

Reliable 1-W CW Operation of High-Brightness Tapered Diode Lasers at 735 nm

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Abstract—The long-term stability of high-brightness diode lasers at 735 nm was investigated. The diodes consist of an index-guided straight section and a gain-guided tapered section. A 1-W continuous-wave operation for 2-mm-long tapered lasers over 3200 h is reported. The experiments demonstrate high reliability with degradation rates below $3.2 \times 10^{-5} \text{ h}^{-1}$.

Index Terms—High-brightness diode lasers, tapered lasers, tensile-strained GaAsP quantum wells.

I. INTRODUCTION

HIGH-POWER diode lasers for the spectral region between 710 and 790 nm are needed for several applications in medicine, spectroscopy, and for pumping of femtosecond solid-state lasers like Cr:LiSAF. For example, diode lasers near 735 nm were used in medicine for photodynamic therapy. They should have an output power larger than 1 W, a good beam quality for efficient coupling into fibers, and lifetimes larger than 3000 h.

Broad area (BA) lasers at $\lambda = 735 \text{ nm}$ with a $100\text{-}\mu\text{m}$ aperture reached an output power of up to 7 W [1]. The long-term behavior of these diodes was investigated by Sumpf *et al.* [2], [3]. High reliability at output powers up to 2 W without any failure over 2400 h could be presented.

These devices have a poor beam quality with a lateral beam propagation factor $M^2 > 10$. There are several possibilities to improve the beam quality and to decrease M^2 . The most promising design is the application of tapered lasers. These devices consist of a straight narrow-stripe section acting as spatial mode filter and a tapered, flared part for the amplification of the radiation. Several realizations of this type of lasers in the wavelength range $\lambda > 900 \text{ nm}$ were reported [4]–[7].

In our group, tapered lasers consisting of a straight index-guided ridge-waveguide (RW) section and a gain-guided tapered section were manufactured for the wavelength range near 735 nm. Devices with different total laser lengths ($L = 2, 2.75, 4 \text{ mm}$) were measured. An optimum concerning high output power $P \geq 1 \text{ W}$ and beam quality with $M^2 \leq 3$ could be found for each laser length adjusting the length of the RW section for mode filtering and the necessary length of the gain section for the amplification [8]. A M^2 below 2.1 at an output power of 2 W were measured for these different laser lengths [8], [9]. Recently, a value of $M^2 = 1.1$ at

$P = 3 \text{ W}$ could be reported for the 2.75-mm-long devices with $\lambda = 735 \text{ nm}$ [10].

In this letter, the long-term behavior of 2-mm-long tapered lasers at an output power $P = 1 \text{ W}$ will be presented. Beside the increase of the current in the constant optical power aging, the beam quality was measured before, at about 1000 h, and after the total aging time of 3166 h.

II. LASER STRUCTURE

The laser structures grown by low-pressure metal–organic vapor phase epitaxy on (100) GaAs substrates consist of a large optical cavity (LOC) similar to those reported in [1]. The LOC is based on a $1\text{-}\mu\text{m}$ -thick $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ waveguide surrounded by $\text{Al}_{0.70}\text{Ga}_{0.30}\text{As}$ cladding layers. The active layer is a 9-nm-thick tensile-strained $\text{GaAs}_{0.67}\text{P}_{0.33}$ quantum well placed in the middle of the LOC.

The tapered lasers ($L = 2 \text{ mm}$) consist of an index-guided section ($L_{\text{RW}} = 750 \mu\text{m}$) and a gain-guided section ($L_{\text{TR}} = 1250 \mu\text{m}$, full taper angle $\varphi_{\text{TR}} = 4^\circ$). The processing steps were kept as simple as possible. Cavity-spoiling grooves for additional mode filtering were not implemented. They would require an additional etch step and a planarization for epi-side-down mounting. It could be supposed that these grooves can lead to reliability problems.

The index-guiding was achieved by an RW formed by reactive ion etching and depositing an insulator on the etched surface. The width of the ridge is about $3 \mu\text{m}$. The tapered section is manufactured by removing the contact layer outside of the region of the p-contact by wet chemical etching. The p-side metallization was performed by evaporating a Ti–Pt–Au multilayer and by electroplating a thick Au layer. After substrate thinning and n-metallization, the wafer was cleaved into bars. The front facets were antireflection coated ($R_f \approx 1\%$); the rear facets high-reflection coated ($R_r \approx 94\%$).

The lasers were mounted p-side (epi-side) down on T-cBN heat spreaders. T-cBN has a very high thermal conductivity of about $600 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. The mismatch in thermal expansion is quite low allowing the mounting of 2-mm-long lasers with hard solder AuSn. For longer devices, a better matched heat spreader like CuW is preferable. All devices were soldered with AuSn using a procedure applied for BA lasers, too. All lasers were mounted on C-mounts. The n-side was contacted by wire bonding.

III. RESULTS

The aging behavior of five tapered lasers ($L = 2 \text{ mm}$, $L_{\text{RW}} = 750 \mu\text{m}$, $\varphi_{\text{TR}} = 4^\circ$) was investigated at $P = 1 \text{ W}$, $T = 25^\circ \text{C}$.

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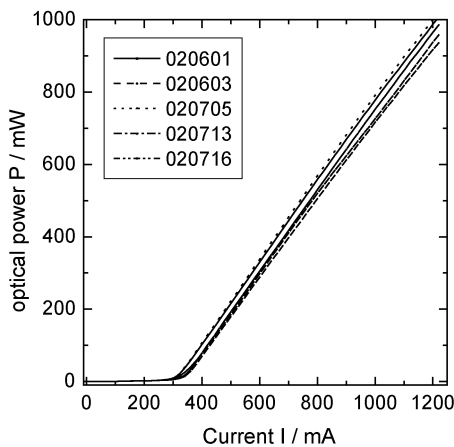


Fig. 1. P - I characteristic for the five 735-nm tapered laser diodes before aging. The cavity length is 2 mm. The temperature is 25 °C.

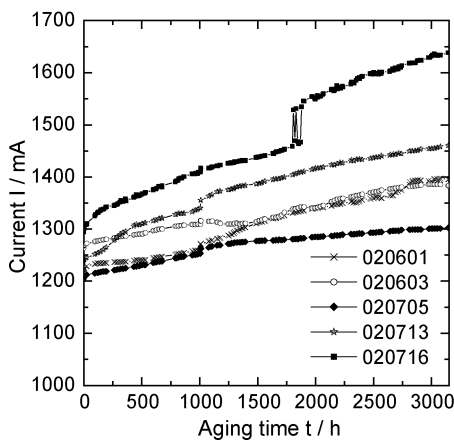


Fig. 2. Aging behavior of five 2-mm-long tapered lasers for 735 nm at an output power of 1 W.

The power-current (P - I) characteristics in continuous-wave (CW) operation of these devices before aging are given in Fig. 1. The threshold current is about 300 mA, which corresponds to a threshold current density below 500 A/cm². The slope efficiency is near 1.1 W/A and comparable to that of BA lasers. An output power of $P = 1$ W was reached for an injection current of about $I = 1.2$ A. The maximum output power of $P = 2.5$ W was achieved for $I \leq 3$ A. The wall-plug efficiency was close to 46%. The fast axis angle was smaller than 28° [full-width at half-maximum (FWHM)].

The beam quality of the lasers was measured before aging. The position of the beam waist and the intensity profiles in the beam waist, at the front facet, and in the far field were measured applying the method of the moving slit (ISO 11146, Annex A). Typically, angles of about 6° (FWHM) and 9° ($1/e^2$) were determined for the lateral far field. At $P = 1$ W, the astigmatism was 500 μ m.

Based on the measured intensity profiles, the beam propagation factor M^2 was calculated. The beam widths needed to calculate M^2 were identified with the $1/e^2$ widths of the intensity profiles in the beam waist and in the far field. At 1 W, the M^2 values were smaller than 1.6 for all devices. $M^2 = 1.3$ was measured for the best devices.

TABLE I
BEAM PROPAGATION FACTOR OF THE 735-nm TAPERED LASER DIODES FROM THE ENDURANCE TEST AT $T = 25$ °C AND $P = 1$ W

Laser	M^2	M^2	M^2
	before aging	after 1007 h	after 3166 h
020601	1.3	1.4	1.2
020603	1.5	4.3	3.1
020705	1.4	2.0	1.3
020713	1.3	1.2	1.3
020716	1.6	1.7	1.4

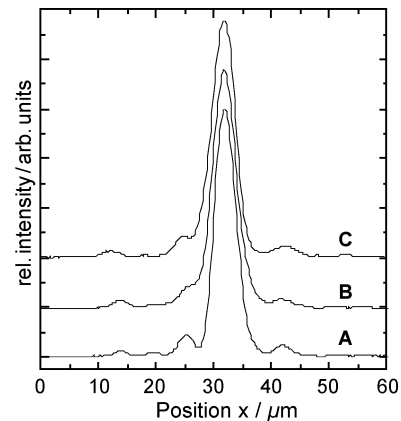


Fig. 3. Intensity in the beam waist of the laser 020601 at $T = 25$ °C and $P = 1$ W. (A) Before aging, (B) after 1007 h, and (C) after 3166 h.

The aging test had an overall duration of 3166 h. None of the five lasers tested failed during the experiment. An intermediate measurement of the electrooptical data was performed after 1007 h. The behavior of the injection current during the test is shown in Fig. 2. The degradation rates determined for the last 150 h were below $3.2 \times 10^{-5} \text{ h}^{-1}$ for all diodes. From this rate, a lifetime larger than 6000 h can be extrapolated (20% current increase).

After the aging test, the beam quality was measured again. The beam propagation factors M^2 from all these measurements are compiled in Table I.

Four diode lasers exhibit only minor changes in the beam profile. Assuming an uncertainty of 20% in the M^2 measurement, the values agree within the experimental uncertainty. The only exception is the laser 020603, for which the beam quality deteriorated slightly.

In Fig. 3, the intensity profiles measured in the beam waist of the sample 020601 before (profile A), at 1007 h (B) and after 3166 h aging (C) are shown in order to illustrate the development of the beam profiles during aging. The profiles are shifted to each other for clearance.

It is obvious that there are only minor changes. There is a weak increase in intensity in the left wing of the profiles B and C of Fig. 3, leading to an increase of the measured beam waist ($1/e^2$ -level) from 7.2 μ m (A) to about 8.5 μ m (B, C).

The far and near fields measured are shown in Figs. 4 and 5, respectively. The far field width ($1/e^2$ -level) decreases from about 10° (A) over 9° (B) to about 8.2° (C). The near-field width was nearly constant. The near-field profile became smoother.

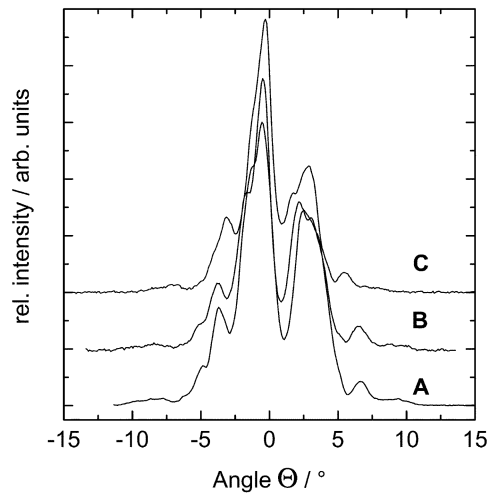


Fig. 4. Far field intensity of the laser 020 601 at $T = 25\text{ }^{\circ}\text{C}$ and $P = 1\text{ W}$. (A) Before aging, (B) after 1007 h, and (C) after 3166 h.

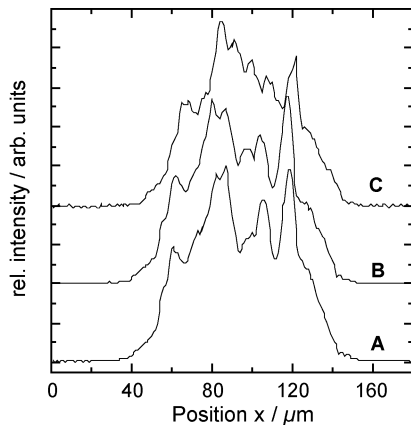


Fig. 5. Near-field intensity of the laser 020 601 at $T = 25\text{ }^{\circ}\text{C}$ and $P = 1\text{ W}$. (A) Before aging, (B) after 1007 h, and (C) after 3166 h.

IV. CONCLUSION

Tapered diode lasers for $\lambda = 735\text{ nm}$ were manufactured and tested. An aging test over 3166 h revealed that these devices work reliably at $P = 1\text{ W}$ output power with only minor

changes in the beam quality. The measured degradation rates smaller than $3.2 \times 10^{-5}\text{ h}^{-1}$ suggest lifetimes of more than 6000 h at $P = 1\text{ W}$. The lifetime fulfills the demands for medical applications of 735-nm laser diodes.

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