Dense wavelength multiplexing for a high power diode laser

Christian Wessling, Martin Traub, Dieter Hoffmann, Reinhart Poprawe
Fraunhofer Institute for Laser Technology, Aachen, Germany

ABSTRACT

At present methods of polarization and wavelength multiplexing with dielectric coatings are used to increase the brightness of diode lasers. The number of suitable diode laser wavelengths is limited by the temperature- and current-dependent spectral characteristics of the diode laser and the slope of dielectric edge-filters. By use of external volume diffraction gratings it is possible to constrict the emission spectra of diode lasers and to reduce the wavelength shift related to temperature or current injection. Due to the stabilization of the center wavelengths and the reduced bandwidth of the diode emission multiplexing of diode laser beams at small distance of the centre wavelengths can be realized.
The performance of wavelength stabilization by use of volume diffraction gratings adapted to AR-coated diode laser arrays in an external cavity as well as to standard high power diode laser arrays is discussed. Furthermore modules of two diode laser beams are combined by wavelength dependent diffraction of an adapted volume diffraction grating. The spectra of the diode lasers of the same wafer are stabilized with a centre wavelength spacing of about 3 nm and more than 95% of the optical output power of each beam within a spectral width less than 0.7 nm. An efficiency of more than 80% for multiplexing of two diode laser bars with good beam quality in fast axis of $M^2 < 2$ is achieved.

Keywords: wavelength stabilization, beam combining, volume diffraction grating, external cavity, high power diode laser

1 INTRODUCTION

Volume diffraction gratings recorded in photo-thermo-refractive glass are well-known optical filters used in fiber optic telecommunications for spectral narrowing and stabilizing the emission wavelength of semiconductor lasers. Due to their thermal stability up to 400°C volume diffraction gratings are capable of improving the spectral characteristics of high power diode laser bars with continuous optical output powers reaching 100 W [6]. The natural spectral performance of high power diode lasers is restricted by the emission line width (FWHM) of about 2 to 5 nm and the wavelength shift with temperature of an InGa(Al)As/GaAs based semiconductor of 0.25 to 0.3 nm/K. Furthermore, the typical deviation of the center wavelength of commercial diode laser bars is about ±3 nm or more.

A volume diffraction grating applied to a semiconductor laser cavity as external mirror provides a narrow optical feedback and by this encourages the laser to operate in a frequency narrowed emission spectrum. The feedback from the grating is defined by its wavelength and angular selective diffraction efficiency. Maximum diffraction efficiency η_0 according to $\eta_0 = \tanh^2(\pi d \Delta n/(\lambda|\cos(\theta)|))$ is obtained from a plane wave of wavelength λ with incident angle θ to the grating normal within the medium that keeps the Bragg matching condition $\lambda = 2n\Lambda|\cos(\theta)|$, where n is the bulk refractive index and Λ the grating period of the sinusoidal refractive index modulation Δn [2]. For wavelength stabilization the propagation axis of the incident beam is coincident with the grating normal ($\theta = 0$). Beam combining is enabled by the wavelength and angular selectivity of the grating if a beam of wavelength λ is Bragg matching at an incident angle unequal to zero ($\theta \neq 0$). The wavelength and angular selective diffraction efficiency of the volume grating can be adjusted by the thickness of the grating d and the refractive index modulation Δn. Grating thicknesses in photo-thermo-refractive glass ranging from 1 mm to 1.5 mm enable a spectral selectivity (FWHM) of 0.2 to 0.3 nm [3]. The maximum diffraction efficiency can reach values from a few percent up to more than 97% in the visible and near infrared spectral region [1]. The achievable centre wavelength (Bragg wavelength) accuracy is ±0.5 nm [2]. By use of volume diffraction gratings in an external cavity diode laser passive wavelength stabilization with residual wavelength shift of less than 0.01 nm/K is achievable. Hence, the spectral performance of high power diode lasers can be improved with respect to line narrowing by a factor of ten and wavelength shift reduction by factor of thirty [5], [2].

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The spectral narrowing of high power diode laser bars by volume diffraction gratings enables twofold, high efficient pumping of solid state lasers and fiber lasers as well as improved wavelength multiplexing properties serve for high brightness fiber coupled diode lasers in direct applications, particularly with regard to dense wavelength multiplexing. Stable emission spectra of high power diode lasers are demanded for efficient pumping solid state and fiber lasers. For example pumping in the narrow absorption line at 976 nm of spectral width of about 7.6 nm (FWHM) of Yb:glass fiber lasers will encourage high efficient absorption of the pump light. In terms of beam combination of high power diode lasers bars conventional coarse wavelength multiplexing techniques is providing a centre wavelength spacing of adjacent emission lines of at least 20 nm whereby dense wavelength multiplexing is considered to be in the range of a few Nanometers. Thereby the number of utilizable wavelengths for beam combining and accordingly the scaling of the attainable optical power in a fiber coupled device by the number of possible beam sources are increased.

2 WAVELENGTH STABILIZATION

Experiments on wavelength stabilization are mainly performed on high power diode laser bars with an additional antireflection coating of the front facet less than 0.5%. The diode laser bars consist of a 19 emitter array with a single emitter contact width of 150 µm and an emitter pitch of 500 µm (filling factor 30%). Output power level and emission wavelength range of the utilized diode laser bars are 40 W (@40 A) at 935-940 nm and 80 W (@90 A) at 973-980 nm. The 40°W bars have resonator length of 0.9, 1.2 and 1.5 mm; the 80 W bars have a resonator length of 2.5 mm. All bars are mounted on water cooled micro-channel heat sinks with a thermal resistance R_{th} < 0.5 K/W (DILAS).
The typical beam divergence angles are 65° (1/e²) perpendicular to the junction (fast axis) and 9° (1/e²) parallel to the junction (slow axis). The divergent beam is firstly collimated by a fast axis collimation microlens (FAC) with a focal length of 0.91 mm. Secondly for collimation of the divergent slow axis beams of each single emitter a lens array with focal length of 2.3 mm is utilized. The volume diffraction grating for spectral narrowing and thermo stabilization of the emission of the high power diode laser bar is placed in the collimated beam. The dimensions of the utilized gratings adapted to the aperture of the collimated diode laser beam are 12 x 1.5 x 1.5 mm (ONDAX) and 15 x 1.5 x 1 mm (PDLD).
The applied volume diffraction gratings have diffraction efficiencies of 20% at 976 nm and 20%, 30% and 40% at 938 nm. Furthermore, volume diffraction gratings with a gradient diffraction efficiency according to one lateral position perpendicular to the grating surface normal in the range from 12% to 33% at 976 nm and 0% to 55% at 938 nm are employed to the set up of diode laser and collimation optics to identify the optimum optical feedback for wavelength stabilization and maximum output power.

Figure 1 shows the spectra of a fast and slow axis collimated high power diode laser bar at maximum optical power of 79 W with and without feedback from a volume diffraction grating. The spectral full width at half maximum is 0.2 nm according to a narrow emission of more than 98% of the optical power within a 0.8 nm wide peak. The side-lobe suppression ratio is greater than 25 dB for the stabilized diode laser bar. The spectrum is stabilized in the entire range of the pumping current. A locking range of at least ±6 nm of diode laser bars with centre wavelengths 938 nm and 976 nm have been confirmed with reflection from the front facet of less than 0.5 %. The power inclusion typically reaches 90% to 98% of the optical power within the stabilized narrow line for the AR-coated diode laser bars. With standard diode laser bars power inclusion in the range from 80% to 96% have been achieved. The locking range of diode lasers with optimal reflection from the front facet of 4% to 5% is about 3 nm.
In comparison to the AR-coated diode laser the emission spectra of a diode laser bar with standard front facet coating of 4% to 5% can be seen in Figure 2. More than 80% of the

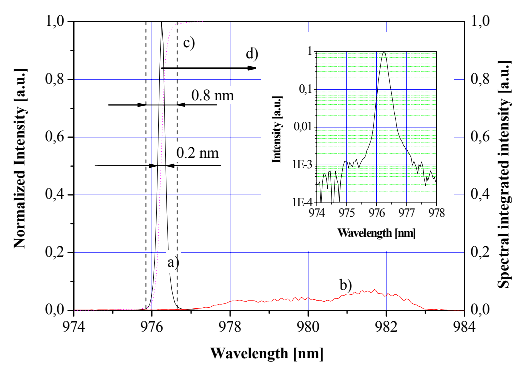

Figure 1: Emission spectra of a diode laser bar with 0.5% AR-coating on facet and volume grating efficiency of 17.5% at optical output power of 79 W.
a) Stabilized spectral width $\Delta\lambda_{FWHM}$ = 0.2 nm
b) Free running
c) 98% of the optical output power within 0.8 nm
d) Spectral side lobe suppression ratio > 25 dB

optical output is locked at constant output power of 32 W. The stabilized emission spectrum remains almost at constant centre wavelength while an increase of the water temperature of the micro channel heat sink is followed by 2,1 nm spectral shift of the resonant peak wavelength of the laser cavity. Power inclusions of up to 96% of the optical power within the stabilized narrow line for standard coated diode laser bars are feasible if the spacing between the Bragg wavelength and the free running emission wavelength is within the spectral width of 3 to 5 nm.

Typical values of the slope efficiency dP/dI received by all fast and slow collimated and stabilized diode laser bars are in the range from 0.89 to 1.0 W/A derived from the linear part of the laser characteristic above threshold. A representative example is given in Figure 3. The maximum slope efficiency for the 80 W diode laser bar is obtained with a grating efficiency of 17.5%. With external feedback the threshold current of the diode laser array is reduced from 20 A to 9.3 A. The slope efficiency is increased from 0.89 W/A to 0.98 W/A. Note that the slope efficiency of the used diode laser bars with standard coating typically is 1.05 to 1.1 W/A und will be reduced by losses at the collimation optics about 5 to 10% as well. The threshold current of stabilized standard diode laser bars with grating efficiencies from 20% to 40% is almost the same as for free running operation but the increased feedback from the grating introduces power losses of 10 to 17%. In [1] the choice of low-reflection coating for generation of a high-efficient narrow line laser diode bar source is not seen to be appropriate in spite of significantly higher suppression of spectral side lobes by grating feedback and better temperature stability. With respect to the approach of spectral beam combing with volume diffraction gratings the low-reflection coating is seen to be essential in order to reach stable and narrow emission without side lobes at all operating conditions and to encourage laser emission at distinct peak wavelength with a distance of some Nanometers to the centre wavelength of the free running diode laser spectrum. The AR-coating has the benefit of the increased locking range and the stabilization of the spectrum in the entire range of the pumping current with a side lobe suppression from 20 to 30 dB.

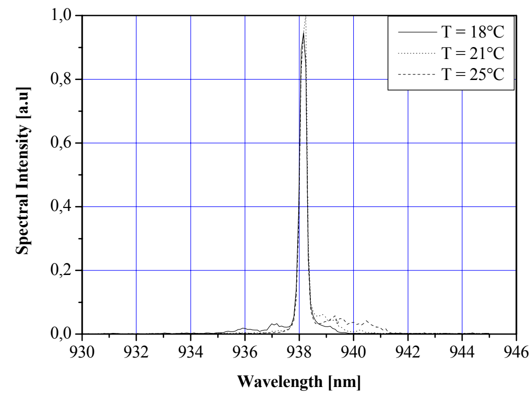

Figure 2: Emission spectra of a diode laser bar with standard AR-coating on facet versus water temperature of the heat sink (volume grating efficiency: 20%, optical output power 32 W, slope efficiency 0.93 W/A).

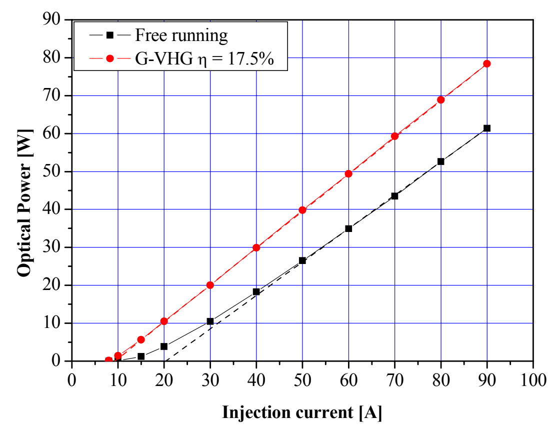

Figure 3: Light-current characteristic for a 80 W diode laser bar with 0.5% AR coated front facet (related emission spectra in Figure 1).
a) Free running
b) Wavelength stabilized with grating efficiency of 17.5%

In order to obtain a high brightness diode laser source based on spectrally narrowed diode laser bars, wavelength stabilization experiments are realized with arrays of 30% filling factor and slow axis collimating arrays. The slow axis lens array collimates the lateral beam and by this reduces the slow axis divergence half angle from typically 5° to less than 35 mrad (90% power inclusion) with an increase of filling factor. The beam divergence angle of the fast axis collimated beam is less than 2.5 mrad. The reduction of the beam quality is mainly caused by quality of the microlens and repositioning and vertical misalignment of the diode lasers with respect to a straight line, the so-called “smile”. Industrial standard is a smile in the range from 0.5 to 2 µm (peak to valley). Collimation of the slow axis beam is not required in order to achieve high efficient wavelength stabilization but with respect to efficient beam combing.

The impact of the lateral displacement of the diode laser emitter to its nominal position on a straight line on the grating feedback to the laser cavity can be seen in Figure 4. A 19 emitter AR-coated and fast axis collimated diode laser bar with a distinctive smile value of 2.25 µm from peak to valley is operated with external feedback from a volume diffraction grating. The grating is tilted in the fast axis direction and hence giving an optical feedback by its angular selectivity to those emitters where the chief ray is coincident to the grating normal. For each lateral position of an emitter according to a fixed fast axis collimation microlens an angular position of the grating will give the maximum feedback to individual emitters with equal lateral displacement. In Figure 4 the images of the emitting aperture of the diode laser bar at four angular positions of the grating are assigned to the vertical position of the emitters. Efficient lasing operation of individual emitters can only be achieved if the feedback from the grating is enabled by the right angular position of the grating. A maximum output power from the diode laser bar is achieved when the grating normal is pointing to the centre line of all lateral emitter positions.
From Figure 4 can be derived that for the given set up of a diode laser bar, fast axis collimation and volume diffraction grating within the collimated beam the peak to valley value for the smile of the diode laser bar should be smaller than 1 µm to enable well balanced feedback from the grating to all emitters. Hence, the alignment tolerance depends on the focal length of the fast axis collimation lens. With respect to the focal length f_{FA} of the fast axis collimation the lateral position of an emitter Δy results in a corresponding angular position $\Delta\alpha$ of the volume diffraction grating which is given by $\Delta\alpha = f_{FA}*\Delta y$. For typical values of the focal length of 1 mm and a smile of ±0.5 µm the alignment tolerance of the grating must be closer than ±0.5 mrad.

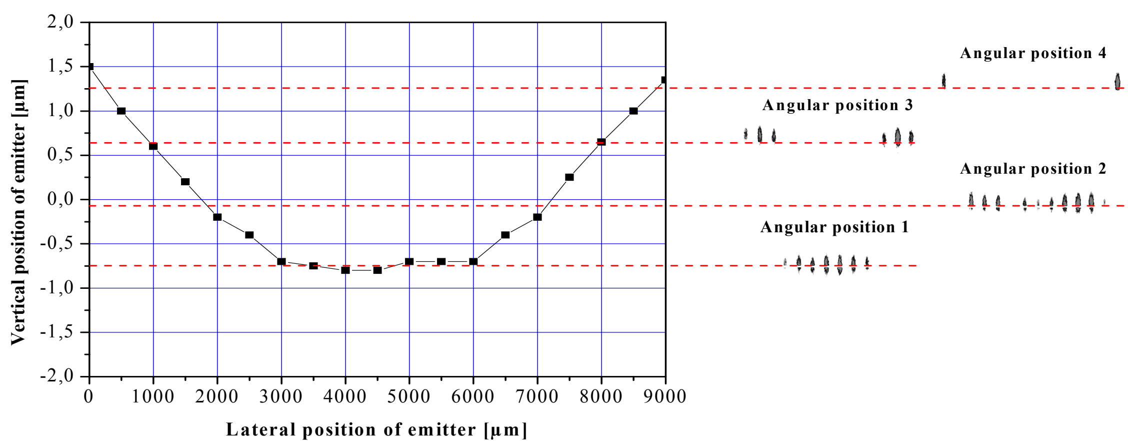

Figure 4: The impact of the smile on the optical feedback from an external volume holographic grating. The images of emitters (right) at four angular positions in fast axis of the diffraction grating are assigned to the vertical position (left) of the emitters.

As has been seen from Figure 4 the smile of the diode laser array has a large impact on the optical feedback from the grating to the diode laser cavity. Each single emitter within the diode laser array receipt a different optical feedback according to its lateral displacement. Large smile values may eliminate the feedback for some emitters at all. Hence, the optimum grating efficiency for a whole diode laser array will still be larger than for a single emitter because external feedback losses have to be compensated by increased diffraction efficiency in order to reach high efficient wavelength stabilization. Slow axis collimated arrays require reduced grating efficiency because of an increased optical feedback to the diode.
For the set up of collimation optics (FAC and SAC) and diode lasers at the 976 nm the optimum grating efficiency is identified to be in the range of 17.5% to 20% at an injection current of 90 A. Similar results are obtained from the 40 W diode laser bars at 938 nm. A gradient diffraction grating provides optimization of the coupling efficiency by adjustable diffraction efficiency at constant wavelength. In Figure 5 the dependence of the optical output power of a AR-coated 40 W diode laser bar shows an optimum diffraction efficiency of 16% to 17% at maximum output power of 40 W. With respect to the reduced optical feedback according to a larger smile of a diode laser array the grating efficiency is to be increased to confirm efficient wavelength stabilization. The recommended grating efficiencies at 938 nm are in the range from 15% to 20% for the AR-coated bars and greater than 20% up to 30% for standard coated bars.

The residual wavelength shift of stabilized diode lasers is no longer dominated by the temperature of the laser diode but by the temperature of the volume grating. The thermal induced shift of the resonant wavelength with temperature of volume diffraction gratings demonstrates linear behavior due to thermal expansion of the material and thermal variation of the refractive index. The thermal coefficient of the utilized volume gratings are analyzed by measuring the temperature of the grating and the related wavelength of the stabilized diode laser beam. The volume gratings have a thermal coefficient of about 10 pm/K. For example the residual wavelength shift of a 47 W diode laser in Figure 6 is reduced by wavelength stabilization to 0.22 nm. The linear increase of the wavelength with the volume grating temperature result in a thermal coefficient of 0.0104 nm/K in Figure 7. Furthermore, the temperature rise is linear with the increase of the laser power that is exposed to the volume grating resulting in a slope of 0.0056 nm/W. The linear increase of the temperature in the grating is caused by absorption of radiation in the bulk of the glass. In Figure 8 the temperature distribution of the volume diffraction grating with an aperture of 30x15x1 mm^3 is demonstrated that is irradiated with an optical power of 47 W. The bottom of the volume grating is in contact to a mount of aluminum. The absorption of radiation from the collimated laser beam generates an elliptical shaped temperature distribution. The lateral heat flow to the edges of the grating shows a greater temperature gradient in direction to the mount. The heat is rejected by heat conduction to the mount and convection cooling in the air. The thermal induced wavelength shift in Figure 6 can be almost eliminated by convection cooling with compressed air. Volume gratings of reduced lateral dimensions down to the level of the collimated beam section (for example 12 x 1.5 mm^2) whose surfaces are surrounded by air demonstrate heat accumulation at the edges. Improvement of the heat rejection is achieved by conduction cooling of the grating with a water cooled heat sink made of copper. The height of the grating is reduced to 1 mm in order to obtain a more likely slab geometry of the grating sandwiched between the heat sink which can be efficiently cooled from the top and the bottom. Thereby the residual wavelength shift of a stabilized diode laser bar is reduced to 0.05 nm ($d\lambda/dP = 0.0006$ nm/W) at maximum optical power of 80 W as can be seen in Figure 9.

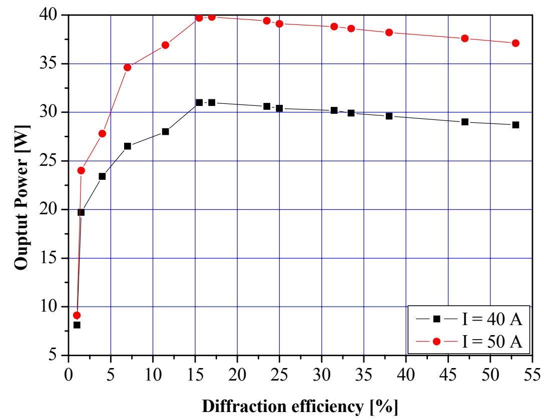

Figure 5: Output power of a 40 W diode laser bar versus peak diffraction efficiency of a volume holographic grating at 938 nm.

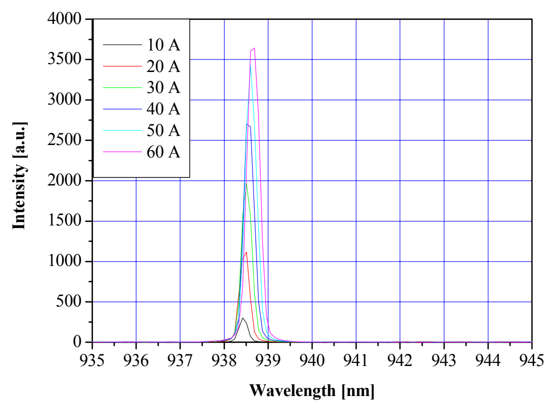

Figure 6: Wavelength shift of 0.22 nm of a wavelength stabilized diode laser bar with maximum output power of 47 W at 60 A.

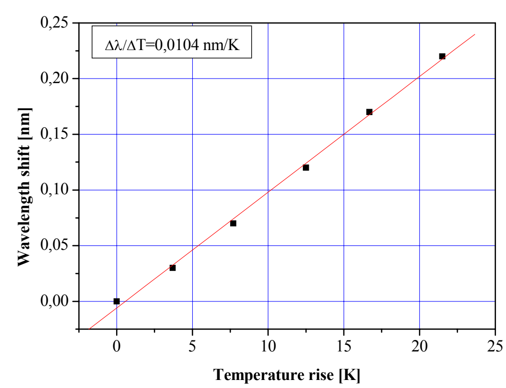

Figure 7: Wavelength shift of a stabilized diode laser bar due to temperature rise of a gradient volume holographic grating.

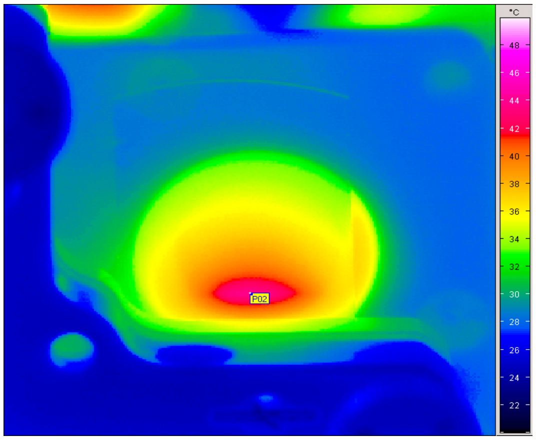

Figure 8: Temperature distribution of a volume holographic grating with an aperture 30x15x1 mm³ irradiated with optical power of 47 W

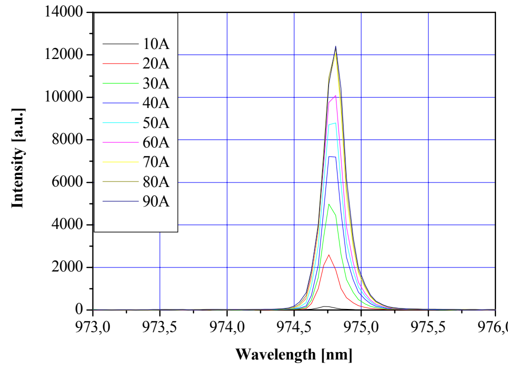

Figure 9: Wavelength shift of 0.05 nm of a wavelength stabilized diode laser bar with water cooled VHG mount (maximum optical power of 80 W)

3 INCOHERENT BEAM COMBINING OF HIGH POWER DIODE LASER ARRAYS

The improved thermal and spectral performance of high power diode laser bars by wavelength stabilization enables incoherent beam combining with centre wavelength spacing of some Nanometers. Volume diffraction gratings in photo-thermo-refractive glass can be used as wavelength and angular selective filters due to their efficient angular and wavelength selectivity. In a first approach the beam combination of two fast axis and slow axis collimated diode laser beams is considered. A reflecting type volume diffraction grating (beam combiner) with a 30-degree diffraction angle is designed to combine two diode laser beams. One beam that is Bragg matched is diffracted into the path of the second non Bragg matched beam that comes from the opposite side and passes through the grating. The spectral selectivity of the grating is greater than the emission bandwidth of the wavelength stabilized diode lasers but less than the spectral distance between the centre wavelengths. Secondly, the angular selectivity of the grating is greater than the angle of divergence of the laser beam. Two 40 W diode laser bars are stabilized at centre wavelengths of 934,9 nm and 938,2 nm. The emission spectra of the diode lasers each have a spectral width of 0.25 nm at maximum output power. The wavelength spacing of about 3 nm is chosen to enable both efficient wavelength stabilization within the tuning range of the diode laser and high diffraction efficiency for the reflecting (Bragg matched) beam as well as close to zero diffraction efficiency for the transmitting (not Bragg matched) beam.

The angular selectivity of the beam combiner in fast axis is about 5 mrad (FWHM) and about 4.6° (FWe^{-2}M) in the horizontal plane (in slow axis) of the grating. The diffraction efficiency of the grating in slow axis in dependence of the deviation from the Bragg angle and the slow axis intensity distribution of a slow axis collimated beam is shown in Figure 10. The far field divergence angle of the slow axis collimated diode laser beam ranges from 1,9 to 2,1° and is close to the angular selectivity of the grating. High beam quality in both directions, slow and fast axis, is required to achieve high diffraction efficiencies of the beam combiner. The beam divergence angles have to be lower than 1.5 mrad in fast axis. These values are achievable with good collimation optics and low smile (< 1 µm PTV) of diode laser bars, but are still a challenge for low cost mass production of collimated high power diode laser bars. The maximum diffraction

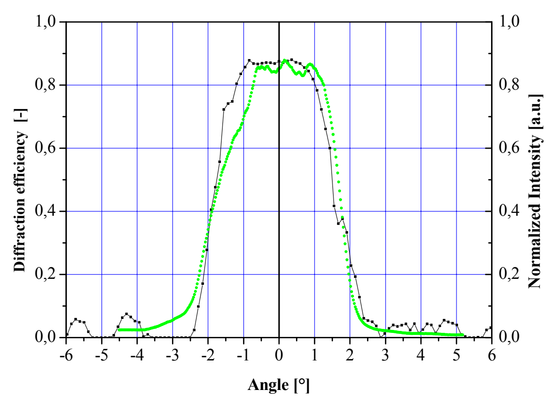

Figure 10: Angular selectivity of the beam combiner in the horizontal plane (slow axis) versus deviation from the Bragg angle and the slow axis intensity distribution.

efficiency of the beam combiner is 88%.
The spectra of the diode lasers are stabilized with a centre wavelength spacing of 3.3 nm and more than 95 % of the optical output power of each beam within a spectral width less then 0.7 nm is reached. In Figure 11 the spectrum of the two beam combined diode lasers is shown. A diffraction efficiency of 79% for the reflecting beam is achieved. About 85% of the optical power from the transmitting beam passed through the beam combiner. The overall beam combining efficiency for both diode laser bars reaches 82%. The peak emission wavelength is shifting 0.2 nm in the full power range. In consequence the diffraction efficiency of the reflected beam drops down to 70% because of a resulting mismatch of the incident Bragg angle. The temperature shift can be compensated by adjusting of the beam combining angle and can be optimized at maximum output power. Note that the wavelength stabilization is performed without water cooled heat sinks. Re-adjusting of the beam combiner could be avoided if the wavelength shift is reduced to less than 0.05 nm as demonstrated in Figure 10 by use of water cooled mounts. The fast axis beam quality in Figure 13 represented by the beam caustic of the combined diode laser beams is $M^2 = 1.63$.

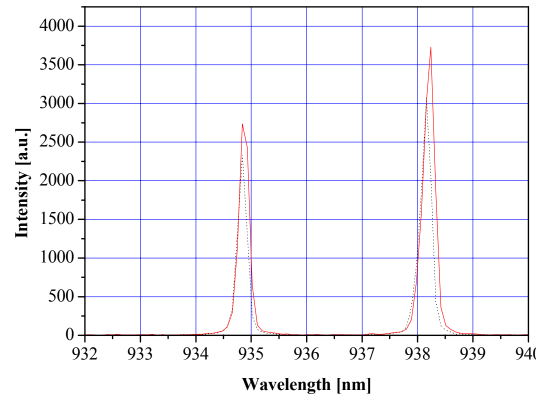

Figure 11: Spectra of two combined diode laser beams at 40 A (dotted line) and 50 A (solid line).

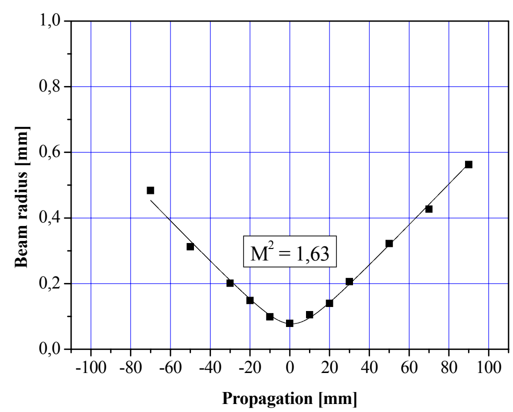

Figure 12: Beam caustic of two combined diode laser beams at 40 A.

3 CONCLUSIONS

The spectral stabilization of diode laser bars at high optical output powers of 80 W features side lobe suppression ratio greater than 25 dB and spectral full width at half maximum of 0.2 to 0.3 nm. High power diode laser bars with antireflection coated front facet provide wavelength stabilization without side lobes in the full power range and reach slope efficiencies up to 0.98 W/A. The thermal shift is reduced down to 0.0006 nm/W by use of water cooled mounts of the volume diffraction gratings and adapted geometry. The improved spectral performance due to spectral narrowing and low thermal wavelength shift allows for spectral beam combining of high power diode lasers.
Incoherent beam combining of two diode laser bars with centre wavelength spacing of 3.3 nm has been demonstrated The combining efficiency of more than 80% is reached for high power diode laser with narrow spectral width and low divergence in slow and fast axis. Limitations on the performance of wavelength stabilization and spectral beam combining arise from the smile of the diode laser bar that should be less than 1 µm from peak to valley.
The use of volume diffraction gratings has the advantage to operate diode laser bars of the same chip material at different centre wavelengths and by this it is possible to scale the power for direct applications by wavelength multiplexing to much larger numbers compared to currently available diode lasers.

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