Advanced Pumping with Ultra-High Brightness Diode Lasers

Wolfgang Gries\textsuperscript{1}, Leif Alexandersson\textsuperscript{2}, Stefan Heinemann\textsuperscript{3}, Wenko Süptitz\textsuperscript{1}\textsuperscript{*}

\textsuperscript{1} DirectPhotonics Industries GmbH, Max-Planck-Str. 3, 12489 Berlin – Germany
\textsuperscript{2} DirectPhotonics, Inc., 124 Montego Key, Novato, CA 94949 – USA
\textsuperscript{3} Fraunhofer USA, Center for Laser Technology, 46025 Port Street, Plymouth, MI 48170– USA

Abstract

The growing market demand for economical and efficient kW-laser systems for material processing has direct implications on the development of diode lasers. An improvement in parameters such as brightness, output power, wall-plug efficiency and price is mandatory. Multiple single emitter (MSE) modules are a promising response to this demand, they allow the highest power and the development of ultra-high brightness diode lasers based on standard broad-area diodes. Using MSE technology, DirectPhotonics Industries have developed a series of new industry-grade diode laser systems.

Turn-key systems from DirectPhotonics Industries provide up to 600 W at 976 nm from a 200 µm fiber, 0.22 NA. A 1-kW solution (100 µm fiber, 0.15 NA) is expected in the beginning of Q1, 2013. Wavelength stabilization to less than 0.5 nm with volume Bragg gratings (VBG) enables efficient pumping also for lasers with a narrow absorption spectrum, and is especially suited for pulsed fiber lasers and resonant pumping. Dichroic mirrors are used for dense spectral beam combining of 4 channels within 10 nm. Control and drive electronics are integrated into the platform and represent a basic building block for a variety of systems, such as a flexible standalone system or various 19-inch rack configurations for applications in laser pumping or laser testing. The technologies can be transferred to other wavelengths including 808 nm, 9XX nm, 14XX or 15XX nm.

Keywords: laser diodes, single emitter, volume Bragg grating, high brightness, fiber-coupled diode laser

Introduction

High-power diode lasers find an increasing number of applications in materials processing and pumping of so-called “new” solid-state lasers (namely fiber and disk lasers) as their brightness increases. Compared to the thus far dominating CO\textsubscript{2} lasers and to conventional solid-state lasers the new solid-state lasers show superior efficiency, highest brightness and a long lifetime. In particular, they promise superior performance for the kilowatt output power class. But for a maximum implementation of kW lasers in industrial applications, a further development in brightness, life time, and efficiency is required. Diode lasers are excellent pump sources for solid-state lasers and offer the highest potential for improvement in those requested parameters. Additionally, high-brightness diode lasers by themselves attract more and more attention since the direct diode

\textsuperscript{*} wenko.sueptitz@directphotronics.com, Phone:+49 30 6392 87247
applications promise even more advantages regarding price and wall plug efficiency of the industrial laser systems. For efficient pumping of high-power fiber lasers, diode lasers have to fulfill a number of requirements. The first is related to its spectral properties. Typical fiber lasers are doped with ytterbium and absorb pump light in two regions, a broad band centered at about 915 nm and a small band at about 976 nm (Figure 1). The broad band is well suited for continuous operation and requires a longer fiber (> 30 m). Over such a long distance nonlinear effects such as stimulated Brillouin scattering accumulate and lead to a reduced conversion efficiency.

Alternatively, the high absorption in the 976 nm region allows for more efficient conversion of pump light into laser power and hence, a shorter fiber. Furthermore, it offers a higher conversion efficiency due to the smaller quantum defect. On the other hand, the small absorption bandwidth adds some requirements to the pump laser diodes: First, the wavelength of the diodes has to match exactly with the absorption band and it must not shift over time or during changes in input power. Usually, high-power laser modules have a spectral width of 3 to 6 nm and shift with diode current (~1 nm/A) and heat sink temperature (~0.3 nm/K). Therefore, the diode wavelength has to be narrowed and stabilized for the pump light to be fully absorbed and to avoid a thermally induced drift.

Secondly, pump diodes must have a high brightness to enable a maximum coupling efficiency in optical fibers. State-of-the-art fiber lasers use pump combiners that fuse 6 pump leads with one signal lead to a single active fiber (6+1:1 pump combiner). The two most common geometries are an active fiber with a 25-µm core and 250-µm cladding (25/250) for pulsed fiber lasers requiring pump leads with 105 µm and 0.15 NA as well as an active fiber with a 20 µm core and 400 µm cladding (20/400) for cw fiber lasers requiring pump leads with 200 µm and 0.2 NA. Low losses in the pump combiner are essential as the power of the diode laser increases. Any cladding light in the pump leads must be avoided and smaller NAs are desirable with further power scaling. As the power from a single fiber laser approaches multiple kilowatts, all glass fiber lasers represent a

![Figure 1: Absorption spectrum of Yb-doped fiber laser. The small pump band at 976 nm offers a reduced quantum defect and higher conversion efficiency for the emission at about 1100 nm.](image)
favorable design mitigating the limited heat conduction of the polymer cladding. However, the NA of the pump core is reduced from 0.46 to 0.28, respectively, reducing the NA of the pump leads to 0.12.

The spectrum of fiber lasers is constantly expanding and pump lasers with various wavelengths (such as 915 nm, 980 nm, 1455 nm, 1469 nm, 1480 nm, 1529 nm, etc.) are required. Due to the quest for higher powers and higher efficiency all of them have to fulfill the demands mentioned above. For many years the wall plug or electro-optical efficiencies for diode lasers used to be around 50%. 71% were reported [2] and around 60% are commercially available for 9xx nm devices. Diodes emitting at 808 nm for conventional solid-state laser pumping are less efficient (around 55%) than diodes emitting at 9xx nm due to the materials used in the epitaxy, GaAlAs/GaAs for 808 versus InGaAlAs/GaAs for 9xx nm, and, together with increased susceptibility for catastrophic optical damage of the facet, thus emit about half the power than 9xx nm diodes [1]. Diodes emitting in the range from 1500 nm to 1900 nm (InGaAs/InP) show about 1/3 of the output power of 9xx nm devices and a typical efficiency of only 25%.

Multiple single-emitter technology

Today, single laser diode emitters provide a maximum of 10 to 20 Watts of laser power from a 95-µm broad emitter. A large number of such single laser diodes has to be combined to supply the industry with kW-class diode laser systems. Several different methods are established for the combination of the radiation of the single emitters. Emitters can be arranged in bars, bars can be combined into stacks or, the radiation of single emitters or bars might be combined later by optical and spectral stacking techniques and coupled into optical fibers. The single-emitter approach has been optimized in the multiple single-emitter (MSE) fiber-coupled diode lasers [3]. MSE fiber-coupled diode lasers have some inherent advantages such as low drive currents, which enable higher modulation frequencies, and simplified cooling systems.

Figure 2: a) Typical setup for optical stacking of 12 single emitters. b) real-world image of the laser diode stack with FAC, SAC and VBG.
The challenge of multiple single-emitter (MSE) fiber-coupled diode lasers lies in high-precision, high-yield manufacturing and not so much the optical design of the device, since only collimating lenses and a focusing optic are used (Figure 2). However, a large number of individual components must be handled and consistently aligned with high precision. The 100-W module and the 600-W system presented here comprise 12 single emitters and 120 single emitters with 82% optical fill factor, respectively. Pointing tolerances and collimation errors of all emitters must not exceed 10% of the spot size to realize the benefits of highest brightness from single emitters compared to bars.

The two major assembly processes of MSE fiber-coupled diode lasers are the precision diode reflow process and the accurate 5-axis alignment of the fast axis collimation lens (FAC).

The reflow process enables positioning of 12 single-emitter diodes on submounts within ±5 μm on a common heatsink. A pick&place robot utilizing an image processing software algorithm performs automated positioning, alignment and fixation of the FAC optics with a consistent accuracy of better than 0.3 μm and 0.12 mrad. It is also deployed for automated alignment of the external volume Bragg gratings (VBG).

**Optical stacking**

Optical stacking is state-of-the-art for power scaling and many different configurations are available for bars and single emitters. Due to the asymmetric emitter dimensions, the fast axis collimation (FAC) and slow axis collimation (SAC) are separated using different focal lengths to obtain a symmetric spot size when focused with a single lens (Figure 2). 95-μm broad-area single emitters are used with a beam quality of about 5.2 mm*mrad in slow axis (SA) and single mode beam quality in fast axis (FA), which are individually collimated in both FA and SA directions and precisely interleaved with the other emitters, enabling highest brightness of the multiple single-emitter module (Figure 2).

![Figure 3: a) Near-field (circle diameter 200 μm), and b) far-field of 120 single emitters launched into a 200-μm fiber (NA 0.2) [4].](image)
An optical transfer efficiency of 85% from the diode facet to the end of the fiber is achieved for diode lasers focusing 12 single emitters (not polarization coupled) into a 100 µm / 0.2 NA fiber. Optical stacking and polarization multiplexing is deployed to couple 120 single emitters into a 200 µm / 0.2 NA fiber achieving an optical fill factor of 82% (Figure 3) and resulting in output powers of >100 W (100 µm fiber) and >700 W (200 µm fiber).

**Wavelength stabilization**

Precise wavelength stabilization becomes necessary to meet the requirements of ytterbium pumping at 976 nm. Methods for wavelength stabilization can be grouped into internal (optics integrated within diode laser) and external solutions (use of separate bulk elements). Distributed feedback (DFB) and distributed Bragg resonator (DBR) are typical solutions for internal wavelength stabilization, whereas a Littrow cavity and a volume Bragg grating are commonly used as external solution. DFB and DBR structures are integrated into the diode and a change in wavelength requires a specific wafer run, while the Littrow and VBG resonator design determines the emission wavelength by the external grating and identical standard diodes can be used for a relatively broad wavelength range. 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.

External VBGs are the method of choice for the MSE technology. The VBG in an external resonator reflects part of the emitted light with the desired wavelength back into the diode. The design of the external resonator,

![Graph showing wavelength stabilization for varying diode drive current. The bandwidth remains smaller than 0.5 nm up to the maximum drive current.](image)

Figure 4: Wavelength stabilization for varying diode drive current. The bandwidth remains smaller than 0.5 nm up to the maximum drive current.
i.e. the diode front facet reflectivity as well as the reflectivity and thickness of the VBG determines the resulting linewidth and locking range. Typically, the linewidth is narrowed from 5 nm (FWHM) to less than 0.5 nm (FWHM) spectrum, equivalent to 95% of the power within 1.2 nm for a batch of hundreds of individual diodes. With the proper resonator design, the peak wavelength remains almost constant when varying the drive current from threshold (0.5A) to full power of 11 A (Figure 4). The peak wavelength shifts only about 0.03 nm/A due to heating of the VBG, whereas without VBG the tuning coefficient with drive current (temperature) is fifty times larger: 1.5 nm/A (0.33 nm/K).

**Dense spectral beam combining (DSBC)**

The narrow bandwidth of wavelength-stabilized diode lasers allows DSBC with a spectral spacing of a few nanometers. The beams can be spectrally combined using thin film filters or matched VBGs. Figure 5 shows the spectrum of a high-performance thin-film edge filter and the spectra of two wavelength stabilized diode lasers, each with 1 nm bandwidth and 2.5 nm spacing. A power loss of < 3% and a bandwidth of less than 4.5 nm (95%) was obtained with this setup. A system with four wavelengths emits 400 W from a 200 μm fiber, 0.1 NA with 12 nm bandwidth [4].

![Figure 5: Wavelength combining using thin-film filters [3].](image)

**Flexible turn key system**

The DirectPhotonics diode laser platform with integrated control and drive electronics is the basic building block for a variety of diode systems. Wavelength stabilization can be applied and multiple platforms can be optically stacked, dense spectrally combined or coupled into a 100- or 200-μm fiber. A flexible turn key system is available as a 19-inch rack and standalone platform (Figure 6). In general, systems can be manufactured with or without wavelength stabilization, including a specified number of diode modules and for various wavelengths. Further customization is available upon request.
Table 1: Output specifications of the fiber couples turn key diode laser system.

<table>
<thead>
<tr>
<th>Fiber Core Diameter</th>
<th>Numerical Aperture</th>
<th>Laser Power ex-Fiber</th>
<th>Linewidth @976 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 µm</td>
<td>0.22</td>
<td>95 W</td>
<td>&lt; 2 nm</td>
</tr>
<tr>
<td>200 µm</td>
<td>0.10</td>
<td>140 W</td>
<td>&lt; 2 nm</td>
</tr>
<tr>
<td>200 µm</td>
<td>0.22</td>
<td>600 W</td>
<td>&lt; 5 nm</td>
</tr>
</tbody>
</table>

Typical applications of the diode laser system for advanced pumping are in solid-state, disk and fiber laser development. Besides the basic function as a pump laser system, the DirectPhotonics systems are used in fiber laser manufacturing for qualification of fibers, burn-in testing and general testing purposes.

The single-emitter architecture enables a high modulation frequencies of up to 500 kHz and predestines the system for pumping of pulsed high-power fiber lasers or pulsed (nanosecond) or ultrashort pulsed solid-state lasers (pico- and femtosecond).

Figure 6: The turn key laser diode system is available a) as a 19-inch rack (100 W) or b) as a standalone version (600 W).

**Outlook**

Further development of the ultra-high brightness diode laser system is underway and will lead to a number of significant improvements in various parameters. First, higher output powers will become available and a kilowatt system will join the DirectPhotonics product family later in Q1 of 2013. For all systems, the already excellent spatial brightness will be improved and the beam-parameter product will be reduced. On the system side several 19-inch rack configurations will be introduced and combinations of two or more systems will become possible. With their latest efficiency improvements, direct-diode laser systems are on their way to replace more sophisticated and less efficient laser systems in many scientific and industrial applications.
References


