Quantum cascade external cavity and DFB laser systems in the mid-infrared spectral range: devices and applications

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Abstract: Quantum cascade laser (QCL) are an excellent tool for MIR-spectroscopy. We report on the design and realization of pulsed and cw-QCL in external cavity (EC) and DFB configurations for the application of NO measurements.

OCIS codes: (300.6320) Spectroscopy, high resolution; (140.5960) Semiconductor lasers.

1. Introduction

QCL have become a well established radiation source in the MIR region. Spectroscopic applications such as process monitoring and environmental measurements can take advantage of the near room temperature (RT) operation possible with these devices and the much stronger linestrengths of the fundamental molecular absorption in the MIR compared to the NIR range. QCL systems have already shown their higher sensitivity for trace gas detection. Although cw-RT operation on several devices are reported, pulsed operation of QCLs in the –25°C to + 50°C is well adapted to most currently available lasers. In order to achieve high sensitivities, various QCL research teams work on measurement techniques like photoacoustic measurements, cavity ring down spectroscopy, direct absorption [1-4], or derivative techniques. To overcome tuning behavior drawbacks of such lasers, EC-QCL were investigated by several groups [5-7]. In this paper we investigate the behavior of antireflection coated QCL in external cavities for the first time. Spectroscopic results are presented with DFB devices.

2. Active Region Design and Device Fabrication

The investigated samples are based on compressively strained GaInAs quantum wells and tensile strained AlInAs barriers giving rise to an increased conduction band offset compared to lattice-matched $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ heterostructures [8]. The individual layer thicknesses and compositions are chosen such that the overall strain is compensated. For the active regions a four quantum well design with “double longitudinal-optical phonon relaxation” [9] together with incorporated AlAs blocking barriers and strain-compensating InAs layers [10] is employed similar to the design published in [11]. Twenty-five periods of alternating active regions and injectors embedded between lattice-matched GaInAs separate confinement layers were grown on InP substrates by molecular beam epitaxy. Then InP serving as upper cladding and contact layers was grown by low-pressure metal-organic chemical vapor phase epitaxy. After growth the wafers were processed into Fabry-Perot mesa-waveguide devices by chemically assisted ion beam etching, a Si_3N_4 passivation layer was deposited, contact windows were opened on top of the ridges and the top contact was provided. Substrate thinning and deposition of the backside contact completed processing. Additionally, index-coupled distributed feedback (DFB) QCL were fabricated. For these devices the first order DFB grating was etched into the top GaInAs separate confinement layer by chemically assisted ion beam etching prior to the overgrowth of InP.

Finally, individual lasers were cleaved from the processed wafers and mounted substrate-side down on copper heat-sinks. In pulsed mode (100 ns pulse length, 1 kHz repetition rate) devices with uncoated facets can be operated up to a heat-sink temperature of 390 K (117 °C). The operating voltage is around 10 V. At 300 K lasing is observed at an emission wavelength of 5.34 µm.

3. Delayed Optical Feedback Properties

In this section we present experimental investigations of the emission properties of an 8 x 1000 µm² QCL subject to delayed optical feedback. The device is operated at a temperature of 88 K in cw operation using a 24 V battery current source. The emitted light is collected by an f/1.6 mirror collimator. An external cavity is realized using a high reflecting gold mirror. The round-trip time in the external cavity amounts to τ = 14.1 ns. About half of the emitted intensity is coupled out of the external cavity and focused onto a peltier-cooled HgCdZnTe photovoltaic detector of ~ 350 MHz bandwidth. After amplification using a low-noise amplifier the detected signal is split by a power divider and analyzed simultaneously by an oscilloscope and an electrical spectrum analyzer (ESA). The power reflectivity of the external cavity amounts to R_{EC} ~ 22 %. The measured rf-spectra of the QCL subject to delayed optical feedback and without optical feedback are shown in fig. 1. In the case without feedback we obtain a flat rf-spectrum. Introducing optical feedback, we found a strong increase of the power at low frequencies in the rf-spectrum and distinct peaks

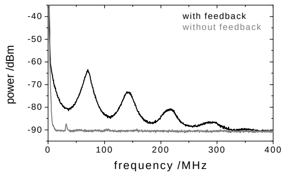

Fig. 1. RF spectra of the emission of the QC laser operated in continuous wave operation with (black line) and without (grey line) optical feedback (I_{pump} = 2.1 I_{thr}).

appear at the round-trip frequency and higher harmonics of the external cavity. Simultaneously, we obtained stronger fluctuations in the time-series measured with the oscilloscope. Thus, delayed optical feedback induces instabilities in the laser emission of the QCL. This indicates that QCLs are as sensitive to optical feedback as interband semiconductor lasers. In order to achieve stable laser emission, optical feedback should be either avoided or spectrally controlled by an optical grating. From interband semiconductor lasers it is well known that controlled optical feedback from a grating with a sufficient resolution results in a stable laser emission with a wide spectral tuning range.

4. Antireflection coating of QCL

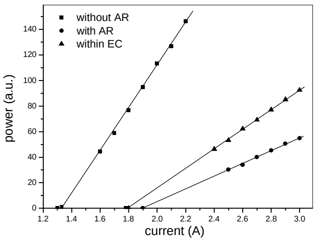

Fig. 2. P-I-curves (pulsed) of a 16 x 2000 µm² FPI - QCL before and after coating and in EC-configuration.

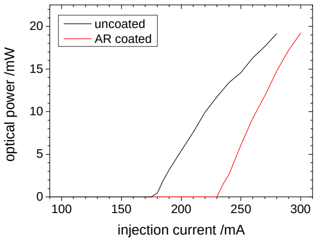

Fig. 3. P-I-curves (cw) of a 8 x 2000 µm² FPI - QCL before and after coating and in EC-configuration.

For the final goal of the realisation of a very compact EC-QCL, we have chosen a Littrow [5,6] configuration. The light from both facets is collimated by a ZnSe lens. To achieve a laser system with the best possible performance, the EC-QCL must have a high quality anti-reflection coating [12] on the front facet of the QCL, and low-noise high-resolution electronics. The quality of the EC-QCL is strongly dependent on the quality of the anti-reflection coating of the QCL's front facet. To achieve an anti-reflection coating below 1%, we sputtered a λ/4 multiple-layer on the front facet of the QCL. The threshold (pulsed) after coating is 1.9 A, while it was 1.3 A before coating, that is a threshold shift of about 40%. With this coating we could achieve a residual reflectivity of below 1 %. Fig. 2 shows the P-I-curves (pulsed) of the QCL before and after coating. Also shown is the threshold reduction within an EC Littrow-configuration. Fig. 3 shows the P-I-curves (cw) of the QCL before and after coating.

5. NO Measurements

A possibility to measure gases with QCLs is to use DFB structured devices. With high bandwidth HgCdZnTe detectors one can benefit from the thermal wavelength tuning of the QCL during pulses of 50-200 ns duration. Using fast A/D conversion of the detector signal allows direct observation of absorption lines within a single laser pulse. A modular, all thermoelectrically cooled QCL measurement system with high speed data acquisition techniques has been developed. Fig. 3 shows an example of a measurement of NO at 5.45 µm with different concentrations [3]. By analysis of the pulse shape under different NO concentrations the system was calibrated. The noise equivalent concentration of 0.7 ppm m $Hz^{-1/2}$ corresponds to a 3 σ detection limit of 2.1 ppm m $Hz^{-1/2}$. This limit enables us to carry out an open path measurement to determine the NO content of the exhaust gas of a bypassing car. For an absorption path of 35m fig. 4 shows clear NO peaks. This measurement is one example of a variety of applications like human breath analysis or combustion control. Furthermore, using another QCL, other gases and applications can be covered. Results on the EC-QCL's spectral properties and spectroscopic measurements will be presented elsewhere.

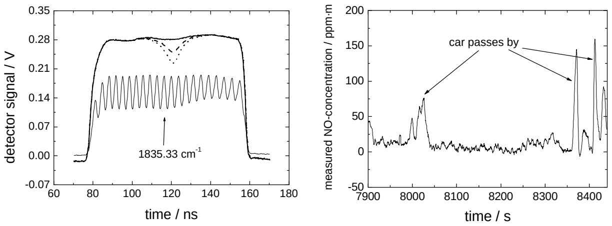

Fig. 4: Left: Typical detector signals far a direct absorption measurement with 2.4 m absorption length. (solid line: QC Laser pulse, dashed: 50 ppm NO, dotted: 100 ppm NO, modulated: Etalon with 0.05 cm^{-1} FSR) These measurements were performed without EC. Right: Open Path measurement of NO in the exhaust gas of a bypassing car, path length was 35 m.

References

[1] D. D. Nelson, J. H. Shorter, J. B. McManus, M. S. Zahniser, "Sub part-per billion detection of nitric oxide in air using a thermoelectrically cooled mid-infrared quantum cascade laser spectrometer," Appl. Phys. B **75**, 343 (2002).

[2] A. A. Kosterev, R. F. Curl, F. K. Tittel, C. Gmachl, F. Capasso, D. L. Sivco, J. N. Baillargeon, A. L. Hutchinson, A.Y. Cho, "Methane concentration and isotopic compositions measurements with a mid-infrared quantum-cascade laser," Opt. Lett. **24**, 1762 (1999).

[3] T. Beyer, M. Braun, A. Lambrecht, "Fast gas spectroscopy using pulsed quantum cascade lasers," J. Appl. Phys.**93**, 3158 (2003).

[4] E. Normand, M. McCulloch, G. Duxbury, N. Langford, "Fast, real-time spectrometer based on a pulsed quantum-cascade laser," Opt. Lett. **28**, 16 (2003).

[5] G.P. Luo, C. Peng, H.Q. Le, S.S. Pei, W.-Y. Hwang, B. Ishaug, J. Um, J.N. Baillargeon, and C.-H. Lin, "Grating-tuned external-cavity quantum-cascade semiconductor lasers", Appl. Phys. Lett. **78**, 2834-2836 (2001).

[6] G. Totschnig, F. Winter, V. Pustogov, J. Faist, and A. Müller, "Mid-infrared external-cavity quantum-cascade laser", Opt. Lett. **27**, 1788-1790 (2002).

[7] C. Peng, G. Luo, and H.Q. Le, "Broadband, continuous, and fine-tune properties of external-cavity thermoelectric-stabilized mid-infrared quantum-cascade lasers," Appl. Opt. **42**, 4877-4882 (2003).

[8] J. Faist, F. Capasso, D. L. Sivco, A. L. Hutchinson, S.-N. G. Chu, and A. Y. Cho, "Short wavelength (λ ~ 3.4 µm) quantum cascade laser based on strained compensated InGaAs/AlInAs," Appl. Phys. Lett. **72**, 680-682 (1998).

[9] D. Hofstetter, M. Beck, T. Aellen, and J. Faist, "High-temperature operation of distributed feedback quantum-cascade lasers at 5.3 µm," Appl. Phys. Lett. **78**, 396-398 (2001)

[10] Q. K. Yang, Ch. Mann, F. Fuchs, R. Kiefer, K. Köhler, N. Rollbühler, H. Schneider, and J. Wagner, "Improvement of λ ≈ 5 µm quantum cascade lasers by blocking barriers in the active regions," Appl. Phys. Lett. **80**, 2048-2050 (2002)

[11] Ch. Mann, Q. K. Yang, F. Fuchs, W. Bronner, R. Kiefer, K. Köhler, H. Schneider, R. Kormann, H. Fischer, T. Gensty, and W. Elsäßer, "Quantum Cascade Lasers for the Mid-infrared Spectral Range: Devices and Applications" in *Advances in Solid State Physics Vol.* ***43***, B. Kramer, ed. (Springer, Berlin, Heidelberg, 2003), pp. 351-368, Chap. 3.

[12] L. Hildebrandt, R. Knispel, S. Stry, J.R. Sacher, and F. Schael, "Antireflection coated 'blue' GaN laser diodes in an external cavity and Doppler-free Indium absorption spectroscopy," Appl. Opt. **42**, 2110-2118 (2003).

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