Generating a high brightness multi-kilowatt laser by dense spectral combination of VBG stabilized single emitter laser diodes

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ABSTRACT

Generating high power laser radiation with diode lasers is commonly realized by geometrical stacking of diode bars, which results in high output power but poor beam parameter product (BPP). The accessible brightness in this approach is limited by the fill factor, both in slow and fast axis. By using a geometry that accesses the BPP of the individual diodes, generating a multi kilowatt diode laser with a BPP comparable to fiber lasers is possible.

We will demonstrate such a modular approach for generating multi kilowatt lasers by combining single emitter diode lasers.

Single emitter diodes have advantages over bars, mainly a simplified cooling, better reliability and a higher brightness per emitter. Additionally, because single emitters can be arranged in many different geometries, they allow building laser modules where the brightness of the single emitters is preserved.

In order to maintain the high brightness of the single emitter we developed a modular laser design which uses single emitters in a staircase arrangement, then coupling two of those bases with polarization combination which is our basic module. Those modules generate up to 160 W with a BPP better than 7.5 mm*mrad. For further power scaling wavelength stabilization is crucial. The wavelength is stabilized with only one Volume Bragg Grating (VBG) in front of a base providing the very same feedback to all of the laser diodes. This results in a bandwidth of < 0.5 nm and a wavelength stability of better than 250 MHz over one hour.

Dense spectral combination with dichroic mirrors and narrow channel spacing allows us to combine multiple wavelength channels, resulting in a 2 kW laser module with a BPP better than 7.5 mm*mrad, which can easily coupled into a 100 µm fiber and 0.15 NA.

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

1. INTRODUCTION

From the beginning of the development of diode lasers, the goal was to generate as much power as in solid state lasers. Due to the basic difference in resonator geometry laser diodes have a very broad spectrum and different quality of divergence in two axes which makes it necessary to collimate the laser radiation as close as possible to the end facet of the laser diode. For generating high power the common approach is to stack multiple emitter very close to each other which generates high power but with a loss of beam quality, the higher the summed output power the larger the summed emitting area which results in larger beam parameter product. A Diode laser system based on a diode laser bar architecture have limitations in design improvements regarding size and brightness of the high power radiation in terms of fiber coupling ability. Whereas 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 form multiple laser diodes, but not based on
bars, 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 kilo watt laser system.

Spectral combining allows the combination of many wavelengths while maintaining the BPP of each laser source. A narrow and stable spectrum of individual diodes is required for subsequent spectral combining of multiple diodes with different wavelengths for very high output power. 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 (FWHM approx. 5 nm) and a change of wavelength by temperature and current (about 1 nm/A). 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 where an external grating (Littrow [4] or Volume Bragg Grating [5]) determines the laser diode wavelength are also possible. 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.

2. **OPTICAL STACKING**

All 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.

Each single emitter is subsequently collimated in fast axis with a pointing error of less than 0.1 mrad in both axes. 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 alignment. The precision machined SAC is passively aligned and mounted to the common heatsink. This design allows nearly full collimation in both axes with a minimum pointing error through only one active alignment step. The number of stacked emitters is determined by the beam quality required for the system. 12 diodes are stacked to couple into a 100 µm fiber with 0.2 NA, whereas in the new module design 8 diodes are stacked for a 100 µm 0.15 NA fiber. 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.

100 W of output power is measured from a single module device with a 100 µm fiber with 0.2 NA and 80 W with the new module design for 0.1 NA fibers.

![Multi single emitter module with monolithic SAC array. Only the FAC lenses are actively aligned in an automated process](image)

Fig. 1 Multi single emitter module with monolithic SAC array. Only the FAC lenses are actively aligned in an automated process
3. WAVELENGTH STABILIZATION BY VBG

For further power scaling polarization mixing and dense spectral combining are deployed. For dense spectral combining with channel spacing of less than 4 nm wavelength stabilization is crucial. Applying the same combining technology with unstabilized diode lasers would need a channel spacing of more than 20 nm due to the shift of wavelength by increased current and temperature. Within the DirectPhotonics modules, the laser diode’s wavelength is stabilized with volume Bragg gratings (VBGs), placed in the combined beam of all diodes (see Fig. 1) at the end of the monolithic slow axis collimator which reflects part of the emitted light with the desired wavelength back into the diode.

Volume Bragg gratings are written by an holographic interference pattern of a laser, often emitting around 325 nm (e.g. He-Cd-laser) in photo-thermo-refractive glasses. The interference pattern of the laser within the PTR causes a periodical change of the refractive index which fixated by a heat treatment. This means those gratings are not affected by any kind of radiation except UV and heat [6]. The main difference to surface gratings is the easily adjustable spectral properties while the glass itself can have any desired shape. Due to the adjustable spectral properties VBGs are very suitable for wavelength stabilization of diode lasers. VBGs offers the possibility of a very small angular sensitivity, on the one hand side this is a challenge for adjusting VBGs but on the other hand side if adjusted the resonator is very stable because only the near fundamental rays are reflected back into diode and it is not possible that there is high power of back reflected light outside of the active area of the laser diode which could cause a COD. In addition the higher transversal modes have higher losses and the brightness is also increased. Especially this VBG parameter demands the high pointing tolerances of all laser diodes of one base module, which is guaranteed by the monolithic design of the SAC and the individual alignment of the FAC.

![VBG Diagram](image)

**Fig. 2** Laser diodes show a high divergency but due to the small angular sensitivity only a small part is back reflected.

The design of the external resonator, i.e. the diode front facet reflectivity as well as the reflectivity and dimensions of the VBG determine the resulting linewidth and locking range. 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. Nevertheless there is very small shift of the peak wavelength of the locked diode lasers. Indirectly this shift can be described as < 0.03 nm/A and arises from a heating of the VBG with increasing power which causes a slight change of the locking wavelength. Compared with the 0.9 nm/A shift of the free running laser diode this effect can be neglected or be avoided with optimized resonator geometry. VBGs with higher reflectivity and/or a different resonator design guarantee locking over the whole range of the drive current.

![Graphs](image)

**Fig. 3** Spectrum of free running diode laser compared with VBG stabilized diode laser.
In previous work [7] different designs of the external resonator, i.e. position of the VBG as well as reflectivity of the VBG and diode facet and their impact on locking range were investigated. The effective feedback into the diode is a combination of the geometry of the resonator design and reflectivities of the VBG and the diode front facet. About 92% of the beam impinging on the VBG is fed back into the diode due to the residual divergence of the collimated diode laser beam (100% Bragg efficiency). The effective feedback was experimentally established to be in the range of 3% to 5.5%.

For subsequent spectral combining the power after the combiner 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 locking. It was found that the reflectivity has no major impact on the power after the combiner. 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. The set-up with the VBG in the fully collimated beam was selected due to significantly reduced alignment effort and cost. Diodes from 900 nm to 976 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 stability Systems with a 100 µm fiber, 0.1 NA emit 130 W 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 [1,8]. With a linewidth of only 70 pm we measured with a High Finesse wavemeter a fluctuation of the center wavelength of only 150 pm within one hour.

![Fig. 4 Long term measurement of the center wavelength fluctuation over one hour.](image)

4. DENSE SPECTRAL COMBINING (DSC)

The very high wavelength stability combined with narrow linewidth allows dense spectral combining with a spectral spacing of less then 4 nm between individual channels using thin film filters (TFF) or gratings/VBGs [3]. In our 500 W modules five wavelength stabilized diode lasers, each with effective 0.7 nm bandwidth (95% of power, including VBG drift) were combined with 4nm channel spacing. The individual channels were locked with VBGs (e.g. to 938nm, 944nm, 948nm, 952nm and 956nm - Figure 5). 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. 4. The individual channels are sequentially spectrally combined with thin film filters TFF. The TFFs have steep edge of less than 2 nm from 0 to 98% transmission are angle tuned to transmit, respectively reflect, the individual wavelengths. Reflection and transmission are polarization sensitive for the selected TFF thus can act also as a polarizer. Turning the TFF by 3 degrees shifts the 50% mark of the steep edge about 4 nm, e.g. from 942 to 946 so the same filter type can be used for a complete 500 W module.
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 was measured to 86% using diodes with 90% polarization ratio. Since the TFF also acts as a polarizer a combiner efficiency of 96% can be concluded. By usage of filters designed for each wavelength channel spacing can be further increased. The actual 500 W module consists of 5 wavelength channels with a combined bandwidth of 17 nm, 4 of these modules are sub sequential combined resulting in 2 kW with a bandwidth of about 90 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. It is also possible to combine very different wavelength as 800 nm, 1060 nm, 1530 nm and 1900 nm with this technique. Beam combining with VBGs is also a good way especially the channel spacing can be very narrow but TFF offers the highest form of modularity.

5. **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 mm by 7 mm and the near field was measured to 180 µm round (Figure 6). 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.

![Beam profile of far field (left) and near field (right) of an individual channel resulting in 4.2 mm*mrad beam parameter product in free space, in far field the 8 individual beam profiles are recognizable where as in focus we measure a nearly flat top beam profile with nearly rectangular shape](image)

6. **SYSTEM**

The five channel module shows a free space beam quality of 4.5 mm*mrad and is usually equipped with an industrial 100 µm fiber with 0.15 NA. It has a footprint of 20 cm by 18 cm and is 14 cm high. In this footprint the driver
electronics are included. The output power is currently 500 W (Figure 7). New diode lasers with improved output power and polarization ratio will scale the output power to 500 W soon. 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. The operating modus of each channel is selectable by the user combining high dynamic performance with excellent reliability.

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 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.

The laser system with drive electronics is the modular building blocks for kilowatt diode laser systems. Individual blocks are combined with coarse wavelength multiplexing enabling efficient power scaling in the range of 2 kW to 4 kW at constant beam quality. These systems are targeted to serve the markets of laser cutting and welding.

7. **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. Coarse wavelength multiplexing will be deployed to build kilowatt systems with a beam quality of 7.5 mm*mrad.

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9 REFERENCES