Tapered Amplifiers for High-Power MOPA Setups between 750nm and 2000nm

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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 as well as amplifiers with an antireflection coating on both facets. In amplifier configuration, they can be used in external cavity or Master-Oscillator-Power-Amplifier configuration with the advantage of a narrow linewidth. Today amplifiers are commercially established with an optical output-power of 1-3W in a wide range of applications in quantum optics, metrology or spectroscopy. By extension of the resonator length up to 5mm combined with optimised processing and coating a new class of high-power tapered amplifiers at different wavelengths between 750nm and 1060nm for master-oscillator-power amplifier configurations of 4-5W output power will be presented. In addition, the tapered concept has been successfully transferred to InP and GaSb based material systems to address the eye-safe spectral range between 1500 and 2000nm. Nearly diffraction limited tapered amplifiers and lasers will be demonstrated in the 1W power range for 1530nm, 1550nm and 1930nm.

Keywords: diode laser, high-brightness, high-power, tapered laser, tapered amplifier, semiconductor, eye-safe

1. INTRODUCTION

The brightness of a diode laser is a measurement for the power per area and solid angle and defined by:

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

M^2 defines the beam quality in both propagation directions of the emitting laser beam. 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 called filaments.

The resonator design mostly used today is the broad-area laser design, which allows to control the optical output power P by the lateral width $w_{lateral}$ of the stripe. But the brightness of such broad-area lasers is limited by heat dissipation ($\theta_{lateral}$) and facet coating technology. The use of tapered designs allows to avoid these limitations [1-3]. This design consists of two sections monolithically integrated on one chip. The so-called ridge-waveguide section acts as a mono-mode diode laser used as a pump source for the second section. In the following tapered section, the active width enlarges from the typically 3-4µm stripe width of the ridge section towards an output facet width of several 100µm, depending on the chosen taper section length and the 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).

Based on 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 at least 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. The facet coating technology will not be the limiting factor any longer as for the broad-area lasers [4].

To combine the advantages of high-brightness tapered laser diodes with narrow linewidth and excellent tunability the tapered lasers can be used as tapered amplifiers with AR coatings on both facets within a Master-Oscillator-Power-Amplifier (MOPA) setup. This configuration consists of a seed laser, an optical isolator between seed laser and tapered amplifier to avoid back-reflections, 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%.

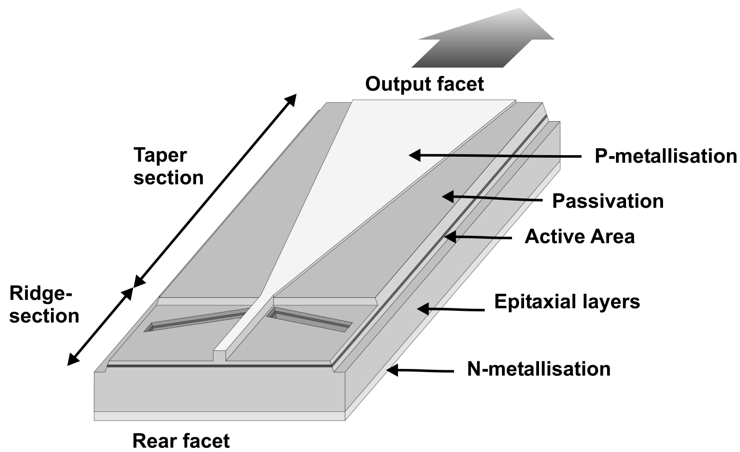

Figure 1: Schematic of a gain-guided tapered amplifier with a ridge-waveguide section for mode filtering.

Tapered lasers and amplifiers are today the key components of many commercial and scientific applications. Nearly diffraction limited systems of up to 3W are already commercially available, but for example for frequency doubling also high output power in the power range of 4-5W and more is a demand. In this letter, we will discuss boundary conditions for tapered amplifiers in this high-power regime.

The tapered concept is universal and can be also transferred to other material systems. Applications like LIDAR requires high-brightness laser concepts in the eye-safe spectral range. As an outlook of this letter we will represent results for the transfer of the tapered concept to the (InGaAs)(InP) material system for 1530nm and 1550nm and the (AlGaIn)(AsSb) material system for 1940nm.

2. FABRICATION OF TAPERED AMPLIFIERS

Different single quantum well GaAsP/AlGaAs/GaAs (λ<850nm) and InGaAs/AlGaAs/GaAs (λ>850nm) laser structures with reduced far fields of 45-50° and optimized layer designs for resonator lengths of 4-5mm were grown by molecular beam epitaxy (MBE) between 750nm and 1060nm. Whereas the laser structure for 980nm has been already optimised for 5mm resonator lengths, the laser structures for all other GaAs based wavelengths investigated in this letter (785nm, 850nm, 890nm, 920nm, 1010nm) are still optimised for 4mm resonator lengths. 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.

For the tapered amplifiers, the ridge-waveguide and taper sections are processed by optical contact lithography and a mixture of dry and wet chemical etching. P-Metal structuring was done by lift-off. Figure 1 shows a schematic of the device. The taper angle was 4 degrees for the GaAs based wavelengths. The ridge section length is 700µm. The ridge width depends on the wavelength and is between 3-4µm. 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. For the taper section length, we have chosen either 3,6mm or 4,3mm, resulting in overall resonator lengths of 4,3mm or 5,0mm.

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 resulting in <0.005% reflectivity. In standard configuration, the devices were mounted p-side down on CuW submounts with AuSn solder. Alternatively, AlN submounts can be used. The submounts were mounted on standard C-mounts or home-designed DHP-mounts (figure 2). Finally, uniform pumping of the laser medium is achieved by current injection via bond wires.

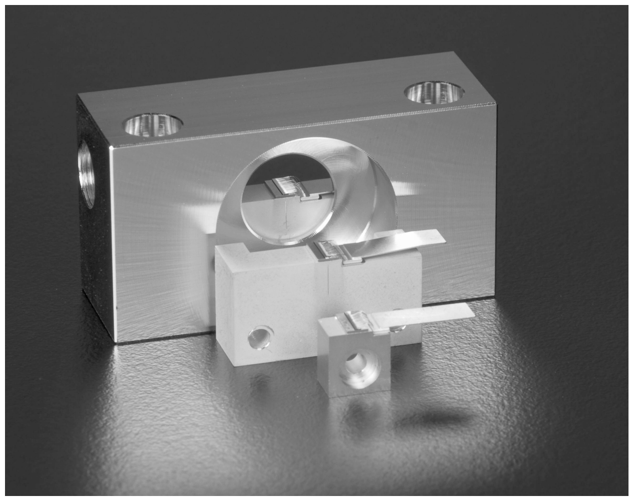

Figure 2: Tapered amplifiers mounted on different heat sink types: c-mount, DHP-inset and DHP-frame.

The eye-safe spectral range can be covered by InGaAs/InP based structures between 14xx nm and 18xx nm and by GaInSb/AlGaAsSb/GaSb structures for the wavelength range beyond 18xx. For demonstration in this letter, we have used laser structures for the common wavelengths 1530nm, 1550nm and 1930nm. The InP based laser structures were grown by MOCVD by an outside vendor, the GaSb based laser structures have been grown by MBE [5-7]. For both material systems, due to much higher internal losses compared to GaAs based structures, we have chosen a ridge section length of 500µm and a taper section length of 2000µm resulting in an overall resonator length of 2,5mm. We have taken a taper angle of 6° to optimize the heat dissipation. Etching depths and ridge section widths have been carefully adapted to the different material systems. Processing and coating can be done as described before, except different chemicals for P-based semiconductor layers. For 1530nm and 1550nm with SiON we received very low antireflection coatings of less than 0,005% comparable to GaAs based tapered amplifiers. For GaInSb/AlGaAsSb/GaSb structures we have achieved only a value of 1% with SiON. Therefore, we decided to build a tapered laser instead of a tapered amplifier for this report. The lowering of the antireflection coating towards 0,005% is under investigation. Except the diodes in figure 5 in the next section, all diodes have been packaged by AuSn solder on CuW submounts and the submounts by Indium solder on C-mounts.

3. EXPERIMENTAL RESULTS FOR GAAS BASED TAPERED AMPLIFIERS

To enter higher power levels for tapered amplifiers, following aspects have to be taken into account:

- Choose the proper resonator length for the aimed operation current in terms of highest wall plug efficiency and highest output power, which improves in addition the beam quality by better thermal management.
- Since the results for tapered amplifiers can differ from MOPA setup to setup due to the used components (e.g. lenses, isolators etc.), the output power at the aimed operation current should be at least 10% above the proposed output power.

- The tapered amplifiers will be used not only in different MOPA configurations but also in different operation modes which are maybe in need for different packagings like different submounts. The performance of the tapered amplifiers should be as independent as possible from different packages, especially the influence of the packaging stress on the beam quality must be carefully investigated.
- Not only the output power will define the tapered amplifier, but also the beam quality at a given power level. The requirements in beam quality can differ from application to application, so it could be that for some application a value of 2 for M^2 is fine, for some application, the value must be even below 1,5. Experience shows that especially the side patterns of the minimum beam waist give some hints about the usability of the tapered amplifiers at a certain power level.

3.1 Resonator length of 5.0mm

It has been proven that the beam quality for tapered lasers is mainly limited by thermal heating [4,8]. For tapered amplifiers, this effect is even stronger since the need for access to both facets in the MOPA setup for the amplifiers limits the contact area in packaging for heat dissipation. In general, a longer resonator length helps for better heat dissipation, but the drawback is a higher threshold current. We have tested the resonator lengths 4,3mm and 5,0mm for all wavelengths and have compared the results at 6A, which is the target operation current for 4-5W. Table 1 and figure 3 show as examples results for tapered amplifiers at 850nm and 980nm, both fabricated with 4,3mm and 5,0mm resonator length. At 850nm the 4,3mm chip outperforms with 4,9W the 5,0mm chip by 500mW resulting in an improved wall-plug efficiency of 48%. For the 4,3mm long chip at 980nm, a thermal rollover starts at 5,5A, visible by the peak efficiency at this operation current. The output power of the 5,0mm long chip exceeds the power level of the 4,3mm long chip by 500mW at 6A, resulting in 5,2W and nearly 58% wall-plug efficiency. As a result, the decision whether 4,3mm or 5,0mm would be preferable, depends on the wavelength and epitaxial design and cannot be answered in general.

Type	**Resonator length [mm]**	**Output power @ 6A [W]**	**Efficiency @ 6A [%]**	**Efficiency max. [%]**	**Operation current for η_{max} [A]**
TA 850	4,3	4,9	48,0	>48,0	>6
TA 850	5.0	4,4	45,6	>45,6	>6
TA 980	4,3	4,7	52,3	53,6	5,5
TA 980	5,0	5,2	57,7	>57,7	>6

Table 1: Comparison of electro-optical results for tapered amplifiers at 850nm and 980nm with 4,3mm and 5,0mm long resonators.

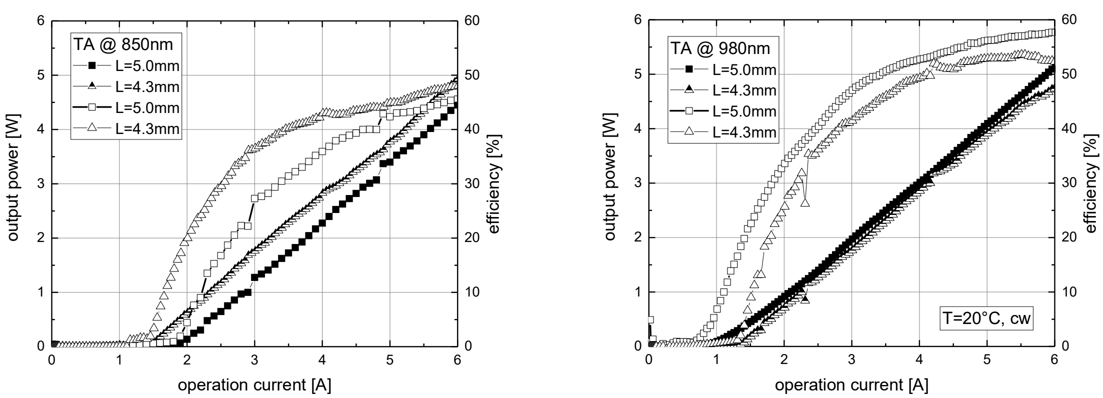

Figure 3: Output power-vs.-current characteristics and current dependent wall-plug efficiencies for tapered amplifiers at 850nm and 980nm with 4,3mm and 5,0mm long resonators. All measurements have been carried out at 20°C in continuous wave mode at a heat sink temperature of 20°C.

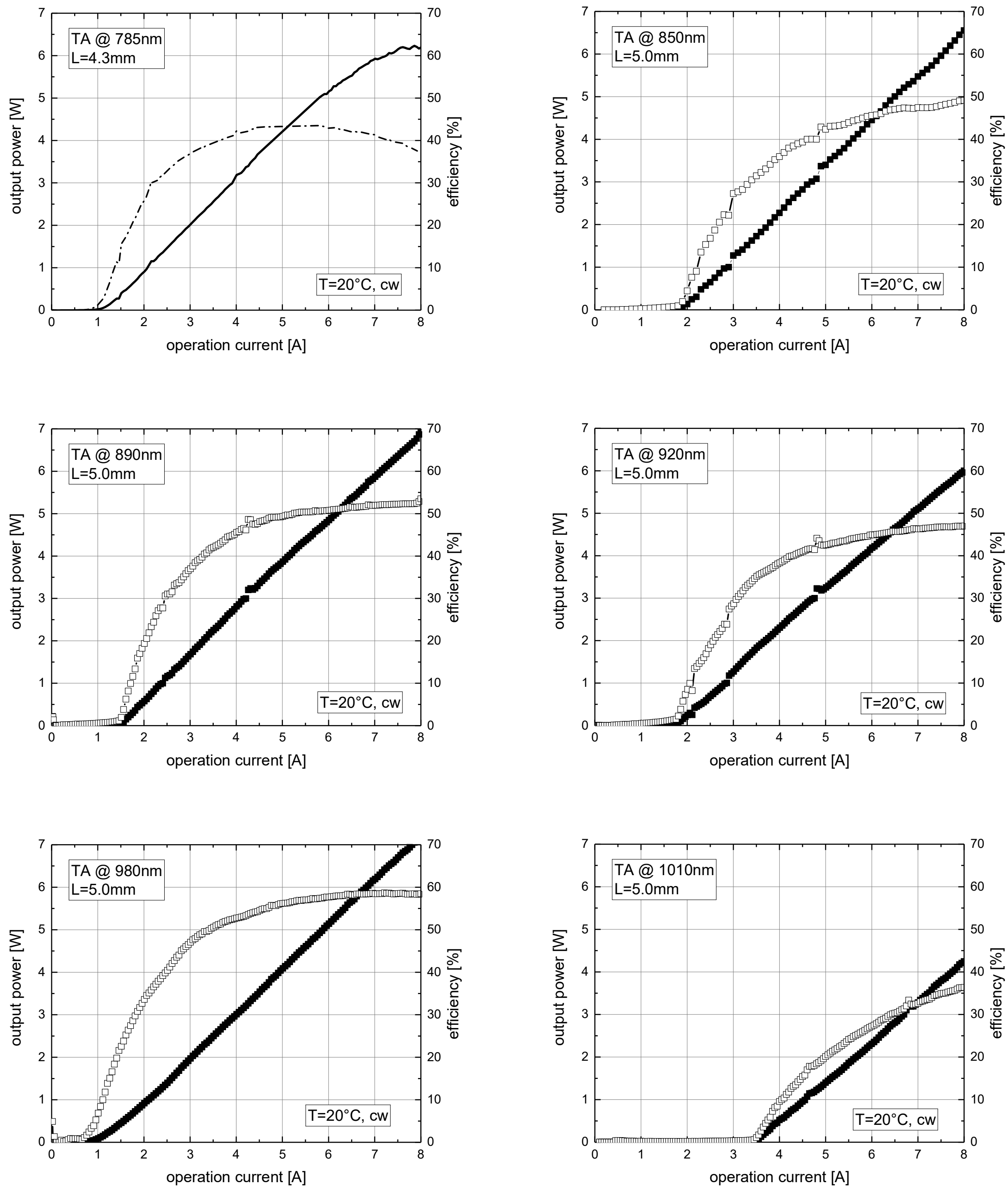

Figure 4: P-I-U curves of different tapered amplifiers with 5,0mm resonator length up to 8A at 20°C heat sink temperature. All tapered amplifiers have been mounted on DHP mount with CuW submounts.

We have fabricated 5,0mm long tapered amplifiers at different wavelengths: 850nm, 890nm, 920nm, 980nm and 1010nm (figure 4, table 2). For comparison, we have also added a tapered amplifier at 785nm with 4,3mm, which is a kind of standard. Except the TA-980, due to the longer resonator length with 5,0mm, all tapered amplifiers show a 50%

higher threshold current compared to amplifiers with 4,3mm resonator length. The TA-980 is an exception, since we have designed in this case a new laser structure especially for 5,0mm resonator length. The output power is between 6W and 7,2W at 8A, resulting in wall-plug efficiencies between 47% and a record value of nearly 59% for the TA-980. The TA-1010 shows a nearly doubled threshold current compared to the other tapered amplifiers which results in only 4.2W output power at 8A. Since slope efficiency for the TA-1010 is in a comparable magnitude like for the other amplifiers, the higher threshold current is most likely based on the chosen ridge design. This is under investigation.

Type	Resonator length [mm]	Output power @8A [W]	Efficiency @8A [%]	Threshold current [A]	s.e. [W/A]
TA 785	4,30	6,19	37,1	1,2	1,13
TA 850	5,02	6,55	49,1	1,7	1,07
TA 890	5,02	6,99	53,5	1,4	1,06
TA 920	5,02	6,01	47,0	1,7	0,97
TA 980	5,02	7,20	58,5	0,8	1,06
TA 1010	5,02	4,24	36,4	3,5	0,94

Table 2: Comparison of electro-optical results for tapered amplifiers between 850nm and 1010nm with 5,0mm long resonators. For comparison reason, a tapered amplifier at 785nm with 4,3nm has been added. All measurements have been performed at 20°C heat sink temperature in continuous wave mode.

3.2 Influence of sub-mount type

Beside thermal effects, the beam quality of the tapered amplifiers will be influenced by stress either induced by processing (mainly metallisation) or by packaging (AuSn soldering and submounts). Typically for tapered amplifiers mounted on copper heat sinks like c-mounts, CuW submounts will be used. But for many applications, especially in pulsed mode, AlN submounts are preferable. We have developed soldering processes for both types of submounts resulting in a comparable behaviour of the tapered amplifiers. Figure 5 shows the same type of tapered amplifier at 850nm with 4,3mm resonator length, but mounted by AuSn soldering on different types of submounts. Output power as well as wall-plug efficiency are comparatively identical within the usual fluctuation between different packaging charges. By a commercial BeamScope system, comparable nearly diffraction limited beam quality parameters M^2 have been measured for both packaging types at an output power of 3W.

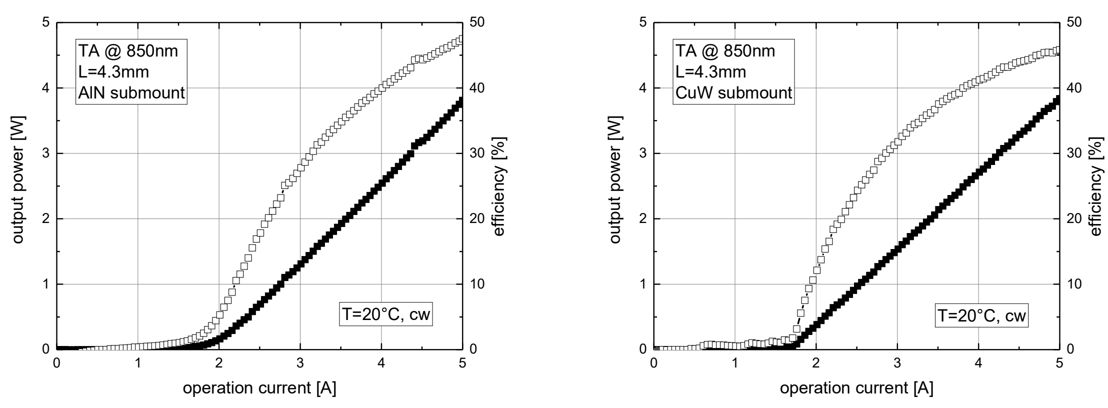

Figure 5: Output power-vs.-current characteristics and current dependent wall-plug efficiencies for tapered amplifiers at 850nm with 4,3mm resonator length and AlN (left-hand-side) or CuW (right-hand-side) submounts. All measurements have been carried out at 20°C in continuous wave mode at a heat sink temperature of 20°C.

3.3 Beam quality parameter M^2 at higher power levels

Figure 6 illustrates the dependence of the beam profiles at the output facet (near field) and at the minimal beam waist on the output power for a tapered amplifier at 980nm with 5,0mm resonator length. 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 new filaments or other disturbances occur at the near field structures. With increasing output power, the filament structure gets more pronounced, but the principal filament structure has been already defined at the lowest power level. The minimal beam waists are Gaussian like up to 8W in the central lobe, but the patterns on the left or right-hand side of the central profile starts to grow with higher power levels. The central lobe defines the percentage of output power which can be e.g. coupled into a single-mode fiber, whereas the percentage of power, defined by the side-patterns, defines the deviation from single-mode behaviour. From these pictures it is clear, that for this tapered amplifier, the M^2 in 2. moment and $1/e^2$ definition should be at least equally spaced for lower power levels, but for higher power levels it strongly depends on the individual pattern of each tapered amplifier.

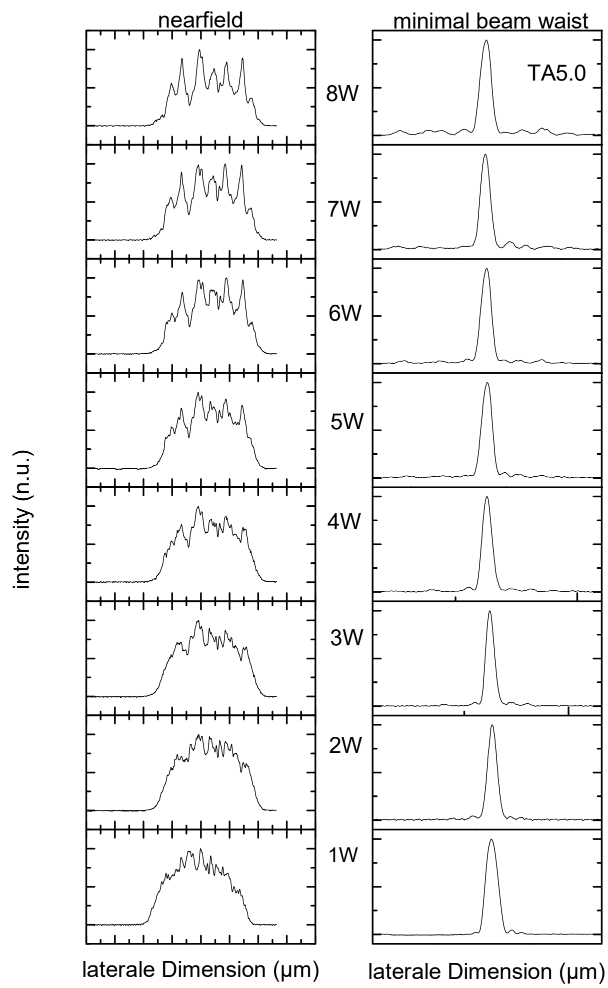

Figure 6: Beam profiles of a 5,0mm long tapered amplifier in MOPA configuration at the front facet (near field) and at the minimal beam waist in dependence on different output powers.

This behaviour can be seen in figure 7: here on the left-hand side 11 tapered amplifiers at 850nm with 5.0mm resonator length have been investigated at 4W. For applications like frequency doubling at least a M^2 value of 2 in 1/e2 definition is needed. 7 out of 11 devices have M^2 values in 1/e2 definition below 2 at 4W, 4 devices are not in specification due to large filaments, inhomogeneities in the soldering or any other reasons. But the main point is that for all devices the M^2 values defined by 1/e2 or by 2. momentum are equidistant, which demonstrates that the side-patterns of the minimal beam waists were not very distinctive. In contrast on the right-hand side of figure 7, we see the beam quality parameter M^2 for tapered amplifiers at 980nm at 6W. 14 out of 20 devices show M^2 values below 2, but the distances between the values in 1/e2 and 2. momentum definition differs strongly from device to device.

Figure 8 shows a "hero" result for a tapered amplifier at 980nm with 5,0mm resonator length. To eliminate thermal effects and thereby to improve the beam quality, we have mounted the tapered amplifier on a CVD diamond as a sub-mount. Within this configuration we could achieve M^2 values below 2 in 1/e2 definition and below 2.5 in 2. momentum definition even at 8W at an operation current of 9A.

In summary, we have shown, that tapered amplifiers can be operated at 4-5W in a wide spectral range between 785nm and 1010nm. At 4W power level we see a reasonable yield for the beam quality parameter M^2 in 1/e2 as well as 2. Momentum definition. For higher power levels like 6W, yield strongly depends on the side-pattern and the needs in beam quality for the individual application.

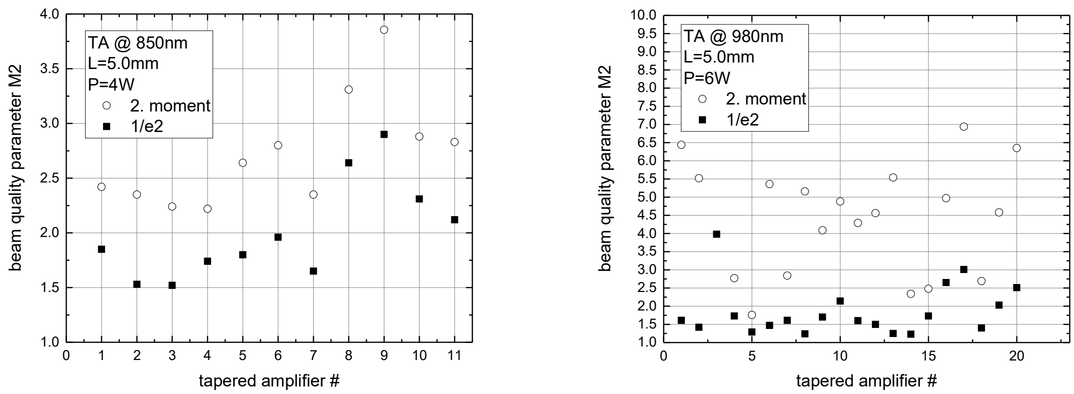

Figure 7: Beam quality parameter M2 for a certain statistic of tapered amplifiers at 850nm at 4W (left-hand-side) and tapered amplifiers at 980nm at 6W (right-hand-side).

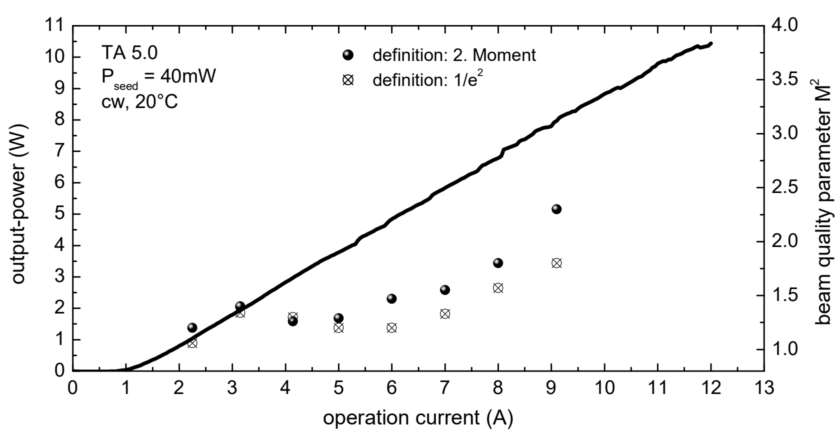

Figure 8: Output power-vs.-current characteristic and beam quality parameter M2 for a tapered amplifier at 980nm with 5mm resonator length. The tapered amplifier has been mounted on CVD-diamond used as sub-mount. All measurements have been carried out at 20°C in continuous wave mode at a heat sink temperature of 20°C

4. EXPERIMENTAL RESULTS FOR TAPERED AMPLIFIERS IN THE EYE-SAFE SPECTRAL RANGE

In this section we want to demonstrate, that the tapered laser concept can be also transferred to other material systems, especially in the longer wavelength regime between 1500nm and 2000nm. This eye-safe spectral region gains high interest due to LIDAR applications for range finding and self-driving cars. Both application areas require high power levels combined with high beam quality.

The devices have been fabricated according to section 2. The tapered amplifiers at 1530nm and 1550nm have been characterised within an external cavity configuration due to the lack of master lasers at these wavelengths. The tapered laser at 1940nm could be characterized stand-alone.

In Fig. 9 the output power and wall-plug efficiency versus operation current characteristics measured at a heat sink temperature of 10°C are shown for the tapered amplifiers at 1530nm and 1550nm. Comparable high peak efficiencies of 23,5% at 1530nm and 24,1% at 1550nm have been achieved. At 6A, power levels of 1,61W at 1530nm and even 1,81W at 1550nm demonstrate the power performance of these chips. The threshold current of around 1A for both wavelengths is comparable to the threshold current of 2.5mm long tapered amplifiers in the GaAs wavelength regime [9].

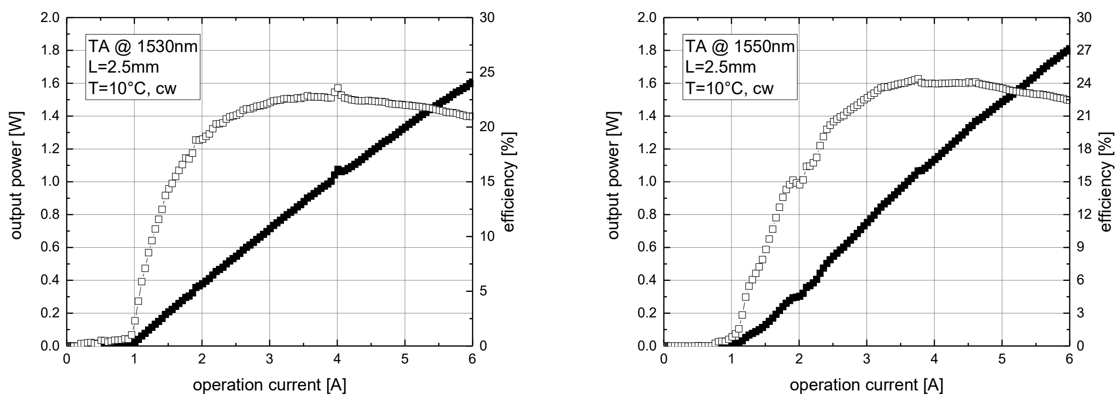

Figure 9. CW output power and wall-plug efficiency vs. operation current characteristics for tapered amplifiers in external cavity setups at 1530nm and 1550nm. All measurements have been done at 10°C heat sink temperature in continuous wave operation.

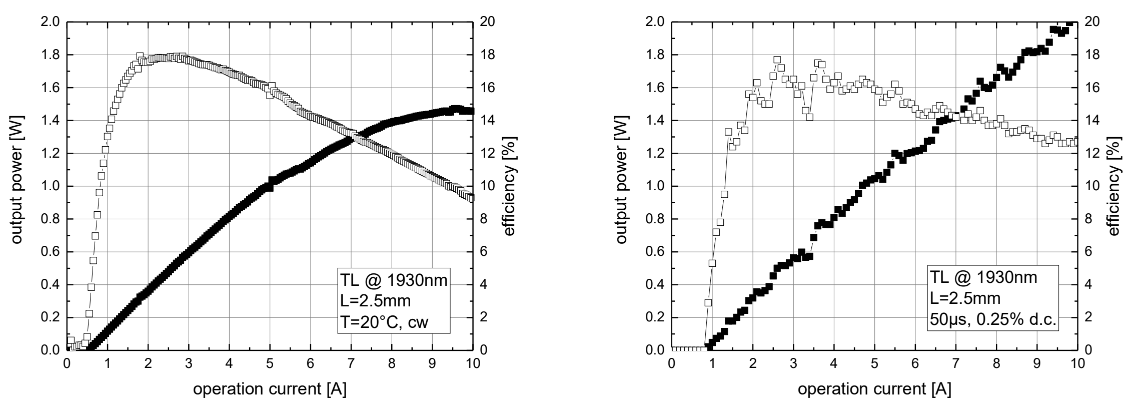

Figure 10. Comparison of output power versus operation current in pulsed (right hand side) and continuous wave operation (left hand side) for tapered lasers at 1930nm. All measurements have been done at 20°C heat sink temperature.

In Fig. 10a, the CW output power versus operation current characteristic recorded at a heat sink temperature of 20°C, is shown together with the corresponding power conversion efficiency. The threshold current is 0.6 A and the initial slope efficiency amounts to 0.25 W/A, leading to a differential quantum efficiency of 39%. The maximum output power equals 1.54 W at a current of 9 A, which is more than twice the value reported [10] and is even comparable to best-of values reached for BA lasers so far [11]. The maximum power conversion efficiency approaches 17,9% at 2.5 A. The power is limited by thermal rollover due to the short resonator length. Therefore, for demonstration we performed pulsed measurements with 10µs pulses at 250-Hz repetition rate (0.25% dc) (Fig. 10b). Under these conditions, a peak power of 2W is reached at 10 A. Table 3 summarizes the main electro-optical results for all three wavelengths, for comparison reasons at 6A.

The beam quality parameter was measured according to ISO 11146 with a commercial beam profile analyser and has been calculated with the common cut method. In the power range up to 1W, the tapered amplifiers at 15xx nm as well as the tapered laser at 1930nm show a nearly diffraction-limited behaviour corresponding to values well below 1.7.

Type	Operation temperature [°C]	Resonator length [mm]	Output power @ 6A [W]	Efficiency @6A [%]	s.e. [W/A]	Threshold current [A]	Peak efficiency [%]
TA 1530	10	2,5	1,61	21,0	0,35	0,93	23,5
TA 1550	10	2,5	1,81	22,4	0,39	1,08	24,1
TL 1930	20	2,5	1,14	14,3	0,17	0,41	17,9

Table 3: Summary of main electro-optical characteristics for tapered amplifiers at 1530nm and 1550nm and for tapered lasers at 1930nm. The measurements have been performed at 20°C heat sink temperature in continuous wave operation.

4. CONCLUSION

We have presented InGaAs/AlGaAs/GaAs based tapered amplifiers between 785nm and 1010nm suitable for 4-5W output power in MOPA configuration. At 4W power level we see a reasonable yield for the beam quality parameter M^2 in 1/e2 as well as 2. momentum definition. For higher power levels, yield strongly depends on the side-pattern and the needs for the individual application. In addition, the tapered concept has been successfully transferred to InP and GaSb based material systems to address also the eye-safe spectral range between 1500 and 2000nm. Nearly diffraction limited tapered amplifiers and lasers could be demonstrated in the 1W power range for 1530nm, 1550nm and 1940nm.

5. ACKNOWLEDGMENT

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