Invited Paper

# 8 W high-efficiency high-brightness tapered diode lasers at 976 nm

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## ABSTRACT

Today tapered diode lasers are mainly used in external resonator configuration for non-linear spectroscopy or frequency doubling for blue-green outputs. Now increased output power and brightness make tapered lasers even attractive for pumping of fibre amplifiers or lasers and fibre coupled modules.
We have realized high-power ridge-waveguide tapered diode lasers emitting at 976 nm. The high material quality of the MBE-grown laser structures yields a high internal efficiency of more than 97% and low internal losses of 0.5 $cm^{-1}$. Tapered single emitters consist of a ridge section with a length of 500 µm and a taper section with a length of 3000 µm. The taper angle was 6°.
A threshold current of 1.07 A corresponding to a threshold current density of 222 $A/cm^2$ has been obtained. The maximum slope efficiency of 1.09 W/A together with the low series resistance of 35 mΩ results in a high wall-plug efficiency of 58% at 5.5 W output power. This high wall-plug efficiency remains nearly constant up to operation currents of 9 A corresponding to output powers of more than 8 W. At an operation current of 15 A an output power of 12.5 W has been achieved, which is to our knowledge the highest output power in continuous wave mode for tapered diode lasers reported so far. At 8 W a nearly diffraction limited behavior with values for $M^2$ of less than 1.5 have been observed resulting in a brightness of more than 660 $MW/cm^2$.

**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 last year[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 section has been shown to be very effective to achieve high 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-Oszillator-Power-Amplifier) configurations or external cavity setups[4,5,6]. But the power requirement for these applications are only in the range of 1 W. 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.

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 8.3 W cw resulting in a brightness of more than 660 $MW/cm^2$.

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## 2. FABRICATION OF TAPERED DEVICES

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[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 1.06 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 976 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 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[9,10].

For a pre-characterisation 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 characterisation. 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 0.5 $cm^{-1}$ are obtained from Fabry-Perot laser diodes of different lengths.

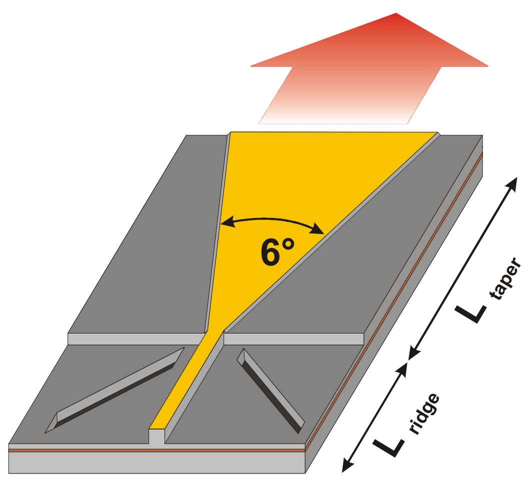


Figure 1: Schematic of a gain guided tapered diode lasers with a ridge waveguide for mode filtering. The length of the ridge section is 500 µm, whereas the length of the taper section is 3000 µm. The taper angle is 6°.

The ridge and taper sections are processed by using optical lithography 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 6° together with a taper section length of 3 mm. This leads to an emitting aperture of 317 µm width. The length of the ridge section is 500 µm resulting in a total device length of 3.5 mm. 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 thinning and cleaving 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. The front facet is coated with a single layer of SiON (< 0.01% reflectivity). 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 CHARACTERISATION

Figure 2 shows the current-power characteristic together with the wall-plug efficiency for a tapered diode laser with an overall resonator length of 3.5 mm. From a fit of the data between 2 A and 4 A a comparatively low threshold current of 1.07 A corresponding to a threshold current density of 222 A/cm$^2$ has been deduced. The inset of figure 2 indicates the non-linear behavior of the threshold region starting at 0.6 A due to the high antireflection coating of less than 0.01% of the device.

The maximum slope efficiency of 1.09 W/A together with the low series resistance of 35 mΩ results in a maximum wall-plug efficiency of 57%. This high wall-plug efficiency remains nearly constant between 6 A and 9 A corresponding to cw output powers between 5.5 W and 8.3 W. At a maximum operation current of 15 A an cw output power of 12.5 W has been obtained without COMD. A thermal rollover starts at quite high operation currents around 9 A demonstrating the good heat dissipation due to the large area of the resonator and the low power loss of the device. The values for the wall-plug efficiency and the output power are to our knowledge the highest values in continuous wave mode for tapered diode lasers reported so far.

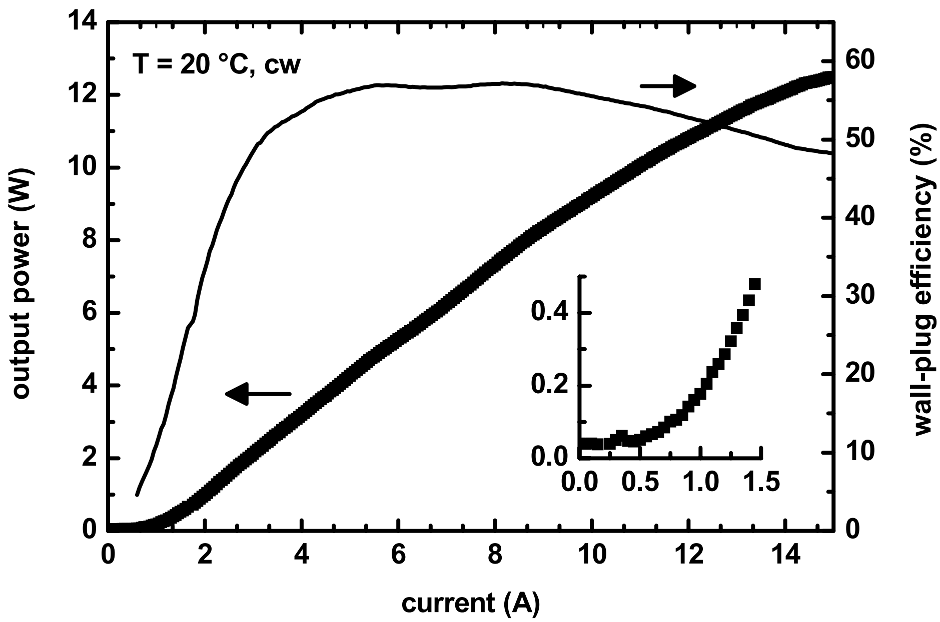


Figure 2: Current-power characteristic and wall-plug efficiency of a tapered diode laser with a taper section length of 3 mm and a ridge section length of 500 µm. The measurements have been done at a heat sink temperature of 20 °C and in continuous wave mode. The inset shows the threshold region of the current-power characteristic.

To identify the main advantages of longer taper section lengths we have compared the tapered laser with 3 mm taper section length with a tapered laser with 2 mm taper section length. The ridge section length was 500 µm for both lasers.

First the tapered diode lasers have been characterised in terms of thermal management. Figure 3 shows the dependence of the peak wavelength on the current for lasers with a taper section length of 2 mm (left hand side) and 3 mm (right hand side). The measurements have been done at a heat sink temperature of 20 °C in cw operation. A current dependent wavelength shift of 1.72 nm/A for lasers with 2 mm taper section length and 0.95 nm/A for lasers with 3 mm taper section length has been measured. From these measurements in combination with current-power characteristics a thermal resistance of 8 K/W has been deduced for tapered lasers with 2 mm taper section length. By using a taper section length of 3 mm the thermal resistance has been halved to 4 K/W, impressively demonstrating the better heat dissipation in the latter case.

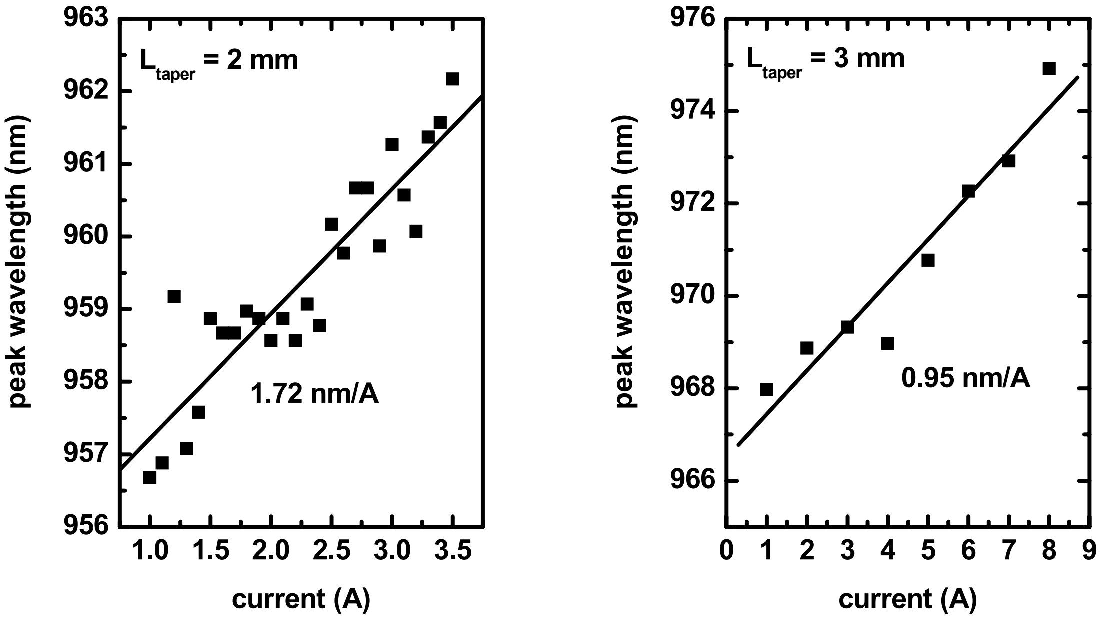


Figure 3: Peak wavelength of tapered diode lasers with a taper section length of 2 mm (left hand side) and 3 mm (right hand side) in dependence on the current. The ridge section was 500 µm long for both lasers. The measurements have been done at a heat sink temperature of 20 °C and in cw operation.

From the temperature dependence of the threshold current $T_0$ has been calculated. Whereas the laser with 3 mm taper section length achieves a remarkable high value of (185 ± 15) K for $T_0$, lasers with 2 mm taper section length show only values around 106 K.

Finally figure 4 demonstrate the differences between the current-power characteristics of both lasers:

- In pulsed mode (puls time: 50 µs, 50 Hz) the tapered laser with 2 mm taper section length shows a higher wall-plug efficiency and an output power of nearly 6 W instead of 5.5 W for a laser with a taper section length of 3 mm.

- The characteristics are reversed in cw operation. Here cw and pulsed characteristics are nearly the same for lasers with 3 mm taper section length, whereas for lasers with 2 mm taper section length, there is a huge reduction in wall-plug efficiency to 40% leading to a lowering of the output power of around 1 W at 6 A.

To understand the results of figure 4 we have simulated the output power in dependence on the taper section length for different thermal resistances (figure 5). Standard equations have been used for electro-optical and thermal calculations except the special losses of tapered diode lasers. In the case of a tapered diode laser the optical losses consist of the internal optical losses $\alpha_i$, the resonator losses $\alpha_R$ and additionally a geometrical part (as additional resonator losses) due to the tapered resonator design and are well described by[11]

$$\alpha_{opt} = \alpha_i + \alpha_R - \frac{1}{2(L_{ridge} + L_{taper})} \ln\left(\frac{W_{ridge}^{\;2} n_{eff}}{4\lambda L_{taper}}\right)$$

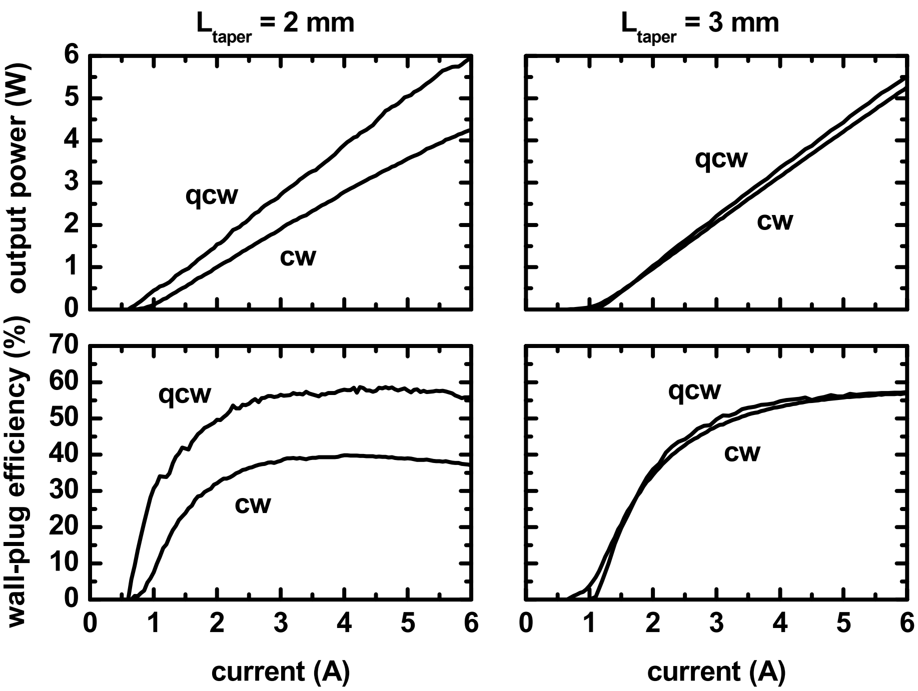


*Figure 4: Electro-optical characterization of tapered lasers with a taper section length of 2 mm (left hand side) and 3 mm (right hand side).The measurements have been done at a heat sink temperature of 20 °C in cw and qcw (pulse time: 50 µs, duty cycle: 10%) operation.*

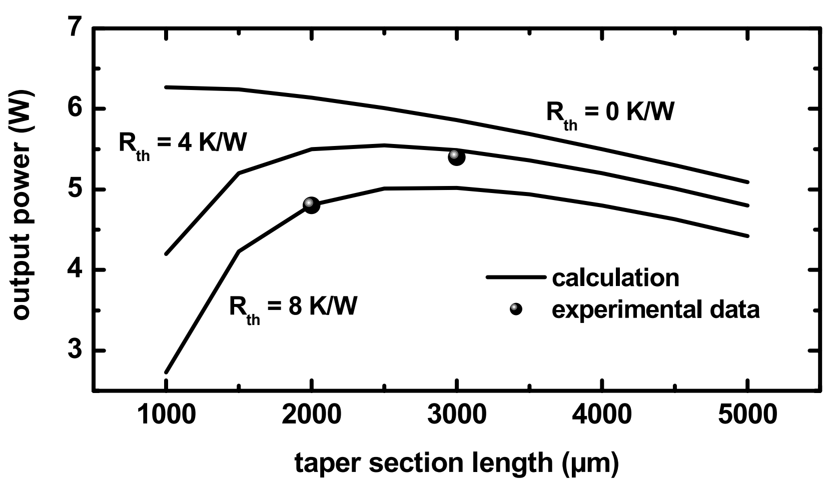


*Figure 5: Simulated (lines) and measured (bullets) values for the output power in dependence on the taper section length and on the thermal resistance. The simulations as well as the measurements have been done at a heat sink temperature of 20 °C and for a fixed operation current of 6 A.*

Following tendencies are visible within the calculations:

*a) without heat effects ($R_{th}$ = 0 K/W)*

In principle without heat effects a longer taper section length leads to lower output power (Figure 5, $R_{th}$ = 0 K/W), because with longer taper section lengths there is an increase in threshold current and a decrease in slope efficiency. So without heat effects (e.g. in pulsed mode) a shorter taper section length seems to be preferable.

*b) with heat effects ($R_{th}$ > 0 K/W)*

For cw operation heat plays an important role, so additional parameters like temperature dependence of the internal parameters, power losses or the thermal resistance should be taken into account for optimizing the output power.

The temperature dependence of the internal parameters can be described by characteristic temperatures and follows exponential laws. If you know the temperature dependence of the internal parameters, the temperature dependence of the threshold current and the slope efficiency of a tapered diode laser can be described by characteristic temperatures $T_0$ and $T_1$. $T_0$ as well as $T_1$ are also temperature dependent. But for simplicity we have calculated both characteristic temperatures for a fixed temperature (20 °C). In principle with longer taper section lengths $T_0$ increases and $T_1$ decreases.

Basically with longer taper section lengths there is a strong decrease in serial resistance, the wall-plug efficiency increases with a maximum value at a taper section length of 3.5 mm. This leads to lower power losses with a minimum value for taper section lengths between 3.5 mm and 4 mm.

All calculations in figure 5 have been made for a fixed injection current of 6 A. We have calculated the curves for three different thermal resistances: 0 K/W (equivalent to pulsed mode), 8 K/W and 4 K/W (both equivalent to cw operation, see figure 3). From these curves one can see, that for lower thermal resistances the optimal taper section length for highest output power decreases. But in fact as we have seen in figure 3, longer taper section lengths (including packaging effects) lead to much smaller thermal resistances. So for cw operation a taper section length between 3 mm and 3.5 mm seems to be the best choice for achieving the highest output power at a fixed injection current of 6 A.

## 4. BEAM QUALITY

In the last section we have demonstrated that longer tapered sections lead to higher output powers. But the brightness will be only increased, if the beam quality remains constant at these higher output powers, too. So the influence of longer tapered section lengths on the beam quality should be analysed.

In figure 6 there is a comparison shown between simulated and experimental nearfield profiles for two taper section lengths of 2 mm and 3 mm. The curves have been simulated and measured for an output power of 5 W. For the simulation as well as for the experiment there is a remarkable shrinking of the filament growth visible for longer tapered section lengths. This behaviour is in good accordance with the predictions presented in[11].

In figure 7 the beam propagation factors of both tapered devices have been compared. The measurements have been done at a heat sink temperature of 20 °C in CW mode with a commercial beam analyzer. The values of $M^2$ have been derived using two different methods: method (a) cuts the measured beam profiles at level $1/e^2$ and uses these widths for calculating $M^2$. Method (b) uses an integral calculation method taking into account side lobes with heights even below $1/e^2$. Normally method (b) leads to higher values of $M^2$.

As predicted in[11] the device with the longer taper section length shows a comparatively better beam quality. For method (a) nearly diffraction limited output powers of more than 8 W have been obtained for the longer taper section length. The value for $M^2$ is less than 1.4 resulting in a record value for the brightness of more than 660 MW/cm$^2$ at 8.3 W (figure 8). For a taper section length of 2 mm values for the brightness around 300 mW/cm$^2$ are achievable.

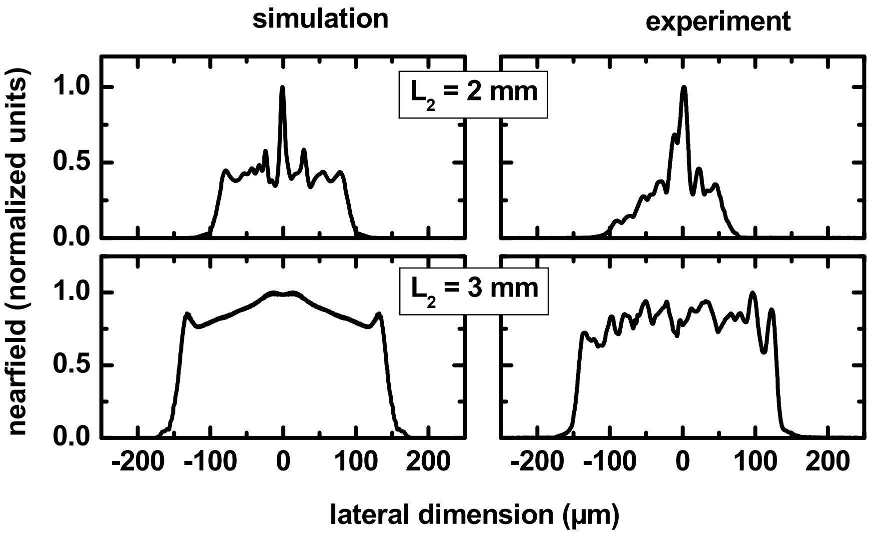


Figure 6: (left hand side) BPM simulations of nearfield profiles for tapered diode lasers with taper section lengths of 2 mm and 3 mm at an output power of 5 W. For the calculations an alpha-factor of 3 has been used. (right hand side) Measured nearfield profiles for tapered diode lasers with taper section lengths of 2 mm and 3 mm at an output power of 5 W. The measurements have been done at a heat sink temperature of 20 °C in cw operation.

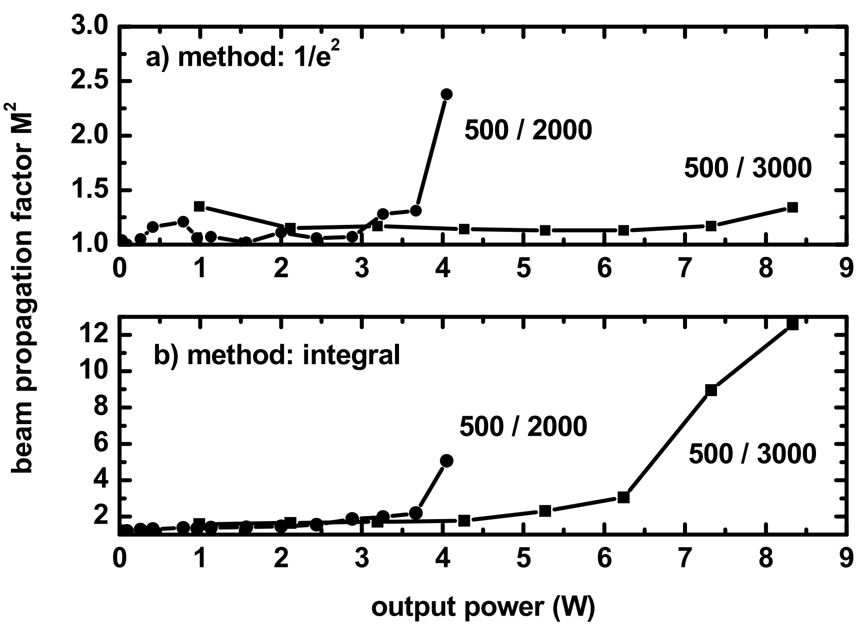


Figure 7: Beam propagation factor $M^2$ in dependence on output power for a tapered diode laser with a resonator length of 2.5 mm (squares) and 3.5 mm (dots). The measurements have been done at a heat sink temperature of 20 °C and in continuous wave mode with a commercial beam analyzer with method $1/e^2$ (a) and with an integral measurement method (b).

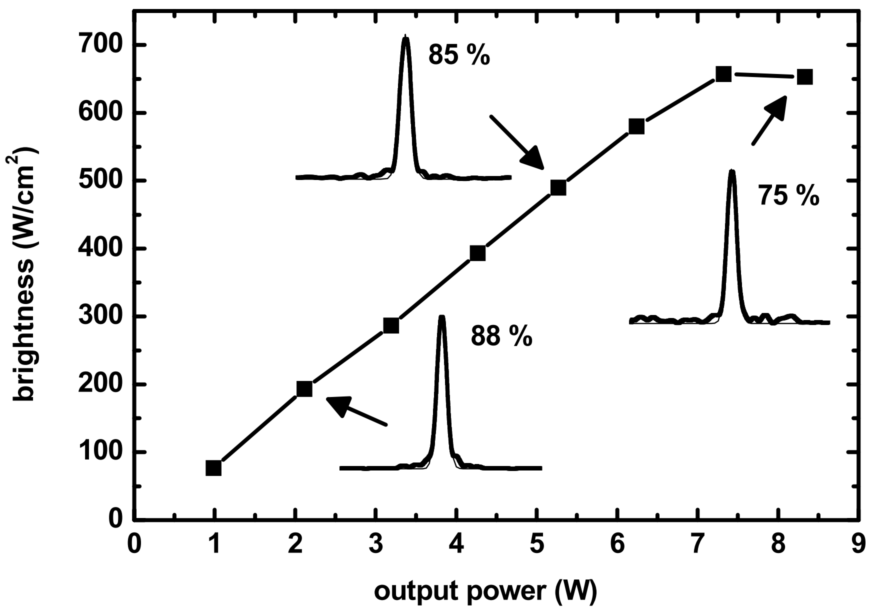


Figure 8: Brightness of a tapered laser with 3 mm taper section length in dependence on output power. The values are calculated from figures 2 and 7. In addition minimal beam waists are shown for 2 W, 5 W and 8.3 W. The percentage gives the fraction of output power in the central lobe of the beam waist.

Using the integral method for calculating $M^2$, nearly diffraction limited values of less than 1.8 have been observed up to output powers of 4.5 W for the tapered laser with 3 mm taper section length. The brightness is around 260 $MW/cm^2$ in comparison to 180 $MW/cm^2$ for a tapered diode laser with a taper section length of 2 mm.

Finally in figure 8 the brightness of the tapered laser with 3 mm taper section length is shown in dependence on the output power. Additionally at 2 W, 5 W and 8.3 W the measurements of the minimal beam waists are given as another quantity for beam quality. At 5 W 85% of the output power is within the central lobe of the beam waist, and still 75% at 8.3 W. So we have demonstrated a tapered laser with more than 6 W diffraction limited output power.

## 5. CONCLUSION

In conclusion we have shown a comparison between tapered lasers with 2 mm and 3 mm taper section lengths. Whereas shorter taper section lengths seems to be preferable for pulsed operations, tapered lasers with longer taper section lengths are particularly suitable for cw operation. The basis of their superiority is the larger chip area and the lower voltage leading to impressively good values for $T_0$ and the thermal resistance. This results in a wall-plug efficiency of 57% and a slope efficiency of nearly 1.1 W/A, which are to our knowledge the highest values in continuous wave mode for tapered diode lasers reported so far. Regarding the beam quality we have verified that tapered diode lasers with longer taper section lengths enable nearly diffraction limited output powers of more than 8 W resulting in a brightness of more than 660 $MW/cm^2$. We have demonstrated a diffraction limited output power of 6 W.

## 6. ACKNOWLEDGEMENT

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