototype with wavelength stabilization are shown in the right diagram of Fig. 3. The central wavelength of the module is fixed at 976.8 nm and the corresponding line width is reduced down to 0.7 nm (90 % power included).

![Figure 3](image1.png)

*Figure 3:* (left diagram) Current vs. power and efficiency curve of the prototype module with VHG at a temperature of 22 °C. (right diagram) Spectrum of the wavelength-stabilized prototype. The peak wavelength is 976.8 nm and the line width is 0.7 nm for 90 % power included.

![Figure 4](image2.png)

*Figure 4:* Spectrum of the wavelength-stabilized prototype for different temperatures from 18°C - 35°C (left diagram) and different currents from 20 - 40 A (right diagram).
To determine the locking range of the prototype module we have performed detailed investigations of the spectral characteristics for different temperatures and currents. The results are summarized in Fig. 4. The left diagram of Fig. 4 shows the variation of the wavelength for a temperature range of 18°C - 35°C at constant operating current. The shift of the central wavelength is only about 0.012 nm/°C. The variation of the wavelength for different operating currents from 20 - 40 A is shown in the right diagram of Fig. 4. The corresponding wavelength shift is only about 0.008 nm/A.

Figure 5 shows a picture of the first prototype with an overall dimension of 285 x 250 x 100 mm³. The basic element of this module is a stiff cage which contains the whole optical setup. All four diode baseplates are plugged in sideways and are screwed to the housing. The modular concept allows that each diode block can be changed separately. The housing of the prototype uses a very robust solid aluminum construction. Therefore the prototype weighs over 8 kg. But if an application requires a reduction of weight then it would be possible to replace the aluminum material with a material with reduced specific weight, like a magnesium alloy. In addition the mechanical layout could be improved further to reduce the weight of this module by about 4 kg.

Optionally, for protection of the diode bars each module can be equipped with a cut-off filter to block the radiation from the solid state laser, which is especially an issue for fiber lasers. Additional features like temperature sensor, fiber interlock, aiming beam, power monitoring or adapters for different fiber types could be included in the system design.

Figure 5: Photo of the first 675 W prototype with an overall dimension of 285 x 250 x 100 mm³.

The next step in development will be an optimization of the diode baseplate and the design of the housing to reduce weight and space of the diode laser module. Initial concepts already indicate that a mass reduction down to a weight of 1.25 kg for the diode laser device seems to be possible.

In addition current improvements of the brightness of the diode laser bars (increasing output power per emitter and / or reducing slow axis divergence) will lead to an increase in output power of the module to 1 kW or even more this year. Taking together these two items this will lead to a 1 kW diode laser device with a low weight of 1.25 kg.
2.2. Design and performance of wavelength stabilized 200 W / 200 µm prototype

The basic unit of the module presented in this section is a baseplate with 7 diode bars and is identical to the submodules used for the 675 W prototype described in the previous section. The main focus during development of this device was on compactness, costs and overall efficiency. Taking into account these boundary conditions the mechanical design yielded an overall size of about 130 x 65 x 39 mm^3 and a low weight of only 904 g. A photo of the module is shown in the left part of Fig. 6. For cooling of the baseplate only industrial water is needed. The design of the module allows the use of standard SMA905 fibers as well as the use of the newly developed SMA0.5 fiber, which will be described below.

The right part of Fig. 6 shows the output power of the module as a function of current. The maximum output power with a 200 µm NA 0.22 fiber was 230 W at a current of 40 A. The target power of 200 W has been achieved at a current of 34.7 A with an electrical to optical efficiency of more than 52%.

Figure 6: (left picture) Photo of the 200 W prototype with connector for Optoskand SMA0.5 fiber. (right diagram) Current vs. power and efficiency curve of the 200 W module at a temperature of 20°C.

For low power applications standard SMA905 connectors are mainly used for fiber coupled modules. However, the capability to handle power losses of these connectors is limited and becomes critical when using it with higher output power above about 200 W, especially in combination with mode-stripped fibers with a small core diameter. One option for such high power modules is the use of robust water-cooled industrial fibers, like the QBH-fiber from Optoskand. However, these fibers have some significant drawbacks with regard to costs and compactness.

Recently a new connector type called SMA0.5 has been presented by Optoskand. The development of this fiber was driven essentially by two demands. First, by the need to reduce costs compared to the typical high-power industrial fibers and second to increase reliability for high-power applications compared to the standard fibers based on SMA905 connector. Figure 7 shows a detailed overview of the new fiber connector, which will also be available in a version with anti-reflection coated fiber facet.

Figure 7: Basic design of SMA0.5 fiber from Optoskand.
We have also applied wavelength stabilization for the module described in this section. The results are shown in Fig. 8. The left diagram of Fig. 8 shows the output power of the wavelength-stabilized prototype with a 200 µm NA 0.22 fiber as a function of current and the corresponding electro-optical efficiency. The maximum power was 200 W at a current of 42 A. The spectral data of the prototype with wavelength stabilization are shown in the right diagram of Fig. 8. The central wavelength of the module is fixed at 976.7 nm and the corresponding line width is reduced down to 0.5 nm (90 % power included).

![Figure 8: (left diagram) Current vs. power and efficiency curve of the 200 W prototype module with VHG. (right diagram) Spectrum of the wavelength-stabilized prototype. The peak wavelength is 976.7 nm and the line width is 0.5 nm for 90 % power included.](image)

3. SUMMARY AND OUTLOOK

In conclusion, we have demonstrated a concept for compact and highly efficient fiber coupled diode laser modules based on specially tailored diode laser bars. At a single wavelength of 976 nm we have shown 775 W of optical output power out of a 200 µm mode-stripped fiber with numerical aperture of 0.22. The maximum electrical to optical efficiency of the prototype was 48 % and still above 42 % at maximum output power. In addition, enhancement of the spectral properties was demonstrated by inserting volume holographic gratings (VHG) for wavelength stabilization. The maximum power of the wavelength stabilized prototype was 690 W with a corresponding electrical to optical efficiency of 42 %. The wavelength of the stabilized prototype was centered at 976.8 nm with a spectral width of only 0.7 nm for 90 % power included. Detailed investigations on the influence of current and temperature variation have shown a good locking range. The residual wavelength shift with current was reduced to about 0.008 nm/A as well as the thermal wavelength drift to about 0.012 nm/°C.

The modular concept of the prototype is based on four basic building blocks providing the diode laser power. For a very compact and lightweight module with reduced power we have demonstrated a prototype based on only one building block. The maximum output power for this prototype was 230 W with a corresponding electrical to optical efficiency of 51 %. With additional wavelength stabilization an output power of 200 W has been demonstrated. In combination with that prototype we have successfully tested the performance of the newly developed SMA0.5 fiber from Optoskand, which is suitable for high-power applications and optimized with regard to costs and overall size.

Based on the presented modular concept further developments, like improvements of the brightness of the diode laser bars and optimization of the basic building block will lead to very attractive high-power, high-brightness and low-weight diode laser devices with kW output power. These devices will find various applications in many fields, like space and airborne industry as well as in the defense industry.
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REFERENCES
