High-Power 808-nm Tapered Diode Lasers With Nearly Diffraction-Limited Beam Quality of $M^2 = 1.9$ at $P = 4.4$ W

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***Abstract*—High-power 808-nm tapered diode lasers mounted as single emitters with very good brightness were manufactured and analyzed. The beam propagation ratio M^2 is 1.9 at 4.4 W; a very low beam propagation ratio M^2 of 1.3 is achieved at 3.9 W. At 808 nm, the high brightness of 460 $\mathrm{MW \cdot cm^{-2}\ sr^{-1}}$ never reported before is a step forward toward new applications of tapered diode lasers.**

***Index Terms*—808 nm, beam quality, high brightness, high power, semiconductor lasers, tapered lasers.**

I. INTRODUCTION

OVER THE last years, high-power diode lasers have gained more and more importance for applications like pumping of solid state lasers and material processing such as cutting or welding. The main advantages of these lasers are high conversion efficiency in connection with low heat dissipation, small size and low costs, high reliability, and easy integration into different applications. In any case, high-power and nearly diffraction-limited beam quality are necessary prerequisites in order to obtain high brightness. There is a growing demand for the wavelength of 808 nm which is especially used for pumping Nd : YAG lasers and material processing.

Broad area (BA) single emitters at 808 nm with an output power of several watts have already been realized successfully based on tensile-strained GaAsP quantum wells (QWs) in AlGaAs waveguides [1]. However, BA diode lasers do not meet the requirements for high brightness due to poor beam quality with beam propagation ratios $M^2 > 10$ for $P \geq 2$ W typically. Taking into consideration the demands for low-cost fabrication, tapered lasers are a promising concept for nearly diffraction-limited beam quality at high output powers. Especially in the near-infrared wavelength range 735–1500 nm, this approach, consisting of an index-guided straight section and a gain-guided tapered section, has been successfully realized [2]–[8].

In the following, we report on 808-nm tapered lasers with nearly diffraction-limited beam quality up to $P = 4.4$ W output power. To our knowledge, for $\lambda = 808$ nm, a beam quality with $M^2 = 1.3$ at $P = 3.9$ W has never been reported before.

II. LASER STRUCTURE

A large optical cavity (LOC) structure with 2-μm waveguide thickness is used for the tapered lasers. This structure has a narrow vertical divergence of 26° [1]. The epitaxial layers were grown by low-pressure metal–organic vapor phase epitaxy on (100) n-GaAs substrates. The tensile strained $\mathrm{GaAs_{0.83}P_{0.17}}$ QW with a thickness of 17 nm is embedded in the $\mathrm{Al_{0.45}Ga_{0.55}As}$ waveguide and highly doped $\mathrm{Al_{0.7}Ga_{0.3}As}$ cladding layers. The layer sequence is completed by a highly doped p-GaAs contact layer.

The tapered laser consists of an index-guided straight section and a gain-guided tapered section. The index-guiding is achieved by a dry etched ridge-waveguide (RW) with a width of $W_{\mathrm{RW}} = 3$ μm. In the tapered section, the contact layer outside of the p-electrode was removed by wet chemical etching in order to reduce current spreading. SiN_x is used for electrical isolation between the semiconductor surface and the p-contact metallization outside of the RW and the tapered region contacts. The metallization on the p-side contact was formed by evaporating a Ti–Pt–Au layer system and electro-plating a thick Au layer, the latter for mounting the lasers p-side (episide) down. After thinning and n-metallization, the wafer was cleaved to obtain a total cavity length of $L = 2.75$ mm. The front facet was antireflection coated $(R_f \cong 0.1\%)$ and the rear facet was high-reflection coated $(R_r \cong 94\%)$, both by ion-beam sputtering. The lasers were mounted p-side (episide) down on CuW submounts with AuSn solder; the thermal expansion coefficient of the submount material is well adapted to GaAs. The n-contact was realized by wire-bonding. A standard C-mount was used as heatsink.

The front facet reflectivity, the length of the RW section, and the effective index step were chosen according to the optimization of the brightness. During the optimization process, lasers of similar vertical structure as described above but with different reflectivities, lengths of the RW section and index steps had been compared. The measurements showed that, for instance, a front facet reflectivity of $R_f \cong 0.1\%$ lead to a $10\%, \ldots, 20\%$ better beam propagation ratio M^2 than $R_f \cong 1\%$. This is a result of different intensities of radiation reflected at both front and rear facet and, as a consequence, pumping filaments in the tapered section. These experimental results correlate well with simulations on tapered lasers at $\lambda = 732$ nm; the suppression of optical pumping and the following improvement in mode filtering for $R_f \cong 0.1\%$ in comparison with $R_f \cong 1\%$ has been shown [9]. Furthermore, the RW section length must be in the range of $L_{\mathrm{RW}} = 750, \ldots, 1000$ μm for sufficient mode filtering and

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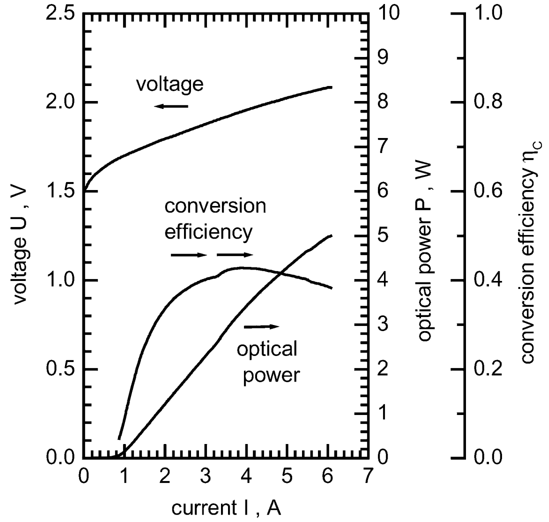

Fig. 1. Power–voltage–current characteristics and conversion efficiency of 808-nm tapered laser with $L = 2.75$ mm at $T = 15$ °C; $I_{\mathrm{th}} = 840$ mA, $S = 1.06$ WA^{-1}.

good beam quality [3]. For the lasers presented, the RW section length was chosen to 750 μm. As a prerequisite for low M^2, the effective index step had to be chosen adequately.

III. RESULTS

Typical power–current and conversion efficiency characteristics under continuous-wave (CW) conditions at $T = 15$ °C are depicted in Fig. 1. The threshold current of the laser is 840 mA, the slope efficiency has a high value of 1.06 W/A near threshold; obtained from threshold to $P = 4$ W, it is even as high as 1.01 W/A. The range of output power with high slope efficiency is as wide as or even wider than shown for tapered lasers at other wavelengths in [3], [5], [6], [8]. The conversion efficiency reaches 42% in the output power range of 3.2–3.8 W.

BA lasers processed from the same vertical structure and with the same contact area size have a lower current density at threshold [1]. The threshold density j_{th} of the tapered laser is 420 A/cm^2; j_{th} of the corresponding BA laser is 210 A/cm^2. But, the slope efficiency of the tapered laser is not significantly lower, $S = 1.06$ WA^{-1} and $S = 1.10$ WA^{-1}, respectively. The different threshold densities result from the resonator geometries of tapered laser and BA laser; the tapered cavity has higher radiation losses. On the other hand, low internal losses of typically $\alpha_i \approx 0.9$ cm^{-1} and high internal efficiency of $\eta_i \geq 95\%$ are the reason for the high slope efficiency [1].

The high output power and conversion efficiency of the lasers presented remains stable at $T = 25$ °C; the slope efficiency of the diode shown in Fig. 1 of 1.06 W/A was identical to that at 15 °C; the maximum conversion efficiency decreased slightly to 37% at $T = 25$ °C. Moreover, the measurements on these diodes showed a high homogeneity; 9 of 11 lasers mounted and measured revealed high efficiencies. For $T = 25$ °C and CW mode, the average values among these 9 diodes are $S = 1.08$ W/A, $\eta_c = 37.5\%$.

TABLE I
BEAM PROFILE WIDTHS AND ASTIGMATISM AT OUTPUT POWER UP TO $P = 4.4$ W, $T = 15$ °C

P (W)	Beamwaist width (μm)	Farfield width (°)	Nearfield width (μm)	Astigmatism (μm)
2.0	5.3	15.7	166	620
3.0	7.7	13.8	164	620
3.9	6.8	11.7	154	630
4.0	9.1	11.3	153	640
4.4	12.6	9.1	147	690

TABLE II
BEAM QUALITY AT OUTPUT POWER UP TO $P = 4.4$ W, $T = 15$ °C

P (W)	M^2	Power in central lobe (%)	Brightness (MW cm^{-2} sr^{-1})
2.0	1.4	86	220
3.0	1.8	89	260
3.9	1.3	79	460
4.0	1.8	81	340
4.4	1.9	67	350

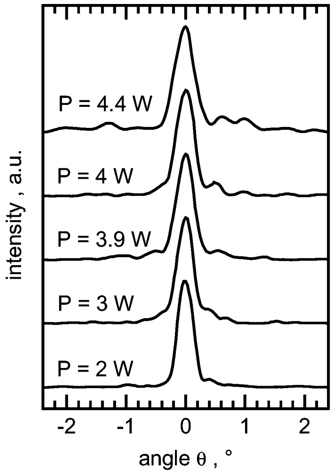

Fig. 2. Effective lateral far-field (beam waist) of 808-nm tapered diode laser with $L = 2.75$ mm at $T = 15$ °C.

The beam quality measurements were performed applying the method of the moving slit (ISO standard 11146, Annex A). In addition to the intensity profiles of beam waist and far-field, also the near-field, i.e., the intensity distribution along the front facet, and the astigmatism were measured. Table I shows the widths $(1/e^2)$ of the intensity profiles measured under CW conditions and the astigmatism; Table II contains the beam quality parameters calculated from the profiles.

The beam waist width and shape are the most relevant parameters for the beam quality. Table I shows that the width remains quite stable up to $P = 3.9$ W CW, but the shapes illustrated in Fig. 2 indicate a clearly pronounced main lobe with only small side lobes even at $P > 3.9$ W. This leads to a low beam propagation ratio of $M^2 \leq 1.9$ for $P \leq 4.4$ W, as shown in Table II. The maximum brightness value is 460 MW $\cdot$ cm^{-2} sr^{-1} at $P = 3.9$ W; M^2 is as low as 1.3 at this power level.

To our knowledge, the maximum brightness and minimum M^2 values presented in this letter have never been reported before for tapered lasers at $\lambda = 808$ nm; furthermore, these values are better than most results presented at different wavelengths [5], [6]. Further improvement of the beam properties might be possible by a modified heatsink, as the power–current characteristics in Fig. 1 indicates increasingly higher laser temperatures above $P = 4$ W.

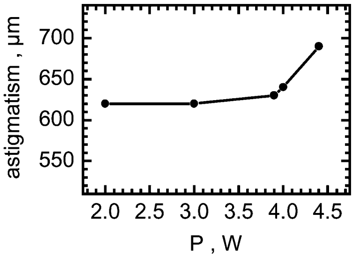

Fig. 3. Astigmatism depending on output power of 808-nm tapered diode laser with $L = 2.75$ mm at $T = 15$ °C.

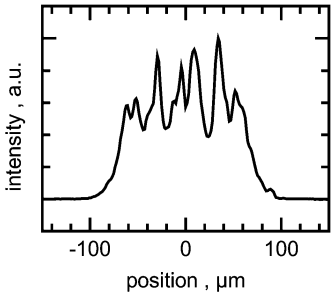

Fig. 4. Near-field (front facet intensity) of 808-nm tapered diode laser with $L = 2.75$ mm at $P = 3.9$ W, $T = 15$ °C.

TABLE III
BEAM QUALITY OF 9 LASERS (11 LASERS MEASURED). POWER IN CENTRAL LOBE AND BRIGHTNESS ARE AVERAGE VALUES. $T = 25$ °C

P (W)	M^2, average	M^2, best	Power in central lobe (%)	Brightness (MW cm^{-2} sr^{-1})
2.0	1.3	1.0	81	236
3.0	1.5	1.2	80	306
4.0	2.8	1.1	61	219

Above $P = 4$ W, the astigmatism value of 690 μm is significantly higher than the rather constant values in the range of 620, … ,630 μm at $P < 4$ W, as shown in Fig. 3. This could possibly follow from wavefront distortions inside the taper due to thermal effects.

High reliability requires a near-field with filaments of small amplitude necessary for low facet load. The near-field (CW) plotted in Fig. 4 is typical for $P \leq 4.4$ W; it illustrates that the tapered diodes presented meet the requirement of low facet load.

As shown in Table III, the measurements are quite homogeneous regarding the good beam quality. Further, the good brightness values remain stable for a higher ambient temperature of $T = 25$ °C. The referring measurements were made under quasi-CW conditions in order to minimize thermal influence of the small heat capacity of the C-mount; as a result, the beam quality measured is more typical for laser structure and geometry. For $P \leq 3$ W, the beam propagation ratio is identical between CW and quasi-CW measurements within the given accuracy due to the sufficient thermal conductivity of submount and heatsink in this power range.

IV. CONCLUSION

We have manufactured and characterized 808-nm tapered lasers consisting of an index-guided ridge waveguide section and a gain-guided tapered section. A record low M^2 value of 1.3 and a superior brightness of 460 $\mathrm{MW \cdot cm^{-2}\ sr^{-1}}$ at an output power of 3.9 W have been presented. The beam quality remains nearly diffraction-limited for the full output power range up to $P = 4.4$ W; further improvement might be possible by a modified heatsink. As the high power, nearly diffraction-limited properties are typical for the lasers characterized; this type of lasers is promising for new high-brightness applications such as high-power pumping of solid-state lasers and direct material processing.

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