QCL absorption spectroscopy for lightweight and multi-species environmental applications

Lukas Emmenegger[1], Badrudin Stanicki[1], Manuel Graf[1], Philipp Scheidegger[1], Morten Hundt[1], Jérôme Faist[2], Filippos Kapsalidis[2], Herbert Looser[1], Mehran Shahmohammadi[2], Béla Tuzson[1]

[1)]Empa, Laboratory for Air Pollution & Environmental Technology, Switzerland

[2)] ETH Zurich, Quantum Optoelectronics Group, 8093 Zürich, Switzerland

Lukas.Emmenegger@empa.ch

Abstract: MIR spectroscopy using QCLs allows sensitive, selective, and fast detection of trace-gases. Recent developments, including dual-wavelength QCLs and segmented circular optical cells, create tantalizing options for drone-based and multi-species environmental analysis.

OCIS codes: (280.1120) Air pollution monitoring; (280.3420) Laser sensors; (140.5965) Semiconductor lasers, quantum cascade; (300.6340) Spectroscopy, infrared (300.6360) Spectroscopy, laser

1. Introduction

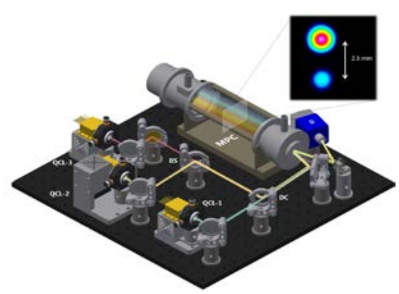
Advances in mid-IR quantum cascade laser (QCL) technology have triggered an impressive progress in instrumental developments. This progress is in line with a continuous quest for high-precision and selective measurements of a large variety of molecular species, as well as for compact, robust, and field deployable gas analyzers. Correspondingly, the applications cover very diverse areas, with deployment in environmental sciences being especially relevant and successful in recent years.

Numerous contributions from our laboratory illustrate the potential of direct absorption spectroscopy using QCLs. In the following, we will focus on two fields of applications: (i) the use of multi-wavelength QCLs for the simultaneous detection of many different greenhouse gases and air pollutants in a compact instrument, and (ii) the development of a lightweight spectrometer that has successfully been deployed on a commercial octocopter for methane sensing.

2. Multi-species, high-precision sensing of air pollutants and greenhouse gases

Instrumentation for environmental monitoring of gaseous pollutants and greenhouse gases tends to be complex, expensive, and energy demanding, because every measured compound relies on a specific analytical technique and dedicated analyzer. An exciting alternative approach is based on mid-infrared laser absorption spectroscopy with dual-wavelength distributed-feedback (DFB) quantum cascade lasers (QCLs). The first spectroscopic feasibility studies used pulsed laser designs that were limited in optical power and laser linewidth [1-2]. Recently, we have developed devices that are either continuous wave or support long pulses up to 100 µs. These rely on two distinct designs: (i) neighbor DFB: two single-mode DFB QCLs are fabricated next to each other, with minimal lateral distance, in order to allow simultaneous beam shaping, suitable for long-path optical gas cells, and (ii) dual-section DFB-QCLs that have two DFB sections above one ridge and emit two wavelengths from a single facet [3].

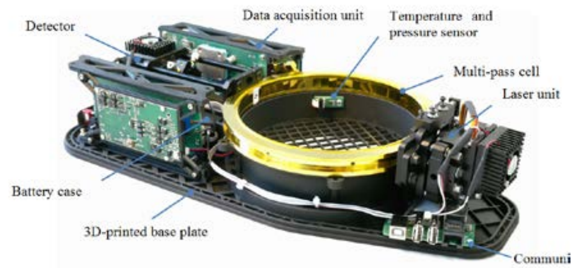
In our latest instrument, we have combined two dual- and one single-DFB-QCL for high-precision measurements of CO, CO_2, NH_3, NO, NO_2, N_2O, H_2O and O_3 simultaneously in a compact setup with a single optical cell and detector. The lasers are driven time division multiplexed in intermittent continuous wave mode [4] with a repetition rate of about 1 kHz for each device. Custom driving electronics and FPGA based data acquisition (125 MS/s, 14 bit) allow a compact design with minimal heat dissipation. The instrument was used for environmental monitoring and benchmarked with established reference instrumentation. The data quality was assessed by Allan-Werle variance analysis and by comparing to standard air quality monitoring equipment [5]. The achieved detection limits are significantly below ppb (parts per billion, 10^{-9}) for all the species, with the exception of CO_2, which has the highest mol fraction in ambient air, and does thus not require such low detectivity. Currently, a neighbor type DFB-QCL at 7.4 µm is being integrated, which will allow CH_4 and SO_2 detection, thus creating a single 19” instrument measuring simultaneously 10 air pollutants and greenhouse gases.



Optical layout of the multi-laser instrument and IR beam profile of the neighbor DFB QCL in the multipass cell.

2. Lightweight Methane Sensor for UAV Deployment

A recently developed circular, segmented multi-pass cell is at the core of a lightweight methane sensor that has successfully been deployed on a commercial octocopter. The novel cell design has demonstrated low optical noise, increased stability against mechanical distortion and a compact footprint [6]. In the open-path optical cell, the beam of a single-mode quantum cascade laser (DFB-QCL) emitting around 7.83 µm interacts at ambient pressure with the air sample. The laser is encapsulated in a TO-3 package including a Peltier element and collimation optics. The overall instrument weights 1.6 kg (excluding battery) and has an average power consumption of around 15 W. The low heat dissipation is achieved by intermittent continuous wave laser driving and a system-on-chip FPGA data acquisition module [7]. The spectrometer is equipped with additional sensors for pressure, temperature, and relative humidity as well as a GPS receiver and a data link. Therefore, it is possible to use the measurement device aboard any drone regardless of their specific communication protocol. The completely autonomous operation capability of the device makes it universally applicable for other applications beyond UAV based platforms.



Photograph of the high-precision methane sensor for UAV deployment.

Ongoing validation measurements indicate excellent performance with a measurement precision at the low parts-per-billion (ppb) level. Thus, the instrument is ready to be deployed aboard drones for in situ detection of near-source methane emissions and investigating their spatial and temporal variability. This concept can, furthermore, be adapted to a multitude of research applications by replacing the QCL or changing the optical path length of the absorption cell.

4. References

[1] J. Jágerská, P. Jouy, A. Hugi, B. Tuzson, H. Looser, M. Mangold, M. Beck, L. Emmenegger, and J. Faist, “Dual-wavelength quantum cascade laser for trace gas spectroscopy,” Appl. Phys. Lett. **105**, 161109–161109–4 (2014).

[2] P. Jouy, M. Mangold, B. Tuzson, L. Emmenegger, Y.C. Chang, L. Hvozdara, H.P. Herzig, P. Wagli, A. Homsy, N.F. de Rooij, A. Wirthmueller, D. Hofstetter, H. Looser, J. Faist, “Mid-infrared spectroscopy for gases and liquids based on quantum cascade technologies,” Analyst (2014).

[3] F. Kapsalidis, M. Shahmohammadi, M. Suess, J. M. Wolf, E. Gini, M. Beck, M. Hundt, B. Tuzson, L. Emmenegger, J. Faist, “Dual-wavelength DFB Quantum Cascade Lasers: sources for broadband trace-gas spectroscopy over the Mid-IR spectrum”, Appl. Phys. B 124: 107 (2018). [4] M. Fischer, B. Tuzson, A. Hugi, R. Brönnimann, A. Kunz, S. Blaser, M. Rochat, O. Landry, A. Müller, and L. Emmenegger, “Intermittent operation of QC-lasers for mid-IR spectroscopy with low heat dissipation: tuning characteristics and driving electronics,” Opt. Express **22**, 7014-7027 (2014).

[5] M. Hundt, B. Tuzson, O. Aseev, C. Liu, P. Scheidegger, H. Looser, F. Kapsalidis, M. Shahmohammadi, J. Faist, L. Emmenegger, “Multi-species laser spectroscopic mid-infrared trace gas sensor”, Applied Physics B: Lasers and Optics, 124(6), 108 (2018)

[6] M. Graf, L. Emmenegger, B. Tuzson, “Compact, circular, and optically stable multipass cell for mobile laser absorption spectroscopy”. Opt. Lett. 43 (11), 2434-2437 (2018).

[7] C. Liu, B. Tuzson, P. Scheidegger, H. Looser, B. Bereiter, M. Graf, M. Hundt, O. Aseev, D. Maas, L. Emmenegger, “Laser driving and data processing concept for mobile trace gas sensing: design and implementation”, Rev. Sci. Instrum., 89 (6), 065107, (2018).