High-Power 980 nm Laser Diodes by MBE

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Abstract

Within the last few years, high power laser diodes with remarkable improvements concerning output power, efficiency, and reliability have been investigated in the wavelength range between 780 nm and 1064 nm. A lot of the work has been focused on 980 nm, the pump wavelength of Erbium Doped Fiber Amplifiers (EDFAs). Pumping of EDFAs requires highest performance diode lasers due to extreme demands in reliability and beam quality. Up to now, the only type of diode laser used in this application 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 small stripe-width limits the reliable output power of these devices to about 300 mW resulting in a fiber coupled output power of less than 250 mW.

In the following we report on high-power 980 nm diode lasers comprising ridge and tapered sections for near diffraction limited output power in the watt regime. The devices are based on MBE grown layer structures in the AlInGaAs material system. They allow for more than 500 mW of optical power coupled into a single mode fiber. First reliability tests show extrapolated lifetimes of more than 7.500 h at an output power of 1.8 W.

Keywords: diode laser, 980 nm, EDFA, fiber coupling, high-power, high-brightness, Raman amplification

1. Introduction

Within the last years the rapid growth of the Internet 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 diodes lasers with near diffraction limited output power at 980 nm wavelength are used as pump sources. This application requires highest reliabilty performance of the devices especially in submarine optical transmission systems where less than 100 FITs (failures in time) are mandatory [1] [2] in order ensure system life times of more than 20 years. On the other hand, higher transmission speeds, longer distances between regeneration sites and the introduction of Dense Wavelength Devision Multiplex (DWDM) transmission systems require for more and more of optical pump power in the fiber amplifiers.

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 [3],[4] 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 [5], [6] which leads to a reliable fiber coupled power of less than 250 mW.

In order to increase the pump power in next generation optical transmission systems, we report on high-power 980 nm diode lasers comprising ridge and tapered sections for near diffraction limited output power in the watt regime [7],[8],[9],[10],[11]. In these devices, the single-mode ridge section serves as a lateral mode filter which 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 4 W. First reliability tests show extrapolated lifetimes of more than 7.500 h at 1.8 W together with a stable beam quality in the order of $M^2 = 2$. These devices allow for more than 500 mW of optical power coupled into a single mode fiber. Furthermore the concept of using tapered devices for near diffraction limited output power can be transferred to the wavelength regime of 14xx nm [12] allowing for more efficient Raman amplification in the S-band and L-band of standard single mode fibers [13].

2. Epitaxial Layer Structure

The fabrication of high power lasers with high conversion efficiency requires an epitaxial layer sequence with both, low internal losses (< 2 /cm) and high internal conversion efficiency (> 0.9). The reduction of the internal losses can be achieved by broadening the waveguide layers [14]. This reduces the overlap of the optical mode with the highly doped cladding layers. For this purpose we have grown a laser structure with a large optical cavity by molecular beam epitaxy (MBE). The epitaxial layer sequence, similar to those reported in [10], is shown schematically in fig. 1. The active region consists of a single InGaAs-quantum well embedded in a 880 nm thick AlGaAs core region with 20 % Al content. The quantum well is 7 nm thick with a nominal In content of 20 %. The optical waveguide is formed by 1 μm thick AlGaAs claddings with 40 % Al. Si and Be have been used for n- and p-type doping, respectively. The doping concentrations start at a level of $5 \times 10^{17}\,cm^{-3}$ near the core and increase to a level of $2 \times 10^{18}\,cm^{-3}$ in the outer cladding regions. The GaAs cap layer is heavily p-doped ($6 \cdot 10^{19} cm^{-3}$) in order to reduce the contact resistance.

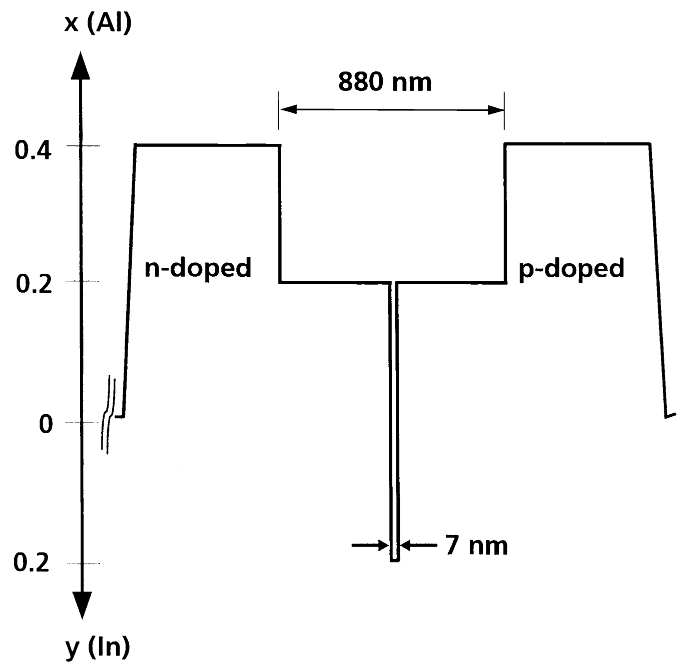
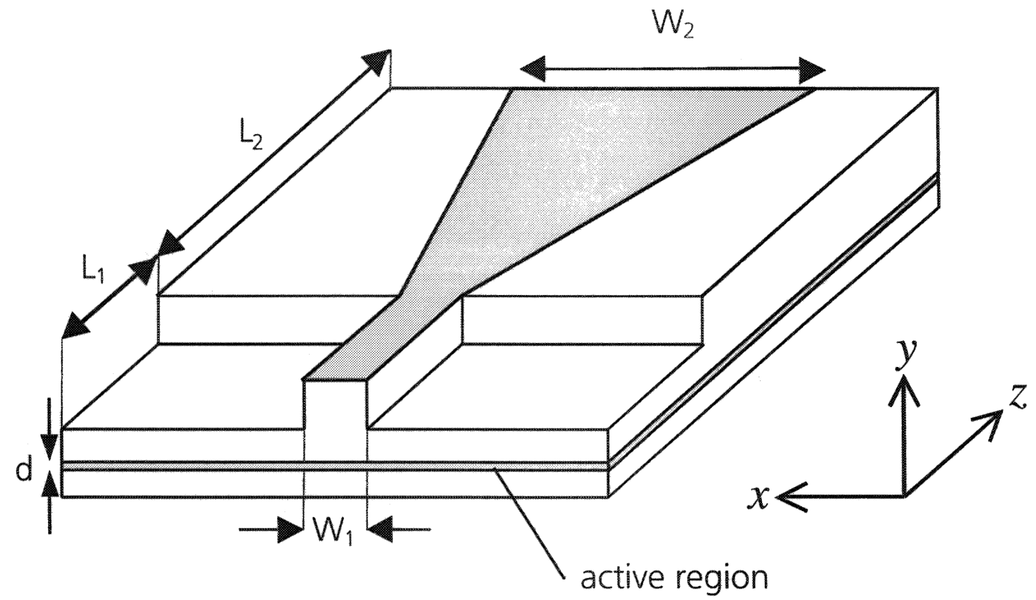


Fig. 1: Epitaxial layer structure of the InAlGaAs high power laser diodes. For 980 nm emission wavelength, the active region is built by a single 7 nm wide quantum well with 20 % of Indium content. A strong carrier confinement is achieved by use of high-band-gap AlGaAs core layers with 20 % of Al content ($E_g = 1.68$ eV).

The layer design 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 [15]. 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 are obtained from Fabry-Perot laser diodes 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. Experimentally, a characteristic temperature of $T_0 = 160$ K is observed for area diode lasers in the temperature range between 15 °C and 80 °C.

3. Device Fabrication

From this material diodes lasers comprising ridge sections as well as tapered sections have been fabricated in a standard process [16]. Fig. 2 shows a schematic of the devices. The length of the ridge section is L_1 = 500 μm, whereas the length of



Fi. 2: Schematic of a tapered laser diode ridge section for mode filtering. The total length of the device is 3 mm.

the tapered section is L_2 =2.5 mm resulting in a total device length of 3 mm. The output facet has a width of approximately 250 μm. The rear facets are coated by a highly reflective double-stack of Si and SiO_2 (95 % reflectivity) and the front facets are anti-reflection coated by a single layer of SiN (< 1% reflectivity). Finally the devices are mounted p-side down on copper C-mounts with indium solder. Uniform pumping of the laser medium is achieved by current injection via bond wires.

4. Experimental Results

Fig. 3 shows the L-I-characteristic of a tapered laser diode together with the conversion efficiency at a heat sink temperature of 20 °C. The device shows a low threshold current of 1 A corresponding to a threshold current density of 300 A/cm^2. A maximum output power of 4.1 W is achieved at a driving current of 6 A. No catastrophic optical mirror damage (COMD) occurs at this power level. The maximum slope efficiency of 0.8 W/A gives a maximum differential quantum efficiency of η_d = 0.86. This, together with the low series resistance of 30 mΩ results in a high conversion efficiency. At 3 W of output power a maximum conversion efficiency of 43 % is achieved and even at the highest output power the efficiency remains above 40 %. The emission wavelength of the device has a spectral width (FWHM) 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 C-mount heat sink.

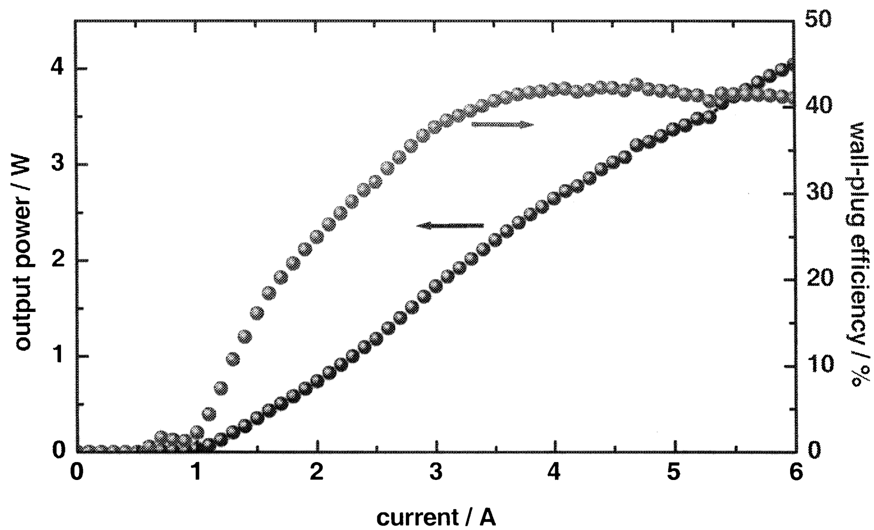


Fig. 3: L-I-characteristic and conversion efficiency of a tapered laser diode with 3 mm resonator length.

5. Reliability

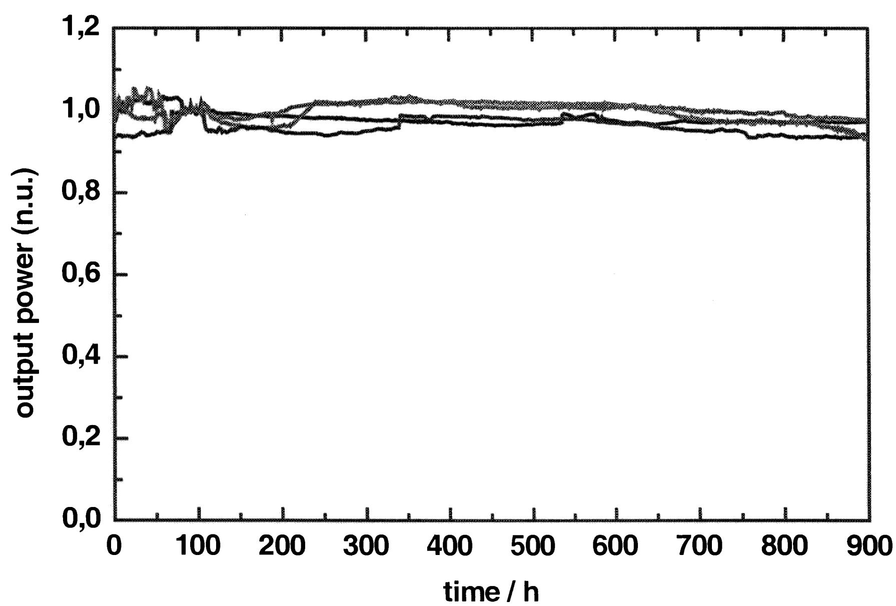


Fig. 4: Reliability test of tapered high power lasers at an output power of 1.8 W and a heat sink temperature of 50 °C. Assuming an activation energy of 0.35 eV, a lifetime of more than 10.000 h can be deduced from these data.

Fig. 4 depicts the result of a first reliability test of these devices operated at a constant current of 3 A (1.8 W of output power) and a heat sink temperature of 50 °C. A device lifetime of 10.000 h can be deduced from the measured data assuming an activation energy of 0.35 eV and a 20 % decrease of the output power as the criterion for the end of life. The devices were tested without screening and no sudden COMD occurred during the test.

6. Beam quality

In order to investigate the beam quality of tapered laser oscillators, the beam quality parameter M^2 was measured after ISO 11146 with a commercial beam analyzing system (Merchantek Beam Scope). The dependence of the beam quality parameter M^2 on the output power is shown in fig. 5 with the lengths of the ridge sections as additional parameter. A beam quality factor as low as $M^2 = 2$ is achieved at an output power of 2 W and even at an output power of 3 W the beam quality factor can be in the range of $M^2 = 3$. The experimental results further show that the length of the ridge section has a strong impact on the beam quality at high output powers. For a ridge length of 100 μm the beam quality starts to decrease at a power level of P = 1W. In contrast to this result, the beam quality of the devices with ridge lengths of more than $L_l =$ 300 μm remain in the range of $M^2 = 3$ up to about 3 W of output power.

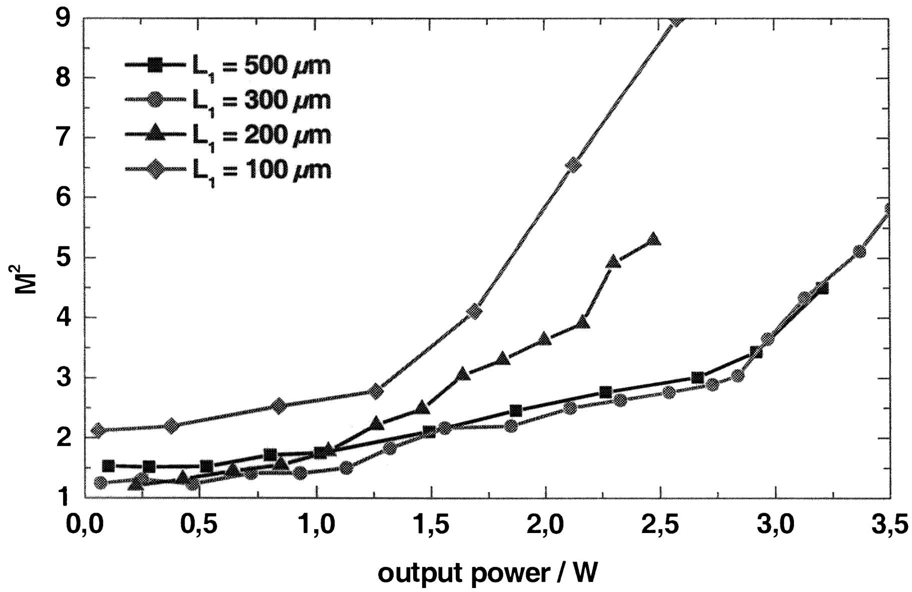


Fig. 5: Dependence of the beam quality parameter M^2 on the output power and the length of the ridge section L_l of high-power tapered laser diodes.

Farfield profiles of the devices were measured after the removal of the quadratic phase front divergence by a cylindrical lens [17]. An example for the evolution of the beam profiles with increasing output power is given in fig. 6. A near diffraction limited and power independent farfield angle of 0.24° (FWHM) is obtained up to an output power of 3 W. The measured M^2-parameters range between a value of $M^2 = 1.2$ at 500 mW and a value of $M^2 = 3.1$ at 3 W of output power. The increase in the M^2-parameter is predominantly caused by the raise of side lobes at high output powers. In the M^2- measurement these side lobes increase the $1/e^2$ width of the fitted gauss profile thereby increasing the calculated beam quality factor M^2, although the farfield angle at the FWHM-level remains at a constant value. At the highest output power, the power content of the side-lobes has been estimated to be less than 20 % of the total power.

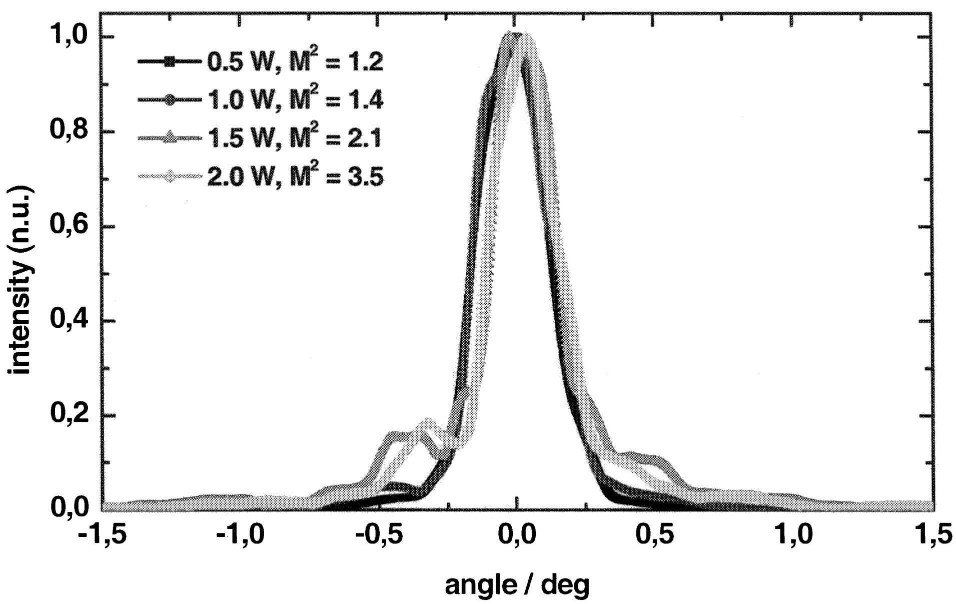


Fig. 6: Dependence of the lateral farfield profiles of tapered high power diode lasers after removal of the quadratic phase curvature by a cylindrical lens.

6. Fiber coupling

The high beam quality of tapered lasers easily allows a high efficient coupling of the emitted optical power into a optical fibers. The experimental setup used for the fiber-coupling comprises a f = 6.5 mm spherical lens for collimating in the vertical dimension of the output power, a. cylindrical lens of f = 200mm for the correction of the strong astigmatism between the gain guided lateral mode profile in the tapered section and the index guided vertical mode profile. With these two lens the beam profile is collimated in both dimensions to a beam diameter of approximately 0.5 cm. The optical power is then focused by a second spherical lens on an optical fiber with 7.7 μm core diameter and a numerical aperture of N.A. = 0.12. This fiber is single mode for a wavelength higher than 1060 nm. Therefore, it is guiding more than one mode at the emission wavelength of the diode laser.

More than 500 mW of optical power could be coupled into this fiber at an output power of 1 W of the tapered diode laser. At this power level the beam quality parameter was $M^2 = 2$. Fig.7 shows the caustic of the optical beam after the 5 m long fiber and collimation by a third spherical lens. The beam quality parameter of the output power of the fiber was determined to be $M^2 \approx 1.8$ which can attributed to the multimode behavior of the fiber below a wavelength of 1060 nm.

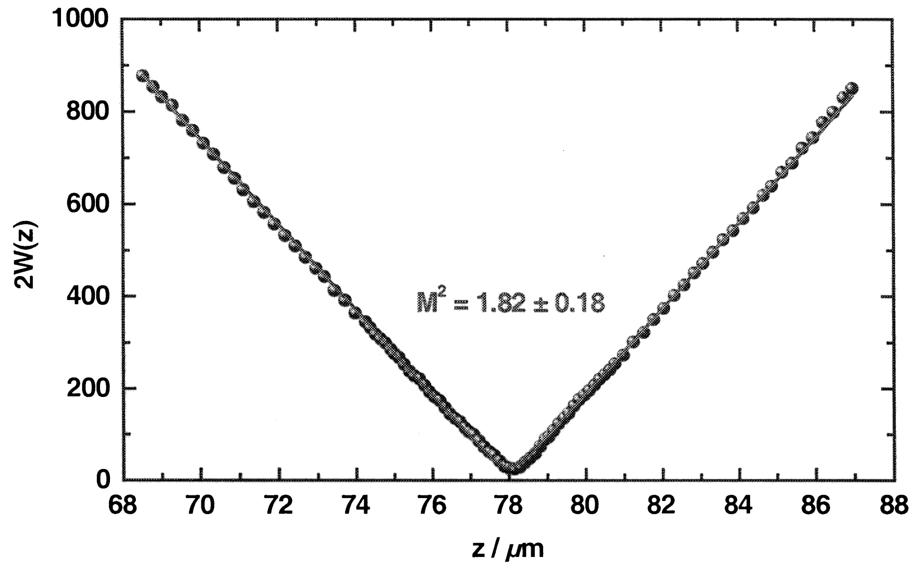


Fig. 7: Caustic of the optical beam after the fiber at a power level of 500 mW. The determined beam quality factor is $M^2 = 1.8$.

7. Conclusion

In conclusion, we have demonstrated MBE-grown InAlGaAs high-power tapered diode lasers with extremely high brightness. Typical devices comprise a 2.5 mm long tapered section together with a 500 μm long ridge section. At an output power of 3 W cw the beam quality parameter of these devices is in the range $M^2 = 3$. The diode lasers show extrapolated lifetimes of around 10.000 h and no decrease of the beam quality could be observed after several hundred hours of testing. The dependence of the quality on the length of the ridge section of these lasers has been shown. Finally, more than 500 mW of optical power could be coupled into a fiber with a core diameter of 7.7 μm.

Compared to well established ridge-lasers for pumping of optical amplifiers these tapered lasers show a threefold increase of output power together with comparable beam quality. This results in an increase of brightness by at least factor of two and enables high coupling efficiencies into single mode fibers. Assuming further increased lifetimes these lasers might be useful as pump sources for next generation optical amplifiers in high-bitrate data transmission systems. Furthermore, the concept of using high-power tapered lasers can be transferred to the 14xx nm wavelength regime allowing for more efficient Raman amplification in the S-band and L-band of standard single mode fibers and further increasing the bandwidth and capacitance of DWDM transmission systems.

8. Acknowledgement

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