Range resolved CO_2 measurements over 3 km using a 10-point fiber-based differential-absorption LIDAR (DIAL) system

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Abstract: We present a multi-frequency DIAL system based on a fast-switching wavelength source and fiber optic amplification to acquire range-resolved dry-air CO_2 concentrations over the city of Boulder, Colorado USA.

1. Introduction

With the ever-increasing impact of climate change, new technology is needed to help monitor greenhouse gas (GHG) emissions such as CO_2 and H_2O. Point sensors provide a weak link to remote sensing of these gasses and column integrated measurements are only able to paint a partial picture when it comes to understanding CO_2 sources and sinks [1]. Differential absorption LIDAR (light detection and ranging, or DIAL) uses two or more LIDAR returns of the on- and off-resonance regions of the absorption line to range-resolve the GHG concentrations [2,3]. DIAL provides information not obtainable from other technologies since range-resolved measurements enable direct construction of three-dimensional GHG concentration maps. These maps allow for a more in-depth understanding of atmospheric variations and a better quantification of GHG sources and sinks.

In this work, we present a fiber-based DIAL system for performing standoff detection of CO_2 and H_2O concentrations over a 3 km range. The compact fiber-based components make the system ideal for the deployment as a mobile platform for measurements at remote locations. In contrast to previous results demonstrated with a low-repetition-rate (PRF) free-space amplifier [4], the high PRF (5 kHz to 10 kHz) fiber-based amplifier takes advantage of a low-dark-count photo-multiplier tube (PMT) with near-continuous acquisition of returns. We demonstrate the DIAL system to observe the dry-air CO_2 concentrations from a local power plant's stack emission located at a range of 1.2 km.

2. Experiment

The system shown in Fig. 1 uses a single, fiber-coupled, external-cavity diode laser (ECDL). The output is 90/10 % split where a 10% leg is frequency shifted using an AOM and then used to Pound-Drever-Hall (PDH) lock the laser to an invar confocal filter cavity (FSR ≈ 300 MHz, finesse ≈ 500). The 90% leg is sent to an electro-optic phase modulator (EOM) that is driven by an arbitrary waveform generator (AWG). For an AOM frequency shift near 250 MHz, the frequencies and amplitudes of the AWG waveform are selected such that only the second order comb tooth from one sideband is transmitted by the cavity (spectral purity > 30 dB) [4] when modulated by a single tone waveform. The output frequency from the filter cavity is stepped over ten different frequencies at a 10 kHz PRF.

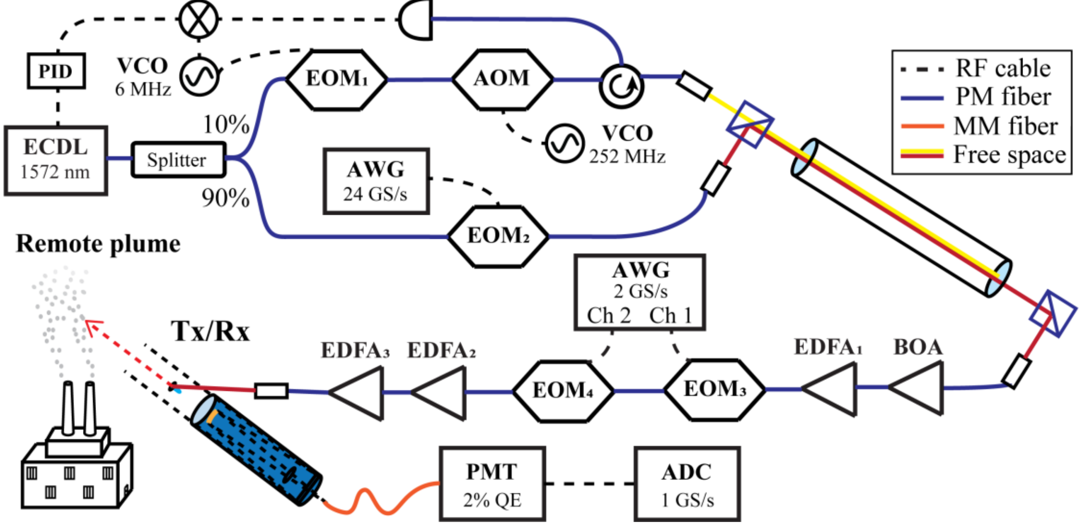

Figure 1: Schematic of the fast-switching wavelength DIAL system for range resolved CO_2 concentration measurements of remote sites.

The fast-switching wavelength source is sent to a pulsed (≈ 1 μs) booster optical amplifier (BOA). The output is amplified in an erbium-doped fiber amplifier (EDFA) then coupled through two EOM-based polarization switches to generate 200 ns pulses with > 40 dB rejection. The fast-switching wavelength source is sent sequentially through four additional EDFA stages where the final commercial amplifier is specifically doped to reduce stimulated Brillouin scattering. The free space output beam is expanded by a factor of 10 to a 1.6 in. (41 mm) diameter. The average output power is near 750 mW to maintain class 1M operation. The transmit beam is directed to the center of the 11 in. (279 mm) Schmidt-Cassegrain receiving telescope that focuses the DIAL retrievals into a 300 µm optical fiber for detection on a PMT (quantum efficiency ≈ 2%) whose amplified output is sampled by a 1 GS/s analog to digital converter (ADC). The final amplifier, optics, and telescope are on a motorized mount for full control of the transmitter/receiver (Tx/Rx) system.

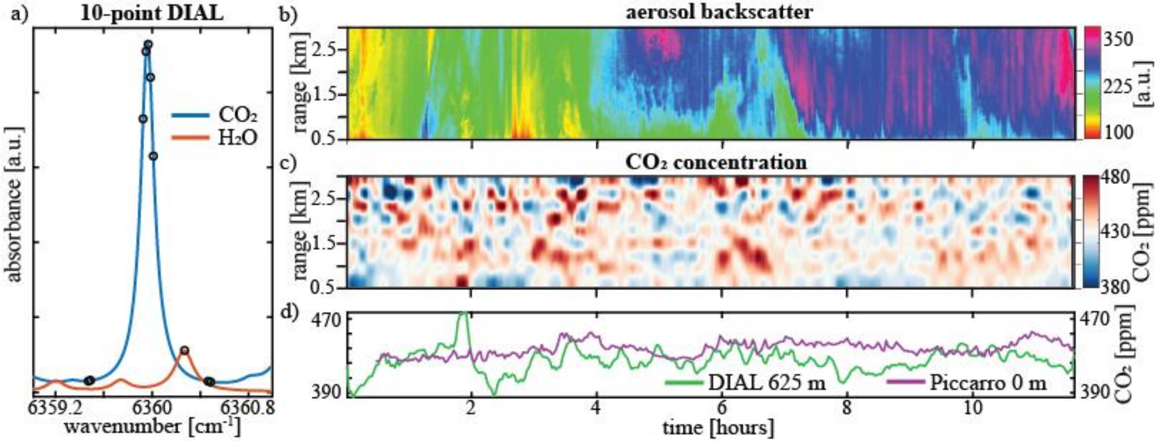

Figure 2: a) Locations of the 10-point DIAL frequencies noted by black circles. b) The total aerosol backscatter signal from the atmosphere on the night of November 8th, 2021. c) The range resolved CO_2 concentrations over the nighttime run, and d) the comparison between the first 250 m range bin (beginning at 500 m) of the DIAL measurement and a point senor.

3. Results

The spectral region investigated here contains the CO_2 line at 6359.962 cm^{-1} and the H_2O line at 6360.267 cm^{-1}. As shown in Fig. 2a, five points are placed around the CO_2 line, in blue, one on the H_2O line, in red, and the rest are background points on either end of the spectra. The data shown in Fig. 2 was acquired from November 8th-9th, 2021 starting at 5:30 pm MST. The DIAL system is spatially scanned over one of the University of Colorado's power plants in 2 min intervals in a trapezoid-top shape. Figure 2b shows the aerosol backscatter return as a function of time and distance from 500 m to 3 km in two-minute intervals. The 10-point backscatter returns are processed to determine the exponential decay due to GHG absorption in the atmosphere. The recovered spectra are fit using a nonlinear least-squares algorithm to the combined HITRAN [5] Voigt profiles of CO_2 and H_2O to solve for the range resolved concentrations. Figure 2c shows the resulting CO_2 concentration map in parts per million (ppm) from 500 m to 3 km, where the two-minute averaged fits are temporally smoothed to an effective ten-minute resolution. We see more than a three-fold increase in the aerosol backscatter throughout the night, while the CO_2 concentration shows uncorrelated deviations from the 430-ppm ambient level.

The DIAL retrievals are compared with cavity-ringdown-based point sensor sampling the ambient air several meters above the DIAL transceiver. Full overlap of the DIAL returns occurs at 375 m and therefore the closest 250 m range bin is at 625 meters out from the sensor location. The comparison between the point sensor, in purple, and the closest DIAL data point, in green, is shown in Fig. 2d. Over the 12-hour period, we see some areas of both good agreement and significant deviation due to the extremely variable nature of the atmosphere content and wind conditions.

In this work, we demonstrate a new fiber-based DIAL system for remote sensing of dry-air CO_2 over a 3 km range and 250 m resolution ranges. Further development of this technology by combining range-resolved wind measurements with the DIAL data will allow for measurements of GHG emission flux from the local power plant. The eventual goal is to validate the measured CO_2 emission flux with that generated from the fuel consumption rate.

4. References

[1] T. W. Hertel, et al. Economic analysis of land use in global climate change policy (2009): 123-153.
[2] G. G. Gimmestad, C. Weitkamp, ed. (Springer, 2005), pp. 187–212.
[3] G. Ehret, P. et. al. Remote Sens. 9(10), 1052 (2017).
[4] G. A. Wagner, and D. F. Plusquellic, " Optics Express 26.15 (2018): 19420-19434.
[5] I. E. Gordon, et. al., J. Quant. Spectrosc. Radiat. Transf. 203, 3–69 (2017).