Optical components for tailoring beam properties of multi-kW diode lasers

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ABSTRACT

One important aspect for the increasing use of diode lasers in industrial applications is the flexibility of diode lasers to tailor the beam properties to the specific needs demanded from the application. For fiber coupled solutions beam shaping with appropriate micro-optical elements is used for efficient fiber coupling of the highly asymmetric diode laser beam, whereas for direct applications optical elements are used to generate specific intensity distributions, like homogenized lines, areas and rings. Applications with diode lasers like solid state laser pump sources often require tailored spectral characteristics with narrow bandwidth, which is realized by using volume Bragg gratings for wavelength stabilization.

In this paper we will summarize several concepts for adapting beam properties of diode lasers by using specific optical components. For building very compact laser modules of up to 2 kW we already presented a concept based on beam shaping of high fill factor bars. In this paper we will focus on further tailoring the beam properties of these very compact laser modules in the wavelength range from 808 nm up to 1020 nm. Fiber coupling of such modules into an 800 µm NA0.22 fiber yielded 1.6 kW without using polarization coupling. Another example is the generation of a 2.5 kW homogenized line with 40 mm length and a width of 4 mm.

Keywords: high-power diode laser, high-brightness, fiber coupling, materials processing, industrial laser, scalable, modular, wavelength stabilization

1. INTRODUCTION

A variety of optical components are used to tailor the beam properties of high power diode lasers. These include general purpose components like spherical and aspherical lenses, mirrors, gratings, and optical fibers. However, due to the characteristics of high power diode lasers, some optical components exist that are specifically designed for diode lasers. While most of these components have been around for many years, progress is still made at a fast pace, driven by innovations in manufacturing technology, new diode laser structures, and new optical concepts that strive to advance the performance of high power diode lasers in terms of efficiency, brightness, and spectral performance.

Fifteen years ago fiber coupling of high power diode laser bars was mostly accomplished by using fiber bundles, coupling each one emitter into a single fiber and then bundling all fibers together to one larger core fiber. However, these devices were limited in beam quality. Beam-shaping optical elements have enabled higher brightness fiber coupled modules while initially using the same 19-emitter laser bars, which had been developed for the use with fiber bundles. Today, a variety of different approaches coexist for fiber coupled high power diode laser modules, each addressing market segments with different, or sometimes overlapping, requirements in terms of power and beam quality. The main concepts are free-space-combined fiber coupled single emitters, fiber bundle based laser bars, laser bars with beam shaping optics, and mini-bars that are specifically designed so they can be coupled efficiently into optical fibers without the need for complex beam shaping optics.

Fiber coupled modules are advantageous compared to free space lasers in multiple regards. The laser module can be placed at a distance from the laser process, isolating it from potential contamination and vibration inherent to many industrial processing equipment. At the same time, fiber coupled modules are generally easy to replace in the field without the need

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to re-align any optical elements. However, fiber coupling of diode lasers involves losses. In particular when spot geometries with a large ratio between both orthogonal axes are required for the application, a free space approach is often beneficial due to the fact that the emission inherent to the diode laser is already highly asymmetric in beam quality.

Innovative laser applications like annealing of semiconductors, cladding to repair worn parts or to coat parts with harder materials, and hardening each require different intensity distributions and power levels. Custom laser developments for each application are often cost prohibitive. By following a modular design approach and adding adjustable optical elements to modify the beam shape, a single laser head can be adapted to multiple applications and thus serve a large customer base, benefiting from economies of scale.

Another area of high power diode laser development which is driven by innovative applications relies on the ability to modify the spectral characteristics of diode lasers. While the emission from high power diode lasers is too broad for some applications, volume holographic gratings (VHGs) can be used to narrow the spectral line width. Many optical pumping applications benefit from a narrow spectral line width. In recent years, advances in diode laser spectral performance have enabled applications in optical pumping of atomic lines like diode pumped alkali lasers (DPAL) as well as spin exchange processes used to generate hyperpolarized helium to advance medical imaging.

The following sections provide a brief overview of key optical components used to tailor the beam properties of high power diode lasers. New concepts for fiber coupled modules, as well as for free space lasers with uniform intensity distribution are shown.

2. OPTICAL COMPONENTS

2.1 Fast-axis collimation lenses (FAC)

Due to the large NA of diode lasers in the so called fast-axis direction, a fast-axis collimation lens is required for most applications. For some applications, like fiber coupling of single emitters, cylindrical fiber lenses can be used. For applications requiring better beam quality, acylindrical lenses are used.

2.2 Slow-axis collimation lenses (SAC)

In slow-axis direction, the divergence of modern high power diode lasers is typically in the range of 6 to 10 degrees full angle. The divergence angle is current-dependent and generally increases with higher operating currents. This needs to be considered when selecting the aperture and focal length of the lens. For diode laser bars, the emitter to emitter spacing (pitch) is another critical factor. Cylindrical micro-lens arrays are often used to collimate laser bars. While it is beneficial to choose the focal length as long as possible, in order to minimize the divergence of the collimated beam, radiation from neighboring emitters will overlap at some point, limiting the focal length of the SAC array to that distance.

2.3 Beam shapers for fiber coupling of diode laser bars

The highly asymmetrical beam quality of high power diode laser bars is not a good match for optical fibers, which are typically symmetric in both, core diameter and NA. Each emitter is nearly diffraction limited in fast-axis direction, while the characteristic in slow-axis direction is highly multi-mode. On top of that, multiple emitters on a laser bar are arranged along the slow-axis direction, thus further increasing the beam parameter product (BPP) of the overall beam in this direction.

In order to symmetrize the BPP of fast and slow-axis, multiple beam shaping devices exist. By rearranging partial beams the BPP can modified. Generally this means that beam quality in slow-axis direction improves, while the BPP in fast-axis direction increases at the same factor. While the initial beam can generally be optically cut into partial beams at any location, it is often beneficial to do so between emitters to avoid losses on edges of optical components. Many concepts and devices exist, however, only a select number can be described within the scope of this paper.

One approach is based on a stack of parallel plates, one for each partial beam, to displace partial beams in fast-axis direction and create ‘steps’ in the near field distribution (Figure 1). A second stack of plates is then used to shift all partial beams so they are all aligned on top of each other in slow-axis direction. Another beam shaping device is the step mirror as described by Treusch et al. [1]. By deflecting partial beams twice, using a stepped mirror structure, partial beams are rotated by 90 degrees (Figure 2a). For a laser bar with 19 emitters and a step mirror with similar pitch (1 emitter equals 1 partial beam), this means that the beam is transformed in the near field from 1 emitter in fast-axis direction and 19 emitters in slow-axis direction, to 1 emitter in slow-axis direction and 19 emitters in fast-axis direction. The resulting beam is a lot closer to being symmetric in beam quality and can now be coupled efficiently into an optical fiber.
A similar result can be achieved by using cylindrical micro-lens arrays [2]. A beam shaper uses two cylindrical micro-lens arrays configured to form a 1:1 Keplerian telescope. The optical element is typically implemented monolithically with curvatures on both sides of one substrate (Figure 2b). This array is now placed in front of the laser bar rotated by 45 degrees around the axis of propagation. As a result, each emitter is rotated by 90 degrees, leading to a beam with 19 emitters stacked in fast axis direction and only 1 emitter in slow-axis direction (Figure 2c).

2.4 Volume holographic gratings

High power diode lasers typically generate a multimode output. The resulting spectral width is typically about 2 nm FWHM for 808 nm devices and about 3 nm FWHM for 980 nm devices. The central wavelength is temperature dependent and shifts to longer wavelengths (red shift) for higher temperatures. The temperature coefficient is in the range of 0.2 to 0.4 nanometer per Kelvin for most high power diode lasers in the near infrared wavelength range.

For some applications the temperature dependency of the wavelength and the spectral width are not desired. Both can be addressed by placing a volume holographic grating (VHG) in front of the laser bar. The VHG provides narrow band feedback into the laser bar, forming an external cavity which increases stimulated emission at the desired wavelength (Figure 3a). As a result, the spectral output of the laser bar is ‘locked’ to the VHG wavelength and can be a lot more narrow compared to the ‘unlocked’ spectrum of the laser bar (Figure 3b). While typical specifications for VHG-locked high power diode laser bars range from 0.5 nm to 1 nm FWHM, some applications, like optical pumping of atomic absorption lines, require much lower spectral line width. Results have been demonstrated by Glebov et al. for a 30 W laser with 10 GHz bandwidth [3]. DILAS has presented a diode laser system with 30 GHz bandwidth and 3 kW of optical output power [4].
2.5 Homogenizers

Many applications require a uniform intensity distribution along one or both axes of the laser spot. For illumination purposes, 2D homogeneous distributions are typical. For materials processing applications like hardening, annealing, or cladding, one uniform axis is often sufficient because the work piece is moved with respect to the laser beam during processing. Line sources with one narrow axis and uniform intensity distribution along the line are typical for these applications.

Depending on the requirements of the application (i.e. uniformity, edge steepness, line length, working distance, etc.) various concepts exist in order to generate homogeneous intensity distributions. Fiber coupled high power diode lasers in conjunction with cylindrical imaging optics can be used to create lines with moderate uniformity requirements, using the fiber as a waveguide that ‘mixes’ the modes, creating a uniform distribution at the fiber exit plane, which can then be imaged onto the work piece. However, in many cases it is beneficial to avoid fiber coupling because the highly asymmetrical beam from the diode laser first needs to be re-shaped for efficient fiber coupling, then the symmetrical beam exiting the fiber needs to be transformed into the desired line. Another approach using a similar ‘mixing’ effect, is the use of a waveguide inside the laser head. Typically these waveguides are rectangular in cross section, matching the desired ratio of line length and width while allowing the use of spherical lenses to image the exit plane of the waveguide onto the workpiece. However, other ratios in conjunction with cylindrical optics may be used. Waveguides generally provide intensity profiles with very steep edges, however, achieving good uniformity along the line requires a large ratio of waveguide length and diameter, in order to achieve a large number of reflections inside the waveguide.

![Homogenizer setup with 2 cylindrical micro-lens arrays and field lens. The incident beam is segmented into multiple beamlets which all overlap in the focal plane of the field lens.](image)
Another widely used concept to create high performance uniform diode laser sources is based on micro-lens arrays [5]. Each element of the lens array samples a small section of the collimated laser beam. In the focal distance of the field lens, all sampled partial beams overlap, forming the desired laser spot (Figure 4). Provided that a large number of micro-lenses is used, and symmetries are avoided, this quasi-random stacking of beam segments has an averaging effect that leads to a highly uniform intensity distribution. Cylindrical micro-lens arrays can be used to generate both, line sources or 2D rectangular beam shapes with uniform intensity distributions in both axes. Other beam shapes can be created by using different element shapes for the micro-lens array, i.e. round, square, or hexagonal lenslets in order to create the respective beam shapes.

3. OPTICAL CONCEPTS

3.1 Fiber coupled modules

Fundamentally there are two different approaches to developing high power fiber coupled diode lasers. The ‘tailored bar’ (T-bar) approach has been followed and published by DILAS for many years. This approach uses laser bars that are specifically designed (tailored) to match the beam quality of the targeted fiber without the need for expensive beam shaping optics. On a first order, this means that the beam parameter product of the chip in slow-axis direction needs to be smaller than the acceptance parameters of the fiber (core radius x NA). After fast- and slow-axis collimation optics, multiple beams can be spatially stacked on top of each other, until the fast-axis beam quality matches the slow-axis, hence forming a square that best fits the round fiber.

This approach has been successfully implemented for a variety of high brightness fiber coupled modules ranging from a few hundred watts to more than 4 kW while maintaining a beam quality of 25 mm x mrad. While diode laser modules in the power range between 200 W and 400 W are based on spatial multiplexing in fast-axis direction only, the highest power version utilizes polarization and wavelengths multiplexing as well.

A 4 kW laser has been presented by Bayer et al., demonstrating the capabilities of this approach [6]. The laser is based on 5 wavelengths ranging from 915 nm to 1060 nm. The design is modular on multiple levels, starting with a 4-bar cooling structure that also holds fast-axis and slow-axis collimation optics. This modularity allows utilizing fully automated assembly processes that ensure both, high repeatability and low cost assembly in high volume. On a larger scale, each of the 5 wavelengths is housed in its own module, allowing easy maintenance in the field and lowering material costs due to economies of scale. The laser achieves optical output power of 4 kW from a 400 µm NA0.12 fiber at 33.6 A operating current. The electrical-to-optical efficiency is 49 %. The required overall drive voltage is 243 V (Figure 5).

![Figure 5: Laser module based on tailored bar technology. 4 kW optical output power at 34 A from a 400 µm NA0.12 fiber.](image-url)
The second approach to developing fiber coupled high power diode lasers focuses on maximizing the output power per chip, which entails a cost saving factor due to minimized chip count. Generally this leads to a very different chip structure compared to the first approach. While the first approach often uses a large emitter spacing and small emitter count, this second approach tries to utilize a maximum of the surface area of the chip by minimizing emitter spacing and maximizing emitter count. Technical limits are typically set by thermal cross-talk between neighboring emitters and minimum required gap sizes for the most common optical concepts.

In recent years, 50 % fill-factor bars have been established as a quasi-standard for a new family of high power fiber coupled modules. Depending on emission wavelength, 200 W to 300 W of optical output power from a 10 mm wide laser bar are state of the art. While typically beam-shaping optics are required to improve beam quality in slow-axis direction at the cost of decreasing beam quality in fast-axis direction, the additional cost and system complexity are often compensated for by the increased power per bar and resulting lower chip count. However, it is not the case that one approach is superior to the other, but it depends on factors like required beam quality, power level, and a variety of boundary conditions, which approach leads to the overall best outcome in terms of performance, cost, manufacturability, and system size and weight.

Unger et al. have presented results for a 6 kW fiber coupled high power diode laser utilizing the second approach [7]. The laser is based on a modular design, similar to the 4 kW laser shown above. Eight modules, each yielding 800 W of optical power, are combined using both spatial multiplexing (4x) and wavelengths multiplexing (2x) and coupled into a 1 mm NA0.2 fiber (Figure 6). Internally each module uses small subunits which are compatible with DILAS’ fully automated manufacturing equipment. The system can be scaled up in output power by adding more wavelengths.

![Figure 6: 6 kW laser module based on 50 % fill factor bars and beam shaping optics. 6 kW of optical output power at 149 A from a 1 mm NA0.2 fiber.](image)

Using the same chip material and subunits as used for the 6 kW laser shown above, DILAS has developed a new fiber coupled module in the medium power range (1.6 kW) with the aim to minimize cost. Key factors to keeping the cost low are the use of common building blocks with other laser modules, a high level of automation, and a simple optical concept. The laser is based on spatial multiplexing only, while avoiding both polarization and wavelengths multiplexing. Keeping the optical setup as simple as possible has a trickledown effect on the mechanical design, as well as on the manufacturing process of the laser.

The laser is based on two macro channel coolers, populated with five 50 % fill factor bars each. A short focal length fast-axis collimation lens (FAC) is used in conjunction with a BTS (see section 2.3). Cylindrical lenses are used to collimate the beam in slow-axis direction. Each beam is then deflected by 90 degrees. As a result, an optical stack of all five beams is generated. Optical stacks from both coolers and are then combined to form an array of 2x5 beams. Spherical lenses are used to couple the beam into an 800 µm NA0.2 fiber. Optionally the laser module can be equipped with a visible aiming beam.

The specified output power of 1600 W is reached at about 213 A drive current. The required drive voltage at 976 nm emission wavelength is about 15 V, leading to an overall electrical-to-optical efficiency of 50.3 % at nominal power (Figure 7).
3.2 Uniform intensity distribution

DILAS has developed a variety of high power diode laser modules with uniform intensity distribution based on micro-lens arrays. Examples have been published for 600 W and 3 kW line sources [8], an 11 kW 2D array [9] as well as a 200 W laser with hexagonal beam shape to illuminate a round gas cell used for optical pumping of rubidium as part of a spin exchange process to generate hyperpolarized helium [10]. A newly developed module advances this technology and adds more flexibility to the laser by making the line length adjustable by the user. The ability to easily adapt the beam shape for multiple processes, compared to replacing optical components or even using different lasers for different processes, serves as a big cost saver for many users, enabling markets where multi kilowatt diode laser systems have been cost prohibitive in the past.

The current design is based on a similar architecture compared to the fiber coupled modules shown in Section 3.1. Using similar building blocks reduces cost and allows the use of existing automated manufacturing equipment. Due to the use of potential-free macro coolers, coolant requirements for the laser are less stringent compared to micro-channels coolers. DI-water is not required, only a particle filter to prevent contamination of the laser head. High fill-factor bars are used in order to achieve high optical output power from each laser bar which, as a result, reduces the total number of laser bars.

Many typical applications for this type of laser are sensitive to the polarization of the beam due to the difference in absorption for S- and P-polarized light for many materials, depending on angle of incidence. The laser design was chosen in a way that avoids polarization multiplexing, thus maintaining the high grade of linear polarization provided by the diode laser bars. Spatial as well as wavelengths multiplexing are used to combine a maximum of 30 laser bars. A set of two micro-lens arrays is used in conjunction with a field lens to generate a uniform line in the focal plane of the field lens. One of the two micro-lens arrays is placed on a motorized linear stage so that the spacing between both arrays can be adjusted. Varying the distance between the arrays leads to a change in line length in the focal plane of the field lens.

Resulting line shapes at various motor positions are shown in Figure 8. The line length can be varied between 10 and 60 mm. This range can be adapted to different customer requirements by changing the micro-lens arrays or by selecting a different focal length field lens. A different focal length lens will also change the working distance of the laser. The LI-curve for a 2.5 kW version of the laser module is shown in Figure 9. The optical output power is 2.5 kW at 164 A. The electro-optical efficiency is 51.2 % at nominal power. The laser module can be configured for an optical output power of up to 4 kW.

Figure 7: Laser module rated at 1600 W optical output power from an 800 µm NA0.2 fiber at 976 nm emission wavelength.
Figure 8: Images of focal spot and intensity cross section along line for various motor positions.

Figure 9: LI-curve of free space diode laser module with 2.5 kW optical output power and uniform intensity distribution along the line generated at the work piece.
4. SUMMARY

A variety of optical elements and methods have been shown, for tailoring the beam properties of high power diode lasers. Most general purpose optics, like lenses, mirrors, gratings, etc. can be used to shape the beam to the desired properties. However, there are also diode laser specific optical elements, developed to match the specific beam properties of high power diodes laser. Due to the high NA of diode lasers in the so called fast-axis direction, FAC lenses are required for most application to capture the beam near the front facet of the diode before it spreads out too much. Cylindrical micro-lens arrays are frequently used to collimate the emission of each emitter in slow-axis direction. Proper selection of focal length is crucial in order to achieve the best possible beam quality, while avoiding power losses due to overfilling the lenslet apertures.

In order to couple radiation from most laser bars into optical fibers, special beam shaping optics are required. Common concepts are based on optical elements that re-arrange the near field distribution of the diode laser in a way that trades beam quality between fast and slow-axis, increasing beam quality in the slow-axis direction, while at the same time lowering the beam quality in fast-axis direction. Optical components like glass plates, micro-step mirrors, and micro-lens arrays are used to either cut the incident beam into segments which are then stacked on top of each other, or by rotating segments of the beam by 90 degrees around the axis of propagation.

Besides tailoring the beam for fiber coupling, customized beam shapes and intensity distributions can be created. Applications like cladding, hardening, and annealing often require a uniform intensity distribution along one or both axis of the focal spot or line that is generated at the work piece. Light guides and micro-lens arrays can be used to generate highly uniform intensity distributions.

Not only can the beam shape be tailored by optical components, but also the spectral characteristic of the diode laser. For some applications, the spectral width of typically 2 – 3 nm for high power diode lasers emitting in the near infrared is too large. The temperature dependency of the central wavelength of diode lasers can also impose a problem for some applications. By placing a volume holographic grating (VHG) in front of the laser bar, both, the spectral width and the temperature dependency of the center wavelength, can be minimized. Typically the wavelength shift is reduced from about 0.3 nm/K to 0.006 nm/K. The spectral width for typical VHG locked laser bars is 0.5 nm FWHM, but results have been shown for devices achieving 10 GHZ bandwidth.

Specific examples for the use of these optical components have been shown, including three fiber coupled modules ranging from 1.6 kW of optical output power to 6 kW. In addition, a laser module is shown that creates a line focus with uniform intensity distribution.

Two different concepts for fiber coupling of high power diode laser bars have been discussed. The first uses ‘tailored’ laser bars that are specifically designed to match the beam quality required for fiber coupling. The second uses diode laser bars optimized for a maximum output power in conjunction with beam shaping optics. The first concept was used to build the presented laser module with 4 kW output power from 400 µm NA0.12 fiber, the second approach was used for the 6 kW laser from a 1 mm NA0.2 fiber. While both concepts are very different, each has its own strength and weaknesses allowing them to coexist. Another laser module presented here has a rated output power of 1.6 kW from an 800 µm NA0.2 fiber. It is also based on the second concept and incorporates many building blocks from the 6 kW laser module to benefit from economies of scale.

Finally, a laser module has been presented, which creates a line focus with uniform intensity distribution. While many custom solutions for similar lasers exist, this laser has an adjustable line length between 10 mm and 60 mm allowing customers to use the same laser modules for a variety of different processes. The module is based on a modular concept and the power can be increased from the shown 2.5 kW to up to 4 kW.

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