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Highly compact laser spectrometers for mobile trace gas sensing applications

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Summary:
Mid-IR spectroscopy using QCLs allow sensitive, selective, and fast detection of trace gases. Recent developments in multipass cell design and acquisition electronics permit the construction of rugged and lightweight instruments for field application. This is demonstrated by the successful balloon-borne water vapor measurement in the lower stratosphere with an integrated QCL-based spectrometer.

Keywords: mobile instrumentation, tunable laser spectroscopy, mid-IR, trace gas

Introduction

Infrared (IR) spectroscopy is a powerful tool for gas sensing. Especially attractive is the mid-IR spectral region, where molecules have their fundamental absorption bands with cross sections significantly larger than in the near-IR. With the advent of quantum cascade lasers (QCL) as rapidly tunable narrowband light sources, the mid-IR spectral region became accessible for this highly selective and sensitive technique. Today, we experience an increasing demand for compact and lightweight spectrometers to be deployed e.g. on board of cars, drones, or balloons. Such mobile settings enable the monitoring of trace gas concentrations at a high spatio-temporal resolution at urban, rural or industrial sites, or even in the upper atmosphere. Prominent examples are the detection of methane sources aboard of unmanned aerial vehicles or the water vapor measurement in the upper troposphere and lower stratosphere (UTLS). However, the required miniaturization for such applications implies extraordinary constraints in terms of mass, size and robustness, as well as resilience towards the variation of environmental conditions such as temperature and pressure.

Segmented circular multipass cell

In order to enhance the precision and detection limit, absorption spectrometers make use of beam extending multipass cells (MPCs) to increase the interaction path length between the probe laser beam and the sample gas, usually to many tens of meters. These cells are generally a decisive factor with regard to small and lightweight instruments, because conventional designs are often limited in achieving sufficient compactness *and* optical stability. We therefore developed a versatile concept for compact and well-controlled beam folding which is especially suited for compact and lightweight spectrometers [1]. Thereby, we combine the constructional advantages of toroidal MPCs [2], i.e. compactness, rigidity and low weight, with optimal optical properties: In contrast to the toroidal MPCs, optical noise from interference fringes is inherently reduced by the optically stable design, realized by including spherical segments to the reflective surface. This, furthermore, leads to the acceptance of a wide range of input beam shapes, such that beam pre-shaping can essentially be omitted. Thus, the optical setup is drastically reduced to only the laser, the MPC, and the detector (Fig. 1.). This layout paved the way for highly compact trace-gas spectroscopy under challenging conditions.

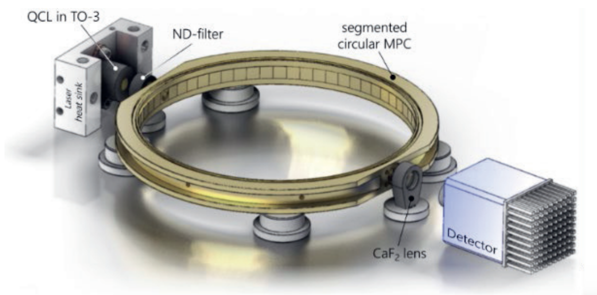

Figure 1: Basic optical layout incorporating the SC-MPC in open-path configuration.

Water vapor in the UTLS

Water vapor is the dominant greenhouse gas, and its abundance in the upper tropospheric and lower stratospheric region (8-25 km altitude) is of great importance to the Earth's radiative balance. Therefore, accurate and frequent measurement of water vapor concentrations at these altitudes is of utmost importance. We present a compact and rugged laser absorption spectrometer that detects water vapor in the very low ppm range with a precision <1% [3]. The spectrometer operates at 6 μm requiring an optical path length of 6 m, which is realized by a specifically designed SC-MPC with a mass of only 100 g. The low overall weight of the spectrometer (3.9 kg) enables its flexible and inexpensive deployment to the stratosphere aboard of meteorological balloons. The autonomously operating instrument further benefits from considerable hardware optimization, including FPGA-based data acquisition and economic laser driving electronics [4,5], resulting in an overall power consumption of 15 W. The successful operation at altitudes up to 28 km was recently demonstrated in a flight campaign.

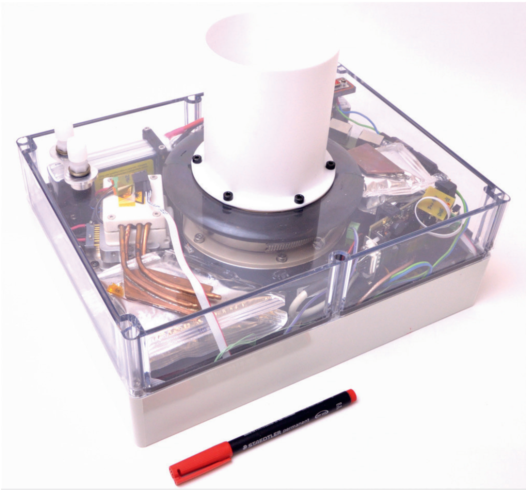

Figure 2: Spectrometer for balloon-borne measurement of water vapor at the UTLS

UAV based methane detection

The assessment of methane leakage from sources such as oil and gas production facilities can be achieved by deploying an unmanned aerial vehicle (UAV) equipped with a methane sensor to map the spatial and temporal variability of emission plumes. We target this application field by an open-path QCL spectrometer that incorporates the presented concepts. The instrument is capable of measuring atmospheric methane at several Hz with a precision below 1 ppb. Its compact and lightweight design (1.6 kg) readily allows its deployment aboard of commercial drones. The instrument was already validated and utilized in numerous field campaigns in Switzerland, Sweden and Romania.

Figure 3: Commercial drone equipped with the methane spectrometer.

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