10 W high-efficiency high-brightness tapered diode lasers at 976 nm

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ABSTRACT

Tapered diode lasers combine high output power and a beam quality near to the diffraction limit resulting in very high brightness. Therefore, they are finding use in a wide range of applications today, such as pumping of rare-earth-doped fibre amplifiers, tunable frequency doubling of diode lasers for blue-green outputs, and non linear spectroscopy. Due to increasing brightness and lifetime tapered lasers even become attractive for material processing and for telecom applications like pumping of Er-doped fiber amplifiers or raman amplifiers.

In order to further enhance the brightness of tapered diode lasers the output power has to be increased while simultaneously the beam quality has to be kept near the diffraction limit. For this purpose we have grown low modal gain, single quantum well InGaAs/AlGaAs devices emitting at 976 nm by molecular beam epitaxy. The lateral design of the investigated laser diodes consists of a tapered section and a ridge-waveguide section. Since it has been shown by previous simulations and experiments that longer tapered sections allow higher output power with unchanged beam quality, we use tapered section lengths of 2000 µm, 3000 µm and 4000 µm. The beam quality parameter M^2 and output powers as well as the nearfields of the different structures were carefully investigated. For longer devices we reach an optical output power of more than 10 W per single emitter in continuous wave mode (cw) without any distinct thermal rollover.

Keywords: High Brightness, Beam Quality, High Power, Diode Laser, Tapered Laser, AlGaAs-InGaAs, Semiconductor

1. INTRODUCTION

Today, the most commonly used types of diode lasers are ridge lasers and broad-area lasers. High beam qualities are realized with ridge lasers emitting a nearly diffraction limited optical beam. The index-guiding of the optical wave in these devices results in just one lateral mode and an almost perfect gaussian shaped nearfield profile. Therefore, M^2 values of close to one are achieved. However, the reliable output power of ridge lasers is limited to some hundreds of milliwatts due to their small stripe width and the onset of facet degradation which depends on the power density on the facet[1]. On the other hand, high output powers of up to several watts are achieved with gain-guided broad area lasers. But these devices still suffer from modal instabilities, filamentations and catastrophic optical mirror damage (COMD) failure[2]. This results in low beam qualities and limited brightness.

The tapered laser design combines the advantages of an index-guided ridge section and a gain-guided tapered section allowing high output power in a single-lobed diffraction limited beam[3,4]. This leads to high values for the brightness of tapered diode lasers which is defined approximately by[3]

$$B = \frac{P}{\lambda_0^2 M^2} \tag{1}$$

where λ_0 is the vacuum wavelength and M^2 the beam propagation parameter. High brightness of 660 MW/cm^2 has already been achieved for a tapered laser emitting a diffraction limited output power of more than 8 W at a wavelength of 980 nm[5]. In order to compete with broad-area diode lasers and to further increase the brightness of tapered lasers even

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higher output powers are desirable while simultaneously the beam quality is kept at the diffraction limit. It has been shown previously that longer tapered section lengths lead to higher output powers[5] since the thermal dissipation energy of the tapered laser is reduced due to a larger area for cooling. Additionally, at a fixed tapered angle a longer resonator length leads to a broader facet allowing for higher output powers pushing the current at which COMD occurs to higher limits.

In this letter we present investigations of tapered diode lasers based on the InGaAs/AlGaAs material system with different tapered section length. For a single emitter device an optical output power well-above 15 W has been demonstrated.

2. FABRICATION OF TAPERED DEVICES

2.1 Epitaxial structure

The fabrication of high brightness lasers with high conversion efficiencies requires an epitaxial layer sequence with low internal losses ($< 2\ cm^{-1}$), low confinement factor (<1.5 %) and high internal conversion efficiency (> 90%). The reduction of the internal losses and of the confinement factor can be achieved by broadening the waveguide layers. 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 1.06 µm thick AlGaAs core region with 20% Al content. The use of high-band-gap ($E_g = 1.68$ eV) AlGaAs core layers with 20% of Al content leads to a strong carrier confinement. The quantum well is 7 nm thick with a nominal In content of 19% resulting in an emitting wavelength of 980 nm. The optical waveguide is formed by 1 µm thick AlGaAs claddings with 40% Al. Si and Be have been used for n- and p-type doping, respectively. The doping concentrations start at a level of $5 \times 10^{17}\ cm^{-3}$ near the core and increase to a level of $2 \times 10^{18}\ cm^{-3}$ in the outer cladding regions. The GaAs cap layer is heavily p-doped ($6 \times 10^{19} cm^{-3}$) in order to reduce the contact resistance. The layer design exhibits an overlap of the fundamental optical mode with the quantum well of 1.1% for 976 nm. It has been shown previously that this low modal gain epitaxial layer structure suppresses beam filamentation in tapered lasers[6].

For a pre-characterisation of internal parameters, Fabry-Perot laser diodes of different lengths (between 900 µm and 1500 µm) are fabricated and mounted on copper heat sinks by Indium solder. The p-side metal is deposited by using a shadow mask, and the n-side contact is applied to the unthinned substrate. After that, the resulting laser bars with as-cleaved facets are mounted p-side up on the heatsinks. The measurements of internal parameters are performed in pulsed mode (10 µs pulse width, 0.25% d.c.) at a heat sink temperature of 20 °C. The high material quality of the MBE-grown laser structures yields a high internal efficiency of more than 97% and low internal losses of less than $0.5\ cm^{-1}$.

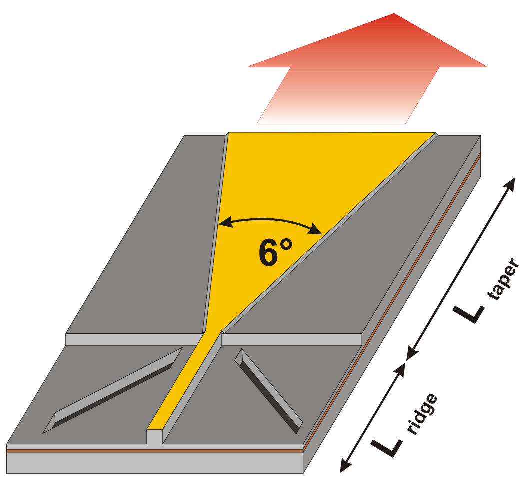

Fig. 1. Schematic of a gain guided tapered diode laser with a ridge waveguide for mode filtering. The length of the ridge section is 500 µm (1000 µm for the long tapered section), whereas the length of the taper section is 3000 µm. The taper angle is kept fixed at 6°.

2.2 Lateral Design

Tapered laser oscillators were fabricated from the above described epitaxial layer structures. The lateral design of the devices is depicted in figure 1. In principle, it consists of an index-guided ridge-waveguide section with the length L_{ridge} and a laterally tapered gain-guided section with the length L_{taper}. Additionally, cavity-spoiling grooves on both sides of the ridge are processed in order to suppress undesired Fabry-Perot-Modes that occur due to reflections from the front facet. In order to obtain different tapered laser designs with the same epitaxial structure a process mask was developed that contains three different tapered sections length of 2000 µm, 3000 µm and 4000 µm. The ridge section length is 500 µm for the first two designs and 1000 µm for the latter one. Therefore, 2.5 mm, 3.5 mm and 5.0 mm long tapered laser diodes are available from the same wafer. The taper angle is kept fixed at 6° for all devices leading to emitting apertures of about 210 µm, 315 µm and 420 µm for the different designs. The width of the ridge was chosen to 3.5 µm.

The processing of the lateral design is done by using inductively coupled plasma (ICP) etching followed by a lift-off step. This results in more defined ridge-structures as compared to those obtained by wet chemical treatment. The ridge height is chosen appropriately for the propagating wave to fill the taper angle. For optical lithography a stepper process is used that allows a well-defined adjustment of the different mask layers. After processing the wafers are thinned and chipped into single emitters. The facets of the devices are coated by reactive magnetron sputtering of Si with oxygen and nitrogen as reactive gases. For the use as a tapered laser oscillator the ridge side is covered with a highly-reflecting mirror coating consisting of two pairs of Si/SiO_2 layers (> 97 %) whereas the front facet is covered with an anti-reflection coating provided by a single layer of index-matched SiON (< 0.01 %). Finally the devices are mounted p-side down on copper mounts with indium solder. Uniform pumping of the laser medium is achieved by current injection via bond wires.

3. ELECTRO OPTICAL CHARACTERIZATION

In figure 2 the optical output power versus current characteristics are shown together with the diagrams of the respective wall plug efficiencies for tapered laser diodes with different tapered section lengths. All measurements were done at a heatsink temperature of 20°C and in continuous wave mode. It is obvious that the optical output powers of the devices increase with the length of the tapered section. For L_{taper}=2mm the output power reaches about 6 W at a driving current of 8 W before thermal rollover starts. The threshold current is I_{th}=0.59A and the slope efficiency is 0.883 W/A. By using a longer tapered section of 3mm the optical output power can almost be doubled to 12 W without any distinct thermal effect. However, the improvement of output power is accompanied by a remarkable increase of the threshold current to a value of I_{th}=1.026A which is counter-balanced by an increase of the slope efficiency to 0.914 W/A. The longest device with a tapered section length of 4mm and a ridge length of 1mm achieves an optical output power well-above 15 W. This is to our knowledge the highest reported value for a tapered single emitter device so far. Again, the longer tapered section and the improvement in optical output power leads to a further increase of the threshold current and slope efficiency that can be determined to 1.347A and 0.979 W/A, respectively.

The improvement in optical output power and slope efficiency goes along with an enhancement of the wall plug efficiency. The device with a tapered section length of 2 mm reaches a maximum wall plug efficiency of 48.1% at a driving current of 5.8 A. After exceeding this top value the efficiency falls rapidly to 43% at a current of 8A which is mainly due to thermal rollover. The device with a tapered section length of 3mm achieves a somewhat higher wall plug efficiency of 49.8% at 7.8 A. Remarkably, the wall plug efficiency shows a nearly constant plateau at this level from a driving current of about 6A up to 12 A before a distinct thermal rollover occurs. A similar behavior can be observed for the device with the longest tapered section of 4 mm. Here, the wall-plug efficiency reaches a top value of 52.8% at 8.9A and remains constantly above 50% from 5.5 A up to 14 A. Not till this quite high operation current a distinct thermal rollover is observed. The high wall plug efficiencies of devices with longer tapered sections and the fact that the efficiency remains constant over a wide range of driving current demonstrate that the heat dissipation is improved due to the larger area of the resonator which is accompanied by a larger area for cooling.

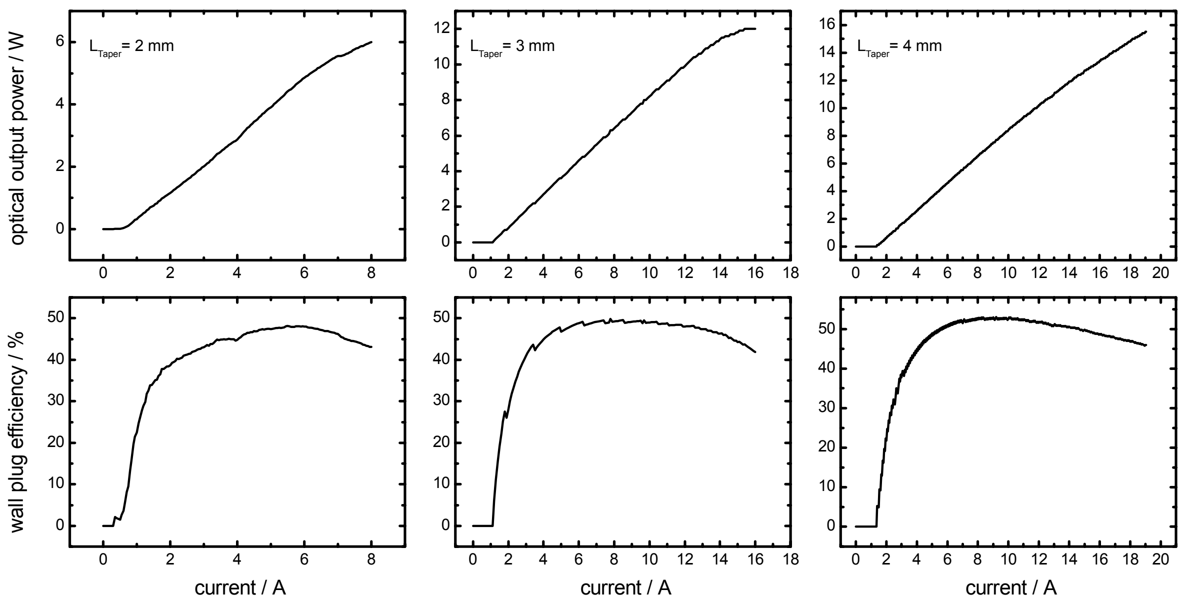

Fig. 2. Electro-optical characterization (top graphs) and wall plug efficiencies (bottom graphs) of tapered diode lasers with tapered section lengths of 2mm (left), 3mm (middle) and 4 mm (right). All measurements were done at a heatsink temperature of 20°C and in continuous wave mode. Please note the different scales of the diagrams. The steps in the diagram of the wall plug efficiency of the 3 mm taper length are due to limited resolution of the power measurement device.

With raising temperature in the optical active region the bandgap of the semiconducting material decreases. Therefore, the improvement in thermal management can be determined by measuring the wavelength as a function of the driving current. Measurements of this wavelength shift for different tapered section lengths have been done at a constant heatsink temperature of 20°C. The results are shown in figure 3. A current dependent wavelength shift of 1.57 nm/A for the 2 mm long tapered section and 1.30 nm/A for the 3 mm long tapered section has been deduced. For the 4 mm long tapered section the slope is only 0.57 nm/A. By assuming a wavelength shift of about 0.32 nm/K for the ternary semiconductor material InGaAs/AlGaAs[7] the respective thermal resistances can be calculated taking thermal power losses into account that are deduced from the respective current-power characteristics. By this method a thermal resistance of only 2.6 K/W is determined for the longest device with a tapered section length of 4 mm. This value is almost three times lower compared to a thermal resistance of 5.9 W/K for the shortest device with a tapered section length of 2 mm. However, it has to be noted that the longest device was mounted on a larger heatsink due to its comparatively huge overall length of 5 mm whereas the other emitters were mounted on standard c-mounts. Nevertheless, these measurements unambiguously confirm the improved heat dissipation for the longer tapered sections.

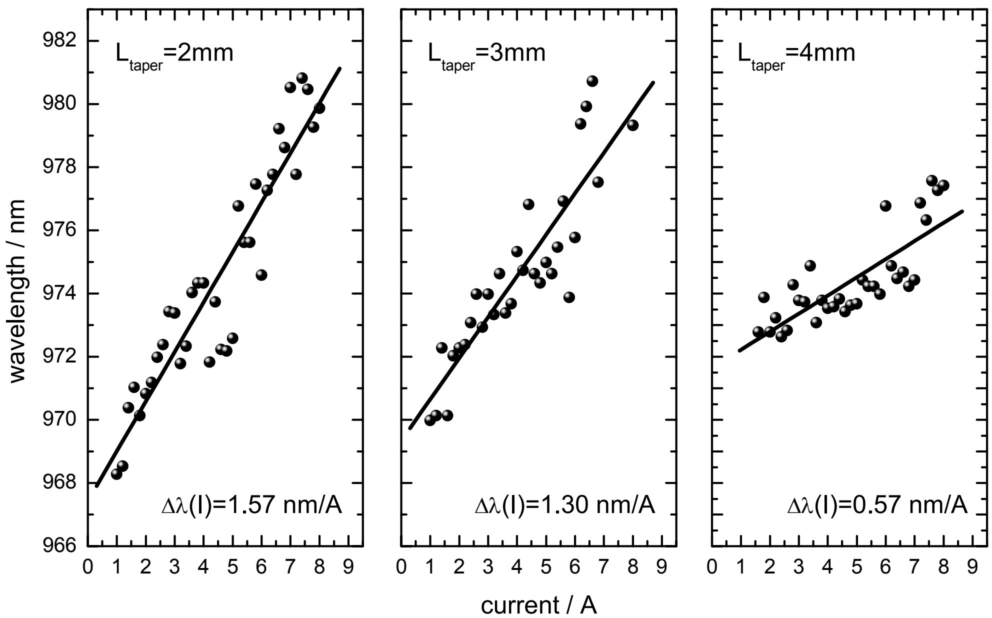

Fig. 3. Wavelength as a function of the driving current for different tapered section lengths. Due to an improved heat dissipation the slope decreases with increasing length of the tapered section. All measurements were done at a heatsink temperature of 20°C and in continuous wave mode.

4. NEARFIELDS AND BEAM QUALITY

In the last section we have demonstrated that longer tapered sections improve the heat dissipation leading to higher output powers and enhanced wall plug efficiencies. But as mentioned above the beam quality has to be kept constant or even has to be improved in order to increase the brightness. The main physical effect that limits device performance when high beam quality is required is beam filamentation. With increasing power level, spatial hole burning occurs due to the interaction between the amplified optical field and the carrier density in the active region. Therefore, the complex optical index becomes inhomogeneous and leads to self-focusing of the optical wave. For this it is instructive to look at the illumination patterns at the output facet, often called nearfield patterns. The structure observed in the near field shows the relative output density at the facet and is most closely related to the effects inside the tapered gain region that degrade the beam quality. In the following we have examined the lateral near fields and the beam quality of laser devices with different tapered section lengths.

In figure 4 a comparison of measured lateral nearfield profiles is shown for different tapered section lengths. The measurements have been performed using a commercial beam spot analyzer at a heatsink temperature of 20°C and in cw operation. As expected the lateral width of the nearfield profiles scales with the front facet width of the respective laser diodes. All nearfield profiles show more or less pronounced side lobes that presumably stem from a not optimal injection of the optical wave from the ridge into the tapered section. For longer tapered section length a distinct decrease of the relative filament height can be observed. The nearfield of the device with a tapered section length of 2 mm is dominated by a strong filament in the center of the facet. In contrast to this the longest device (L_{taper}= 4mm) exhibits only two comparatively small filaments but still shows the two distinct side lobes. However, the reduction of filaments in the nearfield profiles clearly indicates the improved heat flow for longer tapered section lengths.

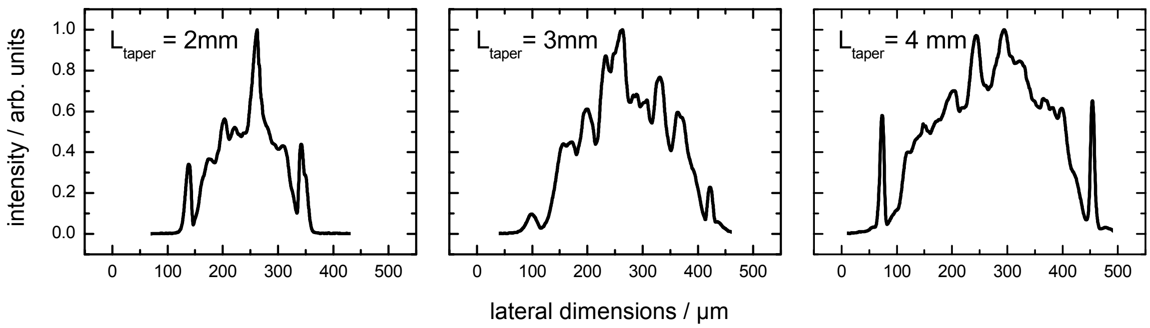

Fig. 4. Measured nearfield profiles for tapered diode lasers with tapered section lengths of 2 mm, 3 mm and 4 mm at an output power of 3W. The measurements have been performed at a heat sink temperature of 20°C in cw operation.

In order to characterize the beam quality of the tapered lasers, the beam propagation parameter M^2 was measured with a commercial beam scope. The beam quality parameter determined by a $1/e^2$-cut as a function of the optical output power for the different tapered section lengths is depicted in figure 5. All devices emit a nearly diffraction limited beam at low output powers with M^2-values well below 2. With increasing output power these values start to raise. Here, a steeper slope is observed for the laser diode with a tapered section length of 3 mm as for the diode with a tapered section length of 4 mm. Whereas the first device reaches an M^2-value of about 3.5 at an output power of 5.4 W the latter one remains almost constant at $M^2 = 2.3$ for comparable output powers.

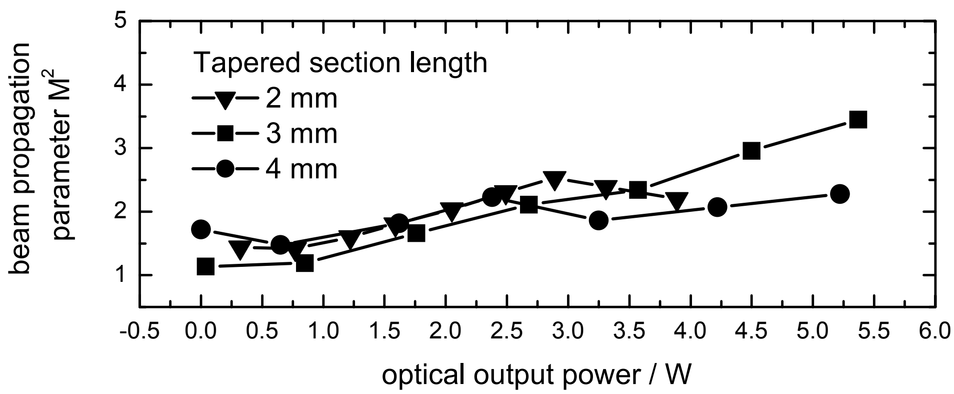

Fig. 5. Measured beam propagation parameter ($1/e^2$-cut) for tapered diode lasers with tapered section lengths of 2 mm, 3 mm and 4 mm in dependence of the output power. The measurements have been performed at a heat sink temperature of 20°C in cw operation.

5. ASTIGMATISM

At the output facet the curved wavefronts of tapered diode lasers diffract according to Snell's law. The beam is astigmatic, since in the direction perpendicular to the quantum well it diverges from the output facet, but in the plane of the quantum well it diverges from a virtual source point that is approximately L_{taper}/n_{eff} behind the front facet (n_{eff} is the effective refractive index of the epitaxial layer structure). Therefore, the length of the tapered section L_{taper} has a remarkable influence on the position of the virtual source.

For the measurement of the astigmatism, a lens is used to collimate the beam in the fast direction (the transverse direction perpendicular to the plane of the quantum well). Because of the astigmatism, the beam in this case is focused in the lateral plane, called corrected farfield. The distance between lens and corrected farfield provides a direct measure of the astigmatism using a simple lens equation and the known focal length f of the measurement lens. Similarly, the width of the waist is a measure of the width of the virtual image.

As mentioned above, the astigmatism of a tapered laser diode can roughly be approximated by dividing the tapered section length by the effective refractive index n_{eff}. For the used epitaxial structure n_{eff} yields to 3.41. Therefore, a distance between the virtual source point and the front facet of 580 µm, 880 µm and 1173 µm is expected for tapered section lengths of 2 mm, 3 mm and 4 mm. The measured astigmatism as a function of the optical output power for tapered diode lasers with respective tapered section lengths is depicted in figure 6. In each case the astigmatism starts for low output powers at the above predicted level. With increasing output power the virtual source point starts to move deeper inside the tapered section which is most likely due to a dependence of n_{eff} on the temperature. However, the three devices show a somewhat different behavior of their astigmatism with raising output power. The tapered laser diode with a tapered section length of 2 mm starts at a distance of about 540 µm between the front facet and the virtual source point. It raises quickly to a value of 610 µm at an output power of 3 W. Here, it appears to remain almost constant at this level. In comparison with that, the shift of the astigmatism of the 3mm tapered laser device is considerably larger. The virtual source point moves about 200 µm farther into the tapered section. Although the increase becomes slower with raising output power a plateau as for the device with the 2mm tapered section is not observed at this output powers. The astigmatism of the device with a tapered section length of 4 mm shows a shift from 1220 µm to 1290 µm up to output powers of 2 W. A further measurement of the astigmatism of this rather long device was not possible due to limitations of the experimental setup.

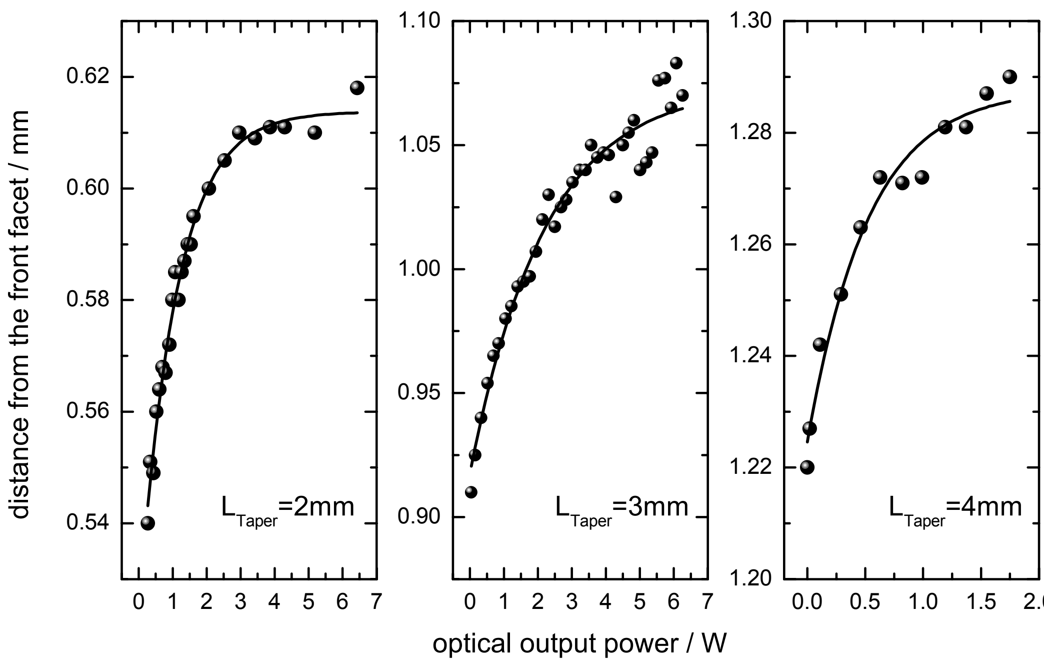

Fig. 6. Astigmatism of three tapered laser devices with different tapered section lengths. Please note the different scales of the diagram. All measurements were done at a heatsink temperature of 20 °C. The lines are to guide the eye. Due to limitations of the experimental setup the astigmatism of the 4 mm taper could not be determined for higher values.

6. CONCLUSION

In conclusion we have shown a comparison between tapered diode lasers with tapered section lengths of 2mm, 3mm and 4mm. The optical output power as well as the wall plug efficiency increases with the length of the taper. For the longest device with a tapered section length of 4mm an optical output power of almost 16 W was achieved. This is to our knowledge the highest output power for a single tapered diode laser reported so far. The increase of output power correlates with a decrease of thermal resistance that indicates an improved thermal management for longer tapered section. In addition to that an enhancement of the near field profiles and beam quality can be observed for longer devices.

7. ACKNOWLEDGEMENT

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