5 W frequency stabilized 976 nm tapered diode lasers

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ABSTRACT

More and more applications, like tunable frequency doubling of diode lasers for blue-green outputs, non linear spectroscopy, or pump laser sources for fiber lasers necessitate diffraction-limited tunable narrow linewidths and high output powers in the multiwatt regime. For these applications, tapered lasers based on a tapered amplifier with gain-guided design can be used in an external cavity set up to guarantee both – frequency stabilization and tunability.
We have realized frequency stabilized high-power ridge-waveguide tapered diode lasers with more than 4W of cw output power. These low modal gain, single quantum well InGaAs/AlGaAs devices emitting between 920nm and 1064nm were grown by molecular beam epitaxy. Tapered single emitters consist of an index-guided ridge section and a gain-guided taper section with an overall length of 3.5mm. The taper angle was 6°. With a high-reflectivity coating on the rear facet and an antireflection coating on the front facet more than 10W of output power have been demonstrated.
To optimize the beam quality at higher output power the two different sections have been operated by different operation currents. For this purpose the tapered diodes have been mounted p-side down on structured submounts. For wavelength tunability and frequency stabilization the tapered diodes, provided with AR coatings on both facets, have been used in external cavity setup in Littrow configuration. The influence of the different operation currents on the electro-optical and beam characteristics has been carefully investigated in detail. Within this operation mode a nearly diffraction limited behavior up to 5W has been established.

Keywords: high-brightness, high-power, tapered diode laser, laser-diodes, lifetime, AlGaAs-InGaAs, semiconductor

1. INTRODUCTION

High power diode lasers are finding use in a myriad of applications today. Several of these applications, such as optical pumping of solid-state lasers and rare-earth-doped fiber amplifiers or fibre coupled modules for medical and material treatment need high-brightness pump modules in the multiwatt regime. Although diode lasers with broad-area waveguide designs have shown impressive improvements regarding to their wall-plug efficiencies in the last years[1], they are still susceptible to modal instabilities and filamentation effects. This results in low beam qualities and values for the brightness are limited around 10 MW/cm^2.

The tapered laser design with gain-guided tapered section and index-guided ridge-waveguide section is one of the most promising concepts to achieve much higher brightness, this means high output power in a single-lobed diffraction-limited beam[2,3]. In fact tapered lasers and amplifiers have been proven the last couple of years to work quite well in MOPA (Master-Oscillator-Power-Amplifier) configurations or external cavity setups[4,5,6]. They are today the key components of many commercial and scientific applications. Nearly diffraction limited tapered diode lasers around 2 W are already commercialized corresponding to a brightness around 125 MW/(cm^{2}sr)[7]. But for tapered diode lasers there is a need for even higher output powers in order to compete with broad-area diode lasers used in fibre coupled modules so far. And for frequency doubling for blue-green outputs also high output power in the power regime of 4W and more is a demand. For both applications the diode laser should be frequency stabilized. And for the last one, fast modulation of the diode should be possible.

In this letter, a high-efficiency tapered diode laser based on the InGaAs/AlGaAs material system with a ridge-waveguide structure is described. For a single emitter a nearly diffraction limited behaviour has been demonstrated up to 8.3W cw resulting in a brightness of more than 660MW/cm^2. In external cavity setup more than nearly diffraction

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limited 3W have been demonstrated. Within a new operation mode, the bisectional operation mode with separated contacts for ridge-waveguide and taper section more than 5W of output power have been established.

2. Fabrication of Tapered Devices and bisectional tapered amplifiers

The fabrication of high brightness lasers with high conversion efficiencies requires an epitaxial layer sequence with low internal losses (< $0.7cm^{-1}$) because of resonator lengths between 3mm and 5mm, low confinement factor (<1.1 %) and high internal conversion efficiency (> 95%). The reduction of the internal losses and of the confinement factor can be achieved by broadening the waveguide layers[8]. This reduces the overlap of the optical mode with the highly doped cladding layers. The laser structures were grown by molecular beam epitaxy (MBE).

The active region consists of a single InGaAs-quantum well embedded in a 1.06µm thick AlGaAs core region with 20% Al content. The use of high-band-gap (E_g = 1.68eV) AlGaAs core layers with 20% of Al content leads to a strong carrier confinement. The quantum well is 7nm thick with a nominal In content of 19% resulting in an emitting wavelength of 976nm. The optical waveguide is formed by 1µm thick AlGaAs claddings with 40% Al. Si and Be have been used for n- and p-type doping, respectively. The layer design exhibits an overlap of the fundamental optical mode with the quantum well of 1.1% for 976nm. It has been shown previously that this low modal gain epitaxial layer structure suppresses beam filamentation in tapered lasers[9,10].

For a pre-characterization of internal parameters, broad-area lasers are obtained from a fast process. The p-side metal is deposited by using a shadow mask, and the n-side contact is applied to the unthinned substrate. Laser bars with as-cleaved facets are mounted p-side up for pulsed characterization. The high material quality of the MBE-grown laser structures yields a high internal efficiency of more than 97%. Low internal losses of less than $0.6cm^{-1}$ are obtained from Fabry-Perot laser diodes of different lengths.

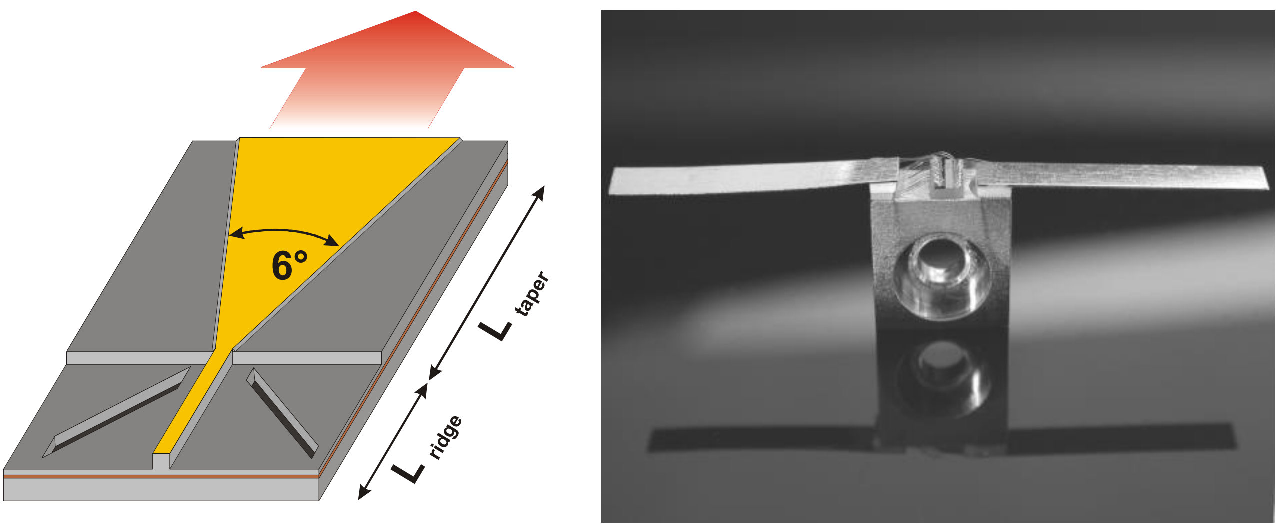

Figure 1: (left hand side) Schematic of a gain guided tapered diode lasers with a ridge-waveguide section for mode filtering. The length of the ridge section is 500µm, whereas the length of the taper section is 3mm. The taper angle is 6°. (right hand side) Picture of a bisectional tapered amplifier with separated electrical contacts for ridge-waveguide and taper sections. The diode is mounted p-side down on a structured AlN submount.

The ridge-waveguide and taper sections are processed by using optical lithography and wet chemical etching followed by a lift-off step. Figure 1 (left hand side) shows a schematic of the device. The structure consists of a taper angle of 6° together with a taper section length of 3mm. This leads to an emitting aperture of 317µm width. The length of the ridge section is 500µm resulting in a total device length of 3.5mm. The ridge width was 3µm. The ridge height is chosen appropriately for the propagating wave to fill the taper angle. Cavity-spoiling groves on both sides of the ridge section suppress undesired Fabry-Perot modes.

After substrate thinning and depositing the n-metallization, the wafers were cleaved. Afterwards for the tapered laser a highly reflective double-stack of Si and SiO_2 (97% reflectivity) is deposited at the rear facet with the help of reactive magnetron sputtering. For the tapered amplifiers the rear facet is coated with a single layer of SiON (<0.01%). The front facet is coated with a single layer of SiON (< 0.01% reflectivity). Finally the devices are mounted p-side down on AlN submounts with AuSn solder. The bisectional tapered amplifiers with separated electrical contacts for ridge-waveguide and taper sections (figure 1, right hand side) are mounted with AuSn solder on structured AlN submounts. The submounts were mounted on standard C-mounts. Uniform pumping of the laser medium is achieved by current injection via bond wires.

3. EXPERIMENTAL SETUP

To combine the advantages of high power high brightness tapered laser diodes with narrow linewidth and excellent tunability an external cavity setup was used (see figure 2). The external cavity consists of a collimating lens with 12.5mm focal length. A half wave plate is used to correct the polarisation for the Littrow-mounted grating. The first order of the dispersed light is reflected back into the highly antireflection coated ridge side of the tapered amplifier. The 1µm thick waveguide acts as a slit to capture a small part of the light at the lasing wavelength which is used to seed the ridge section and then amplified in the tapered section. The front side is antireflection coated such that a small amount of the light is reflected back to provide oscillation.

This type of external cavity has the advantage that no additional seed laser and extra electronics is needed to achieve small linewidths which makes it attractive for applications were cost plays an important role. Additionally no beam walk occurs on the front side while tuning the laser on the rear side. By using tapered amplifiers in the external cavity setup it is possible to reach much higher output powers in comparison with setups were standard ridge lasers are used. This makes such a setup attractive for applications were high power is needed like for Raman-Spectroscopy or frequency doubling.

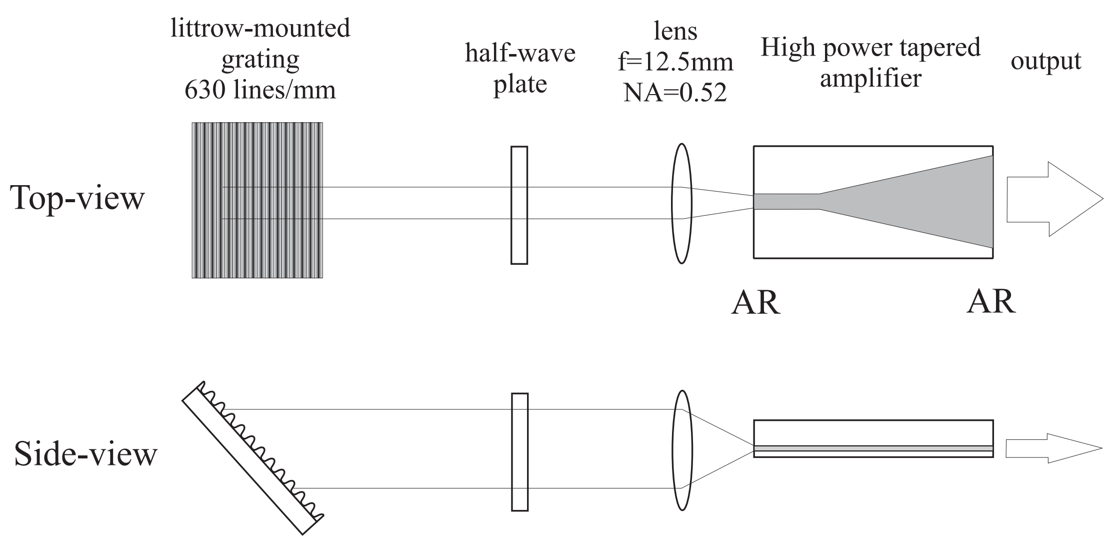

Fig. 2. Principle of the used external cavity setup. First the light of the rear side is collimated. A half-wave plate corrects the polarization for the Littrow mounted grating. The first order of the grating is coupled back into the laser. The output wavelength can be tuned by tilting the grating.

4. TAPERED LASERS

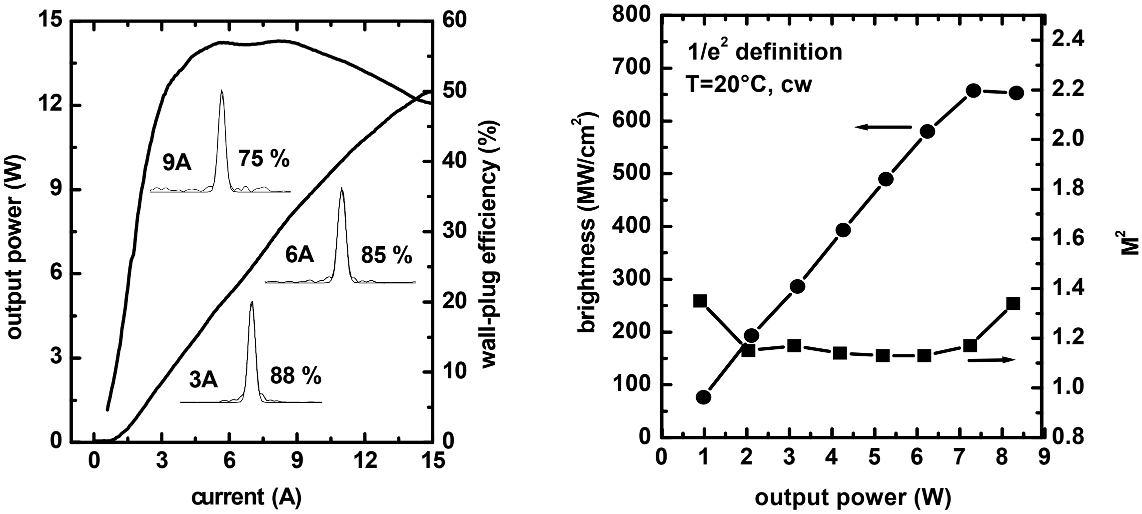

Figure 2: (a) Optical output power against operation-current of a tapered laser with 3.5mm resonator length and a high-reflectivity coating on the rear facet. For 3A (2W), 6A (5.3W) and 9A (8.2W) the focused beam waist has been included. (b) M^2 and brightness against output power. A record value of $660MW/cm^2$ has been demonstrated.

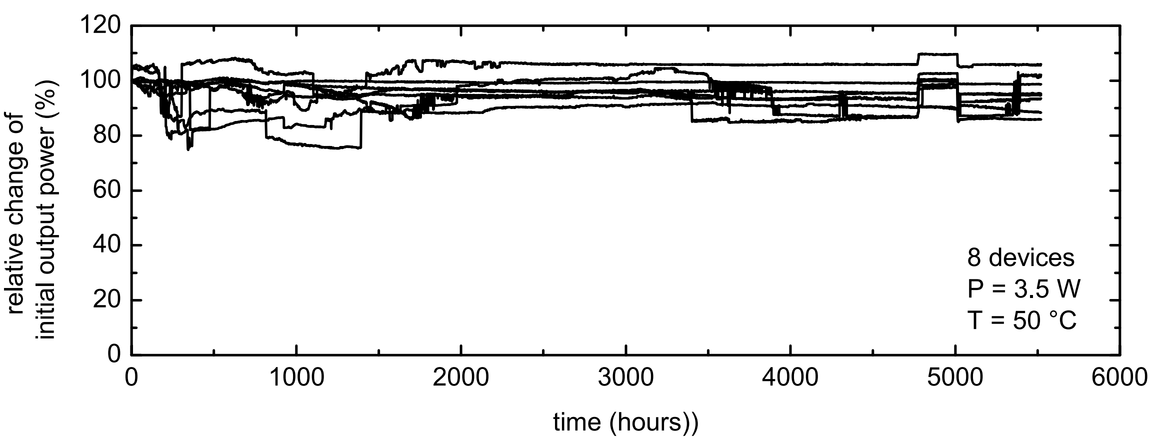

Figure 3: Relative change of initial output power against time of a batch of 8 tapered lasers. The operation conditions were an initial output power of 3.5W and a heatsink temperature of 50°C.

Figure 2(a) shows the current-power characteristic together with the wall-plug efficiency for a high-power tapered laser with 3.5mm resonator length and a high-reflectivity coating on the rear facet. A detailed analysis of the result of this configuration has been given elsewhere[10]. A threshold current of 0.6A and a slope efficiency of 1.04W/A are quite comparable with values of broad-area diode lasers with comparable resonator lengths. The maximum wall-plug efficiency results in 57.2%. At 15A an output power of 12.5W has been demonstrated with an overall efficiency of 48.2%, which is a quite impressive result even for the wall-plug efficiency at such operation currents. In addition the beam waists of the focused beam at 3A (equal to 2W), 6A (5.3W) and 9A (8.2W) have been included demonstrating the outstanding beam quality of this laser. From a Gaussian fit of the beam waists, at 8.2W 75% of the intensity diffraction limited. More than 6W of diffraction limited output power has been demonstrated. In figure 2(b) M^2 and brightness of this tapered laser has been plotted. M^2 was measured with the $1/e^2$-cut-definition. A record value for the brightness of 660MW/cm^2 has been established.

The wafer material and the tapered laser structure can be tested by using a highly reflection coating on the rear facet. In figure 3 a lifetime test for tapered lasers at 976 nm is shown. The test has been done by an operation current of 3.5W and an operation temperature of 50°C. During 5000 hours there is no degradation behavior visible. The wall-plug efficiency was in the range of 40%, this means the power losses are in the range of 5.25W comparable to the power losses of a 4W tapered amplifier as shown in fig. 4.

We have demonstrated that tapered lasers are able to achieve very high values for the brightness. But many applications need not only brightness, they need frequency stabilized brightness. So the next step is the use of tapered lasers as amplifiers in external cavity setups.

5. HIGH-POWER TAPERED AMPLIFIERS WITH 4 W AT 976 NM

Figure 4(a) shows the current-power characteristic together with the wall-plug efficiency for a high-power tapered amplifier used in an external cavity system as described in section 3. The ridge section length was 500µm and the taper section length was 3mm. External cavity systems in principle have lower wall-plug efficiencies due to the incorporation of optical elements which lead to additional optical losses. Additionally only a fraction of the dispersed light from the rear side of the amplifier is coupled back into the ridge-waveguide. The tapered amplifier chip reaches optical output-powers of nearly 4.5W at an operation-current of 6A and a tuned wavelength of 970nm. This corresponds to a comparatively high wall-plug efficiency of more than 42% . The tuning curve for the threshold current and needed injection current for 1W, 2W and 3W of optical output power is presented in figure 4(b). The curves are rather flat and have nearly constant spacing. This is a result of the very broad and flat gain spectrum of the investigated tapered amplifier which leads simultaneously to nearly constant slope efficiencies and high output powers over the whole tuning range.

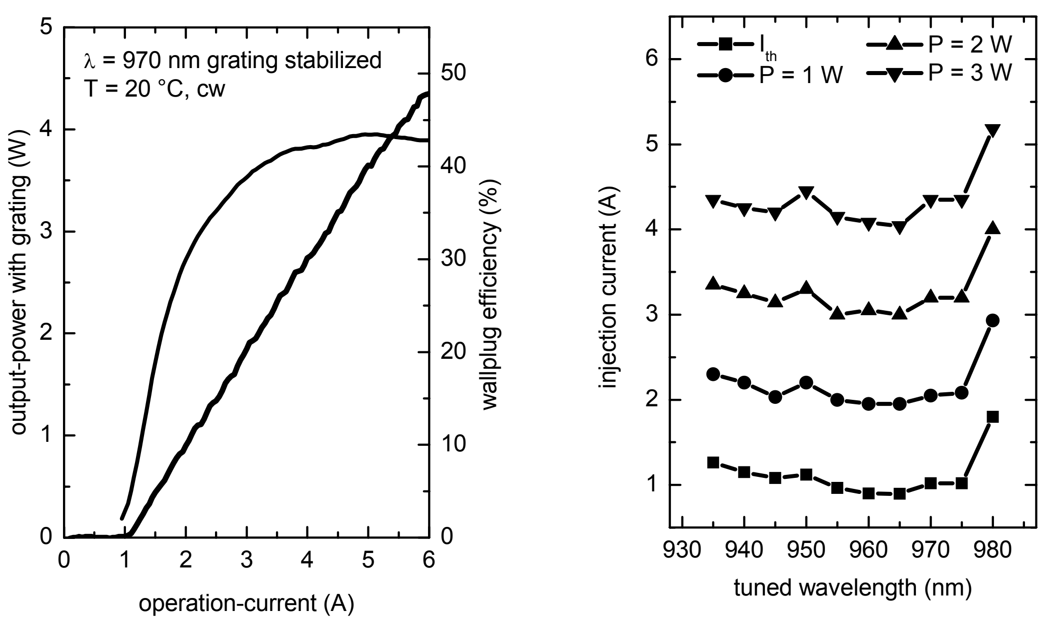

Figure 4: (a) Optical output power against operation-current of a tapered amplifier with grating feedback tuned to 970 nm. Output powers of more than 4W at an operation-current of 6A are reached. The wall-plug efficiency reaches a very high value of more than 40%. (b) Injection current for 1W to 3W of optical output power in dependence of the tuned wavelength. Additionally the threshold current is plotted. The measurements were performed at a heat sink temperature of 20°C in cw-mode.

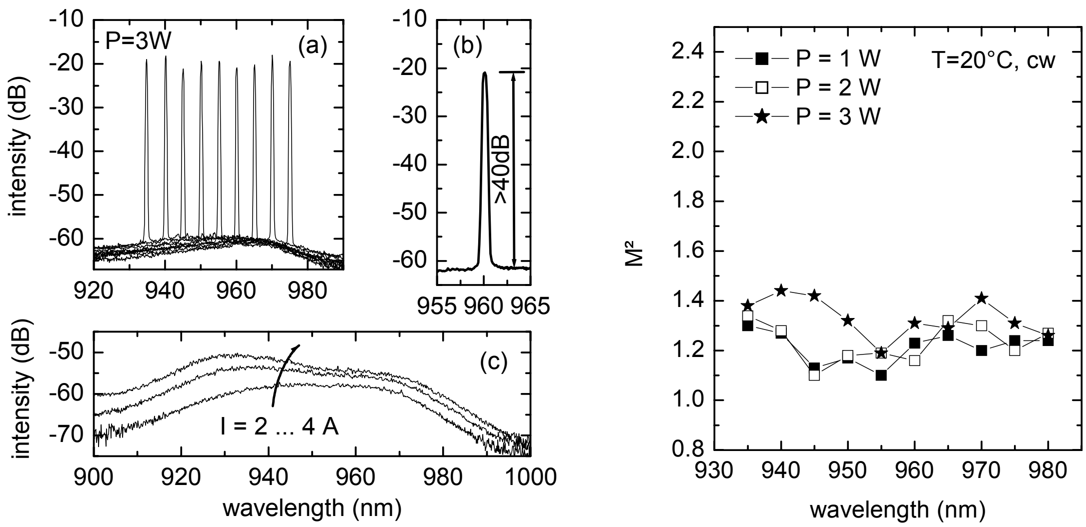

Figure 5: (a) Intensity spectrum at different tuned wavelengths between 935 nm and 980 nm at an optical output power of 3 W. (b) A typical sidemode suppression over the whole tuning range is better than 40 dB. (c) Intensity spectrum for operating-currents between 2A and 4A with grating-feedback blocked. (d) Beam quality parameter M² and astigmatism in dependence of tuned wavelength for constant optical output powers of 1 W (squares), 2W (open squares) and 3 W (stars) measured at 20 °C heat sink temperature in cw-mode.

With an external cavity setup it is possible to reduce the linewidth significantly. To ensure that the amplifier don't suffer from parasitic oscillation even at high injection currents, which are necessary to gain highest output powers, a high quality antireflection coating on the rear and also front side of the amplifier is necessary. The spectral tuning characteristics and linewidth was measured with an Optical Spectrum Analyzer HP70950B. The gain spectrum determines the overall tuning range of the laser. As can been seen in figure 5(a) the power amplifier can easily be tuned from 935nm to 980 nm. A typical sidemode suppression of better than 40dB is reached over the whole tuning range (figure 5(b)). Up to an operation-current of 4A no laser-peaks are visible in the intensity spectrum with grating feedback blocked (figure 5(c)) which verifies the excellent coating quality.

In figure 5(d) the beam quality of the slow axis is plotted for optical output powers between 1W and 3W in dependence of the tuned wavelength. The beam quality was measured using the $1/e^2$ method. A beam quality of $M^2 < 1.5$ is achieved over the whole tuning range up to optical output powers of 3W. If we use an integral method which takes into account sidelobes even below the $1/e^2$ level a beam quality of around $M^2=1.6$ is achieved over the whole tuning range for output powers up to 3W.

6. BISECTIONAL TAPERED AMPLIFIERS AT 976 NM

In the last section we have demonstrated that the operation of a tapered amplifier in an external cavity system lead to frequency stabilized high output powers and also to frequency stabilized high brightness. For some applications like frequency doubling for display applications or LIDAR systems modulation plays an important role. If a pulsed operation mode is necessary, it is quite preferable to use small pulsed operation currents instead of operation currents like 4-6A as in the last section.

The tapered laser concept offers for such applications the possibility to operate the ridge-waveguide and the tapered sections separately. Fig. 1b has shown a typical setup for such an operation mode. In the following we call such lasers bisectional tapered amplifier lasers (BTAL). The BTAL are mounted p-side down on structured AlN submounts with AuSn solder. Both sections have been contacted individually by bond wires to different wings on the left hand and right hand side. Both sections can be operated in cw as well as in pulsed mode. In the following we have operated both sections in cw operation to investigate the principle characteristics of such setups.

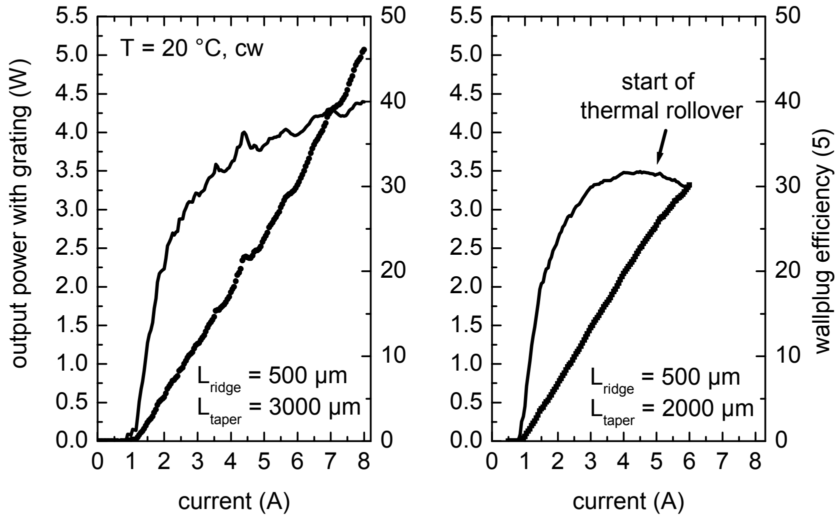

Figure 6: Comparison of electro-optical behavior of bisectional tapered amplifiers for different taper section lengths. The data have been measured at grating stabilized 970nm at a heatsink temperature of 20 °C in cw operation.

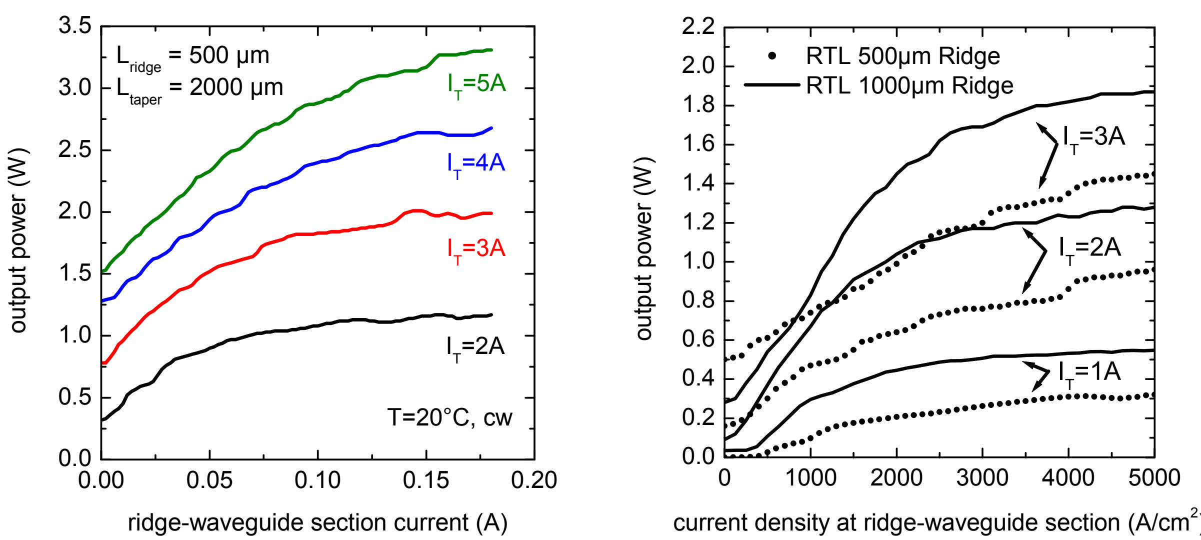

Figure 7: (left hand side) Output power against ridge-waveguide section current for a BTAL with 2.5mm resonator length. The curves have been measured for different taper section currents. (right hand side) Comparison of BTAL with different ridge-waveguide section lengths. The measurements have been done at a heat sink temperature of 20 °C in cw operation.

Fig. 6 shows a comparison of BTAL with different taper section lengths. For a taper section length of 2mm the usable output power is limited at about 2.5W because of the start of thermal rollover at 4A. In contrast for a taper section length of 3mm, an output power of more than 5W has been demonstrated. The wall-plug efficiency still increases at 8A without any thermal rollover effects. Threshold current (2mm: 0.9A; 3mm: 1.07A) and slope efficiency (2mm: 0.71W/A; 3mm: 0.69W/A) of the laser with longer taper section length are slightly lower.

The next figure 7 describes the output power of a BTAL in dependence of the ridge section current for different taper section currents. At a ridge-waveguide section current of 0mA there is still laser output. At a taper section current of 5A an output power of 1.5W has been measured for 0mA ridge-waveguide section current. For higher ridge section currents there is a saturation of the output power visible. The saturation current increases with the taper section current. If the BTAL will be operated at ridge-waveguide section currents higher than the saturation current, there is no increase in output power visible but the ridge-waveguide section will heat up reducing the lifetime. For practical use an operation current of not more than 90% of the saturation current will be preferable. On the right hand side a comparison of two BTALs with 2mm taper section length and different ridge-waveguide section lengths (500µm and 1000µm) is given. The output power at zero ridge-waveguide section current decreases with longer ridge-waveguide section length. In contrast the saturated output power at higher ridge-waveguide section currents increases with longer ridge-waveguide section lengths. For a taper section current of 3A and a current density of 5000A/cm^2 at the ridge-waveguide section, an output power of 1.87W has been measured for a 1000µm long ridge-waveguide section length instead of 1.46W for a ridge-waveguide section length of only 500µm.

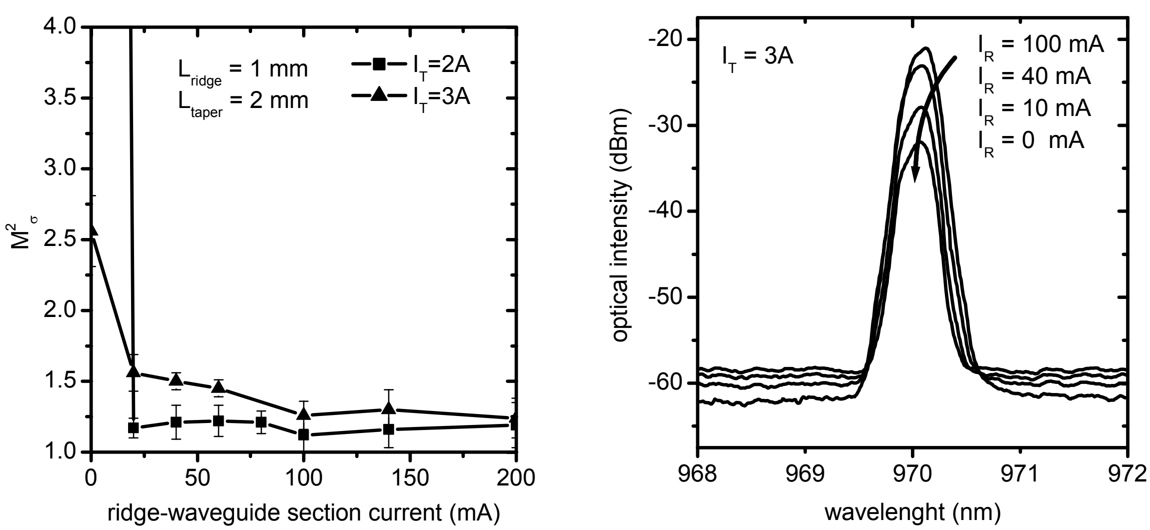

Figure 8: (a) Beam propagation factor M² in dependence on ridge section current for a TLD with ridge section length 1mm und tapered section length 2mm. The measurements have been done for tapered section current 2A and 3A at a heat sink temperature of 20° and in continuous wave mode. (b) Intensity spectrum with different adjusted ridge section current. Measured at the tapered section current I_{taper}=3 A at a heatsink temperature of 20°C in cw-mode. The sidemode suppression reached the highest value of 40dB by saturation the optical power at the ridge section current 100mA.

In fig. 8(a) the beam quality of BTAL in dependence of the ridge section current is given for taper section current of 2 A and 3 A. Except at 0 mA ridge section currents the beam quality is nearly diffraction limited with values of less than 1.5 for M^2. At 0 mA beam quality increases rapidly in dependence on the taper section current. For 3A taper section current we have measured values of more than 2.5 for M^2. The spectrum depends only on the taper section length and keeps constant for different ridge section currents as demonstrated in fig. 8(b).

The extinction ratio is defined by the relation between low-current and high-current output power and depends on the taper section current. For a taper section current of 5 A the extinction ratio is 45%. This is too high for modulation operation. But especially for frequency doubling output power after the frequency doubling depends on M^2 squared. This means that the extinction ratio can be at 1:100 at the moment. This ratio can be lowered in future by a better separation between ridge and taper section and by longer ridge section lengths.

7. CONCLUSION

In conclusion, we reported on tapered lasers, tapered amplifiers in an external cavity setup with Littrow-mounted grating and finally on bisectional tapered amplifiers at 970nm. We have demonstrated for tapered lasers more than nearly diffraction limited 8W of output power and for tapered amplifiers in external cavities more than 3W of frequency stabilized nearly diffraction limited output power. A maximum of 4.5W have been measured for the last one. With the help of bisectional tapered amplifiers with separated electrical contacts for the ridge-waveguide and the taper sections frequency stabilized 5W of output power could be reached.

8. ACKNOWLEDGEMENT

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