Invited Paper

High power, single mode 980 nm DBR tapered diode lasers with integrated 6[th] order surface gratings based on simplified fabrication process

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ABSTRACT

We report on distributed Bragg reflector tapered lasers having 6th order surface gratings and ridge waveguides simultaneously fabricated by wafer stepper lithography and reactive ion etching. Single longitudinal mode emission at 978 nm and a beam propagation ratio of $M^2 = 1.1$ at 4.4 W have been obtained in quasi-continuous wave operation. In CW operation, a maximal output power of 2.5 W with a side-mode suppression ratio of more than 20 dB and a beam propagation ratio of $M^2 < 1.4$ for the central lobe has been achieved.

Keywords: high brightness, DBR laser, multisegment laser, tapered diode laser, high-power, diffraction limited radiation

1. INTRODUCTION

Compact single-frequency and high-brightness lasers sources are key components in emerging laser technologies such as space communication, optical frequency conversion [1], optical radar, and others. A monolithic distributed Bragg reflector (DBR) tapered laser with a grating integrated into the semiconductor chip is a promising candidate for these applications [2, 3]. This device contains a straight ridge waveguide (RW) section and a tapered gain guided section. The straight RW section consists itself of a passive DBR section located at the rear facet and of an active gain section. In Ref. [2] and [3], the grating was incorporated into the layer structure by means of an epitaxial growth in two steps. In contrast, in [4] a technology was reported where the grating is formed as a surface grating, etched into the p-contact, p-cladding and part of the p-waveguide layer. Due to the use of higher (6th and 7th) order gratings with periods around 1 µm, the gratings and the RW can be simultaneously processed using I-line wafer stepper lithography and reactive ion etching. The distributed Bragg reflectors fabricated in such a way exhibit a sufficient reflectivity to ensure single longitudinal mode operation of DBR RW lasers as demonstrated in [4]. Thus, this technology enables an inexpensive manufacture of frequency-stabilized diode lasers.

In this paper, we report on DBR tapered lasers where a 6th order surface grating as described above was employed as Bragg reflector. In the device under study, the current through the active part of the RW section and through the tapered section can be adjusted separately, which allows an independent control of output power, stability of laser frequency, beam quality and moreover a simplified modulation of the output power [5].

2. DEVICE FABRICATION

The vertical laser structure grown by metal-organic chemical vapour phase epitaxy consists of an optical cavity with a 0.5 µm thick $Al_{0.50}Ga_{0.5}As$ waveguide embedded in $Al_{0.53}Ga_{0.47}As$ cladding layers. The active region is composed of a compressively strained InGaAs single quantum well sandwiched between tensile-strained GaAsP barriers. The internal efficiency is larger than 95% and the internal losses are about 2.0 cm^{-1}. Both values are determined from an analysis of the cavity-length dependence of threshold current and external differential efficiency of equivalent broad area (BA) lasers.

Aiming to an emission wavelength of 976 nm, a period of 909 nm was chosen for the 6th order Bragg grating. This period is large enough, that it can be very precisely defined over the whole wafer by an I-line wafer stepper providing a resolution limit of 400 nm. The processing of the lasers started with the deposition of a 600 nm thick photoresist layer and a subsequent exposure by the I-line wafer stepper to define both the RW and the Bragg grating structures at the same time. The width of the RW was chosen to 3 µm. After developing the photoresist, the grating and RW structures were simultaneously transferred into the epitaxial layer structure with a reactive ion etching (RIE) process using a BCl_3/Ar plasma. In order to ensure a sufficient reflectivity of the 6th order grating the effective index step between the etched and unetched areas has to be sufficiently large and the duty cycle has to range between 0.9 and 1.0 [2]. Therefore, an etch depth of about 2 µm was selected for an effective index step of about $\Delta n_{eff} = 15 \cdot 10^{-3}$. In order to achieve the desired duty cycle, the etching parameters were chosen in such a way, that V shaped grooves were obtained (compare Fig. 1). Furthermore, the length of the grating was set to L_{DBR} = 1 mm. According to simulations, the reflectivity of this DBR should be larger than 80%.

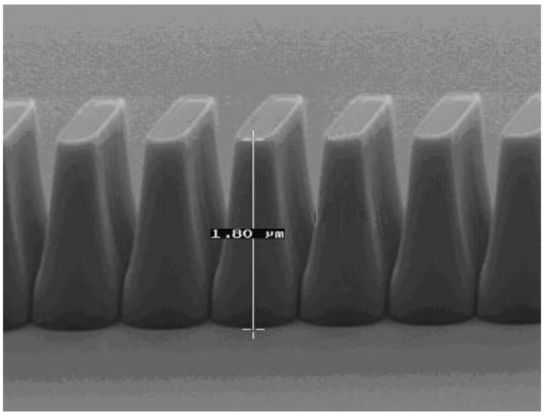

Figure 1. Scanning electron microscope picture of the dry-etched RW section with Bragg grating .

The tapered section was defined by wet chemical etching of the surrounding contact layer and deposition of a Si_3N_4 insulator layer. At the top of the RW and the taper the insulator was opened by reactive ion etching followed by the deposition of the p-electrode and electro-plating of gold in the RW and tapered sections. Finally, the wafer was thinned and the n-electrode was deposited on the back side of the wafer.

A schematic view of the fabricated DBR tapered laser with the integrated surface grating and with separate contacting is shown in Fig. 2. The total cavity length of the device is L = 4 mm, the total RW length is L_{RW} = 2 mm and the length of the Bragg grating is L_{DBR} = 1 mm. The RW width is W = 3 µm and the total flare angle of the tapered section is 6°.

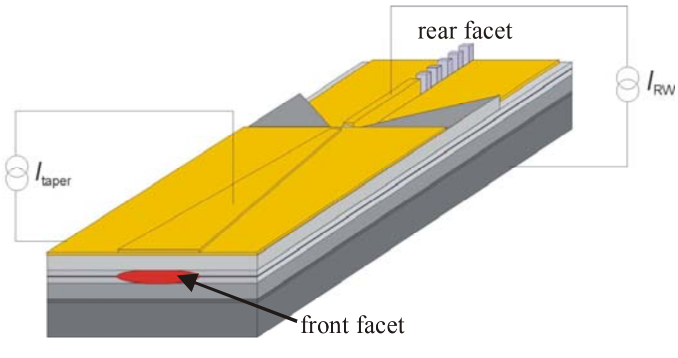

Figure 2. Schematic three-dimensional view of the DBR tapered laser with surface grating .

After the processing the wafers were cleaved into bars. The front facets were low-reflection coated with a reflection coefficient of $R_f \approx 1\%$. The rear facets were antireflection coated ($R_r \approx 10^{-3}$).

For measurements in quasi-continuous wave (QCW) operation the devices were mounted junction side up on standard C-mounts. To reduce the thermal resistance, laser diodes were furthermore mounted junction side up with PbSn-solder on conductively cooled packages (CCP) with dimensions of 25 x 25 x 6 mm^3 for measurements in continuous wave (CW) operation. Thermal resistance (from junction to ambient) of C-mounts is two times higher than CCP.

3. DEVICE CHARACTERISTICS:

The power-current characteristics, the optical spectra, the position of the beam waist, and the intensity profiles in the beam waist and the lateral far field pattern were measured in dependence on the currents through the RW and tapered sections. The RW section was driven in CW operation, whereas the tapered section was operated with current pulses of a duration of 10 µs and a repetition rate of 25 Hz for lasers mounted on C-mount. For lasers mounted on CCP, the tapered section could be also driven in CW operation. All experiments were performed at heatsink temperatures of T = 25°C (QCW) and 16°C (CW).

3.1. Power-current characteristics in quasi-continuous wave operation

The power-current characteristics are shown in Fig. 3. The current I_{taper} through the tapered section was varied between 0 A and 19 A. The current I_{RW} through the RW section was adjusted to 0, 200, 500 and 1000 mA. The threshold current of $I_{th,taper}$ = 0.43 A and the slope efficiency of S = 0.9 W/A up to P = 4 W are almost independent of I_{RW} between 200 and 1000 mA. The highest output power of P = 8.6 W was obtained with I_{RW} = 500 mA at I_{taper}=19 A. Maximum output power is limited by thermal roll over. A further increase of I_{RW} leads to a reduction of the maximum output power.

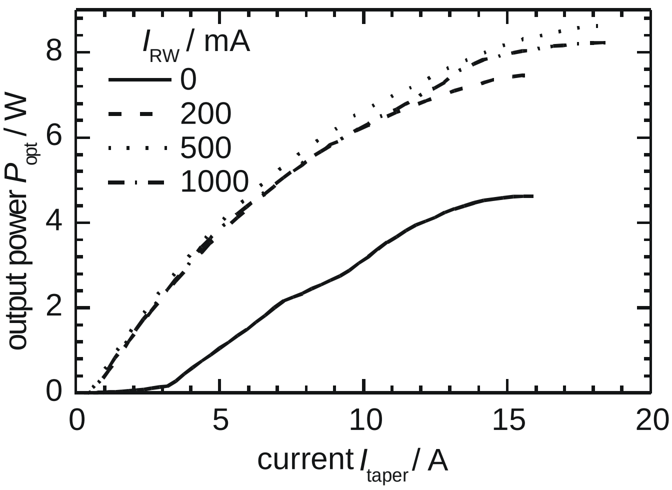

Figure 3: QCW output power versus current through the tapered section for different currents through the RW section at heatsink temperature of T = 25°C.

3.2. Intensity profiles of beam waist and far field in quasi-continuous wave operation

The intensity profiles in the lateral far-field and the beam waist measured at different currents through the tapered section are given in Fig. 4 (a) and (b), respectively. The current through the RW section was chosen to 200 mA which leads to the best beam quality compared to other currents.

The divergence of the far field profile is 18.5° (full width at the 1/e^2 level) at P = 0.5 W. With increase of output power the divergence of lateral far field decreases down to 13° for P = 4.4 W. This is smaller than that given by the flare (≈ 20°). Thus not the whole tapered gain region is optically active. The reason could be that the beam waist is broader than the RW width (6 µm vs. 3 µm) connected with a correspondingly smaller field divergence. With increasing power the modulation depth of the peaks in the far field profile is more pronounced. The intensity profiles at the beam waist position are nearly of Gaussian shape. They exhibit only minor side lobes remaining below the $1/e^2$ level of the intensity. Up to $P = 4.4$ W ($I_{RW} = 200$ mA, $I_{taper} = 6$ A), 90% of the optical power is located inside the central Gaussian-like lobe.

To evaluate the beam quality of the DBR tapered lasers, the beam propagation ratio M^2 was calculated from the $1/e^2$ levels of the measured intensity profiles of the beam waist and the lateral far field. At each investigated power level up to $P = 4.4$ W the M^2 values are smaller than 1.1. These small M^2 values demonstrate the nearly diffraction limited properties of this laser.

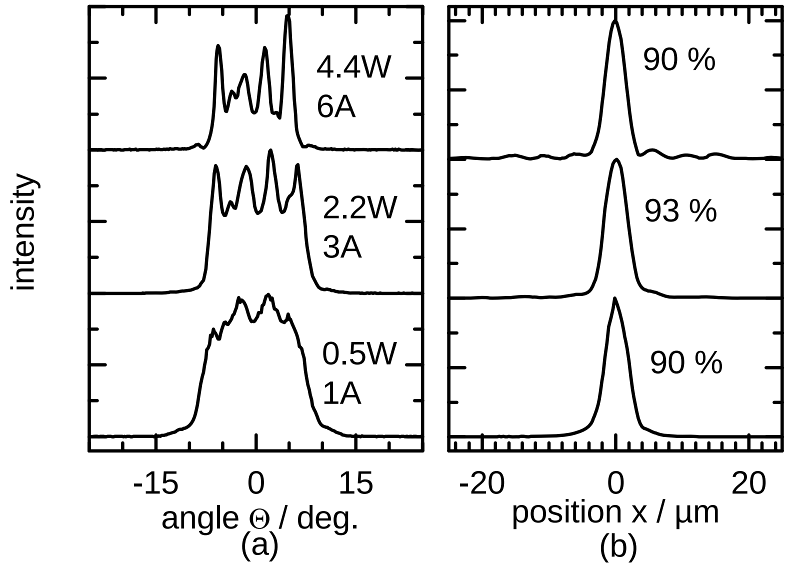

Figure 4: Dependence of lateral far field profiles (a) and the intensity profiles in the beam waist (b) on output power for the same device as in Fig. 3 at heatsink temperature of T=25°C. Parameter is the current through the tapered section. The current through the RW section was kept constant to IRW = 200 mA. The relative power in the central lobe is also indicated.

3.3.Spectral properties in quasi-continuous wave and CW operation

The optical spectra of the DBR tapered lasers in Fig. 5 were measured at a current through tapered section of $I_{taper} = 6$ A. The current in the RW section I_{RW} was varied from 0 mA up to 1000 mA. For this measurement the tapered section was operated in pulsed mode of a duration of 100 µs with a repetition rate of 1 kHz. The spectral output power of the DBR tapered diode laser reveals single longitudinal mode operation. The shift in wavelength is less than 0.2 nm over the operating power range from 1.6 W to 4.2 W. This confirms that the higher order gratings work properly leading to the high spectral selectivity of the DBR tapered lasers.

In order to study the influence of the chirp, optical spectra were measured both in pulsed and CW operation of the tapered section under otherwise the same conditions. The results are depicted in Fig. 6. The current through the RW section was 450 mA and the current through the tapered section 3 A. In pulsed operation, the output power is 2.5 W, the emission wavelength about 978.2 nm and the spectral linewidth (FWHM) 30 pm. In CW operation, the output power is now slightly smaller (1.9 W) and the emission wavelength correspondingly larger (978.4 nm) due to the increased self-heating. The measured spectral linewidth of 10 pm is now limited by the optical grating monochromator (spectral resolution 10 pm).

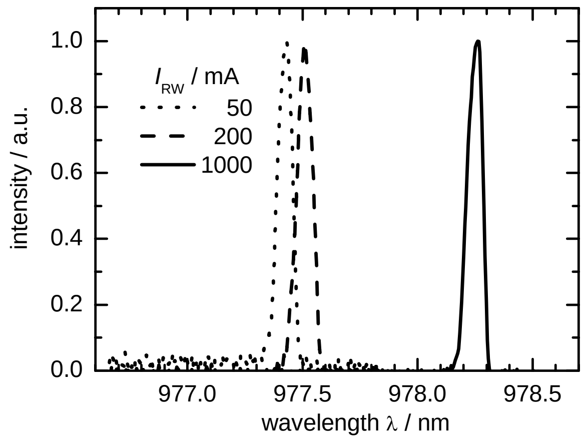

Figure 5: Optical spectra of the DBR tapered laser of Fig. 3 at heatsink temperature of $T = 25°C$. Parameter is the current through the RW section. The current through the tapered section was kept constant to $I_{taper} = 6A$.

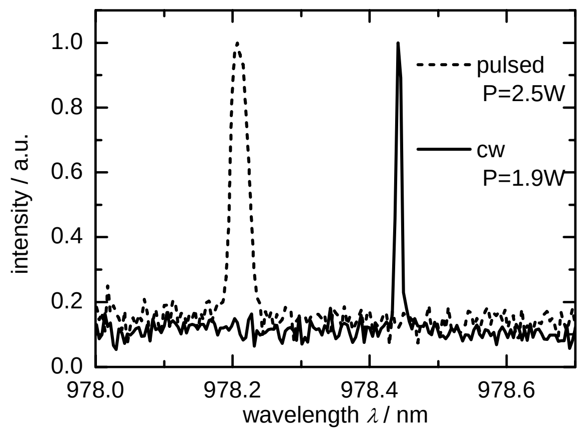

Figure 6: Optical spectra of the DBR tapered laser of Fig. 3 for CW (solid) and pulsed (dashed) operation of the tapered section. The current through the RW section was $I_{RW} = 450$ mA and the current through the tapered section was $I_{taper} = 3$ A. The heatsink temperature was $T = 15°C$.

3.4. Power-current characteristics in continuous wave operation

A typical power-current characteristic of the DBR tapered laser in CW operation is shown in Fig. 7. The current I_{taper} through the tapered section was varied between 0 A and 4.5 A. The current I_{RW} through the RW section was adjusted to 0, 100, 300 and 500 mA. With the increase of I_{RW} the slope efficiency of the device increases from about 0.82 W/A for $I_{RW} = 100$ mA up to 0.89 W/A for $I_{RW} = 500$ mA which is similar to the behaviour in QCW operation. If the RW section is unpumped ($I_{RW} = 0$ mA), lasing action can not be observed. The highest output power of $P_{out} = 2.8$ W was achieved with $I_{RW} = 500$ mA and $I_{taper} = 4.5$ A. Increasing of I_{RW} beyond 500 mA does not improve the output power.

Moreover, Fig. 7 illustrates that at constant current in the tapered section the output power can be modulated by a variation of the current through RW section. This is much easier realized than a modulation of the much larger current through the tapered section. For example, for $I_{taper} = 3$ A the output power can be modulated between 0 and 2.3 W for a variation of the RW current between 0 and 300 mA.

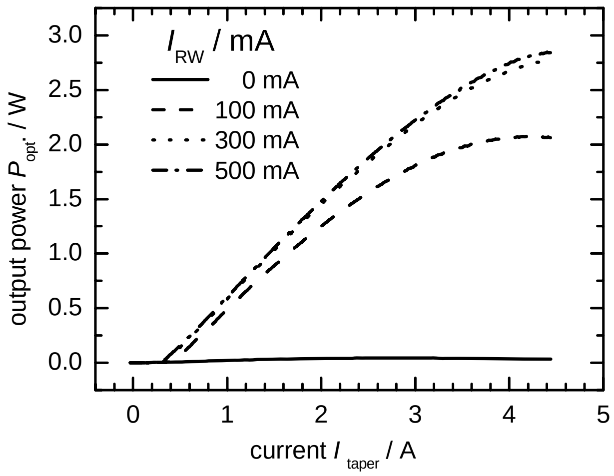

Figure 7: CW output power versus current through the tapered section for different currents through the RW section at heatsink temperature of $T = 16°C$.

3.5. Beam characteristics in continuous wave operation

The corresponding intensity profiles measured at P = 2.5 W are depicted in Fig. 8(a) and Fig. 8(b). The current in the RW section was I_{RW} = 460 mA and the current in the tapered section I_{taper} = 3.8 A. The M^2 value calculated from the 1/e^2 levels is smaller than 1.4 and the optical power located inside the central Gaussian-like lobe amounts to more than P_c = 90%. These results belong to the best of our knowledge achieved in continuous wave operation.

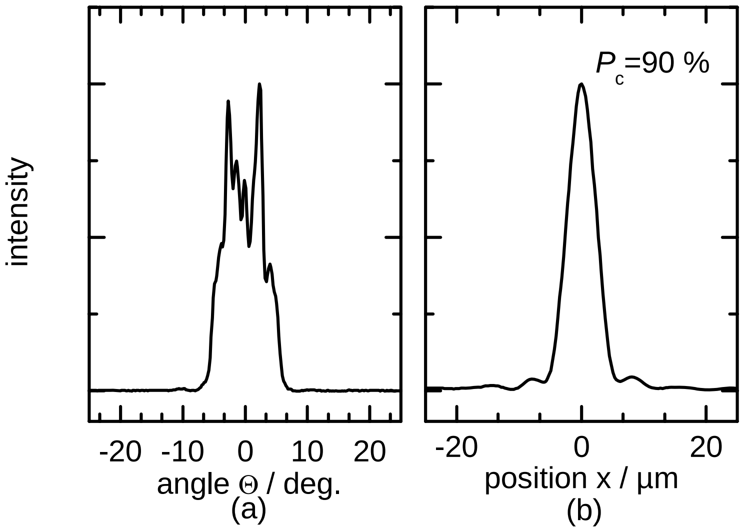

Figure 8: The intensity profiles in lateral far field (a) and the beam waist (b) at 2.5 W output power for the same laser as in Fig. 7. The relative power in the central lobe P_c is also indicated. The heatsink temperature was T = 16°C.

3.6. Spectral properties in CW operation

To improve the spectral resolution an optical spectrum analyser (OSA) with a spectral resolution of 2 pm was used (Advantest Q8347). A spectrum recorded in CW operation at an optical power of 2.5°W is depicted in Fig.°9. The spectral line width Δλ (FWHM) is determined to be smaller than 6 pm, still limited by the resolution of the OSA. Related to the small side peaks the side mode suppression ratio (SMSR) is 20 dB. However, related to the background the SMSR is even larger limited by the dynamic range of the OSA.

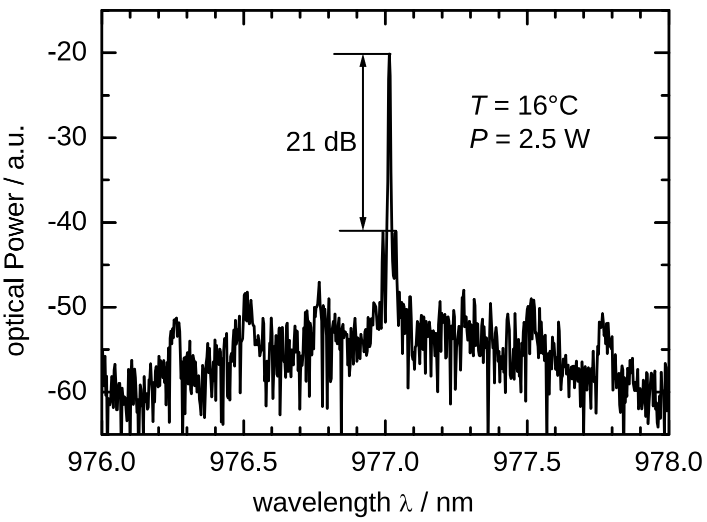

Figure 9: Optical spectrum of the device of Fig. 7 measured at *P* = 2.5 W. The heatsink temperature was *T* = 16°C.

4. SUMMARY

We have fabricated single-growth DBR tapered lasers emitting at 978 nm utilizing 6^{th} order Bragg gratings. The devices showed a high beam quality with a propagation ratio $M^2 = 1.1$ at 4.4 W in pulsed operation and $M^2 = 1.4$ at 2.5 W in CW operation. These small M^2 values illustrate the nearly diffraction limited properties of the lasers. The optical spectrum measured at 2.5 W output power revealed single-longitudinal mode emission. Thus, the technology of fabricating Bragg gratings by projection lithography using a wafer stepper allows a highly flexible, simple fabrication of high-power frequency-stabilized lasers.

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