Highly Modular High Brightness Diode Laser System Design for a wide application Range
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ABSTRACT

For an economic production it is important to serve as many applications as possible while keeping the product variations minimal. We present our modular laser design, which is based on single emitters and various combining technics.

In a first step we accept a reduction of the very high brightness of the single emitters by vertical stacking. Those emitters can be wavelength stabilized by an external resonator, providing the very same feedback to each of those laser diodes which leads to an output power of about 100W with BPP of <3.5 mm*mrad (FA) and <5 mm*mrad (SA). Further power scaling is accomplished by polarization and wavelength multiplexing yielding high optical efficiencies of more than 80% and results in about 500 W launched into a 100 µm fiber with 0.15 NA.

Subsequently those building blocks can be stacked also by the very same dense spectral combing technique up to multi kW Systems without further reduction of the BPP.

These “500W building blocks” are consequently designed in a way that without any system change new wavelengths can be implemented by only exchanging parts but without change of the production process. This design principal offers the option to adapt the wavelength of those blocks to any applications, from UV, visible into the far IR. From laser pumping and scientific applications to materials processing such as cutting and welding of copper aluminum or steel and also medical application.

Operating at wavelengths between 900 nm and 1100 nm, these systems are mainly used in cutting and welding, but the technology can also be adapted to other wavelength ranges, such as 793 nm and 1530 nm. Around 1.5 µm the diodes are already successfully used for resonant pumping of Erbium lasers.[1]

Furthermore, the fully integrated electronic concept allows addressing further applications, as it is capable of very short µs pulses up to cw mode operation by simple software commands.

Keywords: High power diode laser, high brightness diode laser, fiber coupling, spectral combining, narrow bandwidth, wavelength stabilization, short pulses, material processing

1. INTRODUCTION

Since the development of high power lasers for material processing, the goal was to increase brightness and reducing the size and costs of laser systems. The most common laser systems are fiber lasers, but with the increase of brightness of high power diode lasers, those systems find an increasing number of applications not only in pumping of solid state lasers but also in material processing. Laser systems based on diode bar architecture have limitations in design improvements regarding size and brightness of the high power radiation in terms of fiber coupling ability. The single emitter laser diode offers a good brightness based on the diode design itself, highest power from a given aperture size, and very low slow axis divergence. Only the fast axis divergence could be improved further. By using different techniques for combining radiation from multiple single emitter laser diodes, very high output power can be generated by keeping the good beam parameter product (BPP) of the single emitter lasers. In theory, the BPP of the laser diode will be the limiting factor of the brightness of a multi kilowatt laser system.

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Single emitters and minibars allow accessing the highest brightness from the diode aperture. Single emitters typically deliver 12 W from a 100 µm aperture with 11 degrees slow axis divergence resulting in a similar brightness per emitter as minibars with up to 8 W from the same aperture. Minibars require additional optics for beam shaping that can be omitted for single emitters. Single emitters also require only low drive currents up to 15 A, which can be easily modulated with more than 100 kHz. Due to the low current cost effective power supplies are available. Furthermore, single emitter chip on submount (COS) is an established component that is available from various suppliers at a variety of different wavelengths and with exceptional ensemble reliabilities of tens of thousands of hours. In addition within a given laser system the COS could be replaced the moment higher brightness chips are available. This makes it very easy to react on new developments in the laser diode sector.

To get to high power levels optical stacking is state of the art. However, it reduces the BPP of the laser system compared to the laser diode whilst supporting good spectral purity. Although spectral purity is usually not necessary for material processing, it allows the combination of many wavelengths while maintaining the BPP of each laser source. Therefore, spectral combining is a very efficient way for power scaling. A narrow and stable spectrum of individual diodes is required for subsequent spectral combining of multiple diodes with different wavelengths. The spacing of individual wavelengths is minimized to achieve the best possible scaling of brightness, the more narrow the laser source the higher the possible power within a specific bandwidth. Laser diodes have the disadvantage of a broad bandwidth and an strong influence of temperature and current on the wavelength. In order to use diode lasers for spectral combining the laser diodes have to be wavelength stabilized. Besides internal structuring of laser diodes (DFB[2], DBR[3], etc.) which requires specific wafer runs for each wavelength, external resonator designs based on an external grating (Littrow[4] or Volume Bragg Grating[5]) are also possible for the determination of the laser diode wavelength. The external resonator designs offer the possibility of locking standard broad band laser diodes to specific wavelength within the gain curve of the laser diode while the power losses are relatively low. This technology is also applicable to other diode material systems, such as GaAlAs emitting around 800 nm and InP emitting in the range of 1500 nm or 1900 nm.

For a cost productive system design we have developed a basic module (the 500 W building block), which allows to easily adapt any available diode wavelength without significant modification to the system design; only the diodes and the filters (and some VBGs if a narrow bandwidth version is desired) need replacement. Due to this system design it is possible to split up the interior in submodules so preassembly is possible and finalization of a specific module is done within shortest time. As the fiber coupler is an external component to the laser system, it is also easily possible to change the type of fiber connector or deliver a free-space laser beam. In addition this design allows a very cost effective and environmental friendly repair and refurbishing of used systems.

2. **OPTICAL STACKING**

DirectPhotonics laser modules are based on 95 µm broad area single emitters with a beam quality of about 4.5 mm*mrad in SA and nearly single mode beam quality in FA, which are individually collimated in a fully automated pick and place assembly. In that process, each emitter is driven by a high, pulsed current while the manipulation system aligns the fast axis collimation lens individually in front of each emitter. After that alignment process every module has the same beam profile and pointing.

Each single emitter is subsequently collimated in fast axis with a pointing error of less than 0.1 mrad in both axes (Figure 1). The design also evolves around a monolithic slow axis collimator (SAC) array that collimates the individual single emitters and simultaneously stacks them on top of each other without need of further alignment. The precision machined SAC is passively aligned and mounted to the common heatsink. This design allows full collimation in both axes with a minimum pointing error through only one active alignment step minimizing manufacturing costs. The number of stacked emitters is determined by the beam quality required for the system. Eight diodes are stacked to couple into a 100 µm fiber with 0.15 NA. The optical efficiency for collimation and stacking is more than 95% and the far field is inscribed into the accepting aperture of the fiber maximizing fiber coupling efficiency, which is typically > 90% for uncoated fibers. With such a module 80 W output power is typically measured.
3. SPECTRAL PROPERTIES

For further power scaling polarization mixing and dense spectral combining are deployed. Within the new 500 W building block modules coarse and dense spectral combining is possible. The coarse building block consists of five different, non stabilized wavelength channels each with a band width of about 15-20 nm (FWHM 6 nm), resulting in an output power from a fiber with a 100 µm ;0.2 NA core diameter of P > 575 W.

For dense spectral combining with channel spacing of less than 4 nm wavelength stabilization is crucial. Within the DirectPhotonics modules, the wavelength is stabilized with volume Bragg gratings (VBGs), placed in the combined beam of all diodes at the end of the monolithic slow axis collimator which reflects part of the emitted light with the desired wavelength back into the diode. Typically, the linewidth is narrowed from 5 nm (FWHM, free running) to a 0.3 nm (FWHM, locked) spectra, equivalent to 95% of the power within less than 1 nm. Free running laser diodes show a shift of the center wavelength of about 0.3 nm/K, which is basically not observably with a VBG stabilized diode laser.

For subsequent spectral combining the power after the VBG is most relevant. This is determined by the spectral purity (intensity of the beam within a specified line width), the wavelength stability and the power drop due to wavelength locking. It was found that the reflectivity of the VBG has no major impact on the output power. The increased spectral purity and locking range observed for the high reflectivity VBG are balanced by the increased power loss.

The large drop of power for high drive currents is due to the reduced spectral purity, respectively insufficient locking, which is more pronounced for the VBG with lower reflectivity. The drop at low drive currents is due to the high reflectivity of the VBG. Though the geometrical and spectral properties of the VBG stabilized resonator is optimized for highest output at high current and stable wavelength but not most narrow line width. Diodes from 900 nm to 990 nm and around 1532 nm were successfully locked over almost the entire drive current range and all the power was measured within 1 nm bandwidth which also leads to a very high frequency stabilized system with a 100 µm fiber, 0.1 NA and 130 W power output at a single wavelength (Figure 3). The wavelength stability of such a diode laser module is in the range of a free running solid state laser [1,7]. With a linewidth of only 80 pm we measured a fluctuation of the center wavelength of only 150 pm within one hour by using a HighFinesse Wavemeter.
The very high wavelength stability combined with narrow linewidth allows dense spectral combining with a spectral spacing of only 4 nm between individual channels using thin film filters (TFF) or gratings [3]. Five wavelength stabilized diode lasers, each with 0.7 nm bandwidth (95% of power) are combined with < 4 nm channel spacing. The individual channels are locked with VBGs (Figure 3). The measured bandwidth of the individual channels is resolution limited by the spectrometer to 0.3 nm, an exemplary measurement with a high resolution wavemeter is seen in Fig. 2. The individual channels are sequentially spectrally combined with thin film filters TFF. The TFFs can be angle tuned to transmit, respectively reflect the individual wavelengths. Reflection and transmission are polarization sensitive for the selected TFF thus acting also as a polarizer. Turning the TFF by 3 degrees shifts the 50% mark of the steep edge by some nm so the same filter type can be used for a complete 500 W module if custom wavelength should be build in. For all coarse building blocks, each wavelength has its own filter so a preassembly can be done and there is no need for angle tuning of the filter.

Steeper angles of incidence result in longer wavelength. For a given angle of incidence shorter wavelengths are reflected and longer wavelengths are transmitted. The combiner efficiency usually is 89% using diodes with 90% polarization ratio. Since the TFF also acts as a polarizer a combiner efficiency of 96% can be concluded. The coarse 500 W building block module consists of 5 wavelength channels with a combined bandwidth of 80 nm (Fig. 3 left), 2-3 of these modules can be sub sequential spectral combined resulting in 1-1.5 kW with a bandwidth of about 160 nm. That combiner is also realized by those TFF, though the original BPP of the single 500 W modules can be maintained and fiber coupling into a 100 µm 0.15 NA fiber is feasible.
For generating of ultra high brightness dense spectral combining is necessary. Even though VBGs are still necessary for wavelength stabilization the price per Watt will be reduced due to the fact that a less variety of diode wavelength will be required for one 500 W building block as up to 3 VBG stabilized building blocks will fit in the same spectral range of one coarse building block. Consequently within the 80 nm bandwidth up to 1.5 kW output power from a 100 µm fiber is already possible, all without change of the modular design. Generally it will also be possible to extend the wavelength region into the 800 nm or 1500 nm/1900 nm region within the same modular system design.

4. BEAM QUALITY
The beam parameter product (BPP) of the individual channels was determined by measuring the near and far field with a CCD camera. We measured the far field to 7 x 7 mm square and the near field was measured to 180 µm round (Figure 4). The spot size was determined at 13% intensity level. This results in a BPP of 4.2 mm*mrad in free space. A BPP of 6 mm*mrad results when launched into an optical fiber with a typical coupling efficiency of about 92%. Systems with multiple channels are specified with a BPP of 7.5 mm*mrad taking alignment tolerances into account where 95% of the power is located within 0.1 NA.

5. SYSTEM
The five channel module shows a beam quality of 4.5 mm*mrad in free space and is available with a 100 µm fiber with 0.15 NA. It has a footprint of 20 x 18 cm and is 14 cm high. In this volume the complete driver electronics is already included. The output power is 500 W. The 2 kW system is a combination of 4 of those 500 W modules which fits into a 19” rack with the depths of 60 cm and the height of about 16 cm. A compact drive electronics was developed that allows a rise and fall time of less than 10 µs. Each channel is driven by a separate power supply controlled by a fast master control (CPLD) and microprocessor. The user is interfacing the laser via various communication interfaces and can directly address power levels or waveforms. The microprocessor is aware of the system status at all time in real time and will transpose the user interface into the most efficient operating current for each base. The operating modus of each channel is also selectable by the user combining high dynamic performance with excellent reliability.
Fig. 5 principle of the integrated electronics system design

The system individually addresses and monitors each channel. Control is performed in real time, with 500 kS/s data rate. A high speed analog parallel port allows for a maximum delay of 2 μs in processing the input control signals. The system controller interfaces via USB, field buses or .dll-interface to a user friendly control software suite. Moreover the system supports most of the industry standard buses for ease of interfacing. In addition a sample of waveforms can be stored into the built in micro controller for even faster pulses, bursts or repeating work steps.

Fig. 6 left: Current controlled 12 A Pulse (green, low to high) and inversed laser output (magenta, high to low), pulse modulation at highest power and pulse width of < 30 μs; right: external analog current control scheme, level and gate signal allows a wide variation of pulse forming

The laser system with drive electronics is the modular building block for kilowatt diode laser systems. Individual blocks are combined with coarse wavelength multiplexing enabling efficient power scaling in the range of some kW at constant beam quality. For the user the interfaces will remain identical if he purchases a 500 W System or a multi kW System as the very same micro processor will control from one to four building block at the same time. These systems are targeted to serve the markets of laser cutting and welding. This concept combined with the highly efficient way of wavelength multiplexing results in a highly stable output power which shows a fluctuation of < 1 W which corresponds to < 0.2 % of the maximum power, the laser can also be run in a power mode. The laser itself monitors the output power and adjusts the driver parameters to compensate any power losses due to sudden diode failure e.g. within some microseconds.
6. CONCLUSION

Multiple single emitter modules allow high power, high brightness diode lasers in the wavelength range from 800 nm to 1500 nm. Dense spectral combining based on VBG wavelength stabilization and subsequent combining with dichroic steep edge filters allows efficient scaling of brightness. A 500 W module with 4.5 mm*mrad beam quality was developed that also comprises the control and drive electronics which allows 100 kHz pulse modulation, if desired, of each individual wavelength. This module is the building block for scaling the power into the kW range at identical beam quality. The building block system design is highly modular and can be adapted easily to any available wavelength, consequently the building block is a module of the multi-kW-Systems which makes it also easily possible to exchange, repair and refurbish blocks from high power laser systems, minimizing the environmental footprint for a sustainable economy.

9 REFERENCES