High efficiency laser sources usable for single mode fiber coupling and frequency doubling

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ABSTRACT

Semiconductor laser diodes with a tapered gain region provide a beam quality near to the diffraction limit combined with high output power. They can be configured as lasers with a high-reflectivity coating on the rear facet and a high antireflection coating on the front facet. Additionally as amplifier with an antireflection coating on both facets they can be used in MOPA configuration together with a seed laser. Today amplifiers are commercially established with an optical output-power of 1-2W in a wide range of applications such as Raman spectroscopy or frequency doubling.

With a new class of tapered lasers and amplifiers based on improved vertical and lateral designs, the output power for both types can be enlarged significantly. Taper design consists of an overall resonator length of 5mm and a taper angle of 4° providing a small lateral far-field angle <12° (95% power included). Tapered lasers emitting at 976nm have demonstrated 16W at 20A operation current with a wall-plug efficiency of 60% at 8.5W and 59% at 10W. Slope efficiency was 1.05W/A. These values are comparable to 100µm wide broad-area lasers with 5mm resonator length. The long-term stability has been tested by lifetime tests at 10W.

The dependence of the beam quality on different parameters has been investigated especially for the high-current regime up to 15A. Whereas for lower power levels no changes have been found, slightly changes occurred at 10W after 1000 hours. Best beam quality was $M^2<1.8$ at 8W for tapered lasers as well as for tapered amplifiers.

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

1. INTRODUCTION

Conventional high-power diode lasers in the near-infrared wavelength regime like broad-area lasers typically have brightness below 20 MW/(cm^{2}sr). But the success of the fiber laser technology and the request for pump sources has moved the development forward to diode lasers with much higher brightness[1,2]. The brightness of a diode laser is a measurement for the power per area and solid angle and therefore includes beside the output power also a description of the beam properties. The brightness is defined by:

$$B=P/(\lambda^2 M^2_{vertical} M^2_{lateral})=P/(\lambda^2 M^2_{vertical}(\pi/4 w_{lateral}\theta_{lateral}) \qquad (1)$$

M^2 defines the beam quality in both propagation directions of the emitting laser beam. The optical output power P can be controlled by the width $w_{lateral}$ of the stripe. The beam of a diode laser is elliptical: Although in vertical direction the beam is highly divergent, because of its Gaussian beam profile, beam shaping can be done very easily by adequate lenses. In lateral direction a set of optical modes lead to a non-Gaussian intensity distribution and the beam profile shows intensity fluctuations (filaments). The width $\theta_{lateral}$ of the lateral far field is defined by inclusion of 95% of the optical output power.

The brightness of broad-area lasers is mainly limited by heat dissipation ($\theta_{lateral}$) and facet coating technology (limits P in equation (1))[3]. The use of tapered laser designs allow to avoid these limitations of the broad-area laser designs[4,5,6]. A tapered laser consists of two components monolithically integrated on one chip. The so called ridge-waveguide section is a mono-mode diode laser used as a pump sources for the second section. In the following tapered section the active width enlarges from the typically 3µm ridge section width towards an output facet width of several micrometer, depending on the chosen section length and taper angle. For an initial power of several 10mW at the rear end of the taper section it is possible to amplify the optical output power to several Watts at the output facet (figure 1). Because of the tapered geometry, the minimal lateral beam waist in the focus depends on the width of the ridge waveguide section, not on the width of the output facet. In comparison to broad-area lasers with identical output power this leads to a beam width reduced by a factor of 25. The far field, also important for the beam quality, is given by the taper angle. By stretching the length of the taper section the output facet will be broadened and the output power can be increased. The minimal beam width and the far field will remain maintained and therefore the beam quality does not change. So based on this behaviour the facet coating technology will not be the limiting factor any longer as for the broad-area lasers.

To combine the advantages of high brightness tapered laser diodes with narrow linewidth and excellent tunability a MOPA setup was used. This setup consists of a seed laser DL100 from TOPTICA emitting at 976nm, an optical isolator to avoid back-reflections between seed laser and tapered amplifier, a half wave plate to adjust the polarization between seed laser and tapered amplifier and a focusing lens in front of the rear facet of the tapered amplifier. The waveguide of the ridge-section of the tapered amplifier acts as a slit to capture the light of the seed laser. Then the light will be amplified in the tapered section. For the MOPA setup it is essential that both facets of the tapered amplifier are highly antireflection coated with values of less than 0.01%. By using tapered amplifiers in the MOPA 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.

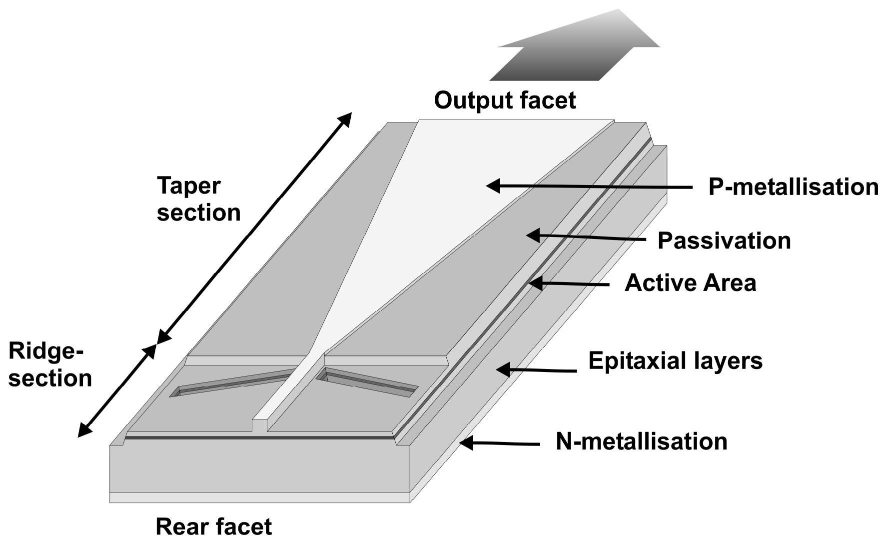


Figure 1: Schematic of a gain-guided tapered amplifier with a ridge-waveguide section for mode filtering.

2. FABRICATION OF TAPERED DEVICES AND BISECTIONAL TAPERED AMPLIFIERS

New single quantum well InGaAs/AlGaAs/GaAs laser structures with reduced far fields of 45° and optimized layer designs for resonator lengths of 4-6mm were grown by molecular beam epitaxy (MBE). Emitting wavelength is 976nm. The fabrication of high brightness lasers with high conversion efficiencies requires an epitaxial layer sequence with low internal losses (< $0.5cm^{-1}$), low confinement factor (<1%) and high internal conversion efficiency (> 95%). The reduction of the internal losses and of the confinement factor can be achieved by asymmetric waveguide designs and adapted doping profiles. In addition heat management within the layer design should be optimized.

To test the new epitaxial structures for the usability of long resonators, broad-area lasers with a stripe width of 100µm were fabricated using standard optical lithography in combination with various etching techniques for lateral structuring, and lift-off metallization for p-contact formation. Backside processing started with substrate thinning followed by the deposition of the n-contact metallisation. Laser bars with cavity lengths of 4-6mm were cleaved and high-reflection / anti-reflection (HR / AR) coatings were applied to the rear / front facet for improved single-ended output characteristics. Finally all emitters were soldered p-side down with AuSn on CuW-submounts and bonded on top of standard C-Mounts with In-solder. As an example figure 2(a) shows the optical output power and power conversion efficiency characteristics of a BA single emitter with (100x5000)µm² geometry measured in cw-mode. A high slope efficiency of around 1.1W/A and a relatively low threshold current of 0.7A leads to a maximum wall-plug efficiency around 65%. Because of a low series resistance the wall-plug efficiency stays well above 60% for injection currents of more than 10A. The heat management have been tested by P-I-curves of BA single emitters with (100x4000)µm^2 geometry at different heat sink temperatures of 20°C to 80°C. From these measurements values of (265+/-20)K for T_0 and (1600+/-200)K for T_1 have been calculated. The device geometry combined with the high wall-plug efficiency and impressive high values for the characteristic temperatures is the reason that nearly no thermal roll-over is visible although the single emitter is passively mounted on c-mount. More results if these broad-area lasers are given at [3].

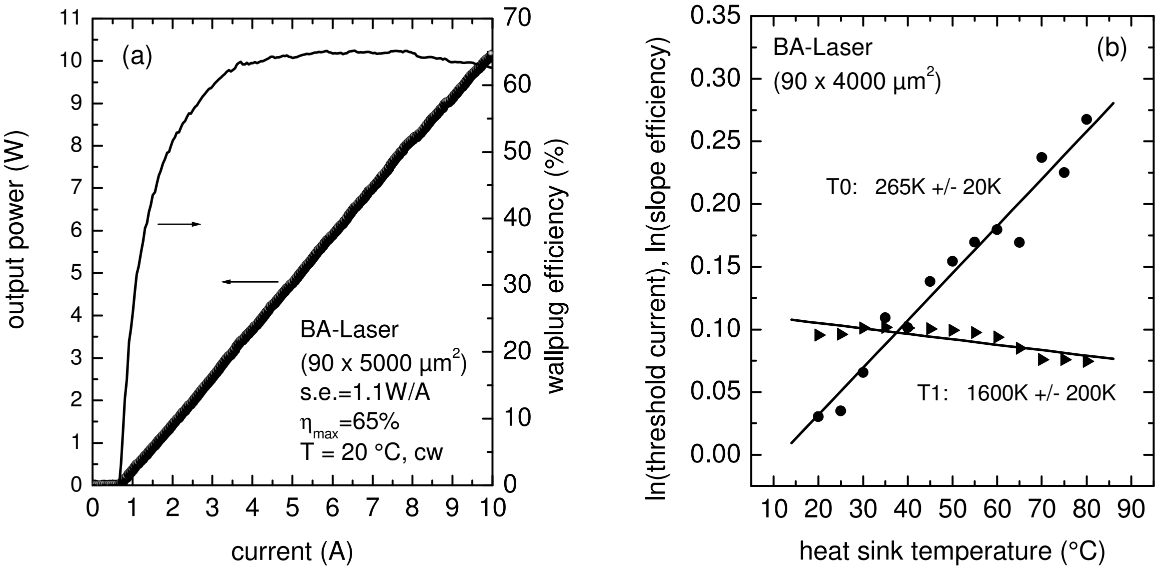


Figure 2: (a) P-I-curve of a BA-laser in (100 x 5000 µm^2) geometry at 20°C heat sink temperature. (b) P-I-curves of a BA-laser in (100 x 4000 µm^2) geometry at different heat sink temperatures. All measurements have been performed in continuous wave operation.

For the tapered lasers, the ridge-waveguide and taper sections are processed by using optical lithography and a mixture of dry and wet chemical etching followed by a lift-off step. Figure 1 shows a schematic of the device. The structure consists of a taper angle of 4° together with a taper section length of 4.3mm. This leads to an emitting aperture width of 280µm. The length of the ridge section was 700µm. 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 amplifiers the rear and front facets are coated with a single layer of SiON (<0.01% reflectivity). For the tapered lasers the rear facet was coated by a double stack of Si and SiO_2 resulting in a high reflectivity of >95%. For the front facet different antireflection coatings of 0.01% (SiON), 1% and 4% (both SiN) have been investigated within this paper. Finally the devices are mounted p-side down on CuW submounts with AuSn solder. The submounts were mounted on standard C-mounts or different DHP-mounts for high-power operation. Uniform pumping of the laser medium is achieved by current injection via bond wires.

3. CHARACTERIZATION OF TAPERED LASERS AND AMPLIFIERS

The beam quality of the 5mm long tapered lasers and amplifiers in a MOPA setup have been investigated by measurements of the beam profiles at the output facet (near fields), the minimal beam waist and the beam quality parameter M^2. For the measurements a commercial measurement setup (BeamScope from Dataray) has been used. All measurements have been made at 20°C heat sink temperature in cw mode.

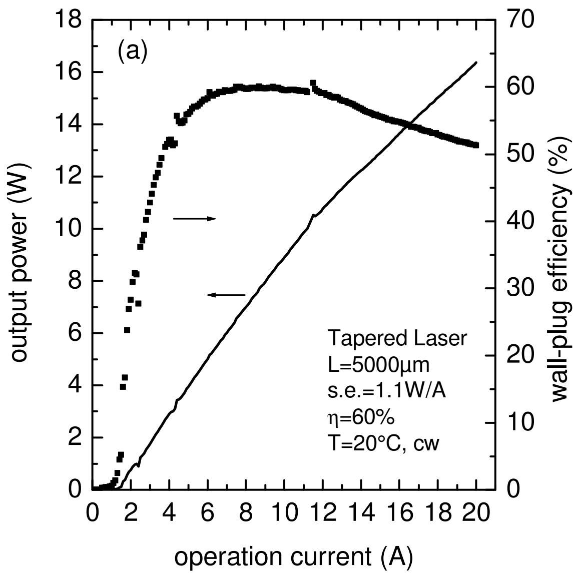
For a tapered laser with 5mm overall cavity length a cw-power of well above 16W was reached (figure 3). Because tapered lasers have additional losses, the so called geometrical losses, which describe the part of light which is not recaptured by the ridge section after one cavity roundtrip, the wall-plug efficiency always is lower than in a BA-laser. Despite this fact a very high wall-plug efficiency of 60% in cw-mode could be demonstrated. Due to the additional losses, the threshold current is with 1.4A twice the value for the corresponding BA lasers, but slope efficiency is with 1.1W/A identical. With a nearly diffraction limited value of 1.8 at 7W we have received a brightness of more than 400MW/cm^{2}sr. Figure 4 demonstrates that with accurate etching techniques it is in addition possible to optimize the M^2 behavior either for the output power range below 8W or for the high power range until 15W. Nevertheless for >8W is was not possible to achieve M2 values better than 8.

Within a MOPA setup with a seed power of 20mW we have achieved 1.06W/A for the slope efficiency and an output power of 13W at 16A operation current. The wall-plug efficiency is stable at 53-54% between 5W and 8W. To our knowledge, these are the highest values for the slope efficiency and the wall-plug efficiency for tapered amplifiers in a MOPA configuration published so far. The higher wall-plug efficiency for the 5000µm resonator design reduces the power losses and therefore the incurred heat. No thermal rollover was visible up to 9.5A.

Within a MOPA setup the typically small linewidth of the seed laser will remain maintained by passing through the tapered amplifier. 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 AQ6370. Figure 6a shows typical spectra of a tapered amplifier without a seed laser (so called free running). No laser-peaks are visible in the intensity spectrum which verifies the excellent coating quality. From the spectra the wavelength range and the amplification of the amplifiers can be calculated. For the usable wavelength range typically a 3dB criteria can be used. For the tapered amplifier a usable wavelength range of 20nm (970nm to 990nm) can be calculated. Used in a MOPA configuration the tapered amplifier with design TA5.0 shows a remarkable side mode suppression of 46dB (figure 4b).

Figure 7 illustrates the dependence of the beam profiles at the output facet (near field) and at the minimal beam waist on the output power. 8W was the maximum output power which could be measured by the BeamScope system without damage for the system. Up to this output power no disturbances of the near field structures could be seen so that from these measurements a nearly diffraction limited behaviour of the tapered amplifier could be expected. The minimal beam waists are Gaussian like up to 7W without any strong patterns on the left or right hand side of the central profile. At 8W on the right hand side of the central pattern slight structures have been measured. From that behaviour it is expected for the M^2 parameter that up to 7W the M^2 in 2. moment and $1/e^2$ definition should be nearly identical and for 7W and 8W there should be a slight difference between both measurements.

Finally figure 5(b) illustrates the beam quality parameter M^2 in dependence on the output power in combination with a current-power curve of a tapered amplifier with 5mm resonator length in a MOPA setup up to 12A. More than 10W have been achieved. As predicted from the measurements of the minimal beam waist, the M^2 values measured in $1/e^2$ and in 2. momentum definition are quite comparable up to 8A (according to 7W) and are below 1.8 which is nearly diffraction limited. At 9A according to 8W the difference between both measurements starts to increase leading to 1.8 for $1/e^2$ definition and 2.3 for 2. momentum definition.



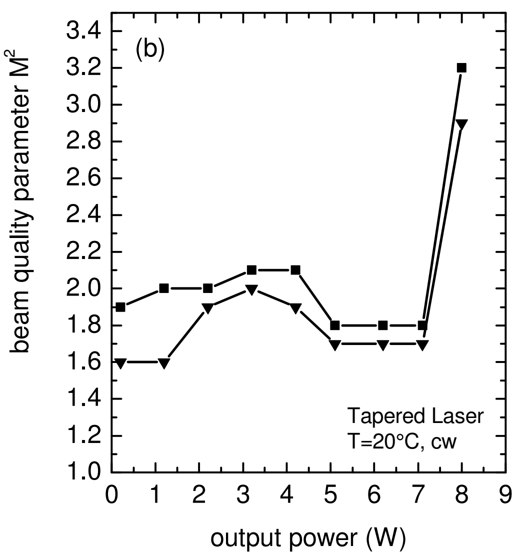


Figure 3: (a) P-I-curve of a tapered laser with 5mm overall resonator length. (b) Measurement of beam quality parameter M2 in dependence of output power. All measurements have been performed at 20°C heat sink temperature in cw operation.

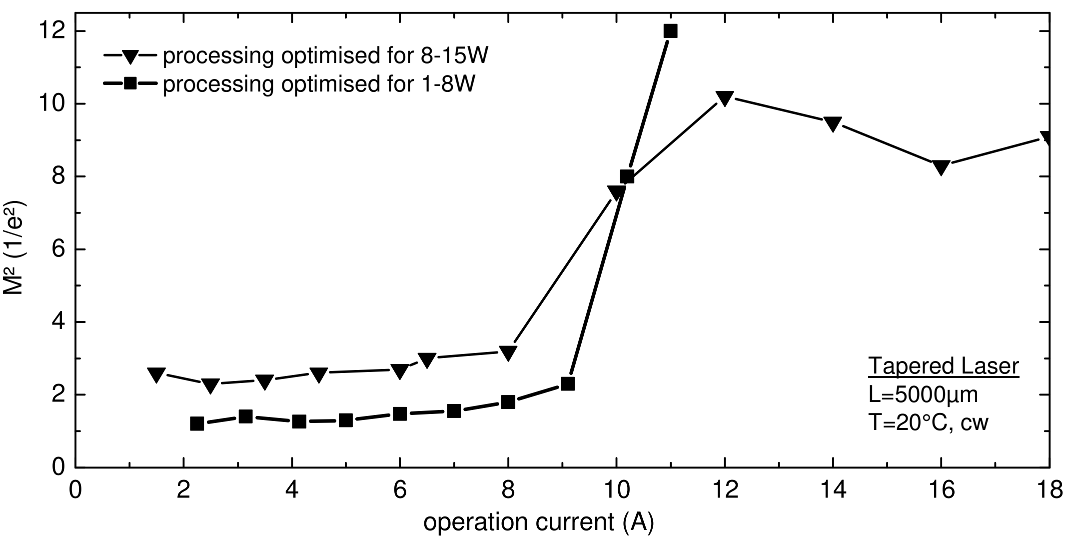


Figure 4: Measurement of the beam quality parameter M^2 for two tapered lasers optimized in etching depth for optimal beam quality below 8W and between 8W and 15W. All measurements have been performed at 20°C heat sink temperature in cw operation.

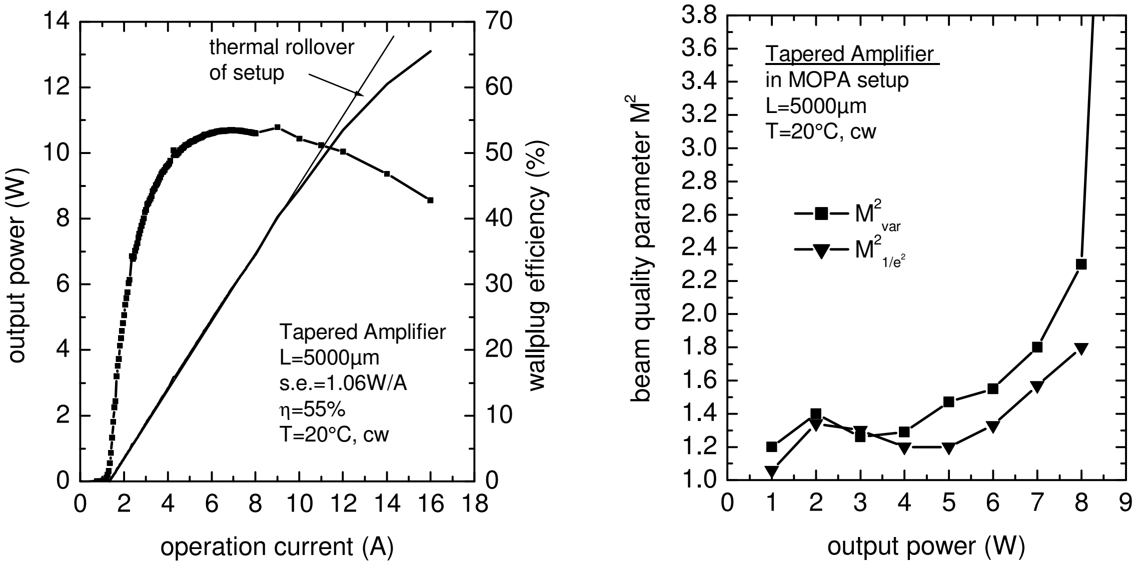


Figure 5: (a) P-I-curve of a tapered amplifier with 5mm overall resonator length in a MOPA setup with 20mW seed power. (b) Measurement of beam quality parameter M2 in dependence of output power. All measurements have been performed at 20°C heat sink temperature in cw operation.

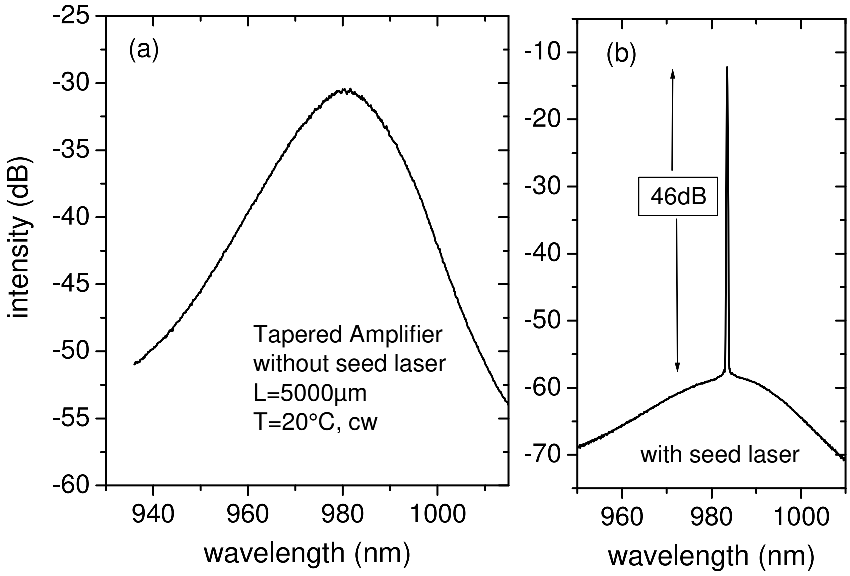


Figure 6: a) free running spectra without seed laser of tapered amplifiers at 976nm with 5mm overall resonator length. b) Spectrum of a tapered within a MOPA configuration. The measurements have been done at a heat sink temperature of 20 °C in cw operation.

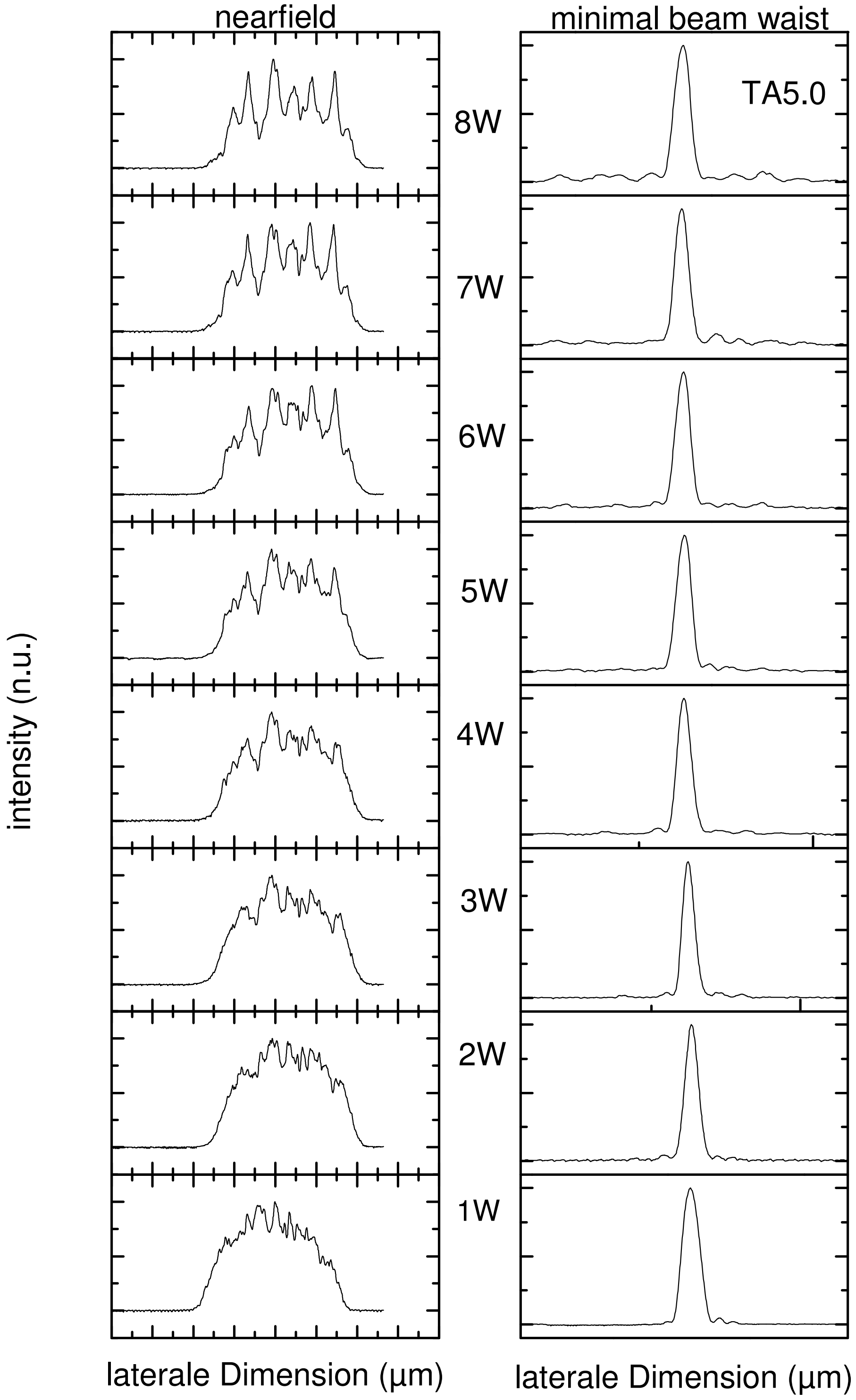


Figure 7: Beam profiles of a 5mm long tapered amplifier in MOPA configuration at the front facet (near field) and at the minimal beam waist in dependence on different output powers.

4. COMD AND LIFETIME MEASUREMENTS OF TAPERED LASERS

COMD (catastrophic optical mirror damage) measurements for tapered lasers with different front facet coatings of 0.01%, 1% and 4% have been performed with pulse times of 50µs and 50Hz repetition rate at a heat sink temperature of 20°C. Table 2 summarizes the main results of the P-I-curves shown in figure 8.

The maximal output power depends on the front facet (AR) coating and therefore on the beam quality. With higher antireflection coating the slope efficiency as well as the wall-plug efficiency decreases. In addition the number of kinks in the P-I-curves decrease with lower front facet reflectivity demonstrating the better beam quality. For the best antireflection coating of 0.01% we have received a slope efficiency of 1.1W/A and a maximum wallplug efficiency of 60%. The maximum output power was measured to be >25W limited by the current source used in this experiment.

AR coating	0.01%	1%	4%
s.e. (W/A)	1.1	1.04	0.91
η_{max} (%)	60	57	50
P_{max} (W)	>25.5	19.4	18.0

Table 1. Overview of electro-optical characteristics of tapered amplifiers with different resonator lengths in MOPA configuration. The data have been measured at a heat sink temperature of 20 °C and continuous wave (cw) operation.

In figure 9a, lifetime measurements for a tapered laser at different power levels are shown. Whereas for 4.8W (6A) and 8W (8A) there is no degradation visible at least for the first 1000 hours, at 10W power level there is a decrease in output power and a device failure after 550 hours. For the survived device at 10W lifetime condition P-I-curves have been measured after 500 hours and 1000 hours. As can be seen in figure 9b the P-I-curves are changing towards a more kinky behavior which leads to a lower COMD level according to figure 8.

At lower power level at 8W the long term stability seems to be much more stable. In figure 10 measurements of M^2 and the astigmatism have been compared for 0, 500 and 1000 hours operation time. Within the accuracy of the measurement methods there are no differences between all the measurements demonstrating the very stable beam behavior.

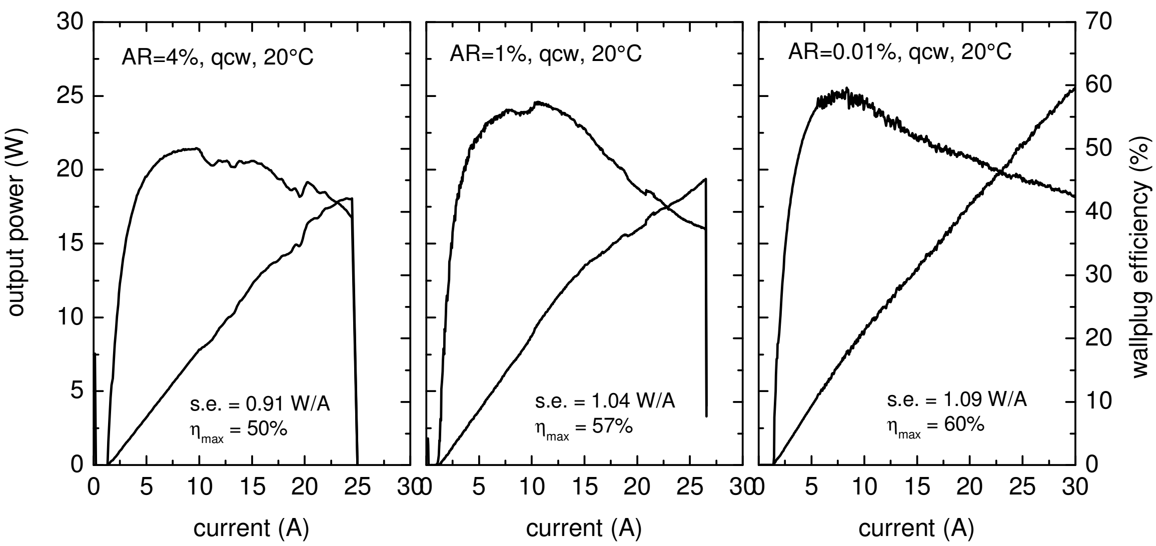
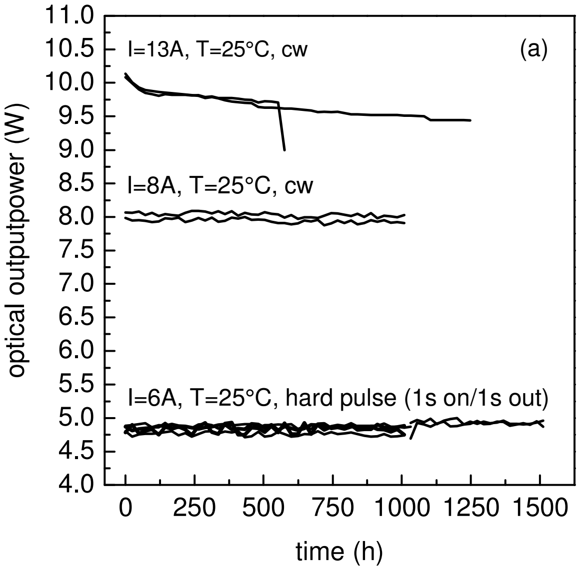


Figure 8: COMD measurements of 5mm long tapered lasers with different front facet coatings. All measurements have been performed at 20°C heat sink temperature at a pulse time of 50µs and a repetition rate of 50Hz.



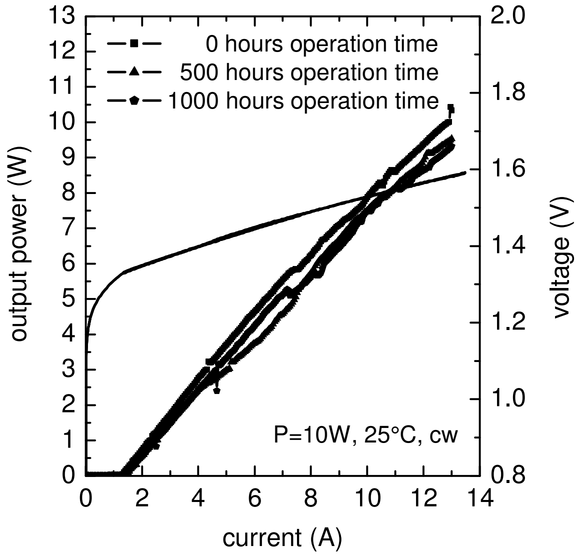
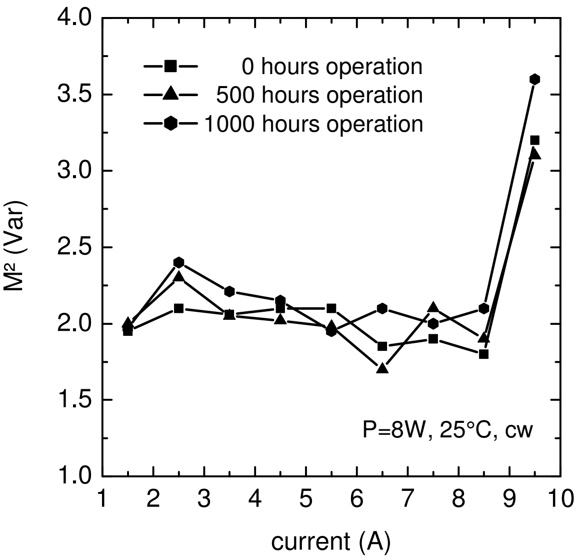


Figure 9: (a) Lifetime measurements of tapered lasers at 6A, 8A and 13A operation current and 25°C heat sink temperature. (b) On the right hand side P-I-curves of one tapered laser operated at 10W after different operation times.



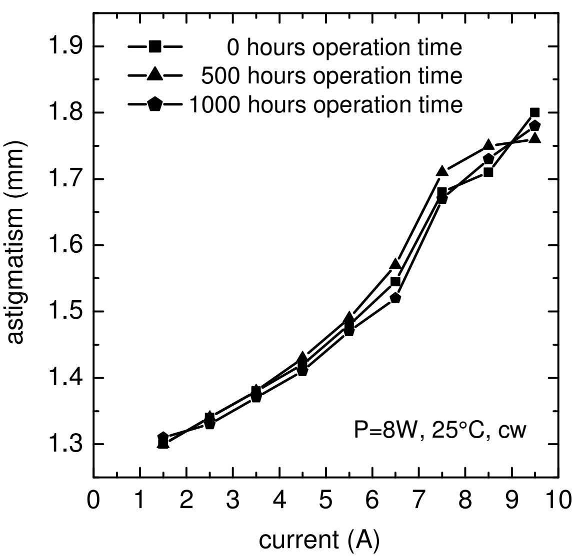


Figure 10: M^2 and astigmatism of a tapered laser operated at 8W in the lifetime test of figure 9a in dependence on operation current after different operation times.

4. Conclusion

Semiconductor laser diodes with a tapered gain region provide a beam quality near to the diffraction limit combined with high output power. They can be configured as lasers with a high-reflectivity coating on the rear facet and a high antireflection coating on the front facet. Additionally as amplifier with an antireflection coating on both facets they can be used in MOPA configuration together with a seed laser. Today amplifiers are commercially established with an optical output-power of 1-2W in a wide range of applications such as Raman spectroscopy or frequency doubling.

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5. ACKNOWLEDGEMENT

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