Multi-kW high-brightness fiber coupled diode laser based on two dimensional stacked tailored diode bars

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ABSTRACT

The demand for high brightness fiber coupled diode laser devices in the multi kW power region is mainly driven by industrial applications for materials processing, like brazing, cladding and metal welding, which require a beam quality better than 30 mm x mrad and power levels above 3kW. Reliability, modularity, and cost effectiveness are key factors for success in the market.

We have developed a scalable and modular diode laser architecture that fulfills these requirements through use of a simple beam shaping concept based on two dimensional stacking of tailored diode bars mounted on specially designed, tap water cooled heatsinks.

The base element of the concept is a tailored diode laser bar with an epitaxial and lateral structure designed such that the desired beam quality in slow-axis direction can be realized without using sophisticated beam shaping optics. The optical design concept is based on fast-axis collimator (FAC) and slow-axis collimator (SAC) lenses followed by only one additional focusing optic for efficient coupling into a 400μm fiber with a numerical aperture (NA) of 0.12.

To fulfill the requirements of scalability and modularity, four tailored bars are populated on a reduced size, tap water cooled heat sink. The diodes on these building blocks are collimated simply via FAC and SAC. The building blocks can be stacked vertically resulting in a two-dimensional diode stack, which enables a compact design of the laser source with minimum beam path length. For a single wavelength, up to eight of these building blocks, implying a total of 32 tailored bars, can be stacked into a submodule, polarization multiplexed, and coupled into a 400µm, 0.12NA fiber. Scalability into the multi kW region is realized by wavelength combining of replaceable submodules in the spectral range from 900 – 1100 nm. We present results of a laser source based on this architecture with an output power of more than 4 kW and a beam quality of 25 mm x mrad.

KEYWORDS: high-power diode laser, high-brightness, fiber coupling, materials processing, scalable, modular, wavelength multiplexing

1 INTRODUCTION

While output power and brightness are key parameters that enable new developments in material processing, simplicity, scalability, efficiency, and low cost of the laser source are indispensable in this highly competitive market. We fulfill all of these requirements, and realize other advantages in laser design through the use of a reduced-footprint heat sink that is populated with four tailored mini diode bars. As has been previously shown, the modular nature of this base diode component scales easily and enables many design forms to be achieved. With the combination of an appropriate number of these building blocks operating at a single wavelength, we can cover a range of laser power from 100W to above 1kW out of a 400μm, 0.12NA fiber. Furthermore, the automated production and optical alignment processes developed by DILAS, both for a single building block as well as vertical stacks of several building blocks, increase the precision and performance while also reducing the cost of each laser unit. The reliability needs of the market are directly addressed by the exchangeability of diode submodules, as well as the elimination of strict water quality constraints imposed by micro-channel coolers. To achieve even higher power levels, we multiplex diode modules operating at up to five different wavelengths and achieve overall power levels of considerably above 4kW at beam quality of 25mm x mrad. 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.
2 DESIGN ASPECTS OF THE MULTI-KW HIGH-BRIGHTNESS FIBER COUPLED DIODE LASER BASED ON TWO-DIMENSIONAL STACKED TAILORED DIODE BARS

This section covers many design aspects of a high power, high brightness laser module that reaches power levels above 4kW at beam quality of 25mm*mrad. At top level, the module presented is based on the combination and spectral multiplexing of 40 building blocks, each populated with 4 diodes resulting in a system consisting of 160 tailored bars.

2.1 Tailored minibar – the basic laser unit

The tailored minibar is the elementary sub-unit 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 400µm core fiber with NA 0.12. With a beam parameter product (BPP) of about 22mm*mrad, the slow axis beam quality of one diode, shaped with appropriate micro optics, fits within the fiber acceptance, whereas the fast axis BPP has enough clearance in BPP for spatial combining of up to 16 bars.

2.2 Reduced footprint heat sink design – sub-unit for the modular and scalable laser modules

For a modular concept, the goal is to arrange a useful number of tailored minibars on one sub-unit as a building block that can be easily combined 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 sub-unit is populated with four tailored bars adjacent to each other in the horizontal dimension. Figure 1 shows a schematic drawing of this sub-unit, which was presented in an earlier design form in 2014. The improvement of this sub-unit results in an updated design that decreases the thermal resistance of its immediate predecessor by about 20%. Furthermore, through improvements in the diode current contacts, we have increased the efficiency of the base component to nearly 65% E-O-efficiency and implemented a new carrier structure for the SAC lenses that decreases the heatsink weight and size by about 10 percent. FAC and SAC lenses are assembled and aligned in the sub-unit in an automated process. At a moderate current level of 40A, a completed sub-unit delivers about 145W in a collimated beam.

2.3 Single wavelength module design – building block for the multi-kW high-brightness fiber coupled diode laser

The addition of sub-units in the vertical dimension minimizes beam path length during spatial combination and realizes a compact layout. A single stack of eight sub-units is rendered in Figure 2. For maximum power at the needed BPP, stacking of 16 bars in fast axis is desirable. In the module presented, this is realized through spatial and polarization multiplexing of 4 such stacks. The spatial combination (including polarization coupling) of the beams in the fast and slow axes is achieved with mirrors and prealigned polarization couplers that are also installed via an automated process. This minimizes pointing errors between bars and ensures an optically stacked array with high accuracy and reproducibility. For each single wavelength module, the final beam shaping is done via 3.5x cylindrical expansion of the slow axis. This reduces beam expansion over...
path length due to slow-axis divergence, and also reduces the size of the angular spectrum in the following wavelength combination steps. The resulting single-wavelength-module has a collimated output beam and is pictured in Figure 3 - physical dimensions are 175 mm x 111 mm x 60 mm. The module has a mechanically referenced interface plate for easy and precise exchangeability, allowing connection to the water supply, gas purge, sensor interface (including temperature, humidity, and power monitors) and the module power supply in a single work step.

Fig. 3: CAD model of a single wavelength submodule unit.

2.4 Wavelength combining and fiber coupling – the multi-kW high-brightness fiber coupled diode laser

To scale the power of the laser to the multi-kW region, we implement wavelength multiplexing of up to 5 submodules with center wavelength of 915nm, 940nm, 980nm, 1020nm and 1050nm. The wavelength combining is realized with dichroic mirrors. The incident angle of the multiplexed beams to the mirror is 22.5° due to the narrow wavelength multiplexing and requirement for a sharp spectral cut-off in the wavelength combiners. To preserve the rectangular arrangement of submodules and housing for saving available space and keep the beam path short, we introduce a triangular beam path for each submodule as shown in Figure 4. Finally, the multiplexed beam is compressed via a cylindrical telescope for the slow axis by a factor of 1.7x to generate a symmetrical beam shape before coupling into a 400µm, 0.12 NA fiber via a spherical objective with a focal length of 58mm. Figure 5 shows the complete laser module, including the five single-wavelength-modules, spectral combination, and fiber coupling stages. The housing itself is tempered to a temperature of 35°C to avoid condensation in humid environments, whereas the isolated water cooling circuit works with temperatures of 20°C-25°C. During operation, the housing temperature does not exceed temperatures of 50°C. The laser source can be integrated in a 19-inch rack and has a height of 7 rack units.

Fig. 4: Schematic drawing of the wavelength combining.  Fig. 5: CAD model of DF040HQ.
3 DF040HQ - RESULTS OF THE MULTI-KW HIGH-BRIGHTNESS FIBER COUPLED DIODE LASER

In this section, we will present the characterization of the multi-kW high-brightness fiber coupled diode laser DF040HQ which has been realized through the concept described in previous sections. The design, alignment, and initial test results for the system are done for 35A, but in general, the unit is capable of operation at current levels up to 50A. The output power and efficiency curve of the laser is shown in Figure 6. At a moderate current level of 35A, the laser has an output power of 4.1kW at an E-O efficiency of 48%. At 40A, the output power reaches 4.6kW at 46% E-O efficiency. Each submodule has a voltage drop of ~50V, resulting in an overall voltage drop of 243.6V at a current level of 35A.

![Fig. 6: Output power and efficiency of DF040HQ.](image)

The spectrum of the laser is shown in Figure 7. The center wavelength of the submodules, when measured at 40A with a cooling water temperature of 22°C, are 915nm, 940nm, 973nm, 1015nm, and 1057nm. Each single-wavelength-module shows a FWHM spectral width in the range of 4nm. More specifically, the spectral widths are: 4.0nm for 915nm, 4.4nm for 940nm, 4.8nm for 973nm, 3.7nm for 1015nm, and 5.4nm for 1057nm.

![Fig. 7: Wavelength spectrum of DF040HQ.](image)
The power stability of the laser in operation is shown in Figure 8. The fluctuation of the output power is less than ±1% over a time period of 60min.

During the assembly and test of the laser, some areas of power loss and possibilities for further improvements were determined. For example, in comparison to the other wavelengths, significantly higher losses were seen in the wavelength combination of the 915nm and 1050nm wavelengths. Measured loss at 915 and 1050nm were 9.5% and 7.8%, respectively, compared to 5% or lower for the other wavelengths. For the delivered dichroic mirrors, the raw diode material for the 915nm module was shifted slightly to wavelengths longer than optimal and, that for the 1050nm slightly to shorter. Furthermore, the performance of the broadband antireflection coating used on the lenses and windows is slightly poorer at 915nm and 1050nm than for those wavelengths in between. This resulted in further power losses of about 2 percentage points relative to the module raw power. These issues will be addressed in upcoming development efforts. In combination, small improvements to the diode material, the electrical contacts, and optical elements in the beam path should allow an output power of >5kW at an E-O efficiency of >50%, to be achieved in the near future while maintaining the same 25mm*mrad BPP.
SUMMARY AND CONCLUSION

In conclusion, the DF040HQ, a multi-kW, high-brightness fiber coupled diode laser based on two dimensional stacking of tailored diode bars, has shown the potential of the modular design approach DILAS has pursued, developed, and improved over recent years. The field replicability of sub-units, low demands on maintenance and operation condition (i.e. usage of tap water cooling, low current), and favorable power consumption (high E-O efficiency) are major advantages for the end-user, and the automated production and alignment processes used in the fabrication of the module insure consistent, high quality as well as good cost efficiency. Performance data measured to date show 4.1kW output power at an operation current of 35A with an E-O efficiency of 48% and a BPP of 25mm*mrad. Already identified and upcoming improvements like diode material selection, more efficient wavelength combination, and improved antireflection coatings lead the way to a laser source with an output power of more than 5kW at an E-O efficiency of above 50% at a BPP of 25mm*mrad.

REFERENCES


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