High-power high-brightness ridge-waveguide tapered diode lasers at 940 nm

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ABSTRACT

Semiconductor lasers with high beam quality and high optical output power are very attractive for a variety of applications such as optical pumping of solid-state lasers, fiber amplifiers and medical treatment. When easy and low-cost fabrication is a further requirement, devices based on tapered gain sections are the most promising candidates. Low modal gain, single quantum well InGaAs/AlGaAs devices emitting at 940 nm were grown by molecular beam epitaxy. The lateral design consists of a tapered gain guided and a ridge-waveguide section having an overall length between 2 mm and 3 mm. Whereas the length of the tapered structure determines the high output power, the high brightness requires a ridge-waveguide structure with sufficient length. Here the length of the ridge section has been chosen to 500 µm. We achieved an optical output power of up to 5.3 W at room temperature in continuous wave mode. The threshold current density depends on the tapered length with values between 200 A/cm^2 and 650 A/cm^2. The slope efficiency is around 0.9 W/A for all devices. The wall plug efficiency reaches 44 % at a current of 3 A. The beam quality factor remains nearly constant up to about 2.2 W having an M^2-value of 1.3. At higher optical output powers M^2 increases fast. The lifetime of such devices has been extrapolated to more than 7500 h at room temperature.

Keywords: high-brightness, high-power, tapered laser diode, laser-diodes, lifetime, AlGaAs-InGaAs, semiconductor

1. INTRODUCTION

High-power diode lasers are finding more and more applications such as laser surgery, direct materials processing and optical pumping of solid-state lasers and fiber amplifiers. For example the rapid growth of the Internet within the last few years has lead to a strong demand for higher data transmission rates in optical networks. One of the key elements in these networks are Erbium Doped Fiber Amplifiers (EDFAs), which are used to improve the fiber span between signal regeneration sites. For these EDFAs, high power diode lasers with near diffraction limited output power at 980 nm wavelength are used as pump sources. To reach even higher transmission speeds, longer distances between regeneration sites and with the introduction of Dense Wavelength Division Multiplex (DWDM) transmission systems more and more optical pump power in the fiber amplifiers is required.

Accordingly for most of these applications, the key requirements are high-power in the 2 W regime, a high beam-quality and long lifetimes. Easy and low-cost fabrication is a further requirement. But standard broad-area waveguide designs are susceptible to modal instabilities, filamentation and catastrophical optical mirror damage (COMD) failure. So they do not have a good beam quality. On the other hand up to now, the only type of diode laser used as pump sources in EDFAs is a single-stripe or ridge-laser which emits in a diffraction limited optical mode and can therefore be coupled into a single-mode fiber with high efficiency. The reliable output power of these lasers is mainly limited by the onset of facet degradation [1, 2] which depends on the power density on the facet. Due to the small stripe width of a few microns, the output power is limited to about 300 mW [3, 4].

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We report on high-power 940 nm diode lasers comprising ridge and tapered sections for near diffraction limited output power in the watt regime [5, 6, 7, 8, 9]. In these devices, the single-mode ridge section serves as a lateral mode filter that increases the beam quality of the diode lasers by at least an order of magnitude. The lasers are based on MBE grown layer structures in the AlInGaAs material system and show a maximum optical output power of more than 5 W. First reliability tests show extrapolated lifetimes of more than 7.500 h at 2 W together with a stable beam quality in the order of $M^2 = 1.5$.

2. EPITAXIAL LAYER STRUCTURE AND DEVICE FABRICATION

The fabrication of high-power diode lasers with high conversion efficiency requires an epitaxial layer sequence with both, low internal losses (< 2 cm^{-1}) and high internal conversion efficiency (> 0.9). The reduction of the internal losses can be achieved by broadening the waveguide layers [10]. For this purpose we have grown an InGaAs/AlGaAs laser structure with a large optical cavity by molecular beam epitaxy (MBE). For 940 nm emission wavelength, the active region consists of a single 7 nm wide quantum well with 12 % of Indium content.

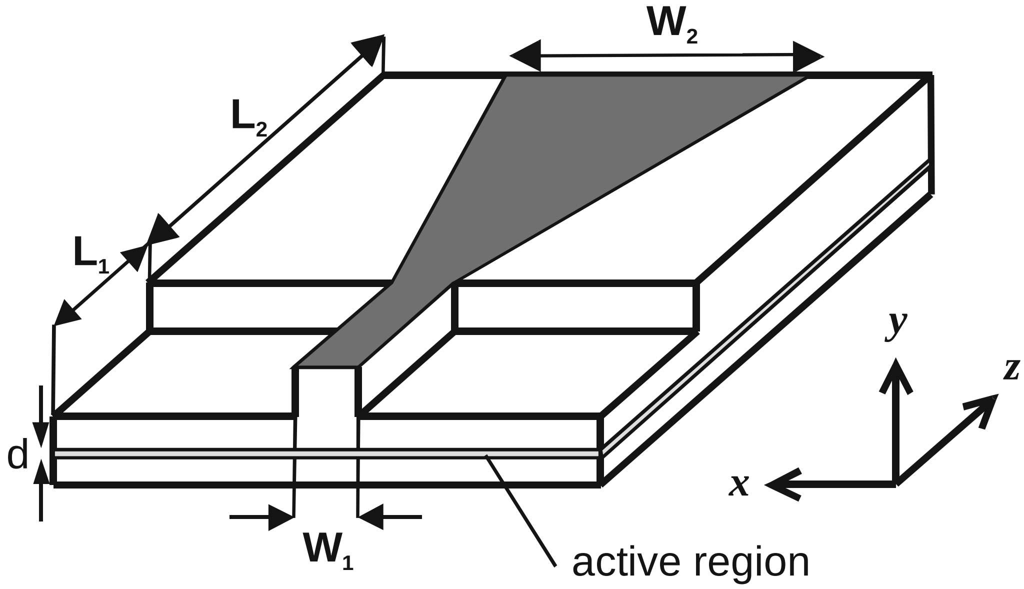

Figure 1: Schematic of a tapered diode lasers with a ridge waveguide for mode filtering. The length of the ridge section L_1 varies between 100 µm and 500 µm, whereas the length of the tapered section varies between 1500 µm and 2500 µm. The tapered angle is 6°.

The vertical layer design, explained elsewhere [8, 11] in more detail, exhibits an overlap of the fundamental optical mode with the quantum well of 1.3 %. We have shown previously that this low modal gain epitaxial layer structure suppresses beam filamentation in tapered laser oscillators and tapered laser amplifiers [12]. As a further advantage of this layer sequence, 95 % of the optical power is concentrated in the undoped core layers and the overlap of the fundamental mode with the doped cladding layers is only 5 %. As a result, low internal losses of 1.5 cm^{-1} are measured from Fabry-Perot laser diodes with the same epitaxial structure but of different lengths. The high material quality of the MBE-grown laser structures yields a high internal efficiency of more than 90 %. 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. This results in laser diodes with relatively temperature insensitive characteristics.

The lateral design consists of a tapered and a ridge-waveguide section. Both have been fabricated in a standard process [13]. Fig. 1 shows a schematic drawing of the device. In addition to a low modal gain, high beam quality requires a ridge-waveguide structure with a width W_1 of about 3 µm. The length of the ridge section my be varied between 100 µm and 500 µm in steps of 100 µm. For the following experimental results laser diodes with a ridge length of 500 µm was chosen. In contrast, high output powers needs a broad pumped area, which is provided by a tapered section [5]. The tapered section length L_2 can be selected between 1500 µm and 2500 µm resulting in a width W_2 of the output facet between 160 µm and 265 µm having a taper angle of 6°.

The rear facets are coated with a highly reflective double-stack of Si and SiO_2 films (95 % reflectivity) and the front facets are anti-reflection coated by a single layer of SiN (< 1 % reflectivity). Finally the devices were mounted junction side down on standard copper heat sinks. Uniform pumping of the laser medium is achieved by current injection using homogenously spread bond wires.

3. ELECTRO-OPTICAL CHARACTERISATION

Figure 2 shows typical current-power characteristics (dots) and the wall-plug efficiencies (lines) of tapered diode lasers with different lengths of the tapered section at a heat sink temperature of 20 °C measured in continuous wave mode (cw).

The threshold currents of the devices are between 0.7 A and 0.8 A corresponding to threshold current densities of 200 A/cm^2 (L_2 = 2500 µm), 370 A/cm^2 (L_2 = 2000 µm) and 650 A/cm^2 (L_2 = 1500 µm). The values of the threshold current densities decrease with the length of the tapered section confirming the assumption of enlarged mirror losses for tapered diode lasers [10]. Theoretical simulations taken additional geometry factors of the enlarged mirror losses into account agree well with these values.

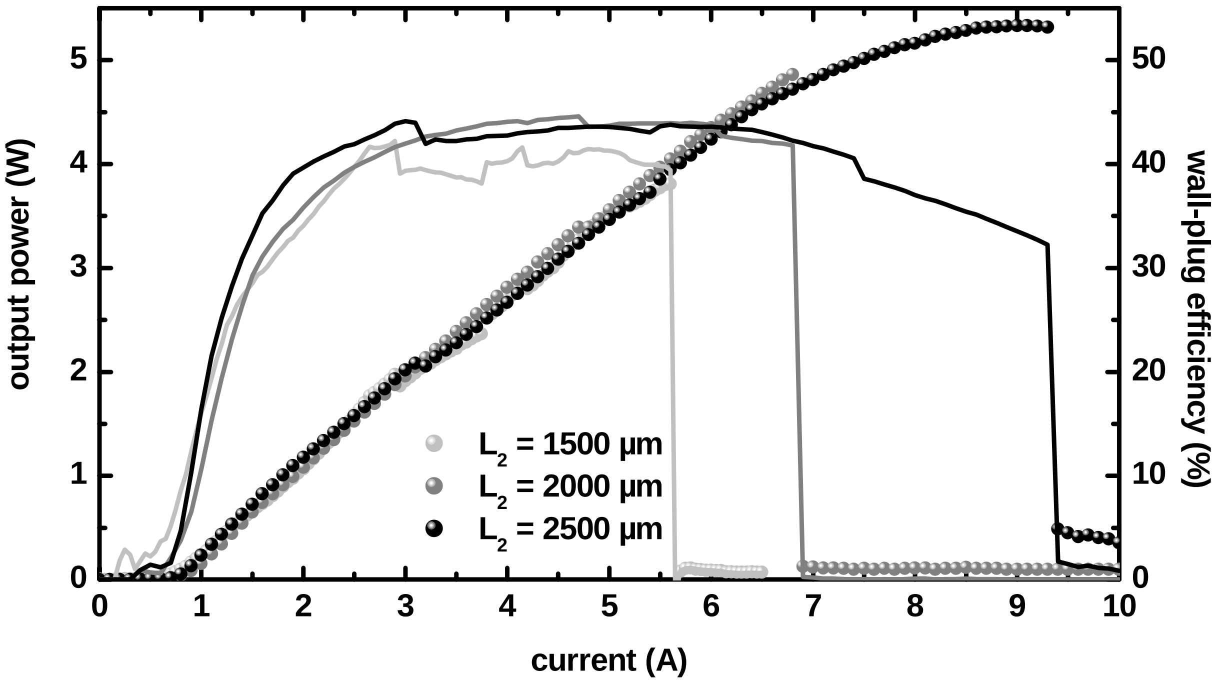

Figure 2: Typical current-power characteristics (dots) and the wall-plug efficiencies (lines) of tapered diode lasers with different lengths of the tapered section at a heat sink temperature of 20 °C measured in continuous wave mode.

In order to investigate the limitation on power of these tapered diode lasers, the driving current was ramped up to the point of sudden failure. A maximum high output power of 5.3 W is realized at a driving current of 9 A for the longest length of the tapered region (black dots). Maximum output powers of 4.9 W at 6.8 A (dark gray dots) and 3.8 W at 5.6 W (light gray dots) are achieved with the reduced lengths of 2000 µm and 1500 µm of the tapered section. High slope efficiencies up to 0.92 W/A in association with the low series resistance of about 30 mΩ for all devices result in high wall-plug efficiencies. At an output power of 2 W a maximum wall-plug efficiency of 44 % is achieved for a tapered section length of 2500 µm. For output powers of more than 3 W the wall-plug efficiency still remains above 40 % for all tapered lengths.

Above 6 A there is a thermal rollover of the current-power characteristic of the diode laser with the longest tapered section length. A catastrophic optical mirror damage at 9.3 A occurred at the front facet. In accordance to high-power broad-area diode lasers the COMD level decrease for higher threshold currents [14]. So for L_2 = 2000 µm the COMD occurred at 6.8 A and for L_2 = 1500 µm at 5.6 A. The power density at the emitting facet is estimated to be about 4 MW/cm^2 for all different tapered section lengths.

The spectral width of the emission wavelength (FWHM) was determined to be of 2 nm at 4 A. From the shift of the peak emission wavelength with driving current a total thermal resistance of 7 K/W can be deduced for the complete experimental setup including the thermoelectric cooling of the copper heat sink.

4. BEAM QUALITY

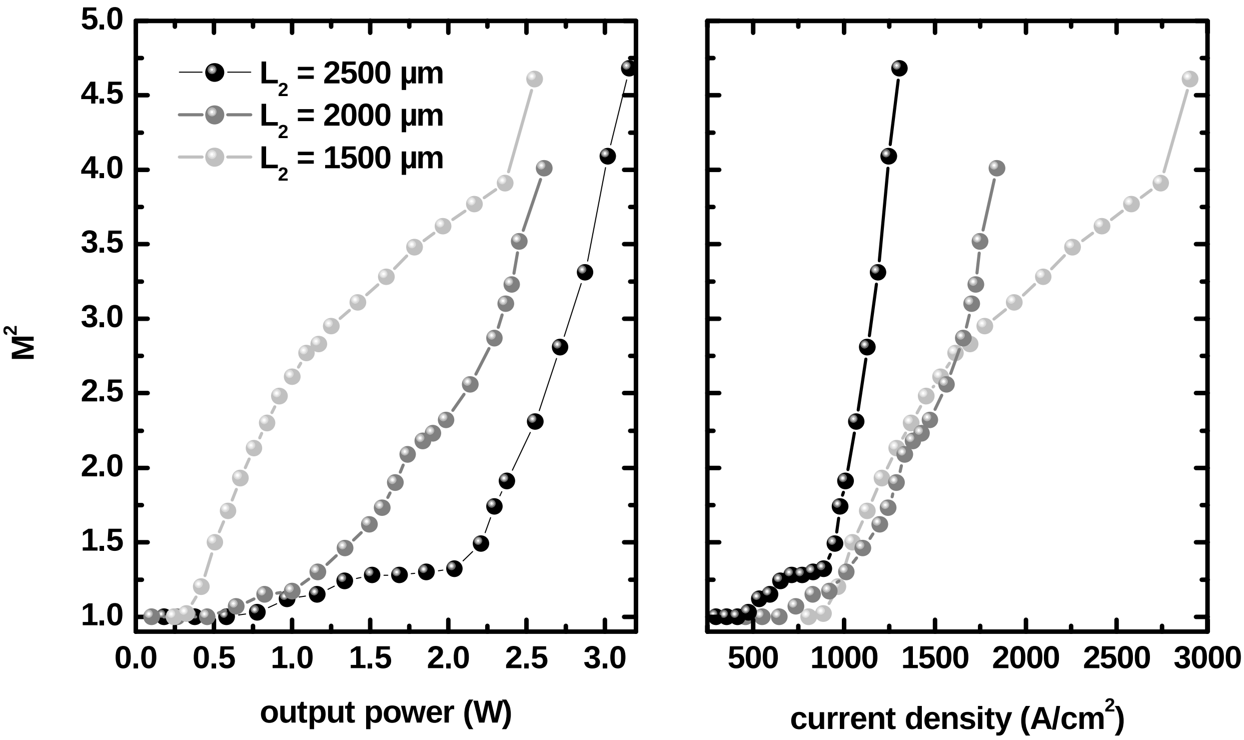

Figure 3: Dependence of the beam quality parameter M^2 on the output power and the current density for different lengths of the tapered section L_2 at a heat sink temperature of 20 °C (cw).

The beam quality parameter M^2 was measured using a commercial beam analyzing system (Mechantek Beam Scope). The dependence of the beam quality parameter M^2 on the output power and on the current density for different lengths L_2 of the tapered section is shown in Fig. 3. The length of the tapered section has a strong impact on the beam quality at high output powers. Whereas the beam quality of devices having a taper length of 2500 µm remains nearly diffraction limited up to about 2.2 W with an M^2-value of 1.3, a taper section length of 2000 µm causes M^2 to increase rapidly from a lower power level of about 1.5 W. For a taper section length of 1500 µm M^2 even increases at a much lower power level of about 0.4 W. At lower output powers M^2 is diffraction limited for all tapered lasers.

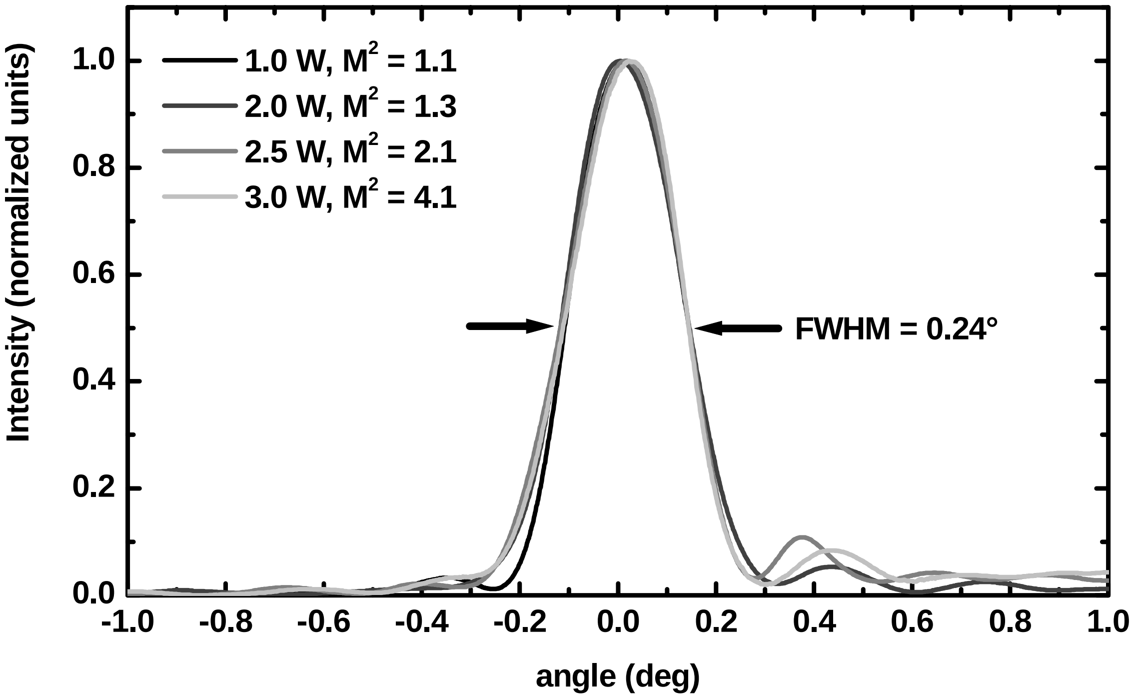

Figure 4: Dependence of the lateral far field profiles of tapered high-power diode lasers (L_1 = 500 µm, L_2 = 2500 µm) on the output power after removal of the quadratic phase curvature by a cylindrical lens at a heat sink temperature of 20 °C (cw). Additionally the measured values of M^2 are given corresponding to the output power.

As can be seen in the second part of Fig. 3, there is obviously a critical current density of about 800 A/cm^2 for the beam quality parameter M^2. Whereas below this critical current density M^2 remains nearly unchanged for the different tapered section lengths, there is a sudden increase of M^2 for higher values. The current density can be seen as a measure for the heat in the tapered structure, since the heat sources are due to nonradiative recombinations of carriers in the active layer, ohmic heating, and absorbed optical power. Such thermal nonuniformities act as seeds for filaments that distort the output phase and intensity profiles and so lead to an increase of the beam quality parameter [15, 16].

Additional experimental results published elsewhere [11] further display that the length of the ridge section L_1 also has a strong impact on the beam quality. The ridge section only works as an efficient lateral mode filter if the ridge length is at least 300 µm long.

Far field profiles of the devices were measured after correcting for the quadratic phase front divergence by using a cylindrical lens (corrected far field) [5]. An example for the evolution of the lateral far field profiles of tapered laser diodes with increasing output power can be seen in Fig. 4. A near diffraction limited and power independent far field angle of 0.24° (FWHM) is obtained for the full range of cw output powers. The measured M^2-parameters range between 1.1 at 1 W and 4.1 at 3 W of output power. The growth of side lobes at higher output powers is responsible for the increase of the beam quality parameter M^2. Conventionally beam diameters have been measured at the $1/e^2$ intensity point; i.e. at 13.5% of the maximum intensity. ISO 11146 mandates the use of a ‘Second Moment’ definition of beam diameter. For this reason the side lobes also increase the calculated beam quality factor M^2.

5. RELIABILITY

The long-term reliability of these diode lasers has been tested by aging a batch of four devices at a heat sink temperature of 50 °C. Under constant current condition at 3 A (see Fig. 5) the output power results in nearly 2 W. All devices show only gradual degradation within the first 900 hours without sudden failure. Defining a 20-%-decrease of the output power as a criterion for the lifetime and assuming activation energy of 0.35 eV, an extrapolated lifetime of more than 7,500 hours can be deduced for a heat sink temperature of 20 °C. The beam quality parameter M^2 remains unchanged after the accelerated lifetime.

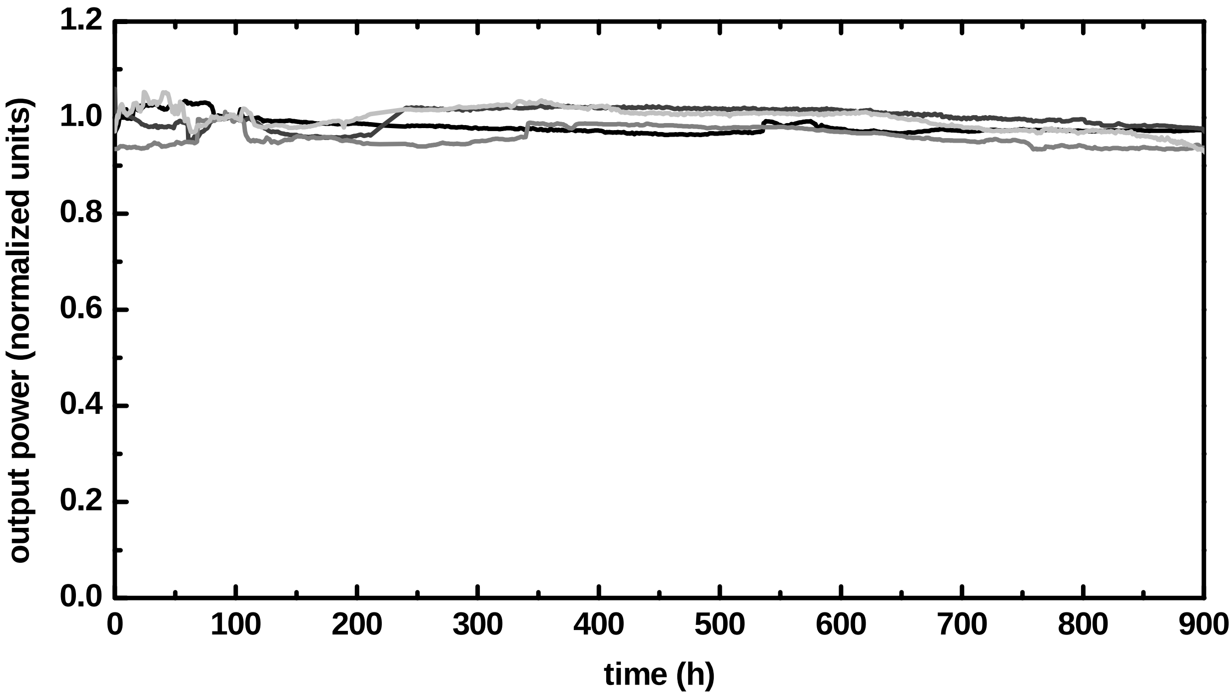

Fig. 5: Reliability test of tapered high power lasers (L_1 = 500 µm, L_2 = 2500 µm) at an output power of 1.8 W and a heat sink temperature of 50 °C. Assuming an activation energy of 0.35 eV, a lifetime of more than 7,500 h can be deduced from these data.

6. CONCLUSION

In summary, we have realized MBE-grown InGaAs/AlGaAs high-power ridge-wave guided tapered diode lasers fabricated from low-modal gain layer structures. It has been shown experimentally that the devices have to comprise a tapered section of 2000 µm or longer to reach a sufficient output power and beam quality. Tapered diode lasers with these design parameters show output powers of more than 5 W. Near diffraction limited far-field profiles could be observed up to power levels of 3 W. The beam-quality parameter of these devices remains well below $M^2 = 1.5$ for output powers up to 2.2 W. The diode lasers show extrapolated lifetimes of around 7,500 h and no decrease of the beam quality could be observed after several hundred hours of testing. The dependence of the results of the output power, the wall-plug efficiency and the beam quality on the length of the tapered section of these lasers has been shown.

In comparison to well established ridge-lasers these tapered lasers show a few times higher output powers together with comparable beam quality. This results in an increase of the brightness by a factor of two or more and makes them applicable for fiber coupling. Assuming a further increase of the lifetime these lasers might be useful as pump sources for next generation optical amplifiers in high-band width data transmission systems. Furthermore, the concept of using high-power tapered lasers can be transferred to other material systems where different wavelengths (e.g. 14xx nm) can be realized. This might be useful for more efficient Raman amplification in the S-band and L-band of standard single mode fibers and allow for further increase of the bandwidth and capacitance of DWDM transmission systems.

7. ACKNOWLEDGEMENT

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