Laterally coupled DFB interband cascade laser with tapered ridge

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In this work, single-mode distributed feedback interband cascade lasers with tapered ridges are presented. The lasers consists of a 500 µm long and 5.7 µm wide ridge wave guide section followed by a 1400 µm long tapered section with an output facet width of 35 µm. The device is operational in continuous wave mode and well above room temperature. At 25°C, the threshold current and threshold current density were 81 mA and 324 A/cm², respectively. We demonstrate a tuning range of over 14 nm with side mode suppression ratios larger than 25 dB. The device showed temperature and injection power tuning coefficients of 0,35 nm/K and 4.09 nm/W, respectively. Output powers of 18 mW single mode and 35 mW multimode were achieved.

Introduction: Distributed feedback (DFB) interband cascade lasers (ICLs) are especially interesting for applications in tunable laser absorption spectroscopy (TLAS) in the mid-infrared (MIR) spectral range from 3-6 µm [1-7]. Due to their low power consumption and compactness ICLs are beneficial for various fields from industrial [8] to medical sector [9]. Besides the ICL there are two other types of semiconductor DFB-lasers [10] which also access the 3 µm region in cw-operation near room temperature, diode lasers based on GaSb utilizing type-I interband-transitions [11] and Quantum cascade lasers [12] using intraband transitions. Diode lasers approach the 3-4 µm region from smaller wavelength and are limited in their output power in this region because they lack appropriate material systems and suffer from high Auger-recombination as well as limited inclusion potential in the valence band. Quantum cascade lasers converge to this region from larger wavelength, they are limited by carrier confinement in the active quantum wells. Despite their huge development in recent years, the energy consumption of quantum cascade lasers is still high compared to interband cascade lasers. Therefore, ICLs are more suitable for in field applications. For various purposes it is advantageous to couple light into optical fibers. To couple directly without additional optics, a low beam divergence is essential for good coupling efficiencies and hence higher output power. ICLs with tapered ridges for high-power and high-brightness were recently published [13]. Nevertheless these devices are not suitable for TLAS due to their multi mode spectrum.

Single-mode ICLs with high output power and small farfield are therefore of considerable interest to expand the application field of ICLs. Commonly used ICLs for TLAS are DFB ridge-waveguide semiconductor lasers [14] with limited output power and a relatively large farfield angle in slow and fast axis.

Growth and Fabrication: The laser structure was grown as described in [15], with minor changes to the design in order to reach the appropriate wavelength on a Te-doped GaSb-substrate by molecular beam epitaxy. The active region consists of 5 stages and it has a thickness of 232 nm. To guide the optical mode the active region was embedded into 340 nm thick GaSb separate confinement layers. The lower and upper super lattice claddings consist of short period AlSb/InAs superlattices with total thicknesses of 2565 nm and 1700 nm, respectively.

The laser is formed by a 5.7 µm wide and 500 µm long ridge wave guide section followed by a 1400 µm long tapered section with an output facet width of 35 µm. The structure was defined by electron beam lithography and etched through the active core by a chlorine/argon plasma base reactive ion etch process. Lateral chrome gratings were defined by electron beam lithography at the ridge waveguide section to achieve longitudinal mode selection [14]. For passivation Si_3N_4 and SiO_2 layers were applied. A contact window was etched through the passivation on top of the ridge waveguide section as well as the tapered section based on CHF_3 plasma base reactive ion etching. For current injection a TiPtAu - top metallization layer was deposited. Subsequently a 11 µm thick Au layer was electroplated. After thinning the substrate to 150 µm, the bottom contact was deposited. The sample was cleaved into bars with 1.9 mm long cavities. To suppress the amplification of higher lateral modes in the tapered section an antireflection coating consisting of a single layer of 485 nm Al_2O_3 reduced the reflection of the front facet to approximately 5%. The back facet was passivated and metal coated for high reflection. After the laser chips were soldered epitaxial-side-down on a C-mount heat spreader, the device was analyzed with respect to temperature dependent spectral properties, L-I-V characteristics as well as the corresponding horizontal farfield.

Results: The ICL with tapered ridge shows output powers of up to 18 mW mono mode (straight line) and 35 mW multi mode (dashed line) in cw mode. Figure 1 shows the L-I-V characteristics at different temperatures. At 25°C the threshold current density is 324 A/cm² and the threshold current 81 mA.

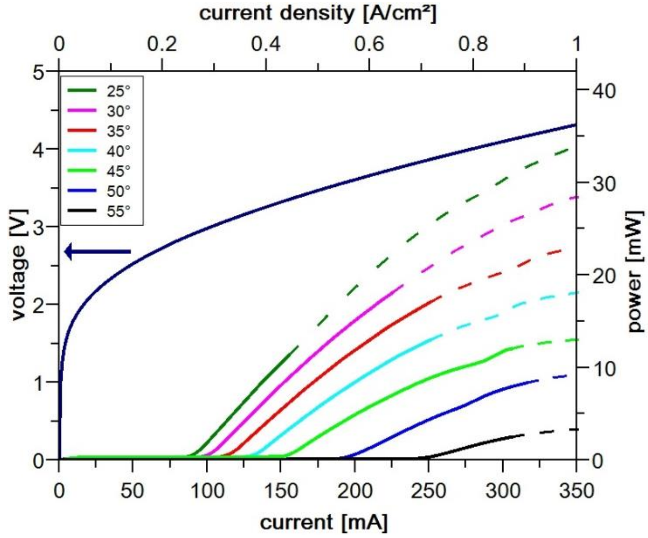

Fig. 1: *Electro-optical characteristics at different heatsink temperatures of the coated ICL device mounted epi side down on a C-mount, Straight lines: single mode operation, dashed lines: multi mode operation.*

In Figure 2, the spectrum of the device at 25°C and a current of 100 mA as well as at 55°C and a current of 310 mA, yielding side mode suppression ratios >25 dB, are observed. The linewidth is limited by the fourier-transform infrared spectrometer resolution of 0.125 cm^{-1}.

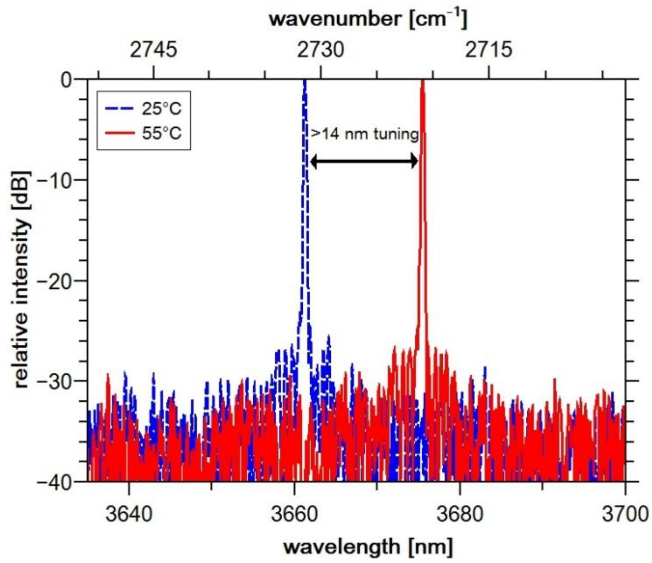

Fig. 2: *Spectral characteristic of the device at 25°C and 55°C heatsink temperature, with >25 dB SMSR and >14 nm tuning range.*

The general tuning characteristic is presented in Figure 3, with heatsink temperatures ranging from 25°C to 55°C. A Fabry-Perot mode hop is observed at 45°C and 50°C. The tuning coefficients were 0.35 nm/K, 0.022 nm/mA and 4.09 nm/W for temperature, current and injection power, respectively. An overall tuning range of >14 nm was achieved utilizing current and temperature tuning.

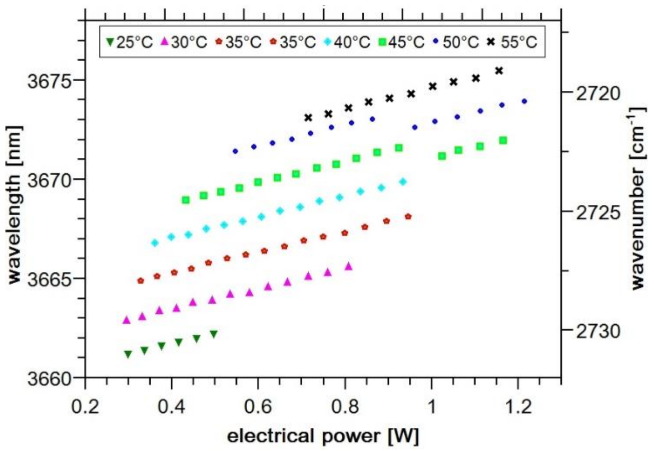

Fig. 3: *Wavelength shift at heatsink temperatures from 25°C to 55°C, as a function of injected electrical power, a Fabry-Perot mode hop occurred at 45°C and 50°C.*

The corresponding farfield in slow axis at 35°C heatsink temperature and 200 mA injection current is given in Figure 4, with a FWHM of 7.4° and a 1/e²-width of 12.5°.

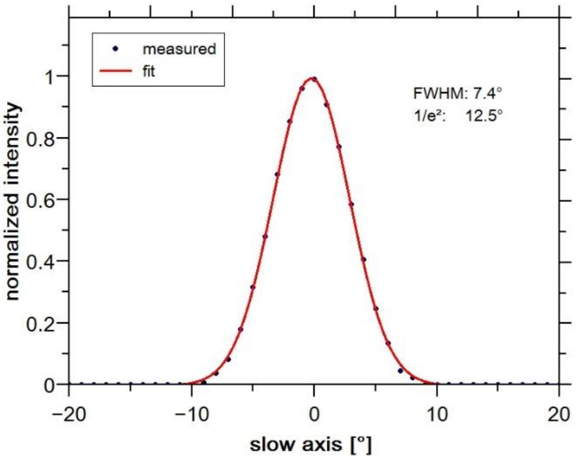

Fig. 4: *Farfield angle in slow axis at 35°C heatsink temperature and at 200 mA injection current, FWHM of 7.4° and 1/e²-width of 12.5°.*

Due to high coupling losses for direct coupling into mid-infrared fibers on one hand and the need for low power consumption for battery powered applications on the other hand, we focused on a suitable balance between high output power, small farfield and low power consumption.

Conclusion: We presented the first DFB ICL with tapered ridges. The ICL was operated in cw mode at room temperature with small farfield width of 7.4° FWHM and high output power for efficient direct fiber coupling, side mode suppression ratio of >25 dB as well as >14 nm tuning range. Single mode operation was observed up to a heatsink temperature of 55°C.

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