2-micron Pulsed Direct Detection IPDA Lidar for Atmospheric CO₂ Measurement

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Abstract--- **A 2-micron high energy, pulsed Integrated Path Differential Absorption (IPDA) lidar has been developed for atmospheric CO₂ measurements. Development of this lidar heavily leverages the 2-micron laser technologies developed in LaRC over the last decade. The high pulse energy, direct detection lidar operating at CO₂ 2-micron absorption band provides an alternate approach to measure CO₂ concentrations. This new 2-miron pulsed IPDA lidar has been flown in spring of this year for total ten flights with 27 flight hours. It is able to make measurements of the total amount of atmospheric CO₂ from the aircraft to the ground or cloud. It is expected to provide high-precision measurement capability by unambiguously eliminating contamination from aerosols and clouds that can bias the IPDA measurement.**

Keywords--- Green House Gases; Pulse lidar

I.   INTRODUCTION

Active sensing of CO₂ concentrations will significantly increase the understanding of CO₂ sources, sinks, and fluxes worldwide [1]. The mid-IR wavelength regions at 1.57µm and 2.05µm are considered suitable for atmospheric CO₂ measurements due to the existence of distinct absorption features for the CO₂ gases at these particular wavelengths. Two instruments operating at 1.57µm have been developed and deployed as airborne systems for atmospheric CO₂ column measurements in U.S. One instrument is based on an intensity modulated continue wave (CW) approach, the other on a high pulse repletion frequency (PRF), low pulse-energy approach [2, 3]. These airborne CO₂ lidar systems operating at 1.57µm utilize mature laser and detector technologies by taking advantage of the technology development outcomes in the telecom industry. On the other hand, lidars operating in the 2µm band offer better near-surface CO₂ measurement sensitivity due to the intrinsically stronger absorption lines. Using a 2.05 µm CW laser absorption spectrometer employing coherent detection method, airborne measurements of CO₂ column abundance has been demonstrated [4]. Since 2010, these three instrument have been flying together on NASA's DC-8 aircraft for taking CO₂ column density measurements. We are developing a new approach to use high energy pulsed 2-micron IPDA lidar instrument via direct detection technique. LaRC had a long history to develop high energy 2-micron lasers. The pulsed lidar approach inherently provides a mean for determining range across the scattering targets. The reflected signals can be resolved between aerosols, clouds, and topographical surfaces. It can directly eliminate contaminations from aerosols and clouds to yield high accuracy CO₂ column measurements. We have chosen to operate the lidar on the long wavelength wing of R(30) CO₂ line at 2050.967 nm (4875.749 cm⁻¹) in the side-line operation mode. The R(30) line is an excellent absorption line for the measurements of CO₂ in 2µm wavelength region with regard to the strength of the absorption lines, low susceptibility to atmospheric temperature variability, and freedom from problematic interference with other absorption lines [5-6]. The computations of differential absorption cross-section will take advantage of the most recent full range of spectroscopic measurements including pressure shifts and pressure dependence of line shape [7]. This paper describes the development of a 2-micron pulsed IPDA lidar instrument that measures atmospheric CO₂ concentration between ground and airborne platform.

II.   DESCRIPTION OF THE IPDA LIDAR

High-precision and accurate atmospheric CO₂ measurements impose stringent requirements on the lidar transmitter and receiver parameters, such as laser energy, pulse repetition rate, laser frequency control accuracy, telescope design and aperture size, high sensitivity with low noise detector and receiver design [8]. Figure 1 depicts the block diagram for the 2-micron pulsed IPDA instrument. It contains laser transmitter, thermal control unit for laser transmitter, wavelength tuning, locking and switching unit, telescope, aft optics and detector unit, signal preamplifiers, data acquisition unit, computer control and signal process unit, and data display.
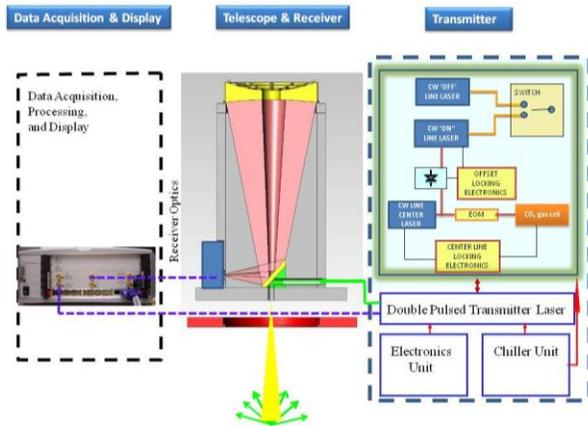
Fig. 1. 2-micron CO_2 IPDA instrument block diagram

A. Laser Transmitter

The compact, rugged, highly reliable laser transmitter is based on the Ho:Tm:YLF high-energy 2-micron pulsed laser technology [9]. This laser transmitter is side pumped by AlGaAs diode arrays at 792nm. The laser transmitter is designed to be operated in a unique double pulse format that can produce two-pulse pair in 10 Hz operation. Typically, the output energies of the laser transmitter are 100mJ and 45mJ for the first pulse and the second pulse, respectively. We injection seed the first pulse with on-line frequency and the second pulse with off-line frequency. This pulse pair repeats 10 times in a second. The double pulse operation is a unique feature of this Holmium (Ho) and Thulium (Tm) co-doped laser. It takes advantage of the long lifetime of the Ho and Tm excited energy level and the quick energy transfer between the Holmium and Thulium atoms. This laser is also capable of producing triple pulses for proper laser design, a feature for three frequency lidar designs. The double pulsed laser produces several advantages. First, the laser can be more efficient. It provides two Q-switched pulses with a single pump pulse. The second pulse energy is from the energy transfer between the Tm and Ho atoms, not from a separate pump pulse. Second, since the time difference between the first and second pulses is typically about 150 - 200μs, the foot print overlap on the ground between the two pulses is greater than 95% for an airborne flight platform. It mitigates the effect of the surface reflection difference between the on-and-off line pulses on the precision of the CO_2 column density measurements. Third, the pulse pair is from the same laser. No beam combining or additional beam control is needed. The temperature of the laser is controlled by two chillers, one controls the laser rod temperature and the other controls the laser bench and laser pump diodes. All the optical mounts are custom designed and have space heritage. They are designed to be adjustable and lockable and hardened to withstand vibrations that can occur in airborne operation. The laser transmitter is 11.5 x 26.5 x 6.4 inch (29 x 67.3 x 16.5 cm) in size, and weighted less than 60lbs.

B. Wavelength Control Unit

The exact wavelengths of the pulsed laser transmitter are controlled by the wavelength control unit. The first pulse and the second pulse are injection seeded alternately by the on-line frequency and the off-line frequency. The on-off line frequency accuracy and stability of the IPDA lidar are critical for making precise and accurate CO_2 measurements. To achieve the frequency accuracy and stability requirements of the pulsed lidar system, the technique of injection seeding is used in which the excellent single frequency and single mode characteristics of low power, spectrally pure continue wave (CW) lasers are imposed upon the pulsed laser. To obtain the wavelength accuracy and stability, a master wavelength reference against a sample of CO_2 in a gas cell is established. One of the CW lasers, called the center-line reference, is locked on the center of the CO_2 absorption line R(30) by a frequency modulation spectroscopic technique [10]. A second laser, called the tunable side-line, is referenced to the center-line laser by a heterodyne technique. By monitoring the heterodyne beat signal between the two lasers, the amount of detuning from the R(30) center can be determined. The detuning range between the two lasers can be set anywhere from a few hundreds of MHz to larger than 6 GHz. An electronic control loop locks the side-line laser at a programmed offset from the line center. The capability of the frequency detuning and locking allows the optimization of the optical depth for measuring atmospheric CO_2 concentrations. The tunable side-line is used for the on-line frequency of the lidar transmitter. Typically, it is locked at 2-4 GHz from the peak of R30 absorption line. A third CW laser provides the off-line wavelength. It is locked against a high precision wavemeter. The wavelength locking accuracy is less than 2 MHz and 30MHz for the on-line and off-line frequencies, respectively.

The locked ON-line CW laser and off-line CW laser outputs are brought into an optical switch that can be electronically addressed to select the on/off wavelengths. The selected wavelength is then sent to injection seed the pulsed laser, so that the frequency of the pulse laser follows exactly the well controlled frequency characteristics of the CW lasers. Three CW lasers, an EO modulator, two detector units, an optical switch, fiber couplers and connectors are all packaged in the custom designed 3U 19 inch rack mountable box.

C. Telescope

The telescope is a custom designed Newtonian type with 40cm diameter primary mirror size. This primary mirror is made of aluminum with diamond turning

machining technique. The shape of the primary mirror is hyperbolic to minimize the aberration, so that the returning signal can be focused to less than 300 micron diameter spot size to fit in the selected detector active area. The telescope is designed to maintain the focus point position in the temperature range between 5 and 35 °C.

D. Aft Optics and Detector

The lidar return signal is divided into two channels, a high gain channel with 90% of signal power and a low gain channel with 10% of the signal power. It helps to increase the dynamic range of the measurements. A high sensitivity with low noise equivalent power (NEP) detector in the 2-micron wavelength region suitable for detecting atmospheric returning signal from airborne or space borne lidar instrument is rapidly advanced, but is not commercial available. However, the detector suitable for detecting the lidar returning signal from hard targets, such as ground surface, in airborne platform is commercially available. The Hamamatsu InGaAs PIN photodiodes, model G5853-203, is selected and characterized for the airborne IPDA lidar application. To obtain fast response and low noise required for the lidar signal detection, the diameter of the detector active area is limited to 300 micron. Thus, the NEP value is specified at 2×10^{-13} W/Hz$^{0.5}$ at -20°C, which is suited for the airborne IPDA lidar.

E. Data Acquisition and process unit

The data acquisition unit is based on two digitizers. The first is a 10-Bit, 2 GS/s digitizer (Agilent; U1065A) for laser energy monitoring and the second is a 12-bit, 420 MS/s digitizer (Agilent; U1066A) for measuring the hard target returns. Detectors are coupled to the digitizers through variable gain, high speed trans-impedance amplifiers (FEMTO; DHPCA-100). Digitizers and data storage are hosted through a personal computer that runs Microsoft XP with a 64-bit/66 MHz PCI bus. The system is capable of transferring data at sustained rates up to 400 MB/s to the host computer.

A simple real time data processing algorithm is implemented to show the lidar returning signal quality. It displays the laser energy monitor signal at on-and-off line wavelengths, the raw data from the ground returning signal, the range information from the lidar return, and the first order estimate of the Differential Absorption Optical Depth (DAOD). These signals help to verify that the laser is operated correctly.

III. IPDA LIDAR AIRBORNE TESTING

After the IPDA lidar has been integrated in class 10000 clean room environment, it was installed inside a mobile trailer for ground testing with horizontal target before moving into aircraft. The ground testing of this new lidar instrument was carried out at a lidar test facility in LaRC. Five targets with calibrated different reflections at 2-micron wavelength were set up at 857 meters away from the lidar trailer. IPDA lidar ground testing included different operating conditions, in terms of signal conditioning settings, target reflectivity and on-line offsets from the CO_2 R30 line center. Preliminary analysis of the ground test data indicated IPDA lidar sensitivity to atmospheric CO_2 concentration. Differential optical depth was obtained by calculating the natural logarithm of the off-line to the on-line return energy after normalization to the transmitted laser energy (laser energy monitor). The theoretical differential optical depth was derived using the US standard atmospheric model [11]. In addition, the IPDA measured differential optical depth was converted to CO_2 dry mixing ratio, using metrological data obtained from instruments that measure pressure, temperature and relative humidity. The measurement results were compared with an *in-situ* CO_2 and H_2O gas analyzer (LiCor; LI-840A) at the site. General temporal profile trend agreement is observed between these two measurements.

The 2-μm CO_2 IPDA lidar is designed for integration into a small research aircraft. The IPDA instrument size, weight and power consumption were restricted to the NASA B-200 payload requirements. This allows the system to be easily adopted in any larger airborne research platform, such as the NASA DC-8 aircraft, for future missions. In addition to the IPDA lidar, other housekeeping instruments were integrated into the B-200 aircraft. These included the *in-situ* sensor (LiCor) for CO_2 dry mixing ratio measurement, GPS for aircraft position, altitude and angles measurements and video recorder for target identification. Besides, aircraft built-in sensors provided altitude, pressure, temperature and relative humidity sampling at the flight position. Time stamps were adjusted to the GPS global timing. Figure 2 shows the integrated IPDA instrument inside the NASA B-200 aircraft.

Fig. 2. Integrated IPDA lidar instrument inside a B-200 research aircraft

The airborne IPDA lidar instrument measures the total integrated column content of CO_2 from the instrument to the ground but with weighting that can be tuned by controlling the transmitted wavelengths. Therefore, the transmitter could be tuned to weight the column measurement to the surface for optimum CO_2 interaction studies or up to the free troposphere for optimum transport studies. This is achieved, for example, by tuning the on-line wavelength to different positions relative to the R30 CO_2 line as shown in figure 3. Except for the frequency offset 1 GHz from the center of the R30 line, the other frequency offsets are all weighted towards the surface where the CO_2 source and sinks occurs. In fact, it is one of the advantages that the 2-micron pulsed IPDA instrument can provide.
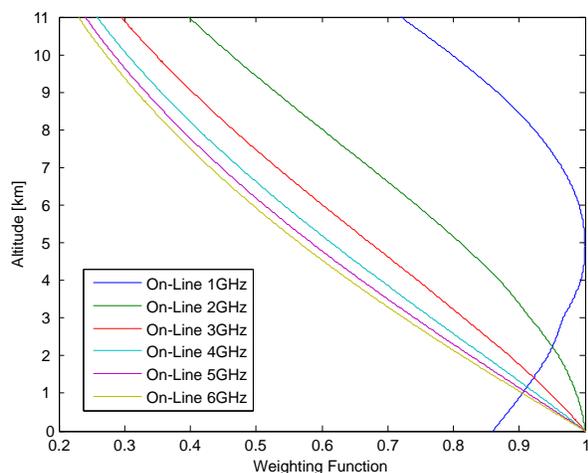

Fig. 3. Pressure-based weighting functions (airborne)

The 2-μm CO_2 IPDA lidar airborne testing was conducted during ten daytime flights, spanning more than 27 hours, during March 20, 2014 through April 10, 2014. Meteorological balloon radiosonde was independently lunched from LaRC site, mostly during the beginning and the end of each flight. This allows for atmospheric pressure, temperature and relative humidity vertical profiling estimates for IPDA modelling verifications. IPDA lidar airborne testing included different operating and environmental conditions. Environmental conditions included different flight altitude up to 8.3 km, different ground target conditions such as vegetation, soil, ocean, snow and sand and different cloud conditions. Besides, some flights targeted power plant incinerators for investigating the IPDA sensitivity to CO_2 plums. Table 1 lists these flights and summarizes the conditions. Flights were conducted from NASA LaRC through Langley Air force Base, Hampton, Virginia. In the first three flights (engineering flights 1, 2 & 3), the objective was to check the IPDA instrument operation and alignment verification in the airborne environment at different altitudes ranging from 3kft to 27.5kft. Ground condition was maintained almost fixed

by targeting soil/vegetation through a flight track to the west of Virginia from Franklin to South Boston. The objectives of the fourth and fifth flights were to test different ground target condition in terms of different reflectivity versus signal return power at a fixed altitude of 6.6km. Taking advantage of an early spring snow storm, flight 4 headed north toward Northern Virginia to investigate the lidar returning signals at ground conditions with soil, vegetation and snow. On the same day, fight 5 headed south toward the Outer Bank of North Carolina to investigate soil, vegetation, sand and water targets. Focusing on the ocean surface return, the sixth flight headed toward the Atlantic where measurement conducted in clear and cloudy conditions. This took the advantage of 4kft altitude cloud coverage over the ocean, where the IPDA instrument was capable to distinguish ocean surface and cloud return with cloud depth measurement. The objectives of flights 7 and 9 were to fly over large power plant, Roxboro Power Station of North Carolina, where the high consumption of coal tends to bias the CO_2 mixing ratio above normal sources. Finally the tenth flight was objected to debugging the CO_2 in-situ sensor, over the Franklin to South Boston trajectory. The lidar instrument is robust during all of the flights. In spite of the mechanical stresses due to shaking and vibration in the small aircraft environment, the IPDA lidar did not lose alignment resulting in about 190 GB worth of raw data.

TABLE 1. Summary of the 2-micron CO2 IPDA lidar flights during March 20, 2014 to April 10, 2014 airborne testing on board the NASA B200 (529) research aircraft

Flight #	Operators author's #	Date	Local Time Start	End	Objective
1	2, 5	3/20	1:50p	3:42p	Engineering
2	1, 3	3/21	2:17p	5:00p	Engineering
3	2, 3	3/24	8:50a	11:50a	Engineering
4	1, 5	3/27	7:15a	10:15a	Surface
5	2, 3	3/27	1:35p	4:00p	Surface
6	1, 3	3/31	1:30p	4:00p	Ocean/cloud
7	1, 2	4/02	9:24a	11:47a	Power station
8	1, 3	4/05	1:10p	4:52p	With NOAA
9	1, 3	4/06	2:10p	5:10p	Power Station
10	1, 5	4/10	3:40p	5:58p	In-situ

On April 5, 2014, the NASA B-200 eighth flight coincided with another NOAA air sampling flight. Due to flight control restrictions, there was a 30 minute time lag between NOAA and NASA flights. Nevertheless, the IPDA lidar on board NASA flight sampled the same geographical location as the NOAA flask samples over the Atlantic Ocean out of the east shore of New Jersey. CO_2 flask-sampling results and meteorological data provided by NOAA were valuable for the NASA LaRC IPDA lidar instrument testing. The altitude information can be deducted by comparing the time delay between

the time emitting the laser pulse and the ground return pulse. Figure 4 compares the flight altitude, obtained from the GPS to the range calculated from the IPDA data. The GPS flight altitude was converted to line-of-sight measurement after correcting for the aircraft pitch and roll angles, obtained from the GPS. Preliminary analysis of the airborne test data indicated the IPDA lidar sensitivity to atmospheric CO_2 up to 6.6 km altitude over ocean target. Figure 5 compares the CO_2 differential optical depth obtained from the IPDA data and modelled from NOAA flask sampling data. IPDA indicated a consistent CO_2 differential optical depth offset of about 0.07, similar to what was observed on ground testing.
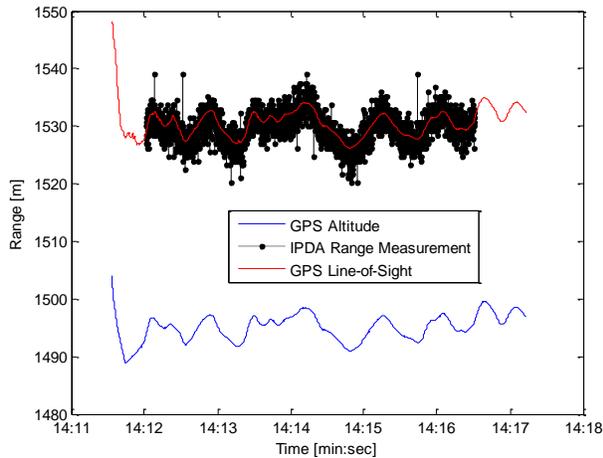
Fig. 4. GPS flight altitude corrected to the pitch and roll angles to obtain the IPDA line-of-sight distance compared to the IPDA range measurement
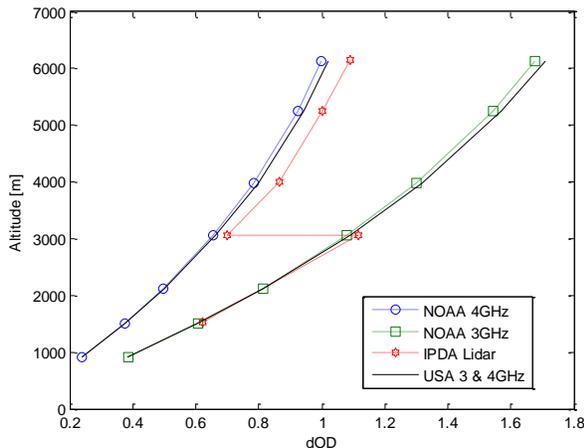

Fig. 5. CO_2 differential optical depth versus altitude calculated from NOAA flask sample data and from the IPDA lidar. Results are compared to US standard model calculations

The detail analysis of the airborne data is in progress. We expect to have final report before the end of this year.

IV SUMMARY

NASA LaRC developed a double-pulse, 2-μm integrated path differential absorption (IPDA) lidar instrument for atmospheric CO_2 measurement. Advantages of the IPDA remote sensing technique include high signal-to-noise ratio measurement with accurate ranging. The 2-μm CO_2 IPDA transmitter is capable of producing 100mJ energy per pulse at 10 Hz repetition rate. High accuracy, stable and repeatable wavelength control and switching unit have been integrated within the transmitter. The IPDA also include a high quality 16 inch telescope and a commercial detector, electronics and data acquisition that has been integrated. The whole IPDA lidar structure is compactly and ruggedly packaged to fit in the NASA B-200 research aircraft. Ground and airborne testing of the 2-μm IPDA lidar was conducted at NASA LaRC through several validation procedures. This included instrument performance modeling through standard atmosphere and meteorological sampling. IPDA CO_2 differential optical depth measurement results agree with ground *in-situ* measurements and with CO_2 airborne sampling conducted by NOAA. Consistent differential optical depth offset, of about 0.1, was observed in the measurement. Further detailed data processing is under work. This airborne 2-μm IPDA lidar provides a unique CO_2 measurement tool that could be scaled to future space missions.

ACKNOWLEDGMENT

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