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808 nm tapered diode lasers optimised for high output power and nearly diffraction-limited beam quality in pulse mode operation

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ABSTRACT

808 nm tapered lasers have been investigated under current pulsing conditions without thermal load. The pulse length was 100 ns. The lasers are based on a super-large optical cavity structure with a very small vertical divergence angle of 18° (FWHM). The output power, beam quality and spectral behavior of the lasers were measured. Resonator geometries with different ridge waveguide lengths and taper angles were used for the optimisation of output power and beam quality. As a result, 27 W output power has been achieved. Nearly diffraction-limited beam quality up to 9 W has been obtained with an optimised lateral geometry. At even higher power, spectral broadening and beam quality degradation of the lasers were observed.

Keywords: Semiconductor laser, tapered diode laser, pulsed laser, beam quality, high brightness

1. INTRODUCTION

High power diffraction-limited beams are needed for numerous applications such as telecommunication, medical treatment, material processing and nonlinear frequency conversion. For nonlinear frequency conversion high peak power increases the conversion efficiency. One way of achieving high peak powers is by using pulsed lasers. Although pulsed gas and solid state lasers are readily available with very high peak powers semiconductor lasers offer advantages like compactness, reliability and low cost. Standard broad-area semiconductor lasers can provide high output powers but with poor beam quality. Tapered diode lasers combine the possibility of high output power with good beam quality as reported by several authors for CW operation^{1,2}.

Pulsed operation of diode lasers can be achieved in different schemes including current pulsing³ and mode-locking⁴. Current pulsing is typically used to generate peak powers in the range of 2...10 times the rated CW power from the laser diodes, while mode-locking is normally used to generate short pulses with high repetition rates. Current pulsing of tapered laser devices has been reported at wavelengths of 1500 nm⁵ and 1930 nm⁶. Peak output powers up to 9.6 W were generated at 1500 nm at a peak current of 45 A and 2.4 W peak power at 1930 nm was generated at a current of 11 A.

In this work, the performance of 808 nm tapered lasers in current pulsed operation is presented, which is relevant for nonlinear frequency conversion and fluorescence diagnostics. The very small vertical divergence of 18° (FWHM) of these lasers is beneficial for efficient coupling into external cavities. Previous experiments have revealed nearly diffraction-limited beam quality at high output power from a tapered laser with the same structure⁷. In the work presented, measurements for the optimisation of the lateral resonator geometry and for an increase of output power are reported. Different ridge waveguide lengths and taper angles of the 4 mm long laser devices were investigated regarding output power, beam quality and spectral behavior. As a result, an increase of the peak output power up to $P = 27$ W at a pulse length of 100 ns was measured. This is the highest reported power in the wavelength range around 800 nm for single-emitter tapered lasers. High beam quality with $M^2 = 2.6$ and 76 % power in central lobe at $P = 9$ W has been obtained for an optimised ridge waveguide length. Finally, the stability of the astigmatism for the different resonator geometries is discussed, as it is relevant for stable beam shaping in external cavities and, therefore, efficient nonlinear

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frequency conversion. CW measurements were used as a reference for the results under pulsing conditions; by this means, the behaviour of the tapered lasers under different thermal conditions could be compared.

2. TAPERED DIODE LASER STRUCTURE

The vertical laser structure consists of a GaAsP tensile-strained single quantum well (SQW) embedded in an $\text{Al}_{0.45}\text{Ga}_{0.55}\text{As}$ waveguide with the thickness $d_{\text{WG}} = 3 \mu\text{m}$ and highly doped $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ cladding layers (super-large optical cavity, SLOC)⁸, as shown in fig. 1 (A). The epitaxial layers were grown by low-pressure metal-organic vapour phase epitaxy (MOVPE) on (100) n-GaAs substrates. Owing to the tensile-strained quantum well, the emission is TM-polarised. The vertical divergence angle of the SLOC structure is as low as 18° (FWHM), as illustrated in fig. 1 (B). The nearly Gaussian shape of the far field profile is an indicator for high beam quality in the fast axis; this enhances the coupling efficiency in external cavities. Measurements of the electro-optical parameters of the structure reveal high internal efficiency of $\eta_i = 88 \%$, low internal losses of $\alpha_i = 0.7 \text{ cm}^{-1}$ and a transparency current density of $j_{\text{tr}} = 150 \text{ A/cm}^2$.

Fig. 1. Layer sequence of the super-large optical cavity structure, $d_{\text{WG}} = 3 \mu\text{m}$ (left, A). Vertical far field profile, measured at uncoated BA lasers of the same structure (right, B).

In lateral direction, the tapered lasers consist of index-guided ridge-waveguide (RW) sections and gain-guided tapered sections. The total length of the lasers is 4 mm; the length of the RW section L_{RW} has been processed to 500 μm , 1 mm and 2 mm. The width of the fundamental mode ridge waveguide, formed by reactive ion etching, is approximately 3 μm . The desired effective index step was obtained by setting the proper etch depth. The tapered section was processed as a low mesa structure. For each ridge waveguide geometry, lasers with taper angles θ_{TA} of 4° and 6° have been manufactured and characterised. The front facets of all lasers were antireflection coated with $R_f \cong 0.1 \%$; whereas the rear facets were high-reflection coated with $R_r \cong 95 \%$. The lasers were mounted p-side (epi-side) down on CuW submounts, whose thermal expansion coefficient is well adapted to GaAs. For the measurements, gold-plated copper C-mounts were used as heat sinks.

Fig. 2. Lateral geometry of the 808 nm tapered lasers, $L_{\text{RW}} = 500 \mu\text{m} / 1 \text{ mm} / 2 \text{ mm}$, $\theta_{\text{TA}} = 4^\circ / 6^\circ$.

3. SETUP

Fig. 3. Experimental setup for measuring the power-current characteristics, the beam quality and the spectra.

A schematic drawing of the experimental setup is given in fig. 3. The lasers were mounted on Peltier-cooled heat sinks. In pulsed mode, the laser driver Avtech AVOZ-A3-B was used, in CW operation a standard laser driver (Profile LDC395). The output power of the lasers was measured with two units, each consisting of a photodiode in an integrating sphere. One unit was calibrated for CW, the other for pulsed operation. For the spectral measurements, a fibre-coupled optical spectrum analyzer with a resolution of 10 pm was used (Advantest Q8384). The beam quality measurements were performed applying the method of the moving slit (ISO standard 11146, Annex A). With the setup, the intensity profiles of beam waist, far-field and near-field, as well as the astigmatism were measured. Beam waist and near-field were magnified by factor 60 into the slit plane by means of L₁ and L₂; the far-field measurement was done with an additional far-field lens (L₃). The CCD camera was used for focussing the beam before the measurement. From the slit width of 20 μm and the magnification factor, a spatial resolution of 0.3 μm at the diode resulted. The accuracy of the astigmatism measurement is 10 μm . After the measurements, the beam propagation ratios M^2 were calculated from the widths of beam waist and far-field profiles ($1/e^2$); the power in central lobe resulted from the beam waist profiles. For all measurements, the temperature of the heat sinks was kept at 25°C. Under current pulsing conditions, the pulse length was $\tau_{\text{pulse}} = 100 \text{ ns}$; the repetition rate was $f_{\text{rep}} = 1 \text{ kHz}$ in case of the power-current measurements and $f_{\text{rep}} = 25 \text{ Hz}$ for the beam characterisation. Reference measurements showed identical output power for $f_{\text{rep}} = 25 \text{ Hz}$ and $f_{\text{rep}} = 1 \text{ kHz}$.

4. CONTINUOUS WAVE OPERATION

4.1 Output power

Results for the power-current (P-I) characteristics under CW excitation for different laser geometries and tapered angles are shown in fig. 4. In fig. 4a the P-I characteristics for lasers with a tapered angle of 4° can be seen. The ridge waveguide length are 500 μm , 1000 μm and 2000 μm . Fig. 4b shows the P-I characteristics for lasers with a tapered angle of 6°. Lasers with a long ridge section and small tapered angle being favorable for low threshold. In contrast the current through a shorter tapered section is higher and the thermal roll over starts at lower currents as can be seen in the P-I characteristics of lasers with 2000 μm ridge and 2000 μm tapered length. The slope efficiency of all devices in the linear range of the power-current characteristics is in the range 0.9 – 1.0 W/A. A summary of the continuous wave power-current characteristics for the measured lasers with geometry is shown in table 1.

Fig 4. Power-current characteristics of tapered diode lasers with 4° tapered angle (a) and 6° tapered angle (b). The heat sink temperature was kept at 25°C .

$L_{RW}/\mu m$	$\theta_{TA}/^\circ$	I_{th}/A	Slope/W/A
500	4	1.9	0.9
500	6	2.4	0.9
1000	4	1.3	1.0
1000	6	1.7	0.9
2000	4	1.3	0.9
2000	6	0.9	1.0

Table 1. Continuous wave electro-optical parameters for tapered diode lasers with a total length of 4 mm and different geometries. L_{RW} is the length of the ridge section and θ_{TA} is the tapered angle.

4.2 Beam quality

In CW mode, the beam quality measurements were performed in the output power range between $P = 0.5 \text{ W}$ and $P = 4 \text{ W}$; most lasers have been measured up to $P = 2 \text{ W}$ in order to keep the beam quality nearly diffraction-limited. Fig. 5 illustrates the beam propagation ratio M^2 depending on the output power for each cavity geometry; fig. 6 shows the results for $P_{c.l.}$ accordingly. $P_{c.l.}$ is the proportion of output power in percent, which is contained in the central lobe of the beam waist. The horizontal lines in fig. 5 and 6 display the levels of $M^2 = 3$ and $P_{c.l.} = 70 \%$, respectively.

For all geometries investigated, a low beam propagation ratio $M^2 \leq 2$ and high power in central lobe $65\% \leq P_{c.l.} \leq 80\%$ were measured up to $P = 2 \text{ W}$. As the diodes with $L_{RW} = 1000 \mu m$ revealed good beam quality at $P = 2 \text{ W}$ for both taper angles θ_{TA} , 4° and 6° , they were measured up to $P = 4 \text{ W}$ and $P = 3.5 \text{ W}$, respectively. Nevertheless, the beam quality of these diodes tends to deteriorate with $M^2 > 3$ for $P \geq 3 \text{ W}$ in CW operation.

Fig. 5. Beam propagation ratios $M^2_{1/e2}$ of 808 nm tapered lasers at $T = 25^\circ\text{C}$ (CW) for different ridge waveguide lengths L_{RW} ; taper angle $\theta_{TA} = 4^\circ$ (left) and $\theta_{TA} = 6^\circ$ (right).

Fig. 6. Power in central lobe $P_{c.l.}$ of 808 nm tapered lasers at $T = 25^\circ\text{C}$ (CW) for different ridge waveguide lengths L_{RW} ; taper angle $\theta_{TA} = 4^\circ$ (left) and $\theta_{TA} = 6^\circ$ (right).

As already mentioned, the astigmatism is another relevant parameter of the beam quality. It is shown in fig. 7 depending on the output power. A significant increase of the astigmatism can be observed with increasing power. This increment is stronger for 4° taper angle compared to 6° , as to be seen especially in the range between 0.5 W and 2 W. The change of the astigmatism with power might follow from thermal lensing. Obviously, this heating effect is stronger in lasers with 4° taper angle due to the smaller injection area compared to 6° ; this behaviour is consistent with the power-current characteristics above. In fig. 7, the theoretical values of the astigmatism are depicted as horizontal, dashed lines. The theoretical values can be estimated from the taper length and the refractive index inside the taper with a simple model. At low output power, i.e. $P = 0.5$ W, the astigmatism is closest to the theoretical values owing to comparatively little heating of the laser; the correlation is better for 6° taper angle as expected according to the considerations above.

Fig. 7. Astigmatism of 808 nm tapered lasers at $T = 25^\circ\text{C}$ (CW) for different ridge waveguide lengths L_{RW} ; taper angle $\theta_{TA} = 4^\circ$ (left) and $\theta_{TA} = 6^\circ$ (right). The horizontal lines denote the theoretical values.

5. PULSED OPERATION

5.1 Output power

The power-current characteristics of the tested lasers are shown in fig. 8. In fig. 8a the P-I characteristics for lasers with a tapered angle of 4° and different length of the RW section up to 17 A pulse current can be seen. Fig. 8b shows the P-I characteristics for lasers with a tapered angle of 6° . The threshold of the lasers is comparable to continuous wave operation but the slope efficiency of the lasers is considerably higher due to lower heating of the active region with values in the range 1.2...1.3 W/A above threshold. The lasers with a tapered angle of 6° have higher thresholds in comparison with the 4° lasers, which can be explained with the larger active area of the tapered section. The reached output power of the 6° lasers is higher due to a better cooling. Also a thermal roll-over in the P-I characteristics for tapered laser with a ridge length of 2000 μm can be seen. A maximum output power is reached with a tapered laser having a 1000 μm RW section a 3000 μm tapered section and a tapered angle of 6° . Fig. 8c shows the P-I characteristic of this laser. At a drive current of 25 A a peak output power of 27 W is reached.

Fig. 8. Power-current characteristics of tapered diode lasers with 4° taper angle (a) and 6° taper angle (b) with RW length of 500 μm , 1000 μm and 2000 μm . Fig. c shows the P-I characteristic of a tapered laser with 1000 μm RW-3000 μm tapered length and 6° . The heat sink temperature was kept at 25°C , the pulse length is 100 ns and the repetition rate is 1 kHz.

5.2 Beam quality

Under current pulsing conditions at $P = 2$ W, the beam propagation ratios are almost identical to the results measured in CW mode; see fig. 9. But in contrast to CW, the deterioration of the beam quality in pulsed mode occurs at higher output power; for diodes with $L_{RW} = 1000$ μm , even at $P \geq 5$ W high beam quality with $M^2 \leq 2.6$ and $P_{c.l.} \geq 68\%$ is achieved, see fig. 9 and 10. $P_{c.l.}$ remains very stable over a wide range of power. The highest power with nearly diffraction-limited beam quality is $P = 9$ W with $M^2_{1/e2} = 2.6$ and $P_{c.l.} = 76\%$, measured at a diode with $L_{RW} = 1000$ μm . The measurements demonstrate that operation in pulsed mode, compared to CW, may extend the range of output power at high beam quality. This might follow from thermal effects; however, this point is still under investigation.

Fig. 9. Beam propagation ratios $M^2_{1/e2}$ of 808 nm tapered lasers at $T = 25^\circ\text{C}$ ($\tau_{\text{pulse}} = 100$ ns, $f_{\text{rep}} = 25$ Hz) for different ridge waveguide lengths L_{RW} ; taper angle $\theta_{TA} = 4^\circ$ (left) and $\theta_{TA} = 6^\circ$ (right). The results for CW are depicted in grey colour.

Fig. 10. Power in central lobe $P_{c.l.}$ of 808 nm tapered lasers at $T = 25^\circ\text{C}$ ($\tau_{\text{pulse}} = 100$ ns, $f_{\text{rep}} = 25$ Hz) for different ridge waveguide lengths L_{RW} ; taper angle $\theta_{TA} = 4^\circ$ (left) and $\theta_{TA} = 6^\circ$ (right). The results for CW are depicted in grey colour.

Those lasers with $L_{RW} \neq 1000$ μm show lower beam quality; particularly, for $L_{RW} = 500$ μm , the beam quality deteriorates significantly for $P > 2$ W. Beam propagation ratio and power in central lobe both follow this trend, because the deterioration of beam quality with increasing power mainly comes from rising side lobes in the beam waist. This effect has been observed especially for $L_{RW} = 500$ μm , which might follow from insufficient mode filtering as a result of

the short RW length. The measurements under current pulsing conditions indicate that the ridge waveguide length is more relevant for the beam quality than the taper angle.

As examples of good beam quality at high power and rising side lobes with increasing power, some typical beam waist profiles depending on the output power are depicted in fig. 11. The graphs show clearly pronounced main lobes up to $P = 9$ W for diodes with $L_{RW} = 1000$ μm .

Fig. 11. Lateral beam waist profiles of 808 nm tapered lasers at $T = 25^\circ\text{C}$ ($\tau_{\text{pulse}} = 100$ ns, $f_{\text{rep}} = 25$ Hz) for $L_{RW} = 1000$ μm , $\theta_{TA} = 4^\circ$ (left) and $\theta_{TA} = 6^\circ$ (right); power in central lobe $P_{c.l.}$.

The astigmatism for pulsed operation and the theoretical values are given in fig. 12. In contrast to CW mode, the variation of the astigmatism in pulse mode is lower than 50 μm for the entire power range between $P = 2$ W and 10 W, typically. This results from reduced heat load and thus reduced thermal lensing in pulsed operation compared to CW. The considerably constant astigmatism makes the diodes especially suitable for applications with external cavities and frequency conversion, due to simplified and stable beam shaping. Fig. 12 suggests, that in pulse mode, the measured astigmatism is closer to the expected value than in CW mode. Also this might come from thermal effects, as well as the better correlation between measured and theoretical values for 6° taper angle than for 4° .

Fig. 12. Astigmatism of 808 nm tapered lasers at $T = 25^\circ\text{C}$ ($\tau_{\text{pulse}} = 100$ ns, $f_{\text{rep}} = 25$ Hz) for different ridge waveguide lengths L_{RW} ; taper angle $\theta_{TA} = 4^\circ$ (left) and $\theta_{TA} = 6^\circ$ (right). The results for CW are depicted in grey colour.

5.3 Spectral behavior

Spectra under pulse excitation were obtained at pulse currents of 5 A and 15 A. For the spectral measurements, the fibre-coupled optical spectrum analyzer was used (Advantest Q8384). Due to the time resolution of the optical spectrum analyzer only an “average spectrum” was measured. Typical examples of spectra are shown in fig. 13 for lasers with 1 mm RW length and 4° (fig. a,b) and 6° taper angle (fig. c,d).

Fig. 13. Spectra for the tapered lasers with 1 mm RW length, 4° taper angle, 5 A drive current (a), 15 A drive current (b), 6° taper angle, 5 A drive current, (c), 15 A drive current (d). The current pulse length is 100 ns and the repetition rate is 1 kHz.

It can be seen, that the pulse spectra measured at 5 A show a longitudinal mode structure, whereas in the spectra at 15 A no pronounced mode structure can be seen. The spectra measured at 15 A are significantly broadened (≈ 4 nm). This can be explained with the chirp during the current pulse. Here, the carrier concentration changed during the pulse inducing variation in the refractive index in the laser cavity and the laser line shifted, so that the resulting average spectrum is broadened.

6. CONCLUSION

Tapered lasers at 808 nm with small vertical far field divergence of 18° have been manufactured and characterized under current pulsed conditions. High output powers of $P = 16$ W and high slope efficiencies of $S = 1.2$ W/A have been achieved for all lateral cavity geometries investigated. For the optimised geometry with a ridge waveguide length $L_{RW} = 1000$ μm and a taper angle $\theta_{TA} = 6^\circ$, even $P = 27$ W output power and $S = 1.3$ W/A up to $P = 20$ W have been obtained. For single-emitter 808 nm tapered lasers, these values have never been reported before. Furthermore, good beam quality with typically $M^2_{1/e2} \leq 2.6$ and high power in central lobe $P_{c.l.} \geq 68$ % was measured at high output power; the best example of nearly diffraction-limited beam quality was $M^2_{1/e2} = 2.6$ and $P_{c.l.} = 76$ % at $P = 9$ W. An optimum of the ridge waveguide length regarding the beam quality has been found for $L_{RW} = 1000$ μm . The nearly diffraction-limited beam quality at high output power makes these low-divergence diodes excellent candidates for applications like frequency conversion and fluorescence diagnostics. In the external cavities of these applications, the diodes presented ensure stable beam shaping due to the high stability of the astigmatism over a wide range of power.

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REFERENCES

1. F. Dittmar, B. Sumpf, J. Fricke, G. Erbert and G. Tränkle, "High-power 808-nm tapered diode lasers with nearly diffraction-limited beam quality of $M^2 = 1.9$ at $P = 4.4$ W", IEEE Phot. Tech. Lett. **18**, 4, 601-603, 2006.
2. M. T. Kelemen, J. Weber, G. Kaufel, G. Bihlmann, R. Moritz, M. Mikulla and G. Weimann, "Tapered diode lasers at 976 nm with 8 W nearly diffraction limited output power", Elec. Lett. **41**, 18, 1011-1013, 2005.
3. Y. Liu, V. Kireev and Y. Braiman, "Frequency locking and wavelength tuning of nanosecond pulsed broad-area semiconductor lasers", Appl. Phys. Lett. **84**, 21, 4265-4267, 2005.
4. K. Yvind, P. M. W. Skovgaard, J. Mørk, J. Hanberg and M. Kroh, "Performance of external cavity mode-locked semiconductor lasers employing reverse biased saturable absorbers", Physica Scripta, **T101**, 129-132, 2002.
5. T. Tamanuki, T. Sasaki and M. Kitamura, "High power and narrow lateral far-field divergence 1.5- μm eye-safe pulsed laser diodes with flared waveguide", Opt. Quant. Elec. **28**, 513-517, 1996.
6. C. Pfahler, M. Eichhorn, M. T. Kelemen, G. Kaufel, M. Mikulla, J. Schmitz and J. Wagner, "Gain saturation and high-power pulsed operation of GaSb-based tapered diode lasers with separately contacted ridge and tapered section", Appl. Phys. Lett. **89**, 021107-1-3, 2006.
7. F. Dittmar, A. Klehr, B. Sumpf, A. Knauer, J. Fricke, G. Erbert and G. Tränkle, "9 W output power from a 808 nm tapered diode laser in pulse mode operation with nearly diffraction-limited beam quality", J. of Selected Topics in Quant. Electron., submitted, 2007.
8. A. Knauer, G. Erbert, R. Staske, B. Sumpf, H. Wenzel and M. Weyers, "High-power 808 nm lasers with a super-large optical cavity", Semicond. Sci. Technol. **20**, 621-624, 2005.