Beam Combining Techniques for High-Power High-Brightness Diode Lasers
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ABSTRACT
Laser diodes are efficient and compact devices operating in a wide range of wavelengths. Boosting power by beam combining while maintaining good beam quality has been a long-standing challenge.

We discuss various approaches for beam combining with emphasis on solutions pursued at DirectPhotonics. Our design employs single emitter diodes as they exhibit highest brightness and excellent reliability. In a first step, after fast axis collimation, all single emitter diodes on one subunit are stacked side-by-side by a monolithic slow-axis-collimator thus scaling the power without enhancing the brightness.

The emissions of all diodes on a subunit are locked by a common Volume Bragg grating (VBG), resulting in a bandwidth < 0.5nm and high wavelength stability. Second, two subunits with identical wavelength are polarization coupled forming one wavelength channel with doubled power and brightness. Third, up to five channels are serially spectrally combined using dichroic filters. The stabilized wavelengths enable dense spectral combining, i.e. narrow channel spacing. This module features over 500W output power within 20nm bandwidth and a beam parameter product better than 3.5mm*mrad x 5mm*mrad (FA x SA) allowing for a 100µm, 0.15NA delivery fiber [1].

The small bandwidth of a 500-W-module enables subsequent coarse spectral combining by thin film filters, thus further enhancing the brightness.

This potential can only be fully utilized by automated manufacturing ensuring reproducibility and high yield. A precision robotic system handles and aligns the individual fast axis lenses. Similar technologies are deployed for aligning the VBGs and dichroic filters.

Keywords: High power diode laser, high brightness, volume bragg grating, wavelength stabilization, spectral beam combining, wavelength beam combining, direct diode

1. INTRODUCTION
Since the development of high power lasers for material processing the goal was to increase power and beam quality and reducing price and size of the laser systems. Concerning beam quality, the diode laser may not be able to compete with solid state lasers or fiber lasers, however in the last decades, diode lasers went into focus of development more and more, leading continuously to new records of power and beam quality almost every year opening doors to new applications which were reserved to solid state or fiber lasers.

Diode lasers provide advantages to conventional laser systems such as higher reliability which diode lasers continue to give proof every day in established pump systems. If the pumping step is excluded, direct diode lasers can increase the wall plug efficiency to more than 40%.

To address additional markets direct diode lasers need further continuous improvements. The major challenges are: higher power and better beam quality summarized as brightness. Its enhancement is the most important goal enabling the direct diode laser to excel conventional systems with higher efficiency and higher reliability. Though ultimately the brightness has to be sufficient for the intended application, otherwise reliability, efficiency or price are useless.

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As the brightness of direct diode lasers is constantly improving, BPP of less than 5mm*mrad have been reported with multi kW output power [2]. In material processing power densities at the work piece exceed 1MW/cm² with commercially available processing heads. These power densities are sufficient for cutting, welding and ablation.

Especially single emitter-based diode lasers further offer the advantage of very fast current modulation due to their low drive current and therefore low drive voltage.

The power of diodes rises on and on. Today single emitter with an cw output power of more than 20W are known [3]. Diodes with an output power <14W are available commercially with a BPP in slow axis of 5mm*mrad and below. As already mentioned, aside of output power enhancement an improvement of the brightness is crucial, i.e. while boosting power at least a constant beam quality has to be maintained. There are several activities known which lead to a consolidation of the slow axis [4] for example by reducing the thermal blooming and improvements of the beam quality.

Single emitter diodes available today can reach a brightness of more than 90MW/cm²sr. The enhancement of power always sets new demands on the cooling concept, leading to higher complexity. Therefor much higher brightness in the range of 150MW/cm²sr is not achievable due to heat generation. As the brightness of a single emitter is limited by cooling options, other ways to scale the brightness have to be applied like polarization multiplexing or wavelength combination and ultimately dense spectral combining. Each mentioned combining technique leads to a brightness enhancement by a factor of 2 or more.

For a cost productive system design DirectPhotonics has developed a basic module (the 500 W building block), which uses all these combining techniques and drives brightness to high levels while delivering also highest reliability. Due to this system design it is possible to split up the interior in submodules which allows preassembly and finalization of a specific module within shortest time. As the fiber coupler is an external component to the laser system, the beam delivery can easily be varied between various fiber connector types or even 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 AND POLARIZATION MULTIPLEXING**

Due to limitations in the brightness and power of single emitters the upscaling of power by using multiple emitters is state of the art. To gain back the brightness one has lost by stacking the emitters there are a lot of options. However, a diode array has to be spatially efficient because all the empty space in a diode array reduces the brightness and is lost if not corrected by complex corrective optics. Bars for example are twisted by special lenses to rotate each emitter by 90° equaling in a stack in fast axis orientation which allows a brightness increase by a factor >10.

Another way to gain back brightness is to chop the slow axis of the emitters in half and stack them in fast axis. By doing so one gains brightness by a factor 2 (Figure 1)

![Figure 1: The base module of Laserline; the emitters are cut in half (Circle A), repositioned (Circle B) and restacked together in fast axis (Circle C) by special optics [5].](image-url)
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 (Figure 2). 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%. With such a module over 80 W output power is typically measured.

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 3). 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.

Figure 2: Multi single emitter module with monolithic SAC array. Only the FAC lenses are actively aligned in an automated process

Figure 3: Beam profile of far field and near field of an individual channel resulting in 4.2 mm*mrad beam parameter product in free space
Another simple combination method is polarization multiplexing. Since diodes have a good polarization purity of 90% and more, polarization multiplexing is a cost effective and power efficient method of almost doubling the brightness (Figure 4). The efficiency is almost only determined by the polarization purity of the diodes.

![Figure 4: Schematic polarization multiplexing of two pump laser modules](image)

3. SPECTRAL COMBINING

For further power scaling wavelength beam combining is used. The DirectPhotonics 500W building block consists of five wavelength channels. Each wavelength channel consists of two multi single emitter modules which are polarization multiplexed prior the final fiber coupling. Every wavelength channel is built up with diodes operating at a different wavelength. The channel spacing between two channels is about 20nm (Figure 5).

![Figure 5: Spectrum of a coarse spectral combined 500W building block](image)

The wavelength channels are combined with dichroic filters with very high efficiency. The transmission is more than 97% and the reflection efficiency is over 98%. This allows a >500W building block with more than 94% combining efficiency. The spectral width of this 500W light engine is 80nm.
Figure 6: Left: P-I Curve for a common, coarse spectrally combined 500W building block. Right: Combining efficiency of all five wavelength channels. The efficiency varies for the different channels in low power modes. Each channel has its own digital controller so that 95% efficiency can be obtained over the whole power range (right)

The spectral combining or also called coarse spectral combining is a common method to stack laser power spectrally. The major limitation factors for this combining technique are the spectral width, regarding the demands of the intended application and the availability of high power single emitters.

4. **WAVELENGTH LOCKING & DENSE SPECTRAL COMBINING**

There are many reasons for further narrowing the spectral width. As mentioned before the availability of diodes plays a huge role. Through wavelength stabilization it is possible to use one type of diode for three or more channels in one building block and by doing so reduce the complexity (Figure 7).

Figure 7: Spectrum of one channel of the building block, reduced down to <0.7nm locked over the whole current range

Another, more technical advantage is the spectral width of a building block, which is reduced to 20nm. The wavelength stabilization of the diodes, applied by volume holographic gratings, is the key to scale the brightness of the 500W building blocks to a new brightness level. This dense spectral combining enables the output power scaling by combining up to four building blocks within the same spectral width as a coarse combined one, while brightness and power is multiplied by a factor of 4 leading to an optical output power >2kW with 7.5mm*mrad beam quality.
Dense spectral combining inside each building block as well as the combination of the four building blocks is achieved by ultra steep edge thin film filters. The edge steepness is <1.5nm (5%-95%) resulting in a combining efficiency of 90% for the dense spectral combined multi kW laser systems (Figure 8) with a channel spacing of 4nm.

5. CONCLUSION

Different combining techniques applied efficiently can boost the brightness of a system vastly. Polarization Multiplexing leads to almost double the brightness. With wavelength beam combination the brightness grows by a multiplier equaling the number of wavelengths.

Further narrowing the spectrum of each channel and developing efficient ways of combining with smaller channel spacing will lead to even higher brightness scales in the future.

6. REFERENCES