

Wavelength stabilized high-power diode laser modules

Bernd Köhler^{*}, Thomas Brand, Matthias Haag, Jens Biesenbach

DILAS Diodenlaser GmbH, Galileo-Galilei-Str. 10, 55129 Mainz-Hechtsheim, Germany

ABSTRACT

In this work we report on high-power diode laser modules with enhanced spectral brightness by means of volume holographic gratings for wavelength stabilization.

High-power diode laser modules typically have a relatively broad spectral width of about 3 to 6 nm. In addition the center wavelength shifts by changing the temperature and the driving current, which is obstructive for pumping applications with small absorption bandwidths. Wavelength stabilization of high-power diode laser modules is an important means for more efficient pumping of solid-state lasers with a narrow absorption bandwidth.

However, for efficient and reliable wavelength stabilization the parameters of the volume holographic grating and the parameters of the diode laser bar have to be adapted carefully. Important parameters are the reflectivity of the volume holographic grating, the reflectivity of the diode laser bar and the angular and spectral emission characteristics of the diode laser bar. In addition, the lateral structure of the diode laser bar and the microoptical elements for beam shaping have to be considered.

In this paper we present a detailed characterization of different diode laser systems with wavelength stabilization in the spectral range from 790 - 1000 nm. The laser modules are divided into systems with and without fiber coupling. We will present data for a wavelength stabilized single diode laser bar with an output power of 69 W at a wavelength of 808 nm. Another example is a wavelength stabilized fiber-coupled diode laser module with an output power of 456 W for a fiber with a core diameter of 400 μm (NA 0.22).

Keywords : High power diode laser, wavelength stabilization, volume holographic grating, broad area diode laser, tapered diode laser, fiber coupling

1 INTRODUCTION

High-power diode laser systems 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, one drawback of high-power diode laser systems is their relatively poor spectral brightness. Typical diode laser bars have a broad spectral width of about 3 to 6 nm and in addition the peak wavelength drifts with driving current and temperature.

Traditionally neodymium (Nd) doped solid state crystals are pumped at the relatively broad 808 nm absorption band. The spectral requirements for pumping at 808 nm are easily met by standard diode laser systems. However, in the last few years the operating current and the power of diode laser bars have been continuously increased resulting in a larger wavelength shift from threshold current up to the operating current. To ensure stable and efficient pumping over the whole operating range, it is helpful to control the spectrum of the pump diodes in such a way that the spectral bandwidth of the laser diode is always consistent with the absorption bandwidth of the active laser medium.

The rapid progress in the fiber laser area has increased the demand for pump lasers at other wavelengths. For pumping standard Ytterbium (Yb)-fiber lasers around 1080 nm fiber coupled diode laser systems at 915, 940 and 980 nm are required. Especially the pump region at 980 nm is important because of the high absorption coefficient in combination with a small absorption bandwidth.

* b.koehler@dilas.de, tel. +49 (0)6131 9226 133; fax +49 (0)6131 9226 255; www.dilas.de

Another example for a new pump wavelength is pumping Nd:YVO₄ at 888 nm, which is advantageous because of its isotropic absorption region with equal absorption coefficients in both polarization directions and the reduced quantum defect compared to the pump region at 808 nm¹.

One of the most demanding applications with regard to spectral linewidth is optically pumping of alkali vapor lasers (e.g. rubidium or cesium) which requires a linewidth of about 10 GHz. For these demands spectral control of a diode laser pump source is absolutely mandatory for efficient pumping².

Another drawback of high-power diode laser systems with broad area diode laser bars is their relatively 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-direction³.

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

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. Whereas the beam quality in the fast-direction is about 1 mm-mrad and thus nearly diffraction limited, the beam quality of a standard 10 mm broad area diode laser bar in the slow-direction is in the region of 400 - 500 mm-mrad, which is far beyond the diffraction limit.

In recent years the brightness of diode laser bars has been significantly improved mainly by increasing the output power per emitter and by reducing the slow-axis divergence. The development led to the design of new types of diode laser bars with reduced number of emitters and increased pitch between the emitters. These minibars have advantages compared to the traditional 10 mm broad diode laser bars⁴.

Further brightness enhancement of diode laser systems is achieved by polarization coupling and wavelength multiplexing. Polarization coupling is limited to a factor of 2, whereas wavelength multiplexing is only limited by the number *n* of available wavelengths. As a matter of course, power scaling by wavelength multiplexing is achieved at the cost of spectral brightness.

Wavelength multiplexing with standard diode laser sources and wavelength couplers based on dielectric coatings requires a spectral distance of about 30 nm. Using diode laser sources with stabilized narrow emission spectra and volume holographic gratings as combination elements the spectral distance can be significantly reduced down to 3 nm⁵. As a consequence, the number of diode laser bars that can be multiplexed for a given spectral range increases, resulting in an enhancement of brightness.

Further advantages of spectrally stabilized diode laser modules are a reduced sensitivity to temperature and driving current allowing for less complex cooling systems. The requirements on the specification for the chip material is also reduced leading to a higher yield with regard to the selection of the chips on a wafer. The change of the wavelength with diode lifetime ("red shift") is also eliminated. However, it should be mentioned that all these advantages depend on the locking range of the volume holographic grating and can not be fulfilled simultaneously.

In the next section different approaches for wavelength stabilization setups will be compared.

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

2 BASIC CONCEPTS FOR WAVELENGTH STABILIZATION

2.1 Approaches for wavelength stabilization

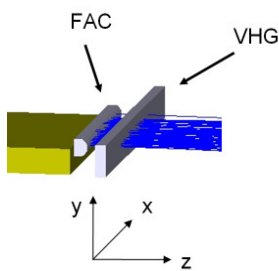
Different methods have been investigated in the past for improving the spectral brightness of diode laser bars. These approaches can be divided into internal and external solutions. For internal solutions the wavelength stabilizing structure is integrated into the diode laser bar itself, whereas for external solutions separate bulk elements with integrated Bragg grating are used for wavelength stabilization.

An example for a diode laser bar with internal wavelength stabilization is a distributed feedback diode laser (DFB) where the grating for selective spectral feedback is integrated in the structure of the active region of the laser bar itself. With such a device the wavelength shift with temperature is reduced down to about 0.08 nm/K and in addition the spectral bandwidth is reduced to less than 1 nm^{6,7,8}. It is evident that the fabrication process of such a DFB-diode laser is more complex leading to an increase in costs. Another drawback is the reduced efficiency of a DFB-diode laser, when compared to a standard broad area diode laser bar.

In contrast to this internal approach wavelength stabilization by external components has also been investigated. One example for an external wavelength stabilizing element is a thick volume grating based on a photo-thermo-refractive (PTR) inorganic glass. Recording of highly efficient Bragg gratings in such photosensitive glass is achieved by periodic variation of the refractive index by UV exposure. Such volume diffractive gratings are commercially available from different vendors with slightly different nomenclatures, like volume Bragg grating (VBG)⁹, volume holographic grating (VHG)¹⁰, or volume Bragg grating Laser (VOBLA)¹¹, whereas the latter also includes the diode laser source.

In contrast to the internal solution no modification on the chip structure is required for external wavelength stabilization, i.e. that standard diode laser bars can be used for wavelength stabilization with external volume holographic gratings. This is an important advantage of the external solution. Furthermore, external stabilization leads to a further reduction in temperature drift and spectral bandwidth, when compared to the internal solution. The temperature drift can be reduced down to about 0.01 nm/K and the spectral bandwidth to less than 0.3 nm. However, one important disadvantage of external components is the requirement for sensitive and high-precision alignment of the VHG.

A typical setup for a diode laser bar with external stabilization is shown in Fig. 1. Because of the angular sensitivity of the VHG it is advantageous to reduce the divergence of the diode laser bar especially in the fast-axis direction by collimating the beam with a fast-axis collimating lens (FAC). This will significantly increase the optical feedback by the VHG. Collimation of the beam in the slow-axis with a SAC is not mandatory. The VHG is positioned directly behind the FAC. The table in Fig. 1 shows typical alignment tolerances that are required for efficient wavelength stabilization.



typical tolerances for rotation		
x-axis	y-axis	z-axis
± 0.5 mrad	± 10 mrad	± 10 mrad

Fig. 1: Typical setup for a wavelength stabilized diode laser bar with a VHG positioned directly behind the fast-axis collimating lens (FAC). The table shows typical alignment tolerances with respect to the shown setup.

2.2 Influence of diode parameters on the performance of external wavelength stabilization

For efficient and stable operation of wavelength stabilization all relevant parameters have to be controlled carefully. The parameters of the diode laser bar include the reflectivity of the AR-coating of the output facet, the emitter structure, the cavity length, the smile, the angular emission characteristics and the mounting technology, which has an influence on the wavelength drift with driving current and temperature.

The properties of a VHG are optimized by adapting the refractive index modulation, the spatial frequency and the thickness. These three independent parameters define the Bragg angle, the diffraction efficiency and the spectral and angular selectivity of the grating. In principal, for each configuration these VHG parameters have to be optimized separately. However, based on experience a value for the VHG reflectivity of about 20 % is a good starting point for most common diode laser bars. An example for optimization of the reflectivity is described in Sect. 3.2. As a matter of course, inserting a VHG for wavelength stabilization will reduce the output power for a given current when compared to the diode bar without stabilization. A VHG with a higher reflectivity will increase the locking range at the cost of a higher power loss. This means that optimization of wavelength stabilization will always be a trade-off between locking range and power loss. Furthermore it is important to notice that the optimum reflectivity also depends on the demands of the application. For some applications the VHG has to be optimized for a large locking range, whereas for other applications low losses for fixed operating conditions could be requested.

As described in Sect. 2.1 the most common setup for wavelength stabilization with an external VHG is a separate bulk VHG positioned directly behind a fast-axis collimation lens. One important disadvantage of this setup is its sensitivity for smile. As a consequence of smile some emitters are not exactly on the optical axis leading to a deflection angle after collimation and finally to a displacement of the reflected light with respect to the initial position of the emitter (cf. Fig. 2). The emitters that are not exactly located on the optical axis will receive less optical feedback as shown in the right diagram of Fig. 2.

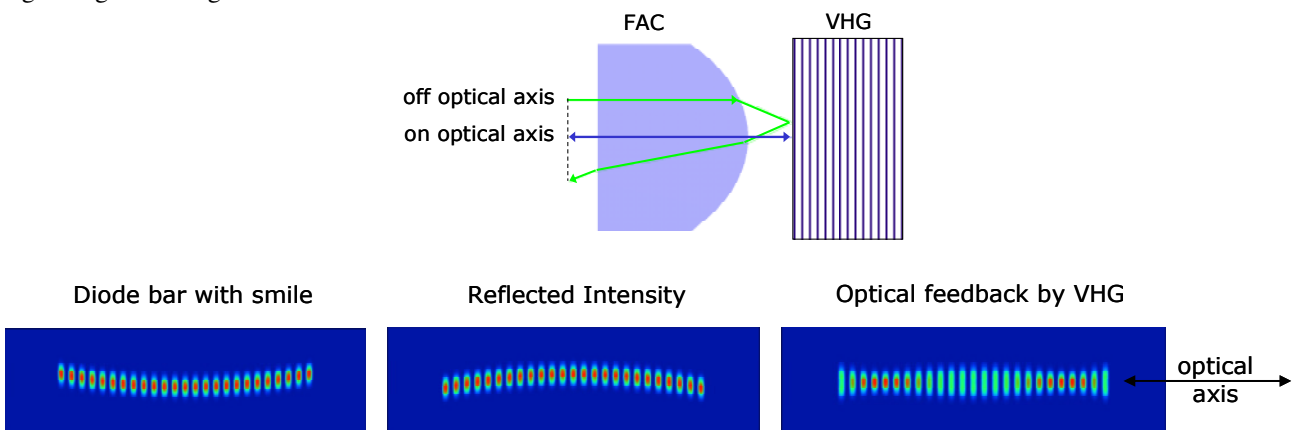


Fig. 2: Influence of smile on the optical feedback of a diode laser bar with a volume holographic grating for wavelength stabilization.

One means to overcome the sensitivity for smile is the integration of the grating structure into the FAC itself¹². Such an element is more insensitive to smile and misalignment. Due to the large angular divergence of the uncollimated beam and the small angular selectivity of the grating only a small part of the beam is reflected back into the diode laser cavity. In the case of misalignment or smile another part of the beam will be reflected to provide feedback. In contrast, for an ideal two component setup with good collimation and no smile nearly all light reflected from the VHG is coupled back into the diode laser cavity. On the other hand this implies that for efficient wavelength locking a significant increase of the reflectivity of the VHG-FAC to about 70% is required.

A further advantage of a FAC with integrated VHG is that only one single element has to be handled and aligned. One disadvantage of a VHG-FAC is the relatively low refractive index of the PTR-material, which is typically based on silica ($n=1.45$). FACs are usually fabricated with high refractive index material like S-TiH53 or N-LAF21. By using low refractive index material, a smaller radius of curvature is required for the same focal length which is disadvantageous with respect to lens aberrations for high NA operation.

3 CHARACTERIZATION OF SINGLE BARS WITH WAVELENGTH STABILIZATION

In this section we present experimental results of wavelength stabilization for a variety of different configurations from single bar assemblies up to fiber coupled modules with 12 bars. Both, actively and passively cooled devices will be discussed. For all these modules we used standard diode laser bars with no optimization of the AR-coating of the output facet. This is one important condition with regard to costs, because an optimization of the AR-coating for maximum performance of the VHG would be very expensive for low volume applications.

3.1 Single diode laser bar on a passively cooled heatsink @ 792 nm

The wavelength range around 790 nm is of interest for pumping fiber lasers operating at eye-safe wavelengths, like thulium (Tm) doped fiber lasers operating around $2 \mu\text{m}^{13}$ and for optically pumping of alkali vapor lasers². Especially for the alkali vapor lasers a very narrow spectrum is required. Diode laser bars can only be used as a pump source for such alkali vapor lasers with additional wavelength stabilization.

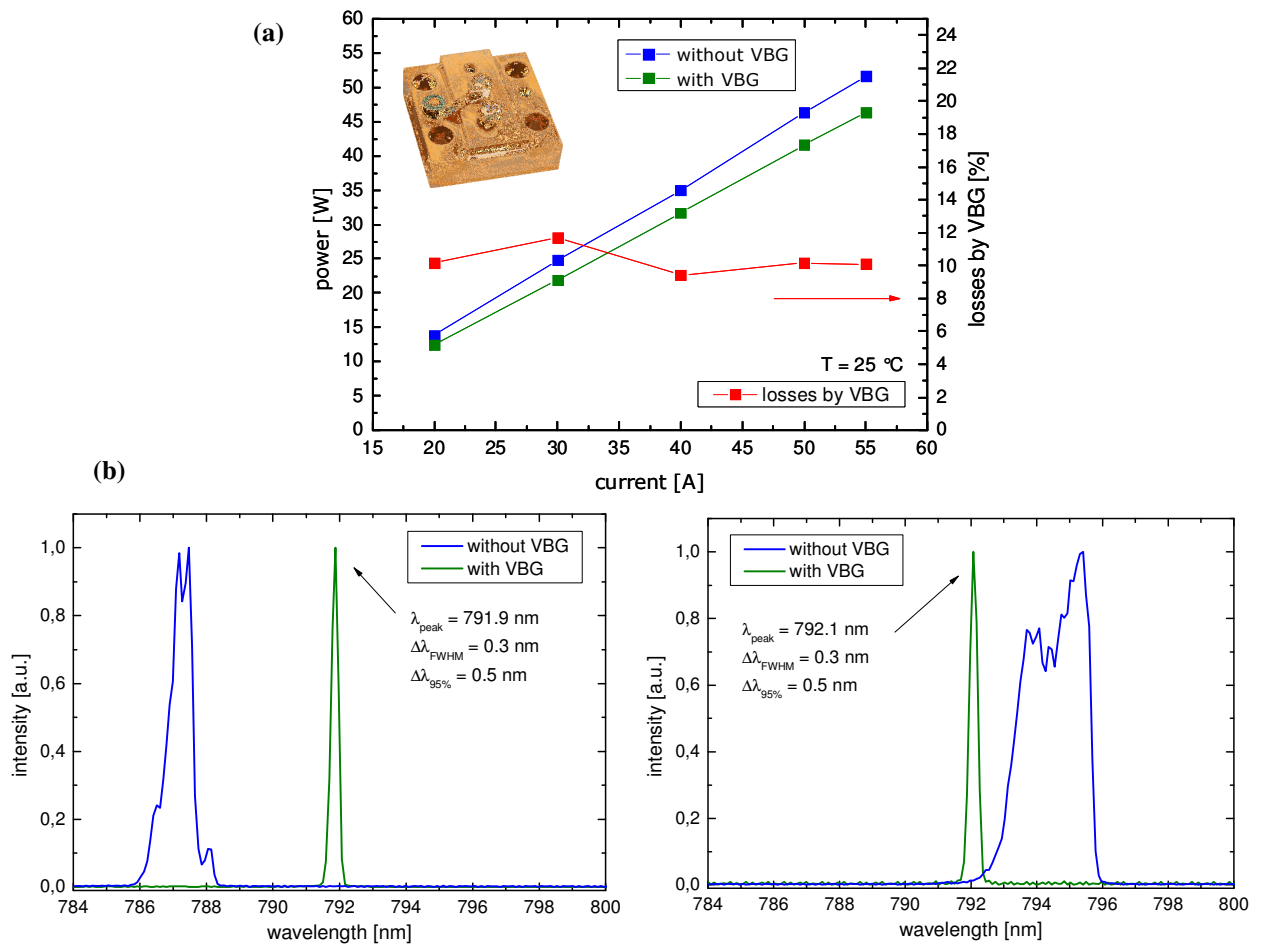


Fig. 3: (a) Power vs. current curve of a wavelength stabilized diode laser bar with an external VHG at 792 nm. (b) Spectra of individual diode laser bar with (green) and without (blue) wavelength stabilization at a current of 20 A and a temperature of $20 \text{ }^\circ\text{C}$ (left diagram). The right diagram shows the spectra at different operating conditions of 55 A and a temperature of $30 \text{ }^\circ\text{C}$.

A typical power vs. current curve for a wavelength stabilized single diode laser bar mounted on a passively cooled heatsink is shown in the upper part of Fig. 3. The VHG is mounted directly behind the fast-axis collimating lens and has a reflectivity of about 20 % centered at 792 nm. The AR-coating of the diode laser bar is not optimized for VHG operation.

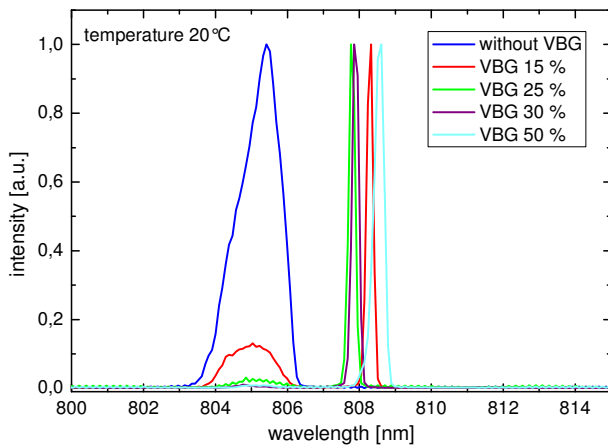
The maximum power with VHG is 47.6 W at a current of 55 A. The insertion of the VHG causes a power loss of about 10 % at 55 A. The lower part of Fig. 3 shows the spectrum of the diode laser bar with and without stabilization for two different operating conditions. The temperature has been increased from 20°C up to 30°C and additionally the current from 20 A up to 55 A. Without stabilization this leads to a shift of the central wavelength from 787 nm up to 795 nm. With VHG the central wavelength of the spectrum is nearly stable and increases only by 0.2 nm from 791.9 nm up to 792.1 nm. In addition, the spectral width of the diode laser bar is significantly reduced down to 0.3 nm. The measurement indicates a locking range of about 10 nm for this configuration.

3.2 Single diode laser bar on a microchannel cooled heatsink @ 808 nm

One important parameter for efficient wavelength stabilization is the reflectivity of the VHG. In this section we compare the performance of wavelength stabilization for different reflectivities of the VHG for a diode laser bar mounted on an actively cooled heatsink. The basic setup is similar to Sect. 3.1, i.e. the diode laser bar is first collimated in fast-axis direction by a FAC and the VHG for wavelength stabilization is positioned directly behind the FAC (cf. Fig. 1).

Fig. 4 shows the spectra of the diode laser bar for four different reflectivities of the VHG from R=15 % up to R=50 % in comparison with the spectrum of the free running diode laser bar. The measurements were done at a temperature of 20°C and an operating current of 50 A. For a reflectivity of the VHG of 15 % the spectrum is not fully locked resulting in a considerable side lobe of the spectrum. By increasing the reflectivity of the VHG the side lobe gets smaller due to the increased feedback and for a reflectivity of 30 % the side lobe has nearly vanished. As a consequence of the increased feedback the power insertion loss compared to the diode laser bar without VHG also rises from only 8 % for the VHG with R=15 % up to 24 % for the VHG with R=50 %. The results for different VHG reflectivities are summarized in the table of Fig. 4.

It is remarkable from Fig. 4 that the peak wavelength for different reflectivities of the VHG slightly varies from 807.8 nm to 808.6 nm. However, it should be mentioned that the peak wavelength in principle does not directly depend on the reflectivity of the VHG. The variation is rather due to the fact that the VHG's were from different vendors and different fabrication processes. A typical tolerance for the central wavelength of commercially available VHG's is ± 0.5 nm.



VBG reflectivity	losses by VBG	peak wavelength
15%	8%	808.3 nm
25%	10%	807.8 nm
30%	12%	807.9 nm
50%	24%	808.6 nm

Fig. 4: Spectra of a wavelength stabilized diode laser bar at 808 nm with external VHG for different reflectivities of the VHG from 15 % up to 50 %. The measurements were done at a temperature of 20°C and a current of 50 A. The blue curve shows the spectrum of the diode laser bar without wavelength stabilization. The table in the right part summarizes the losses and the peak wavelength of the stabilized spectra for different reflectivities.

The comparison of the results for different VHG-reflectivities shows that a reflectivity of about 25 – 30 % is suitable for efficient and stable wavelength locking of this diode laser bar at 808 nm. Fig. 5 (a) shows the power vs. current curve for this combination. For an operating current of 80 A the optical power with VHG was 69 W. The insertion loss of the VHG was about 10 %. The spectra of the diode bar are shown in Fig. 5 (b) for two different currents of 20 A and 80 A, respectively. The peak wavelength increases from 807.67 nm to 807.95 nm resulting in a wavelength drift by operating current of less than 0.005 nm/A.

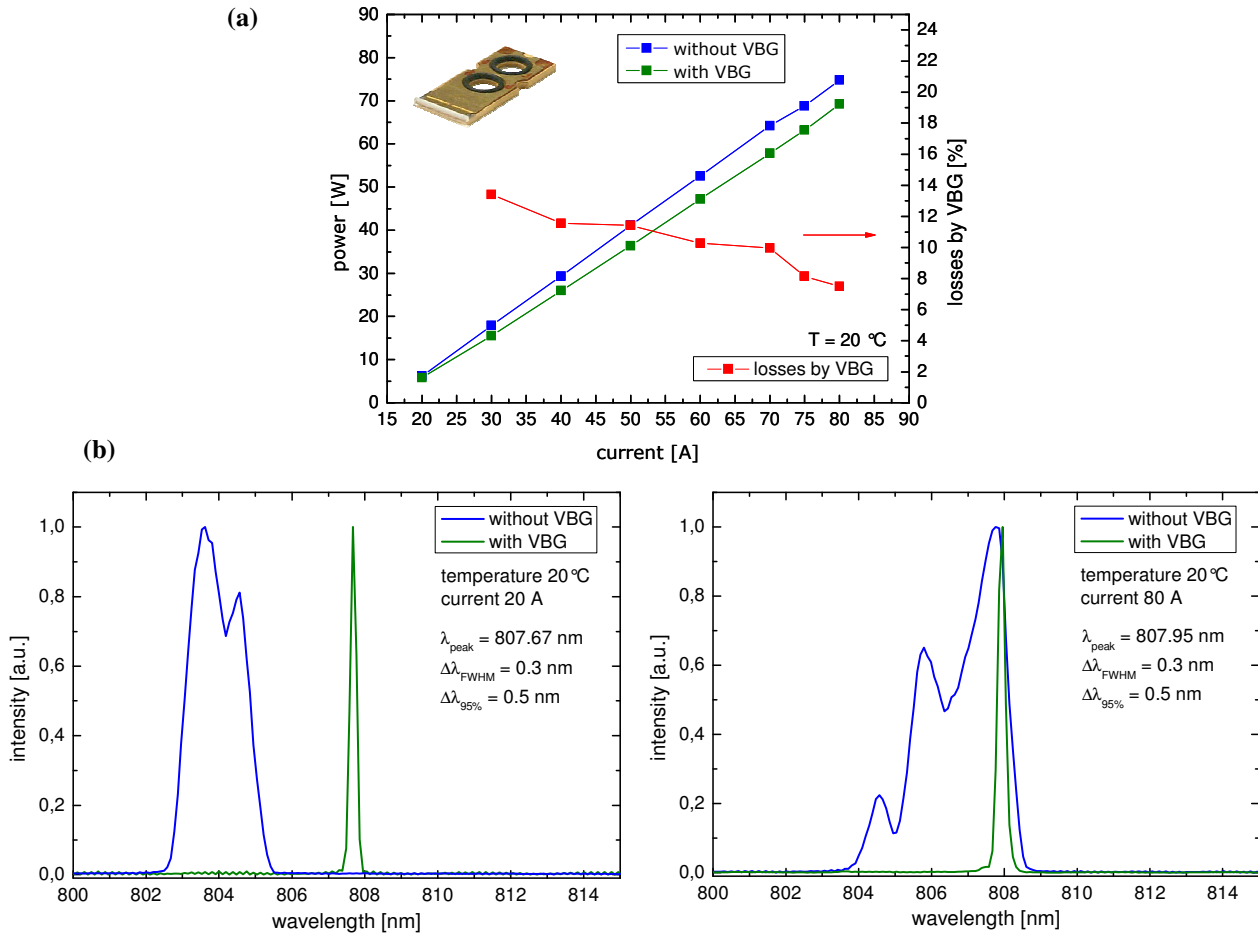


Fig. 5: (a) Power vs. current curve of a wavelength stabilized diode laser bar with an external VHG with R=25% at 808 nm. (b) Spectra of diode laser bar with (green) and without (blue) VHG at a current of 20 A and a temperature of 20°C (left diagram). The right diagram shows the spectra at different operating conditions of 80 A and a temperature of 20°C.

3.3 Single diode laser bar on a passively cooled heatsink @ 940 nm

Another example for wavelength stabilization of a passively cooled diode laser bar is shown in this section. The principle setup is again equal to Sect. 3.1, with a VHG positioned directly behind the FAC. Fig. 6 demonstrates the influence of temperature on the locking performance. The spectra of the diode laser bar with VHG and without VHG are shown for three different temperatures and an operating current of 55 A.

By increasing the temperature from 17°C to 35°C the central wavelength of the unstabilized spectrum increases from about 938.4 nm up to 941.6 nm. This corresponds to a wavelength shift of about 0.3 nm/°C, which is a typical value for a diode laser bar. In contrast, the peak wavelength of the stabilized spectra is nearly constant and increases only from 938.57 nm up to 938.65 nm. With wavelength stabilization the thermal drift is significantly reduced down to below 0.01 nm/K.

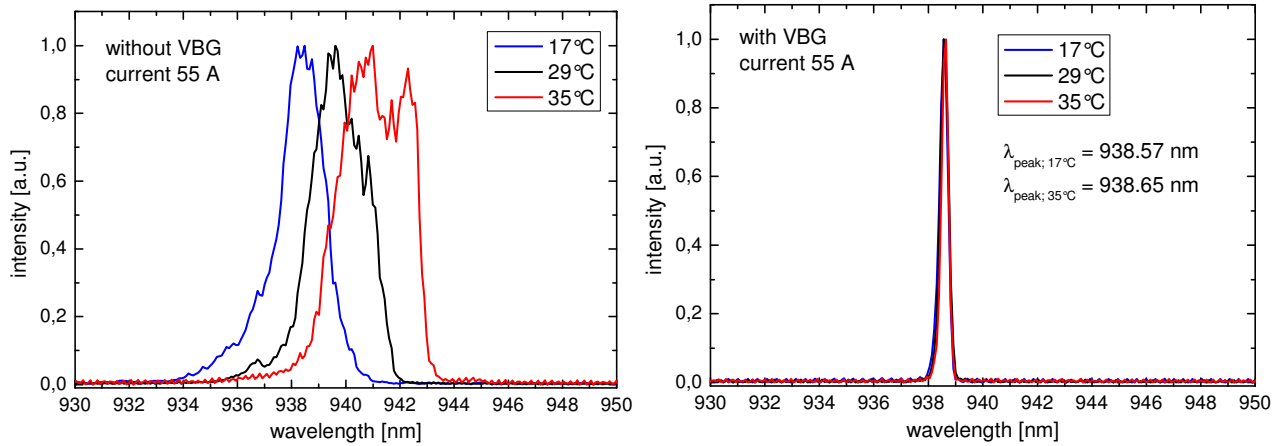


Fig. 6: Spectra of a diode laser bar with wavelength stabilization at a current of 55 A and different temperatures from 17°C up to 35°C (right diagram). The left diagram shows the corresponding spectra without wavelength stabilization.

3.4 Single diode laser bar on a passively cooled heatsink @ 976 nm

Shown in Fig. 7 is an example for the wavelength shift with current for a wavelength stabilized passively cooled diode laser bar at 976 nm. Again wavelength stabilization was achieved by means of a VHG positioned directly behind the FAC. The peak wavelength of the stabilized spectrum varies from 976.2 nm at 20 A up to 976.7 nm at 60 A. This corresponds to a wavelength shift of about 0.013 nm/A. For a free running diode laser bar this value is about 0.1 nm/A. Therefore, with wavelength stabilization this value can be reduced by a factor of about 10.

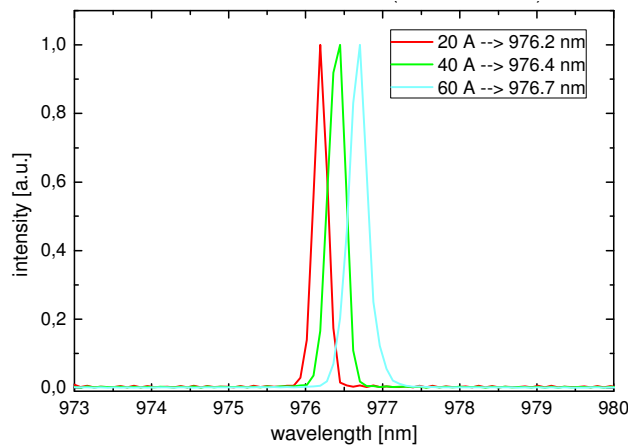


Fig. 7: Spectra of a passively cooled diode laser bar with wavelength stabilization a 976 nm at a temperature of 25°C and different operating currents from 20 A up to 60 A.

The examples shown so far are all based on diode laser bars with standard broad area emitters with no special AR-coating. In contrast to broad area diode laser bars, tapered diode laser bars typically have a significant lower reflectivity of the output facet which is advantageous for wavelength stabilization. We already demonstrated efficient wavelength stabilization of tapered diode laser bars at 976 nm¹⁴. By wavelength stabilization a spectral width of only 0.26 nm was observed with a power loss of only 6 % by inserting the VHG. Wavelength stabilized tapered diode laser bars are very attractive elements for diode laser systems with high spatial and spectral brightness.

3.5 Fiber coupled single diode laser bar module @ 981 nm

In the previous sections wavelength stabilization was shown for direct diode laser bars with FAC. This section shows an example for a fiber coupled diode laser bar at a wavelength of 981 nm. The fiber coupled module is based on a passively cooled diode laser bar as shown in Sect. 3.1. Additional microoptical elements for beam symmetrization are applied in combination with the VHG to make the diode laser bar suitable for fiber coupling. Fig. 8 shows the power vs. current curve for this module with a fiber diameter of 200 μm and a numerical aperture of 0.22. The maximum output power is 32.7 W at a current of 55 A. The right diagram in Fig. 8 shows a typical spectrum of the stabilized module.

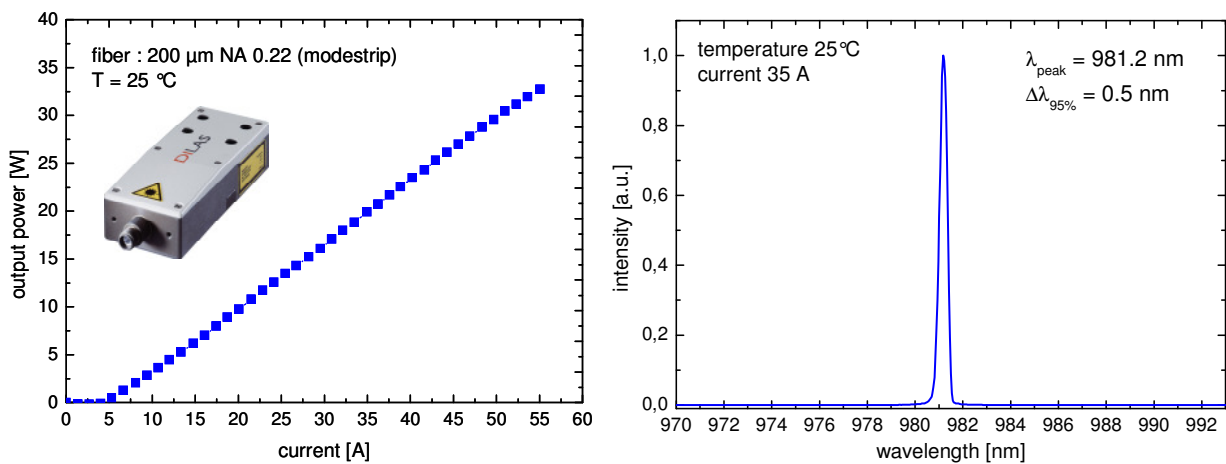


Fig. 8: Power vs. current curve for a wavelength stabilized diode laser bar with fiber coupling. The fiber had a core diameter of 200 μm and a numerical aperture of 0.22 (left diagram). The right diagram shows a typical spectrum for a temperature of 25 $^{\circ}\text{C}$ and a current of 35 A.

4 FIBER COUPLED MULTIPLE BAR MODULES WITH WAVELENGTH STABILIZATION

In Sect. 3 wavelength stabilization was demonstrated for different configurations, each based on a single diode laser bar. However, for single bar systems the output power is limited to about 50 W. For further power scaling diode laser bars can be combined by optical stacking and polarization coupling. In this section we describe different systems with multiple bars and additional wavelength stabilization. All systems are based on passively cooled diode laser bars with additional microoptical elements for fiber coupling.

The first example is a two bar module that is based on the passively cooled diode laser bars of Sect. 3.1. By combining two of these diodes with appropriate microoptical elements for fiber coupling an output power of 50 W at a current of 51 A was achieved. The fiber had a core diameter of 200 μm and a numerical aperture of 0.22. The peak wavelength was centered at 792.3 nm and the spectral width was only 0.5 nm (95% - value).

4.1 Four bar module @ 976 nm

Based on the diode laser bars of Sect. 3.4 we have realized a system with four diode laser bars with wavelength stabilization. The laser bars were coupled into a 400 μm fiber with numerical aperture of 0.22. The output power was 150 W at a current of 71 A. The spectrum was centered at 977.2 nm and the overall spectral width of the module was as low as 1.0 nm (95% value).

Further scaling of the output power is achieved by increasing the number of bars. However, it should be noticed that an increase of the number of bars makes wavelength stabilization more difficult, because the tolerances of the free running diode laser bars and the tolerances of the VHG's add together. Furthermore, potential non-uniform cooling of the individual diodes also increases the bandwidth of the free running system. However, we have shown that even for a system with twelve passively cooled diode laser bars efficient and stable wavelength locking is possible. These results are shown in the next section.

4.2 Twelve bar module @ 976 nm

This section describes a high power wavelength stabilized system at 976 nm. Power scaling for this module is realized by optical stacking and polarization coupling of twelve diode laser bars. The outer dimensions of the module are 70 x 220 x 320 mm^3 as shown in the right part of Fig.9. The power vs. current curve for this module is shown in the left part of Fig. 9. The maximum power was 456 W out of a 400 μm fiber with numerical aperture of 0.22 and an operating current of 60 A.

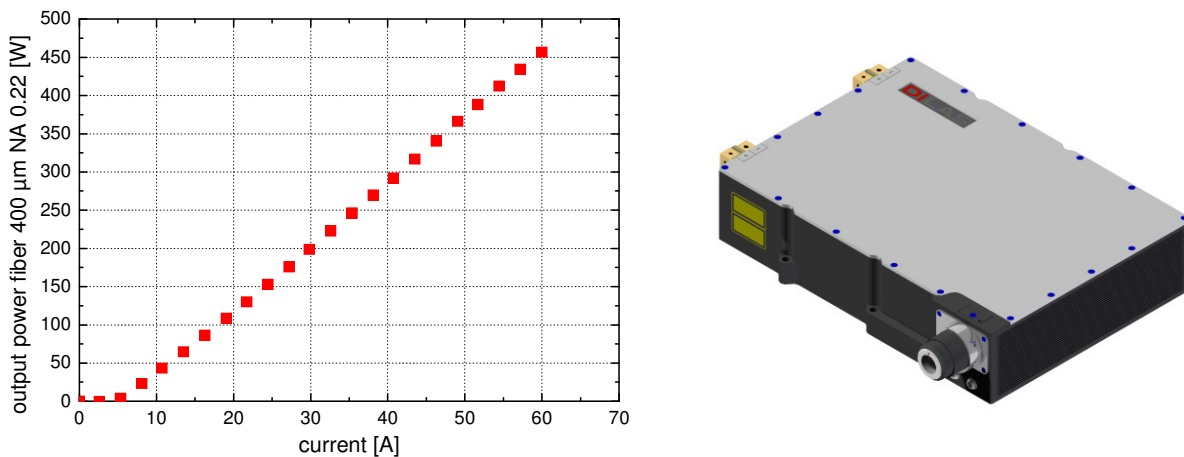


Fig. 9: Fiber coupled and wavelength stabilized diode laser module with twelve diode laser bars. The dimensions of the module are 70 x 220 x 320 mm^3 . The left diagram shows the power vs. current curve for this module. The fiber had a core diameter of 400 μm and a numerical aperture of 0.22.

Shown in the left diagram of Fig. 10 is the spectral range of the twelve individual diode laser bars without wavelength stabilization for an operating current of 50 A and a temperature of 25°C. The wavelength range of the unstabilized diode laser bars extends from 970 nm up to 980 nm. The right diagram of Fig. 10 shows the spectrum of the stabilized module for the same operating conditions. The center wavelength is located at 976.5 nm and the spectral width is reduced from 10 nm down to 1 nm (95% value).

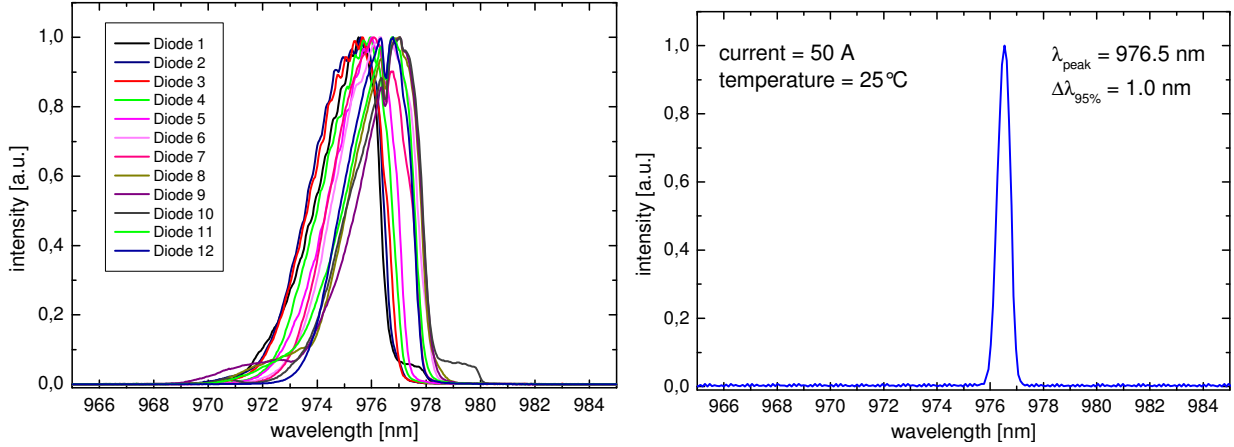


Fig. 10: Spectra of individual diode laser bars without wavelength stabilization at a current of 50 A and a temperature of 25°C (left diagram). The right diagram shows the complete spectrum of the 12 bar module with wavelength stabilization by means of a volume holographic grating.

5 SUMMARY AND OUTLOOK

In conclusion, we have demonstrated efficient and stable wavelength locking for a couple of different configurations ranging from single bar devices to multiple bar setups with up to 12 individual diode laser bars. For all these configurations we used standard diode laser bars with no optimization of the AR-coating of the output facet.

Wavelength stabilization was realized for direct diode laser systems and for fiber coupled systems with fiber core diameters from 200 μm and 400 μm (NA 0.22). In summary, we have shown wavelength stabilization for five different wavelengths at 792 nm, 808 nm, 940 nm, 976 nm and 981 nm.

The maximum output power of a wavelength stabilized system with fiber coupling was 456 W out of a 400 μm fiber (NA 0.22). The center wavelength of this module was 976.5 nm and the spectral width of the combined diode laser bars was only 1.0 nm (95% value). The maximum power of a single bar device with wavelength stabilization was 69 W at a center wavelength of 808 nm. The spectral width of this bar was less than 0.5 nm (95% value).

In addition, we analyzed the influence of different parameters on the performance of the wavelength stabilization. Among these parameters were the reflectivity of the volume holographic grating, the smile of the diode laser bar, the operating current and the temperature. The thermal drift of the spectrum was reduced from about 0.3 nm/K for an unstabilized module down to below 0.01 nm/K for the module with wavelength stabilization. The wavelength drift with operating current was also significantly reduced from 0.1 nm/A down to 0.013 nm/A.

In summary, we have pointed out that high-power diode laser modules with enhanced spectral brightness are very attractive devices for more efficient pumping of solid-state lasers with a narrow absorption bandwidth. In addition, such wavelength stabilized devices are important for further scaling the brightness of diode laser systems. In the next few years a further increase in brightness of diode laser systems towards a BPP of 20 mm·mrad with multi-kW output power is expected. This will enable diode laser systems to replace lamp pumped solid state lasers in industrial laser applications. Wavelength stabilization will become more important for such systems because of the extended operating range with respect to current and temperature. In addition, dense wavelength multiplexing with wavelength stabilized systems will help to realize these high brightness diode laser modules.

ACKNOWLEDGEMENTS

A part of this work was sponsored by the German Bundesministerium für Bildung und Forschung (BMBF) within the German National Funding Initiative "Integrated optical components for High-Power Laser Sources (INLAS)".

REFERENCES

1. L. McDonagh et. al.; "*High-efficiency 60 W TEM₀₀ Nd:YVO₄ oscillator pumped at 888 nm*"; Optics Letters Vol. 31, pp. 3297 (2006)
2. A. Gourevitch et. al.; "*Continuous wave, 30 W laser-diode bar with 10 GHz linewidth for Rb laser pumping*"; Optics Letters Vol. 33, pp. 702 (2008)
3. Friedrich Bachmann, Peter Loosen, Reinhart Poprawe „*High Power Diode Lasers*“, pp.121-123, pp.162-174, Springer Series in Optical Sciences (2007)
4. M. Haag et. al.; "*Novel high-brightness fiber coupled diode laser device*"; Proc. SPIE Vol. 6456, 6456-28 (2007)
5. C. Wessling et. al.; "*Dense wavelength multiplexing for a high power diode laser*"; Proc. SPIE Vol. 6104, 6104-21 (2006)
6. M. Maiwald et. al.; "*Reliable operation of 785 nm DFB diode lasers for rapid Raman spectroscopy*"; Proc. SPIE Vol. 6456, 6456-0W (2007)
7. M. Kanskar et. al.; "*High power conversion efficiency and wavelength-stabilized narrow bandwidth 975 nm diode laser pumps*"; Proc. SPIE, Vol. 6216, 6216-09 (2006)
8. L. Vaissié et. al.; "*High-power diode lasers advance pumping applications*"; LASER FOCUS WORLD (June 2008)
9. B.L. Volodin et. al.; "*Wavelength stabilization and spectrum narrowing of high-power multimode laser diodes and arrays by use of volume Bragg gratings*"; Optics Letters Vol. 29, pp. 1891 (2004)
10. C. Moser et. al.; "*Filters to Bragg About*"; Photonics Spectra, pp. 82 (June 2005)
11. G.B. Venus et. al.; "*High-brightness narrow-line laser diode source with volume Bragg-grating feedback*"; Proc. SPIE Vol. 5711, pp. 166 (2005)
12. C. Schnitzler et. al.; "*Wavelength Stabilization of HPDL Array – Fast-Axis Collimation Optic with integrated VHG*"; Proc. SPIE Vol. 6456, 6456-12 (2007)
13. B. Samson et. al.; "*Diode technology advances fiber-laser pumping*"; LASER FOCUS WORLD (September 2008)
14. B. Köhler et. al.; "*Diode laser modules based on new developments in tapered and broad area diode laser bars*"; Proc. SPIE, Vol. 6876, 6876-1B (2008)