

Diode laser modules based on new developments in tapered and broad area diode laser bars

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ABSTRACT

In the last few years an increasing demand for high-brightness diode laser sources is observable, which is mainly driven by applications for fiber laser pumping and materials processing. A number of different approaches have been investigated in the past for the realization of such systems. In this paper we compare different concepts for high-brightness, high-power diode laser modules that are based on the new generation of tapered diode laser bars and new developments in broad area diode laser bars, respectively.

One of the main advantages of tapered diode laser bars is the good beam quality in the slow-axis direction, which allows the design of high-power laser systems with a symmetric beam profile without the necessity of using sophisticated beam shaping systems. Such laser modules with multiple bars aiming for kilowatt output power can be realized with different incoherent coupling principles, including spatial multiplexing, polarization multiplexing and wavelength multiplexing. On the other hand, modules with a single or only a few tapered diode laser bars aim for very high brightness suitable for fiber coupling with fiber diameters down to 50 μm with a numerical aperture (NA) of 0.22.

In this paper we present a detailed characterization of the new generation of tapered diode laser bars, including typical electro-optical data, measurements of beam quality and lifetime data.

Tapered diode laser bars typically suffer from a broad spectrum which is extremely obstructive for pumping applications with small absorption bandwidths. To overcome this disadvantage we used volume bragg gratings (VBG) to improve the spectral quality of tapered diode laser bars. In addition to further improve the brightness of such diode laser systems we investigated external phaseplates to correct for smile and lens aberrations.

Keywords: High power diode laser, tapered diode laser, high brightness, beam quality, fiber coupling, incoherent coupling, volume bragg grating

1 INTRODUCTION

High power diode laser systems based on broad area diode laser bars are well established laser sources for a variety of applications including materials processing and solid state laser pumping. The main advantages of such systems are high wall-plug efficiency, high optical power, reliability, long lifetime, relatively low investment costs and a small footprint. However, besides these numerous advantages, the major drawback of high power diode laser systems with broad area diode laser bars is their poor beam quality and brightness B as defined in Equ. (1). The brightness of a diode laser beam is defined by the laser power P and the beam parameter product (BPP)^a in slow- and fast-axis-direction¹.

$$B = \frac{P}{\pi^2 \cdot BPP_{total}^2} \quad ; \quad BPP_{total}^2 = BPP_{slow}^2 + BPP_{fast}^2 \quad (1)$$

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^a defined as $BPP = w_0 \cdot \theta$ (half beam waist diameter $w_0 = d_0/2$ times half far field divergence angle θ)

A simple geometrical consideration shows that efficient fiber coupling of a diode laser beam requires a total BPP given by Equ. (2)¹ :

$$BPP_{total} = \sqrt{BPP_{slow}^2 + BPP_{fast}^2} = \sqrt{2} \cdot BPP_{sym} \leq \frac{d_{fiber}}{2} \cdot NA_{fiber} \quad (2)$$

The output beam of a common broad area diode laser bar is characterized by a highly asymmetric profile with regard to beam dimension and divergence angle. Typical values for the source width are 10 mm for the lateral direction in the plane of the pn-transition (slow-axis) and 1 μm for the vertical direction (fast-axis), respectively. The beam divergence angles are typically 35° in fast-direction and 5° in slow-direction, respectively^a. Consequently, the resulting beam parameter products are highly asymmetric. Whereas the beam quality in the fast-direction is about 1 mm-mrad and thus nearly diffraction limited, the beam quality in the slow-direction is in the region of 400 - 500 mm-mrad, which is far beyond the diffraction limit.

Efficient fiber coupling of such a diode laser bar is only possible if the different BPPs are adapted by shifting beam quality from one direction to the other direction. This symmetrization of the BPPs is equivalent to a minimization of the overall beam parameter product BPP_{total} .

In the last few years the brightness of broad area diode laser bars has been steadily improved by increasing the output power per bar and improving the beam quality in the slow-axis direction. The enhancement of beam quality has been realized by reducing the filling factor and in addition by reducing the slow-axis divergence. However, despite these technical advances for standard 10 mm wide bars it is still necessary to use beam shaping optics for symmetrization to build diode laser systems, which are suitable for fiber coupling into a 200 μm fiber with NA 0.22.

The introduction of fiber lasers has increased the demand for such high-brightness fiber coupled pump modules. To meet the requirements for fiber laser pump sources diode laser systems with fiber coupling into a 200 μm fiber (NA 0.22) and an output power of more than 100 W are needed. In the next section different approaches for the realization of such diode laser systems will be compared.

2 BASIC CONCEPTS FOR HIGH-BRIGHTNESS DIODE LASER MODULES

2.1 Properties of tapered diode laser bars

The vertical structure (fast-axis) of tapered diode laser bars is similar to that of common broad area diode laser bars. The significant difference between tapered diode lasers and broad area diode lasers becomes apparent when regarding the lateral structure (cf. Fig. 1). In contrast to a broad area multimode emitter, the single emitter of a tapered diode laser bar consists of a small ridge waveguide followed by a tapered amplifier section. The high beam quality is defined by the ridge waveguide and the high output power is provided by the tapered section, while maintaining the beam quality of the ridge waveguide. Typical data for the single emitter of a tapered diode laser bar are summarized in Table 1.

One important consequence of the tapered structure is the difference of source position for the fast- and the slow-axis. Whereas the source position of the fast-axis is on the output facet of the diode bar, the source position of the slow-axis is located inside the diode bar at the transition between the ridge waveguide and the tapered part. This astigmatism defines the characteristics of the microoptics, particularly with regard to the position and the focal length of the slow-axis collimation lens (SAC).

For individual tapered single emitter devices output powers up to 8 - 9 W have been reported with nearly diffraction limited beam qualities^{2,3}. However, to achieve this good beam quality the front facets of these single emitters typically have a very low reflectivity of less than 0.1 %. As a consequence these devices are very sensitive to external back reflections, e.g. from lenses or uncoated fibers. To avoid these back reflections usually optical diodes are used in such setups. For industrial applications optical diodes cannot be used for obvious reasons, like costs and overall size. Therefore the reflectivity of the output facet of a tapered diode laser bar cannot be as low as for single emitter devices. As a consequence up to now the power and beam quality of the single emitters of a tapered diode laser bar do not reach the values of single emitter devices.

^athe divergence angles are defined as half far field divergence angle (95% - value)

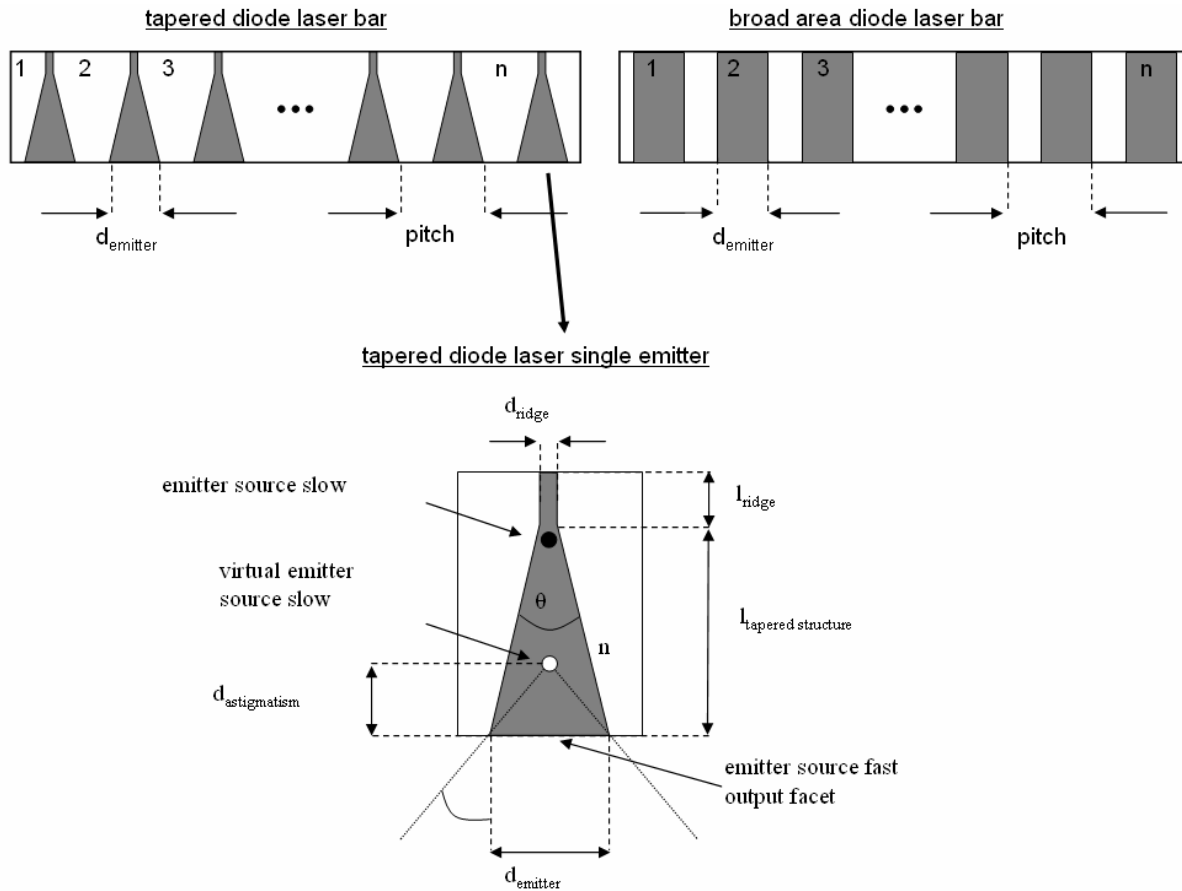


Fig. 1: Lateral structure of a tapered diode laser bar (top left) compared to a broad area diode laser bar (top right). Typical data for the different diode laser bar structures are summarized in Table 2. Typical data for a single emitter (bottom) of a tapered diode laser bar are summarized in Table 1.

Table 1: Typical data for the single emitter of a tapered diode laser bar (cf. Fig. 1).

power [W]	output facet $d_{emitter}$ [μm]	source width d_{Ridge} [μm]	l_{Ridge} [μm]	l_{Taper} [μm]	refractive index	$d_{astigmatism}$ ($\approx l_{taper}/n$) [μm]	taper angle [$^\circ$]	M^2 single emitter slow	BPP single emitter slow [mm* μrad]
2.5	200	5 - 20	500	2000	3.5	600	6	4	1.2

2.2 Different Approaches for High-Brightness Systems

The overall goal for a fiber coupled diode laser module that can be used for both pumping and materials processing applications, is to achieve high brightness (i.e. small fiber diameter) at minimum cost/watt.

As described in the last section for a 200 μm fiber module built with conventional 10 mm diode bars symmetrization of the BPP is necessary for efficient fiber coupling. The contribution of sophisticated microoptics including alignment and mounting can easily reach or exceed 50 % of the total manufacturing costs. Consequently to reduce this cost factor symmetrization optics has to be eliminated. Generally such a high brightness diode laser system should meet the following criteria :

- the beam quality of the individual bar in slow-axis direction is suitable for fiber coupling without beam symmetrization
- to reduce the costs of microoptics only fast-axis collimators (FAC) and slow-axis collimators (SAC) for filling factor enhancement in the slow-axis direction are used
- for multiple bar systems symmetrization of the total BPP is realized by stacking bars on top of each other in the fast-axis direction

As the relatively poor beam quality is a basic feature of a broad area diode laser bar, an improvement of the beam quality can only be achieved by a modification of the lateral chip structure. In the last few years different approaches have been reported for the enhancement of slow-axis beam quality of diode laser bars. Among these are the use of tapered diode laser bars⁴, specially tailored broad area laser bars (T-Bar)⁵ and single emitter array laser bars (SEAL)⁶. Typical data for these different approaches are summarized in Table 2 and Table 3. In addition the values for a conventional 10 mm diode bar (broad area type A) are shown for comparison.

Table 2: Comparison between different diode laser bars for high brightness applications (for explanation see text).

	number of emitters	emitter width slow [μm]	pitch [μm]	filling factor [%]	beam divergence slow axis (full angle 95%) [°]	M ² _{slow} single emitter	BPP _{slow} diode bar with SAC [mm*mrad]	fibre core diameter NA 0.22 [μm]
broad area type A	19	150	500	30	9	18.9	112	1500
tailored broad area bar	5	100	500	20	7	9.8	15.3	200
tapered structure A	25	20	400	5	14	4	31.2	400
tapered structure B	12	20	400	5	14	4	15.0	200
tapered structure C	25	10	400	2.5	14	2	15.6	200
SEAL	49	5	200	2.5	14	1	15.3	200

In Table 2 the emitter width in the slow-axis direction for the tapered structures is the virtual emitter width, which is defined by the M²-value and the slow-axis divergence (cf. Sect 2.1). For a diffraction limited beam with M²=1 the beam parameter product is given by $BPP = \lambda/\pi \approx 0.31 \text{ mm} \cdot \text{mrad} @ 980 \text{ nm}$.

The beam parameter product in the slow-axis direction BPP_{slow} is calculated for optimal filling factor enhancement by means of a SAC. The fiber core diameter in Table 2 is the minimum allowed value for a symmetrized beam to avoid overfilling the fiber according to Equ. (2). In Table 3 the relative brightness is normalized with respect to the conventional 10 mm diode bar.

Table 3 : Relative brightness and facet load for different diode laser bars for high brightness applications (for explanation see text).

	number of emitters	emitter width slow [μm]	emitter width slow @ output facet [μm]	power per bar [W]	power per emitter [W]	M ² _{slow} single emitter	relative Brightness	facet load	
								Linear power density [mW/μm]	power density [MW/cm ²]
broad area type A	19	150	150	60	3.2	18.9	1	21	2.1
tailored broad area bar	5	100	100	25	5	9.8	3.1	50	5.0
tapered structure A	25	20	180	50	2	4	3.0	11	1.1
tapered structure B	12	20	180	25	2.1	4	3.1	12	1.2
tapered structure C	25	10	180	100	4	2	12.0	22	2.2
SEAL	49	5	5	40	0.8	1	4.9	163	16.3

Compared to a conventional 10 mm broad area diode bar the brightness for tapered structures A and B is increased by a factor of three. In comparison to the tailored broad area bar the tapered structures A and B have no advantages if only brightness is considered. The brightness of the SEAL-bar is even higher when compared to tapered structures A and B. However, taking into account the facet load, which is one of the main failure mechanisms of diode laser bars, the benefits of the tapered structure become evident. As a consequence of the tapered structure the emitter width in slow-direction on the output facet is increased, which leads to a significant reduction of the power density on the output facet. Compared to the tailored broad area bar the facet load is reduced by more than a factor of 4 while maintaining the same brightness. The facet load of the SEAL is more than 13 times the facet load of the tapered structures.

Another advantage of the tapered diode laser structure is the potential for higher brightness without increasing the facet load by the same amount. For tapered structure C the brightness is increased by a factor of 4 when compared to tapered structures A and B. On the other hand the facet load is only doubled. For this tapered structure C the brightness is already doubled when compared to the SEAL-bar.

2.3 Diode laser modules with tapered diode laser bars

As described in Sect. 2.2 the basic unit for a high-brightness tapered diode laser module is an individual tapered diode laser bar with FAC and SAC. The lateral structure of the tapered bar is adapted to the required fiber diameter (cf. Table 2). Similarly to conventional high power laser systems based on broad area diode bars, power scaling is achieved by stacking individual tapered diode laser bars on top of each other in the fast-axis direction. As described in Sect. 2.2 symmetrization of the laser beam is simply realized by selecting the appropriate stack height.

Further power scaling can be realized with different incoherent coupling principles, including spatial multiplexing, polarization multiplexing and finally wavelength multiplexing⁴.

Fig. 2 shows a calculation of the total beam parameter product as a function of the M^2 -value of an individual emitter of the tapered diode laser bar. For a bar with 25 emitters a M^2 -value of 4 per emitter is sufficient for efficient fiber coupling into a 400 μm NA 0.22 fiber, whereas for a 200 μm fiber only 12 emitters are allowed if the M^2 -value is 4. It becomes evident that fiber coupling of a symmetrized diode laser stack requires a better M^2 -value per emitter when compared to a single bar if the same fiber diameter is used. This is a consequence of the factor $\sqrt{2}$ in Equ. (2).

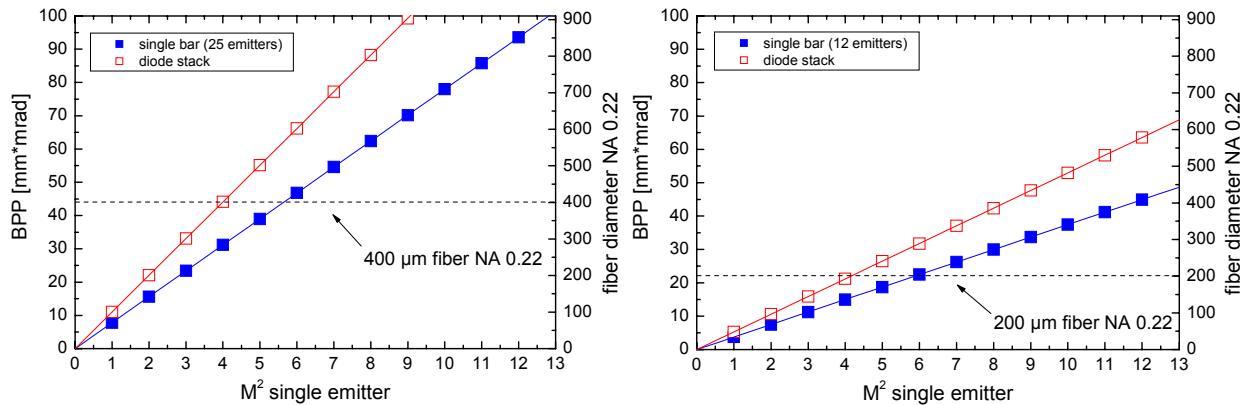


Fig. 2: Calculation of beam parameter product (left axes) as a function of the M^2 -value of an individual emitter of the tapered diode laser bar. The calculation is shown for a bar with 25 emitters (left diagram; filled square) and a bar with 12 emitters (right diagram), respectively. The open symbols show the calculation for a symmetrized diode laser stack. The right axis shows the corresponding fiber diameter if using a numerical aperture of 0.22.

For very high-brightness modules with fiber diameters below 200 μm different approaches are possible. Among these are a further reduction of the number of emitters, an improvement of the beam quality per emitter and the use of microoptics to symmetrize the beam. Although the approach of symmetrization by optical means is in contrast to the arguments of Sect. 2.2 it could be advantageous in terms of costs if only a few very high-brightness modules are built compared to the number of modules with standard tapered bars suitable for 200 μm and 400 μm fibers, respectively.

3 CHARACTERIZATION OF TAPERED DIODE LASER BARS

3.1 Electro-optical data of individual bars

The power-current characteristics of different types of tapered diode laser bars are shown in Fig. 3. The left diagram of Fig. 3 shows the measurement for a 10 mm wide bar with 25 emitters at a wavelength of 940 nm. The maximum output power of the 10 mm bar was 58 W at a current of 70 A with an efficiency of nearly 50 %. The right diagram in Fig. 3 shows the power-current characteristics for two 5 mm wide bars with 12 emitters at 980 nm. In addition the right diagram compares the performance of the tapered diode laser bars mounted on an actively cooled heatsink with microchannels and a passively conduction cooled heatsink. A maximum output power of 32 W at a current of 35 A was achieved for both actively and passively cooled parts, respectively. The efficiency reached as much as 56 %. In Table 4 additional electro-optical data, like threshold, slope efficiency, spectrum and angular far field data are summarized. In addition the data for a tapered diode laser bar with a wavelength of 808 nm are also shown in Table 4.

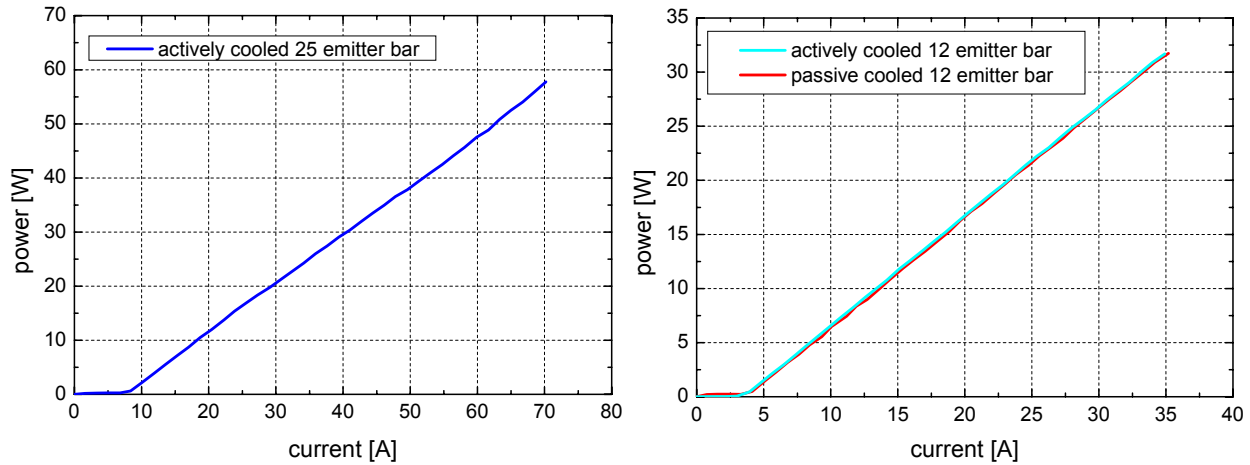


Fig. 3: Power-current characteristics for different types of tapered diode laser bars. The left diagram shows the curve for an actively cooled 10 mm wide tapered diode laser bar with 25 emitters at a wavelength of 940 nm. The right diagram shows the power curve for 5 mm wide tapered diode laser bars with 12 emitters at a wavelength of 980 nm and a comparison between actively and passively cooled bars.

Table 4 : Summary of electro-optical data for different types of tapered diode laser bars.

wavelength [nm]	bar width [mm]	number of emitters	threshold [A]	slope efficiency [W/A]	power [W]	current [A]	efficiency [%]	spectral width [nm]	far field slow-axis (full angle 95%) [°]	far field fast-axis (full angle 95%) [°]
940	10	25	8	0.9	58	70	49	6	15	65
808	5	12	7	1	28	35	42	2	12.4	67
980	5	12	3.7	1	32	35	56	3	15	67

3.2 Beam Quality

We measured the beam quality of the tapered diode laser bars indirectly by measuring the fiber coupling efficiency. The goal was a M^2 -value of 4 per emitter (cf. Table 2). As shown in Fig. 2 good coupling efficiencies should be achieved with the 10 mm wide bars (25 emitters) for a 400 μm fiber (NA 0.22) and with the 5 mm wide bars (12 emitters) for a 200 μm fiber (NA 0.22), respectively. The optical setup for the fiber coupling experiments consisted of a collimation with FAC and SAC and a spherical focusing optics.

Fig. 4 shows the results of the fiber coupling experiments for two different 5 mm wide tapered diode laser bars with 12 emitters. The maximum output power behind the 200 μm uncoated mode stripped fiber at 808 nm was 21.9 W at a current of 35 A. The corresponding power-current characteristic is shown in the left diagram of Fig. 4. Taking into account the Fresnel losses at the input and output facet the coupling efficiency achieved nearly 90%. The maximum output power behind the 200 μm uncoated mode stripped fiber at 980 nm was 22.3 W, which corresponds to a fiber coupling efficiency of 91 %. However, at 980 nm the losses at the microoptics and focusing optics were significantly higher compared to the losses at 808 nm. These losses cannot be explained solely by the slightly larger slow-axis divergence (cf. Table 4) of the 980 nm bars and have to be analyzed further.

For a 10 mm wide bar with 25 emitters the maximum output power behind a 400 μm mode stripped fiber was 46.7 W, which corresponds to a fiber coupling efficiency of 86 %. This fiber had a numerical aperture of 0.2 and coated end faces. In Table 5 the results of the fiber coupling results are summarized.

In summary the good fiber coupling efficiencies in combination with the calculations in Fig. 2 indicate a good beam quality of the individual emitters of the tapered diode laser bar with an average M^2 -value of the single emitters in the region of 4 – 6.

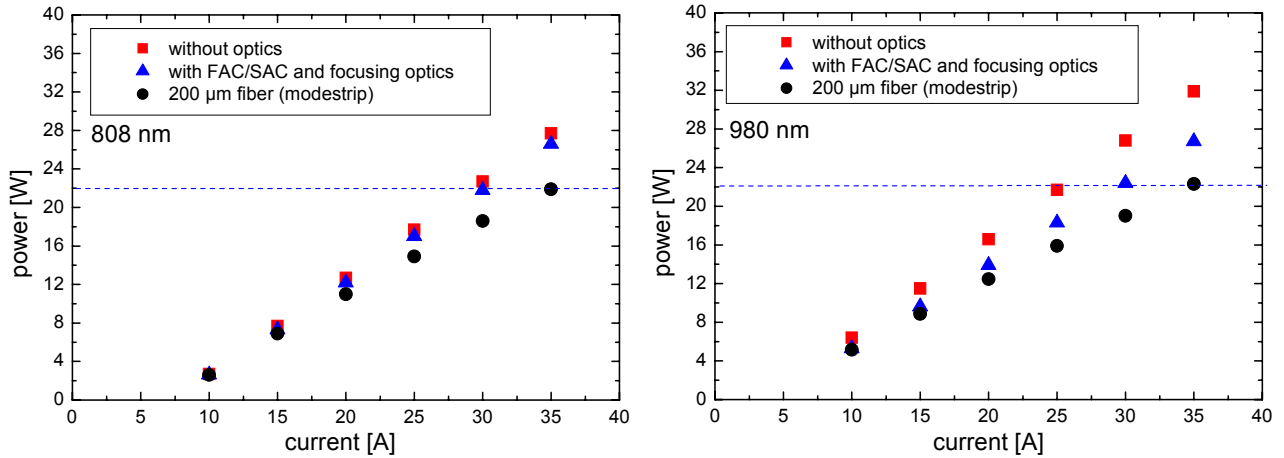


Fig. 4: Results for fiber coupling of 5 mm wide tapered diode laser bars at 808 nm (left diagram) and 980 nm (right diagram).

Table 5 : Summary of fiber coupling results for tapered diode laser bars. The 400 μm fiber had coated end faces, whereas the 200 μm fiber was uncoated. The efficiencies are corrected for the Fresnel losses of about 7 % for the uncoated fiber.

wavelength [nm]	bar width [mm]	number of emitters	fiber diameter NA 0.22 [μm]	measured output power behind fibre [W]	current [A]	fiber coupling efficiency [%]	additional losses at microoptics [%]	total efficiency [%]
940	10	25	400	46.7	70	86	7	80
808	5	12	200	21.9	35	89	5	85
980	5	12	200	22.3	35	91	16	75

3.3 Lifetime Considerations

For industrial applications life time issues are at least as important as beam quality and brightness. Until now for tapered diode laser bars only lifetime data with an operating time of less than 1000 h have been reported⁷.

Fig. 5 shows a 3000 h lifetime test for 10 mm wide tapered diode laser bars with 25 emitters. The bars were mounted on actively cooled microchannel heatsinks. The lifetime test was performed for two different operating conditions. The left diagram in Fig. 5 shows the lifetime performance of 4 samples in continuous wave operation at a current of 50 A. The right diagram shows the data for 4 different samples in pulsed mode operation with 1.5 Hz and 50% duty cycle at a current of 50 A. The current modulation in the pulse mode was 100% between zero Ampere and the nominal current of 50 A. For both operating conditions no failure was observed after 3000 h. For the pulsed operation mode this corresponds to a pulse number of more than 16 MShot. A comparison between the power-current characteristics before and after the lifetime test revealed a power loss of less than 4 % after 3000 h of operation.

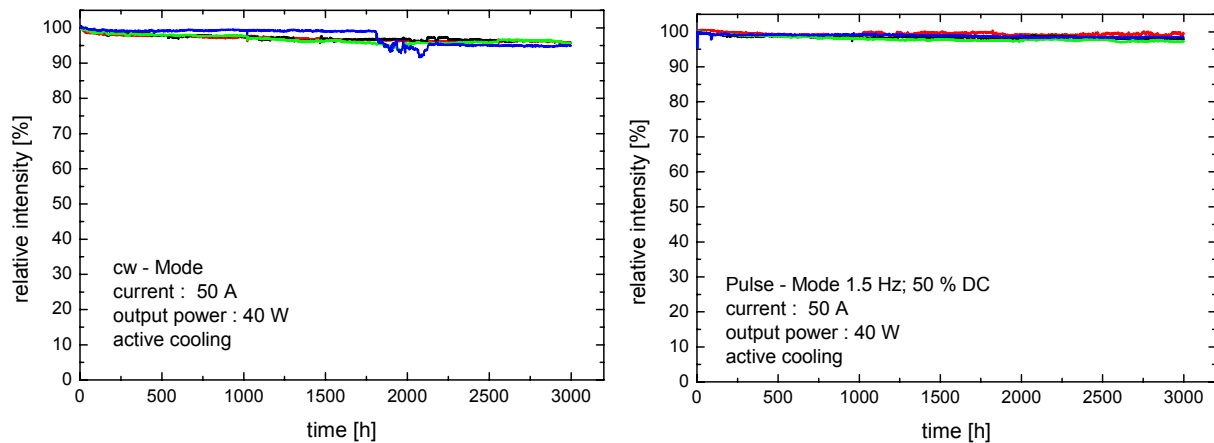


Fig. 5: 3000 h lifetime test on 10 mm wide tapered diode laser bars mounted on actively cooled micro channel heatsinks with a current of 50 A and a temperature of 20°C. Left diagram shows continuous wave operation mode and right diagram shows pulsed operation mode at 1.5 Hz and 50% DC with 100% current modulation.

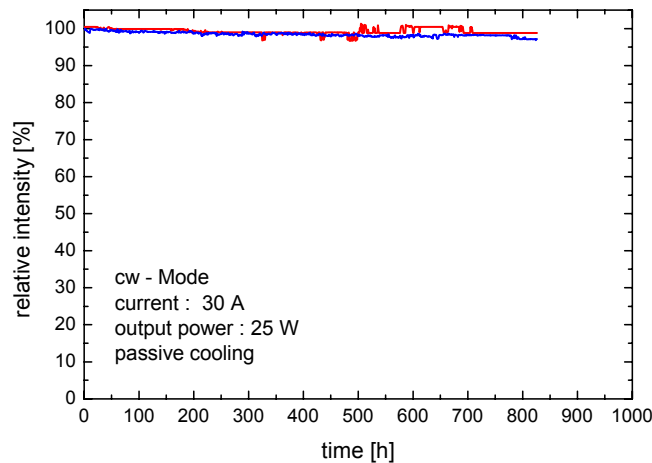


Fig. 6: 800 h lifetime test on 5 mm wide tapered diode laser bars in continuous wave operation mounted on passively cooled heatsinks with a current of 30 A and a temperature of 20°C.

For a number of different reasons modules based on passively cooled heatsinks are required for a lot of applications. Fig. 6 shows lifetime data for two 5 mm wide bars with 12 emitters mounted on passively cooled heatsinks. The bars are running in continuous wave operation at a current of 30 A, which corresponds to a current of 60 A for the 10 mm wide bars. After a runtime of more than 800 h no degradation is observable.

4 FURTHER IMPROVEMENT OF BEAM QUALITY

4.1 Enhancement of spectral beam quality

As shown in the previous sections the beam quality in slow axis direction is significantly improved by tapered diode laser bars. On the other hand tapered diode laser bars typically suffer from a broad spectrum, which might reduce the efficiency for pumping applications with small absorption bandwidths. To overcome this problem the spectral properties of tapered diode lasers can be improved by inserting a volume bragg grating (VBG)^{8,9}. The effect of using a VBG is a well-defined optical feedback within a very small spectral range which stabilizes the spectrum of the tapered diode laser bar.

With an accurate adjustment of the reflectivity of the VBG in relation to the reflectivity of the output facet of the diode laser bar the power loss by inserting a VBG is less than 10 %. A typical bandwidth of the stabilized spectrum is about 0.3 nm and the thermal shift of the spectrum is reduced from 0.3 nm/°C down to 0.01 nm/°C.

Fig. 7 shows a comparison between the spectrum of a tapered diode laser bar with and without spectral stabilization. The spectra are shown for two different currents of 15 A and 35 A. The power loss at 35 A was less than 6 % when inserting the VBG. The center wavelength of the stabilized spectrum was 975.8 nm and the spectral width was only 0.26 nm.

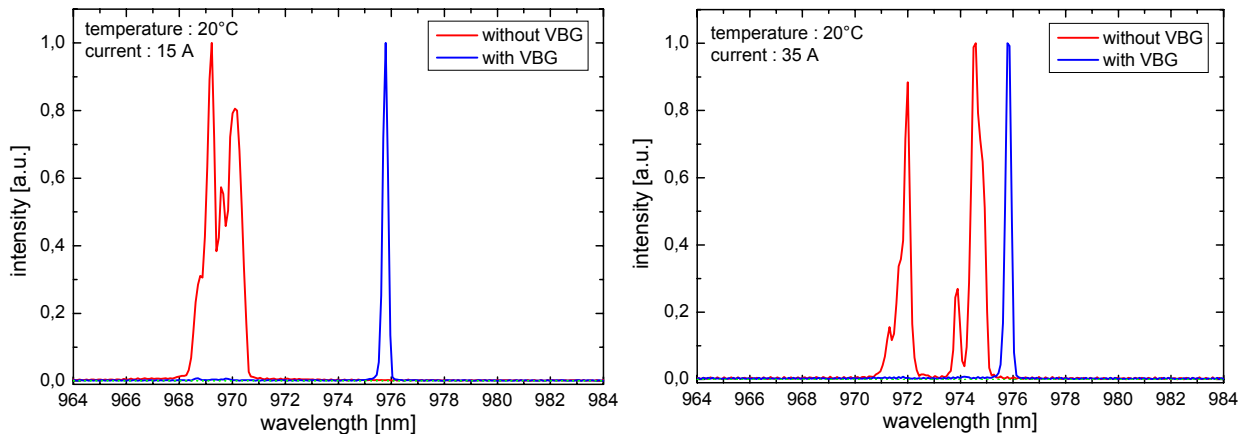


Fig. 7: Spectrum of a 5 mm wide tapered diode laser bar with 12 emitters for two different currents of 15 A (left diagram) and 35 A (right diagram) at a temperature of 20°C. The red lines indicate the spectrum of the free running diode and the blue lines represent the spectrum with stabilization by means of a volume bragg grating.

4.2 Enhancement of beam quality in fast-axis direction

The brightness of a diode laser system with multiple bars strongly depends on the beam quality in the fast-axis direction. As shown in Sect. 2.2 the number of bars that can be used in the fast-axis direction to symmetrize the total beam parameter product is a function of the beam quality in the fast-direction of the individual diode laser bars. In addition stacking faults, i.e. angular deviations of the individual beams will further reduce the beam quality.

It is evident that an enhancement of the fast-axis beam quality is directly proportional to the usable number of bars in fast-direction. This directly affects the power and last but not least the brightness of such a system.

The left diagram in Fig. 8 shows a measurement of the divergence of a vertical diode laser stack with 12 individual diode laser bars, each consisting of 25 emitters. The total divergence is about ± 2 mrad, which already indicates a good beam quality in fast-direction. However, with a correction phaseplate the divergence can be reduced approximately by a factor of two down to ± 1 mrad¹⁰. As a consequence for the stack with the correction phaseplate the number of bars in the fast-direction can be increased by a factor of two while maintaining the total beam parameter product. Finally the output power and the brightness of the stack are doubled by inserting the phaseplate and by increasing the number of bars.

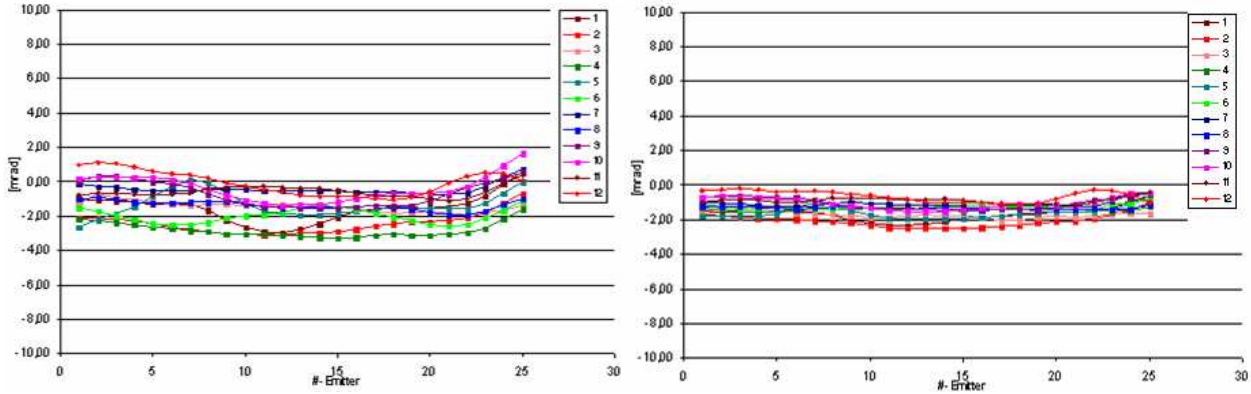


Fig. 8: Measurement of fast-axis beam divergence for a diode laser stack with 12 individual laser bars, each consisting of 25 emitters. Each point represents one emitter. The left diagram shows the measurement for a standard stack and the right diagram shows the measurement for the same stack with an additional correction phaseplate.

5 SUMMARY AND OUTLOOK

In conclusion, we have compared different concepts for high-brightness diode laser modules. We have pointed out the advantages of tapered diode laser bars as basic units for a high-brightness module. One of the main benefits is the reduced facet load and the potential for further enhancement of beam quality by improving the beam quality of the individual emitters.

We have shown a detailed characterization of the new generation of tapered diode laser bars. The bars were divided into two different configurations suitable for 400 μm (NA 0.22) and 200 μm (NA 0.22) fiber coupling. Output powers of up to 58 W for the 10 mm wide bar and 32 W for the 5 mm wide bar could be demonstrated with efficiencies up to 56 %. For the first time detailed lifetime tests for tapered diode laser bars have been presented with a runtime of 3000 h without failure or significant decrease in output power. Fiber coupling experiments confirmed a beam quality of about $M^2 = 4$ per emitter.

In addition, we demonstrated enhancement of spectral brightness by means of wavelength stabilization elements. Furthermore an increase of brightness by a factor of two was realized by inserting a correction phaseplate to correct for smile, stacking faults and lens aberrations.

In summary, the results show that diode laser modules based on tapered diode laser bars are very attractive as basic elements for high-brightness diode laser modules.

However, to keep up with the ongoing developments of broad area diode laser bars, the performance of tapered diode laser bars has to be improved as well in the future. The goals for the next generation of tapered diode laser bars should be output powers of more than 5 W per emitter with a beam quality of $M^2 < 3$ per emitter.

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