Mid-IR Laser Spectrometer for Balloon-borne Lower Stratospheric Water Vapor Measurements

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Abstract: A lightweight instrument has been developed to measure water vapor up to the lower stratosphere aboard meteorological balloons. The sensor relies on a segmented circular multipass cell which is especially suited for mobile field applications.

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1. Introduction

Laser absorption spectroscopy is the method of choice for precise, fast, and contact free measurements of trace gases in a large variety of research fields. Today, we experience an increasing demand for compact and lightweight instruments 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 spatiotemporal resolution at urban, rural or industrial sites. One of the most challenging application field is the research of water vapor in the higher atmosphere. Water vapor (wv) is the dominant greenhouse gas and its variation in the upper tropospheric/lower stratospheric region (UTLS, 8-25 km altitude) is of great relevance to the Earth's radiative balance. Reliable predictions of the climate evolution as well as the understanding of certain cloud-microphysical processes are currently limited by the inexistence of accepted in-situ instruments to accurately *and* frequently measure wv at these altitudes. Balloon-borne deployment provides low-cost access to the UTLS; however, it poses extraordinary constraints to the instrument in terms of mass, size, and stability. In order to fulfill these stringent requirements, we are developing a lightweight direct laser absorption spectrometer (<2 kg) that measures wv in the mid-IR spectral range and addresses many of the challenging issues.

2. Segmented Circular Multipass Cell

The high-precision measurement of low abundance gas concentrations by means of direct laser absorption spectroscopy requires the use of multipass cells (MPCs). These cells are of crucial importance as they define both the performance and the size of an instrument. However, established designs have limitations with respect to compactness and/or optical performance. We present a highly versatile concept for compact and well controlled beam folding, called *segmented circular multipass cell* (SC-MPC). The inherent mechanical symmetry makes it predestined for its application in mobile instruments that operate under rough environmental conditions. Motivated by the constructional advantages of monolithic toroidal cells [1], i.e. compactness, rigidity, and low weight; we reconsidered the reflective internal surface structure to eliminate their inherent optical instability [2]. Following fundamental resonator theory, the implementation of locally curved segments leads to a stable mirror configuration, as depicted in Fig. 1(a) [3]. Thereby, the interference-caused optical noise is drastically reduced to low 10^{-4} on a normalized transmission scale (Fig. 1(b)). Additionally, the confocal design of the segments allows the direct coupling of collimated laser beams without any additional beam-shaping optical elements. This results in a highly compact optical setup only consisting of a laser, a detector and the multipass cell. Since SC-MPCs can be scaled according simple mathematical rules, they represent a highly promising solution for a variety of future applications wherever enhanced mobility is desired.

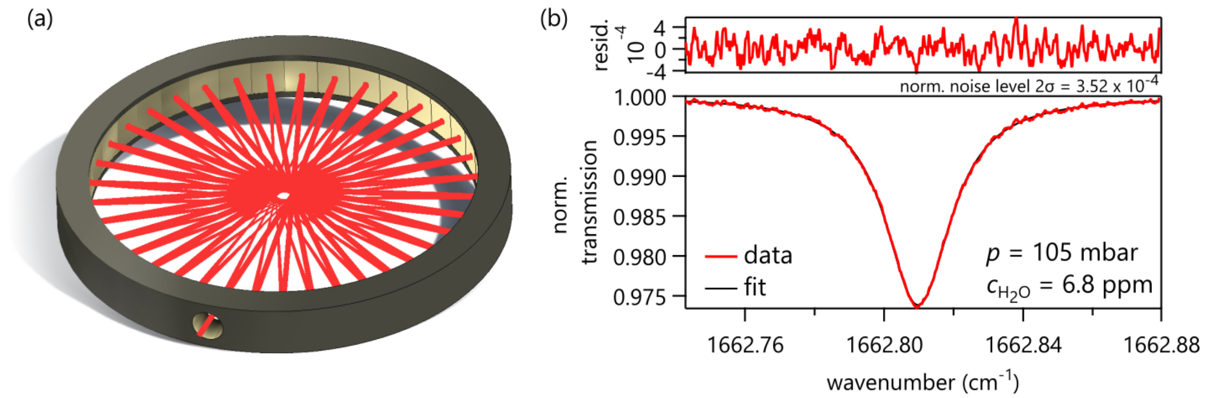

Fig. 1. (a) The segmented circular multipass cell (SC-MPC) provides stable laser beam folding by individual shaping of the internal surface. (b) H_2O spectrum acquired at 1 s averaging. For validation of the instrument, the multipass cell (6 m optical path length) is closed in order to achieve tropopause-like pressures and mixing ratios.

3. Sensor Development and Application

The spectrometer uses a continuous wave quantum cascade laser (DFB-QCL) emitting at 6 µm, where H_2O exhibits strong fundamental ro-vibrational transitions. The laser is encapsulated in a high heat load (HHL) housing including a Peltier element and a collimation lens. Further thermal stabilization is implemented using phase change materials (PCMs) as buffer medium. Driven by the high flexibility and enhanced resilience towards mechanical distortion, the device features an optimized SC-MPC with an effective optical path length of 6 m. The exceptionally low optical noise level allows measuring wv-mole fractions of less than 10 ppm at UTLS-conditions with a precision better than 1% at averaging times of 1 s. To ensure a fast response and to reduce interference by spurious water desorbing from surfaces, the cell is operated in open-path mode. Thus, in a balloon-borne setting, the ambient air flows freely through the cell as a consequence of the ascending motion. The overall instrument weighs 2 kg (excluding battery) and has an average power consumption of 15 W. The production of excess-heat is minimized by intermittent continuous wave (ICW) laser driving and a system-on-chip FPGA data acquisition module [4]. Extensive stability assessments in a climate chamber as well as further validation experiments using dynamically generated, SI-traceable water vapor mixtures acquired in collaboration with the Swiss Federal Institute for Metrology (METAS) are ongoing. The instrument is prepared for deployment aboard meteorological balloons for in-situ measurement of water vapor in the UTLS investigating its spatial and temporal variability. However, the completely autonomous operation capability and its outstanding compactness makes it universally applicable also for other compounds and applications e.g. detecting methane on UAV based platforms.

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