High-brightness 1040 nm tapered diode laser

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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 1040 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 of 2.5 mm. An output power of more than 11 W in qcw mode, lifetimes of more than 20,000 h and a record value for the beam quality factor M^2 of less than 1.5 up to a cw output power of 3.5 W are achieved resulting in an improved brightness of more than 255 MW/(cm^{2}sr). In addition an external-cavity diode laser including a ridge-waveguide tapered amplifier structure is demonstrated to emit more than 2 W cw. The wavelength is tunable over a 60 nm range centered at 1020 nm. The beam quality parameter M^2 remains below 1.4 for output powers of 1 W over the whole range demonstrating the nearly diffraction limited behaviour.

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 molecular spectroscopy, fiber optic communication systems and nonlinear frequency conversion for laser TV. Most of these applications require high output powers in combination with very high beam qualities. Today broad-area diode lasers are used to achieve high outputs. But standard broad-area waveguide designs are susceptible to modal instabilities, filamentation and catastrophical optical mirror damage (COMD) failure. This results in low beam qualities and values for the brightness limited around 10 MW/(cm^{2}sr). On the other hand high beam qualities are realized with ridge-laser emitting in a diffraction limited optical beam. The reliable output power of these lasers is mainly limited by the onset of facet degradation which depends on the power density on the facet [1]. Due to the small stripe width of a few microns, the output power is limited to about 350 mW [2] resulting in a brightness of less than 30 MW/(cm^{2}sr). In this paper we present high-power diode lasers comprising ridge and tapered sections for near diffraction limited output power in the multiwatt regime optimized for the wavelength range around 1040 nm. The brightness has been improved by a factor of more than 20 in comparison to broad-area devices. Details of the structure, as well as the light-current characteristics and a careful analysis of the beam quality are reported.

Several of the applications mentioned above, such as the pumping of rare-earth-doped fibre amplifiers, tunable frequency doubling of diode lasers for blue-green outputs, and nonlinear spectroscopy, necessitate diffraction-limited tunable narrow linewidths and high output powers in the 1 W regime. The tapered amplifier gain-guided design [3] has been shown to be very effective to achieve high output powers in a single-lobed diffraction-limited beam in a variety of material systems [4]. Based on the developed tapered diode lasers we report on a tapered semiconductor external-cavity laser with diffraction limited output powers of more than 1 W over a 60 nm wavelength range.

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2. LASER STRUCTURE

The fabrication of high-power diode lasers with high conversion efficiency requires an epitaxial layer sequence with both, low internal losses of less than 1.5 cm^{-1} and high internal conversion efficiency (> 0.9). The reduction of the internal losses can be achieved by broadening the waveguide layers in combination with an optimized doping profile [3]. For this purpose we have grown an InGaAs/AlGaAs laser structure with a large optical cavity by molecular beam epitaxy (MBE) on n-GaAs substrates. The vertical layer design is similar to that presented in [5]. The active In$_{0.25}$Ga$_{0.75}$As quantum well with a thickness d of 8.3 nm is embedded in Al$_{0.2}$Ga$_{0.8}$As waveguides and Al$_{0.4}$Ga$_{0.6}$As cladding layers. So the emitting wavelength is 1040 nm. A highly doped p-GaAs contact layer completes the layer sequence. The lateral design consists of a tapered and a ridge-waveguide section. Both have been fabricated in a standard process [5]. In addition to a low modal gain, high beam quality requires a ridge-waveguide structure with a width W$_1$ of about 3 μm and a ridge length L$_1$ of 500 μm [3]. In contrast, high output powers need a broad pumped area, which is provided by a tapered section [6]. The tapered section length L$_2$ was chosen to be 2000 μm resulting in a width W$_2$ of the output facet of 200 μm. The taper angle is 6°. Fig. 1 shows a schematic of the device.
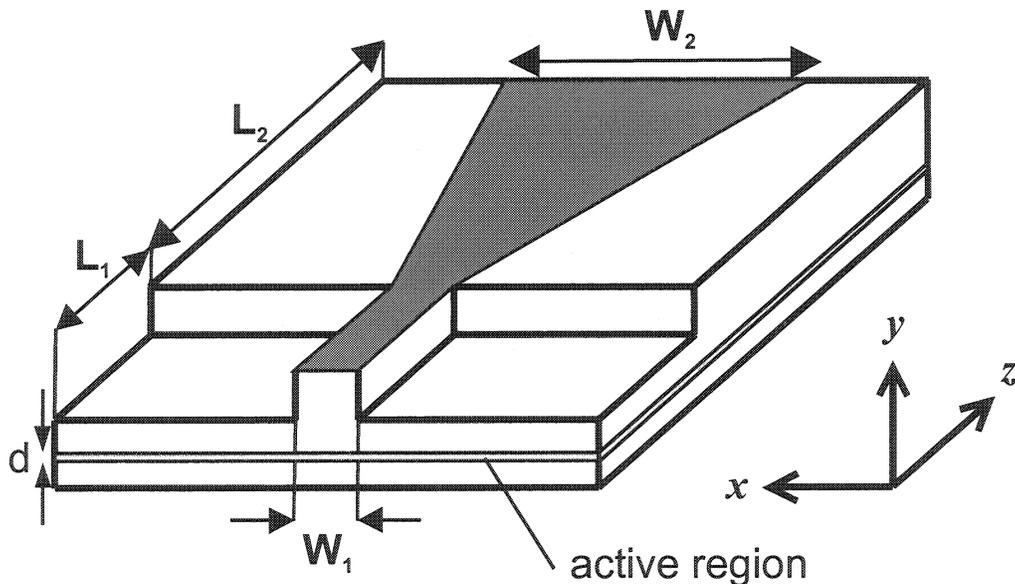

Figure 1: Schematic of a tapered diode laser with a ridge waveguide for mode filtering. The length of the ridge section L$_1$ is 500 μm, whereas the length of the tapered section L$_2$ is 2000 μm resulting in a total device length of 2.5 mm. The taper angle is 6°.

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 (0.5 % reflectivity). The devices were finally 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

Fig. 2 shows a typical current-power characteristic (dots) and the wall-plug efficiency (line) of a tapered diode laser at a heat sink temperature of 20 °C measured in continuous wave mode (cw). The threshold current of the device is 0.65 A corresponding to a threshold current density of 300 A/cm^2. A high output power of nearly 4 W is realized at a maximum driving current of 6 A, limited only by the current source. A homogeneous slope efficiency of 0.76 W/A without a

thermal rollover in association with the low series resistance of about 50 mΩ results in wall-plug efficiencies of more than 40 %, which are high values for tapered lasers owing to the additional radiation losses caused by the tapered cavity. At an output power of 2.5 W a maximum efficiency of 41 % is achieved and still remains above 39 % up to 4 W.
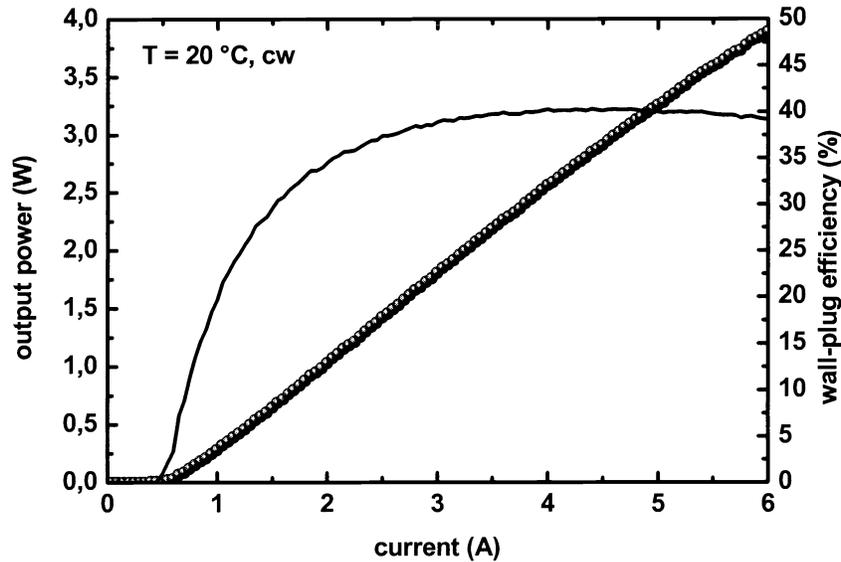

Figure 2: Typical current-power characteristic (dots) and wall-plug efficiency (line) of a tapered diode laser emitting at 1040 nm at a heat sink temperature of 20 °C measured in continuous wave mode (cw).
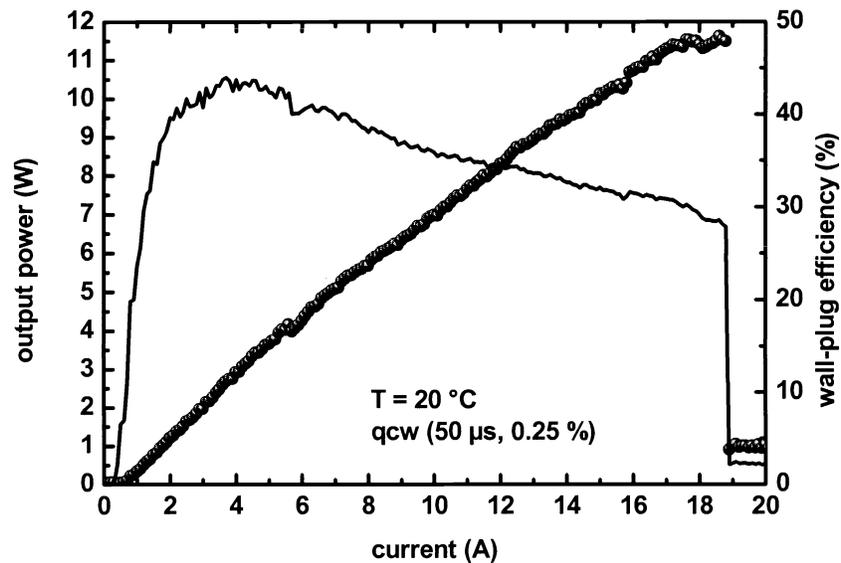

Figure 3: Typical current-power characteristic (dots) and wall-plug efficiency (line) of a tapered diode laser emitting at 1040 nm at a heat sink temperature of 20 °C measured in quasi continuous wave mode (50 μs, 0.25% duty cycle).

In order to investigate the limitation on the output power of these tapered devices, the driving current was ramped up in quasi continuous wave mode (qcw) to the point of sudden failure (Fig. 3). The pulse time was 50 μs, the duty cycle 0.25 %. A record of 11.6 W output power for tapered diode lasers is achieved at a driving current of 18.5 A. A catastrophic optical mirror damage occurred at 18.8 A at the front facet. The power density at the emitting facet is estimated to be about 6 MW/cm^2, which is quite comparable to broad-area diode-lasers [7].

The long-term reliability of these diode lasers has been tested by aging a batch of six devices at a heat sink temperature of 50 °C. Under constant current condition at 4 A (see Fig. 4) the output power is 2 W. All devices show only gradual degradation within the first 1100 hours without sudden failure. Defining a 20-%-decrease of the output power as a criterion for the lifetime, an extrapolated lifetime of more than 10,000 hours can be deduced for a heat sink temperature of 50 °C. Under a cautious assumption of 0.2 eV for the activation energy, a lifetime of more than 20,000 hours can be deduced from these data. The beam quality parameter M^2 remains unchanged after the accelerated lifetime test.
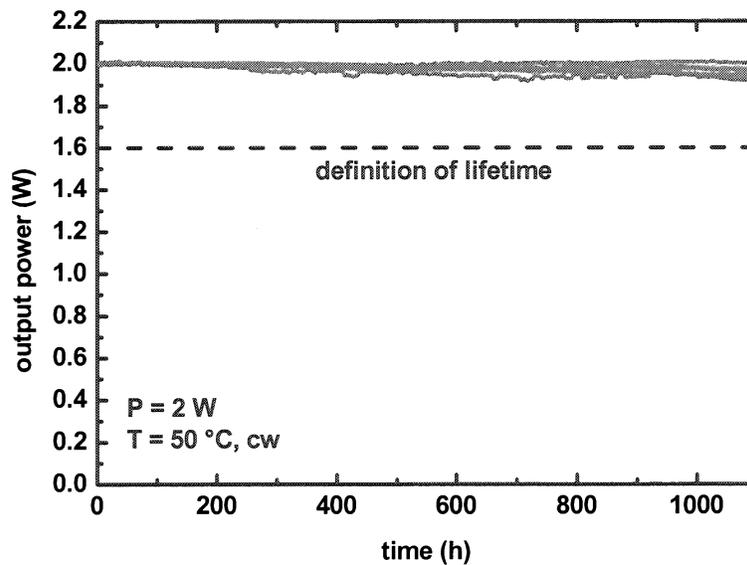

Figure 4: Reliability test of a batch of six tapered diode lasers at an output power of 2 W and a heat sink temperature of 50 °C. A lifetime of more than 20,000 h can be deduced from these data at 20 °C.

4. BEAM QUALITY

With growing output facet reflectivity, an increasing percentage of the optical field is reflected into the resonator, enhancing the formation of dynamically varying longitudinal and transverse structures in the intensity distribution [4]. So it is meaningful to reduce the facet reflectivities to less than 0.1% [3] to avoid such a phenomenon. But there also exists the dependence of the filamentation process on the linewidth enhancement factor α_H. α_H itself depends strongly on the carrier density and therefore on the threshold current density [8]. So it may be advantageous to accept higher facet reflectivities to lower the threshold current density. Here the facet reflectivity was chosen to be 0.5%. A measurement of a tapered diode laser with a tapered section length of 1500 μm and a ridge section length of 500 μm with this facet reflectivity leads to a value of around 1.5 for the linewidth enhancement factor. This means a reduction of the linewidth enhancement factor by a factor of 2 in comparison to the same tapered device having a reflectivity of less than 0.1% [8]. Thus the beam quality has been carefully investigated to demonstrate any improvements.
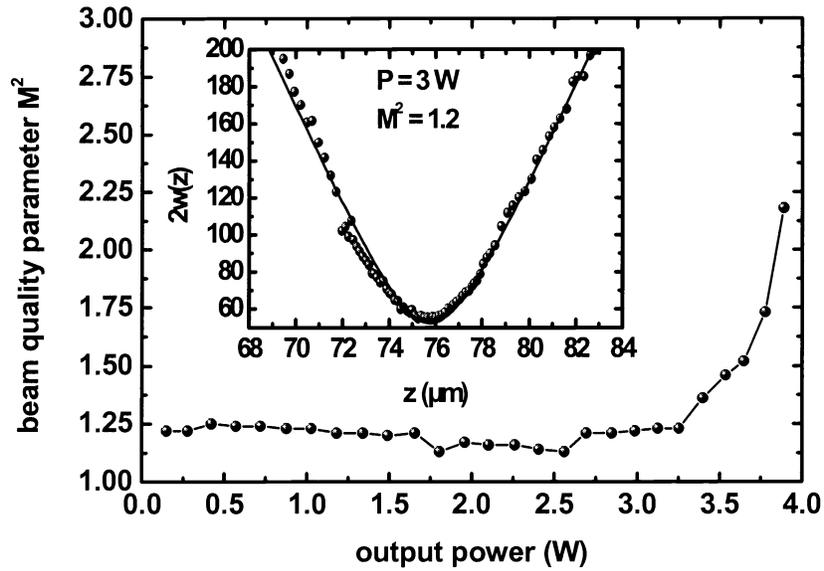
Figure 5: Dependence of the beam quality parameter M^2 on the output power at a heat sink temperature of 20 °C (cw). The inset shows as an example the fit curve of M^2 for an output power of 3 W. A value of 1.2 for M^2 is reached.
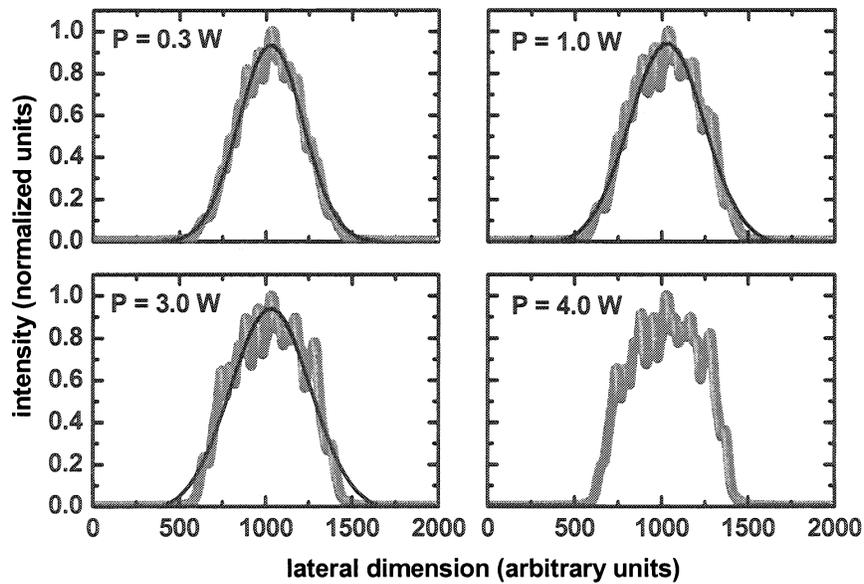

Figure 6: Dependence of the near field profiles on the output power at a heat sink temperature of 20 °C (cw). The gaussian like fit curves demonstrate the diffraction limited behaviour of the tapered diode lasers up to 3 W.

The beam quality parameter M^2 was measured in dependence on the output power using a commercial beam analyzing system (Fig. 5). M^2 remains nearly diffraction limited up to about 3.5 W with values below 1.5. Higher output powers

cause M^2 to increase rapidly, but even at nearly 4 W output power we have record values of around 2 for M^2. Such beam qualities at these output powers result in a very high brightness of 255 MW/cm^{2}sr.

Fig. 6 shows the dependence of the beam profile at the facet (near field) on the output power for a tapered diode laser. Up to 3 W the near field profiles can be described with gaussian curves demonstrating the diffraction limited behaviour. For higher output powers filamentation effects slightly occur. Far field profiles of the devices were measured after correcting the quadratic phase front by using a cylindrical lens [4]. An example for the evolution of the lateral far field profiles of tapered laser diodes with increasing output power can be seen in fig. 7. A near diffraction limited and power independent far field angle of 0.43° (FWHM) is obtained for the full range of cw output powers demonstrating the high beam quality.
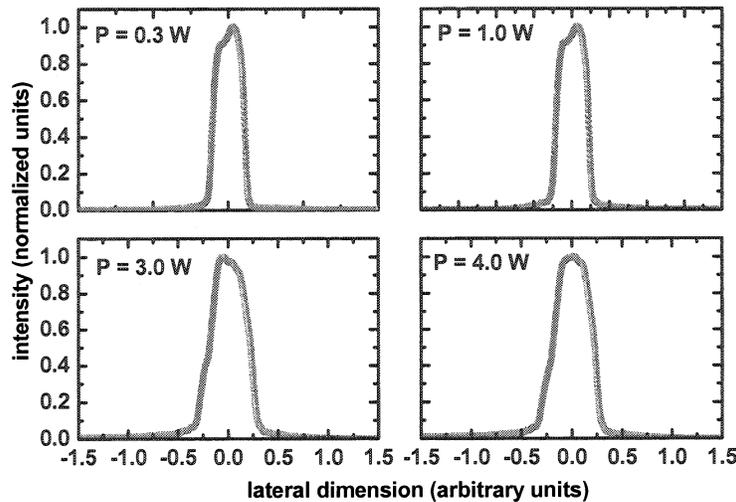

Figure 7: Dependence of the corrected far field profiles on the output power at a heat sink temperature of 20 °C (cw). A diffraction limited and power independent far field angle of 0.43° (FWHM) is obtained.

5. TUNABLE LASERS

Many applications, such as tunable frequency doubling of diode lasers for blue-green outputs or nonlinear spectroscopy, necessitate narrow linewidths. This cannot be achieved with ordinary tapered diode lasers, which have a linewidth of more than 4 nm (Fig. 8). With the help of external cavity configurations the linewidths can be reduced to less than 0.1 nm [9, 10].

For this purpose both facets are highly anti-reflection coated to suppress parasitic oscillation. The external cavity, consisting of a 6.5 mm focal length collimating lens and an 1200 mm^{-1} holographic diffraction grating in the Littrow configuration [11, 12], selects the wavelength of laser operation by dispersing the diffracted light parallel to the junction plane. The 3 μm opening acts as a aperture to capture light at the lasing wavelength, whereafter it is amplified in the broad tapered stripe. The length of the ridge section helps to improve the beam quality by working as a mode filter and additionally pre-amplifies the light. After reflection at the output facet, a small amount of the amplified beam is recaptured by the waveguide, seeding the oscillation.
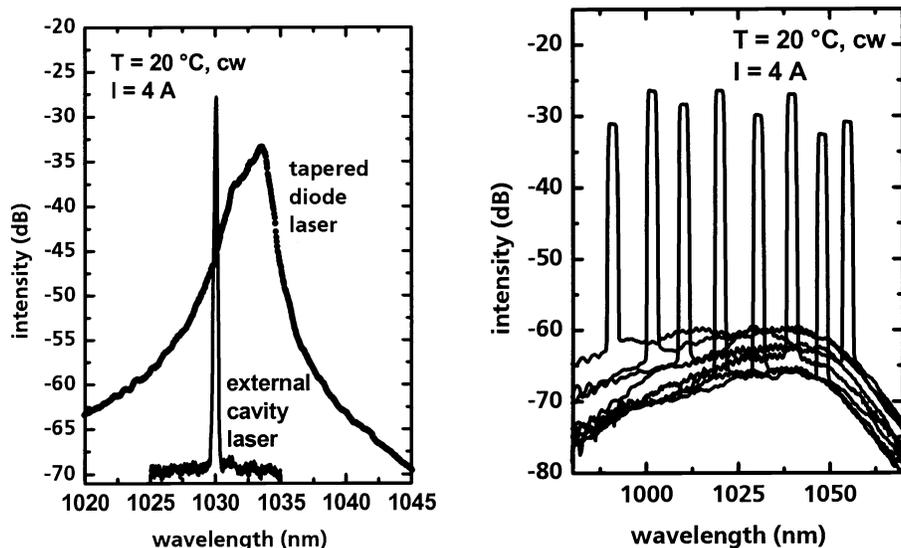
Fig. 8: Tunable wavelength spectrum of an external cavity laser in comparison to a wavelength spectrum for a tapered diode laser at 1 W output power and a heat sink temperature of 20 °C (on the left, Δλ = 1 nm). The external cavity laser is tunable from 895 nm to 960 nm (on the right, Δλ = 0.08 nm).
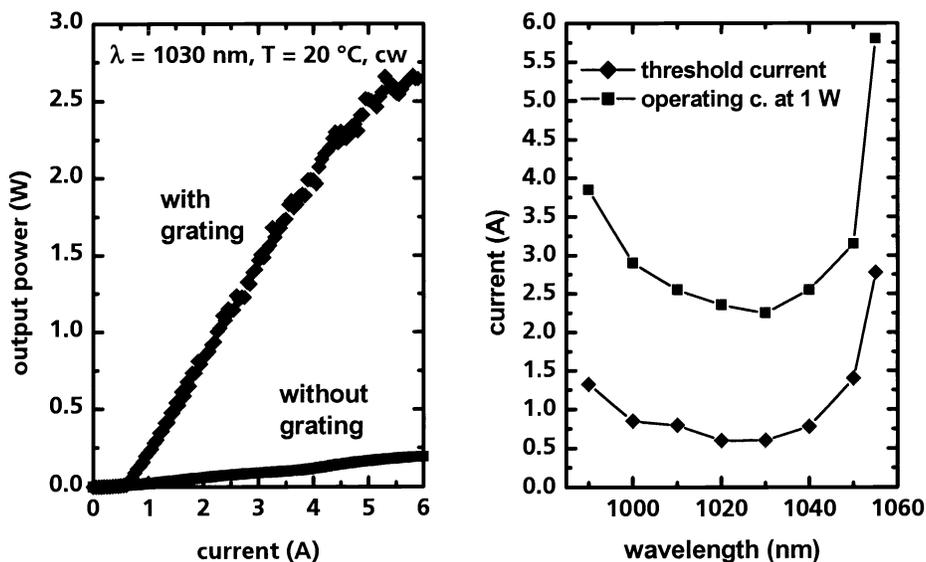

Figure 9: Current-power curve of tunable laser at 1030 nm wavelength and 20 °C heatsink temperature (on the left). Measured threshold current and 1 W operating current against tuned wavelength (on the right).

The linewidth and spectral tuning characteristics of the tunable diode laser were studied with an Optical Spectrum Analyzer HP70950B. As can be seen in fig. 8, the diode laser is tunable from 990 nm to 1055 nm. The spectral width was limited by the 0.1 nm resolution of the spectrum analyser, however it shows a sidemode suppression of more than 35 dB. The current-power curve of the external cavity laser operating at 1030 nm exhibited a threshold of 0.6 A and a

slope efficiency of 0.60 W/A up to twice the threshold current resulting in a 2.6 W cw output power for 6 A (Fig. 9). By comparison, 0.2 W of output power is obtained at 6 A when the grating feedback is blocked. In addition the tuning curve for the threshold current and 1 W operating current is shown. The slope efficiency remains nearly constant over the entire 60 nm tuning range.

The dependence of the beam quality parameter M^2 on the tuned wavelength for an output power of 1000 mW is shown in fig. 10. The beam quality of the devices remains nearly constant over the tuning range for an output power of 1 W. Also the beam is nearly diffraction limited in this range with M^2 values of less than 1.4.
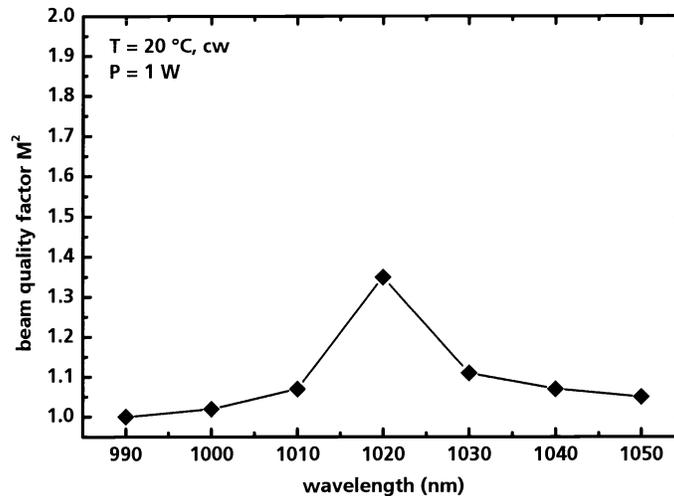

Figure 10: Beam quality parameter M^2 against tuned wavelength at a heat sink temperature of 20 °C for a constant output power of 1 W over the tuning range.

6. CONCLUSION

In summary, we have realized MBE-grown InGaAs/AlGaAs high-power ridge-waveguided tapered diode lasers emitting at 1040 nm. These diode lasers show output powers up to 4 W in cw mode and record values of 11.5 W in quasi cw mode. The beam-quality parameter remains well below record values of $M^2 = 1.5$ for output powers up to 3.5 W demonstrating a near-diffraction limited behaviour. Because of the very high brightness, this type of diode laser is promising for medical applications and the pumping of fiber lasers. Using these lasers with external cavity configurations, a small spectral bandwidth can be reached and so these lasers are also well suited candidates for nonlinear frequency conversion needed for laser TV applications.

The broad linewidth of tapered diode lasers of more than 4 nm can be reduced to less than 0.1 nm with the help of external resonator designs. So we have realized MBE-grown InGaAs/AlGaAs high-power ridge-wave guided tapered diode laser tunable over a 60 nm span centered at 1020 nm. These external-cavity diode laser show output powers of more than 1 W. The beam-quality parameter of these devices remains well below $M^2 = 1.4$ for output powers up to 1 W.

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 more than two 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.

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