Diode Laser-based Sensor for High Precision Measurements of Ambient CO2

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Abstract: We report on the development of a high precision sensor for monitoring ambient CO₂. Our TDL ICOS absorption spectrometer operates at 2 µm and achieves a precision of 1:3000 for the CO₂ mixing ratio.

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1. Introduction

Climate change is of direct concern to scientific research, governmental bodies, and society at large. Important policy decisions are currently being made or planned in order to minimize human-induced climate change. Policy decisions relating to resource utilization and energy production are based on various chemical models of climate change and regional air quality. Predictions based on these models rely on the accuracy of field measurements to determine the levels of various trace species and their sources and sinks. Improvements to the database in turn rely on the development of high accuracy, reliable field instrumentation combined with long term monitoring programs.

US efforts to develop monitoring programs are the mission of the US Carbon Cycle Science Program, which is an interagency project under the U.S. Global Change Research Program. The North American Carbon Program (NACP) is one component of the CCSP. The NACP has identified, as one of its highest priority near term enabling focal points, the development of high accuracy in situ sensors for measurements of CO₂, CO, and CH₄ [1]. In addition, the NACP is currently planning the Mid-Continent Carbon Intensive study for 2007. This is its first major measurement/monitoring program. The 2007 Intensive will measure the carbon budget on a regional scale and will focus on determining the strength, extent, and mechanisms of the North American sink for atmospheric CO₂.

Currently, ambient CO₂ measurements are made at monitoring networks such as the Cooperative Air Sampling Network maintained by NOAA/ESRL’s Carbon Cycle Greenhouse Gases Group (CCGG), which is part of the Global Monitoring Division. The Cooperative Air Sampling Network is an international program that includes regular discrete samples from 4 NOAA baseline observatories, other sites, and commercial ships. Some tall tower sites in the US have in situ sensors. However, the majority of measurements are made via air samples that are collected approximately weekly from a globally distributed network of sites in flasks. The flasks are shipped to the CCGG where the samples are analyzed by sensors based on non-dispersive infrared (NDIR) absorption spectroscopy. These sensors are commercially available at several performance/price levels. Current CO₂ NDIR sensors nominally having the desired measurement performance still require some modifications and are available only at a cost more than a factor of 2 above the desired target price, thus precluding widespread network deployment. Versions that are available at the desired acquisition cost do not meet the desired performance specifications, either because of long term drifts of zero and span, or because of sensitivity to water vapor [2].

The creation of a new high precision, economical, robust, autonomous CO₂ sensor for widespread deployment in networks, requires both a suitable measurement technology and an integrated device architecture. We are developing a sensor based on Integrated Cavity Output Spectroscopy (ICOS). ICOS has several strong advantages for the present application as compared to other possible measurement techniques. ICOS is a Cavity Enhanced Spectroscopic (CES) technique that uses a pair of highly reflective mirrors to create optical pathlengths approaching 1 km in a physical pathlength on order of 10 cm. We combine ICOS with Wavelength Modulation Spectroscopy, WMS, to provide the required measurement precision. Recently, Cavity RingDown Spectroscopy (CRDS), another variant of CES, has been shown to have the high precision necessary for the current application. Richman and coworkers have reported a precision of 1 part in 4073 while measuring 380 ppmv CO₂ with a 5 min averaging period [3]. We have demonstrated a precision of 1 part in 3000 for the dry air mixing ratio of CO₂ for a 1 minute averaging period. The ICOS approaches also results in a measurement cell having a small sample volume, which decreases the consumption of calibration gases. We also use an integrated control and signal processing electronics board to achieve the small footprint required for the sensor.
2. Sensor Configuration

The ICOS-based sensor consists of a TE-cooled, cw 2-μm tunable DFB diode laser coupled to a high finesse cavity. We chose to operate at 2 μm instead of 1.55 μm for several reasons:

- The increased absorption strength at 2 μm enables the use of a shorter optical path
- The shorter optical path enables lower reflectivity mirrors at lower cost
- Lower R mirrors result in higher throughput
- Lasers of equal maturity are available commercially

Spectral modeling shows that the R16 line peak absorption is approximately 20% for conditions of 370 ppm, 296 K, and 1 atm for an ICOS cell having mirrors with R = 0.999 spaced 10 cm apart to produce a 50 m optical path.

The laser mounts directly on the single, 6-in. square, system controller board. This platform contains a laser current driver, as well as a temperature controller. In addition to the laser control, the controller contains 2 integrated digital lock-in amplifiers. The platform is designed to modulate the laser with a sinusoidal signal at 10 kHz and demodulate at 10 kHz (F1) and at 20 kHz (F2). Transmitted light is detected using a 1 mm diameter, extended responsivity InGaAs detector that is mounted directly onto a preamplifier daughter board. The output of the preamplifier is sent to the system board, with its digital signal processing (DSP) and an embedded microcontroller, for processing. The unpackaged sensor is shown in Figure 1.

![Fig. 1. ICOS CO2 sensor modules](image)

3. Sensor Performance

The performance of the sensor is demonstrated by flowing a precision mixture of CO2 in air through the sensor absorption cell. The flow is controlled typically using a critical orifice and a simple rotary vane pump. The lock-in amplifier outputs are sampled for several thousand seconds. The ratio of the F2/F1 signals is then calculated. Since F2 is proportional to concentration and F1 is proportional to the output power of the laser, the ratio represents power-normalized concentration. We then perform an Allan Variance analysis on the data and define the signal-to-noise ratio, SNR, as:

\[
SNR = \frac{F2/F1}{\sqrt{Allan\ Variance\ (F2/F1)}}
\]

Typical data for the measured ratio and the calculated SNR are presented in Figure 2. The data show the classic behavior with the variance decreasing and SNR increasing with increasing averaging time until long term drifts become important. This point occurs for a sampling time on the order of 10-20 sec for this system. The SNR is ~1000 for a signal averaging time of 10 sec. This level of performance is obtained using a piezo element modulating the cavity input mirror and by line locking the laser central frequency, which is accomplished in software.
The component modules of the prototype sensor are currently being packaged in a common platform in a single enclosure. The sensor will be ~ 2 x 8 x 8 in, weigh ~ 5 lbs, and require ~ 10 W power. The cell will be temperature stabilized. A small blower will draw air through a Nafion drier and into the cell. In collaboration with our colleagues, the prototype will be demonstrated at the University of New Hampshire Observing Station at Thompson Farm, which is located in Durham, NH. One of NOAA's Climate Reference Network meteorological stations is also located at Thompson Farm. Among the Station’s complement of sensors is a Li-COR model 7000 CO₂/H₂O sensor. Enhancements to this sensor and its operating procedure are currently being implemented with respect to NOAA/CCGG recommended practices [4]. Intercomparisons between the various sensors will be carried out during the Spring and Summer of 2008. We will also demonstrate the sensor at the NOAA Earth System Research Laboratory in Boulder, CO in Summer of 2008.

4. Acknowledgement

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5. References

[1] For background information on the NACP, see www.esig.ucar.edu/ncap.

