DEVELOPMENT OF A GROUND-BASED 2-MICRON DIAL SYSTEM FOR ATMOSPHERIC BOUNDARY LAYER AND CLIMATE STUDIES

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1. INTRODUCTION

To fully understand the global atmospheric CO_2 cycle requires measurements of atmospheric CO_2 profiles on continental and global scales that are not available. The difficulty in making remote profile measurements arises from CO_2 exhibiting small variations in concentration over large spatial scales [1]. Atmospheric gradients of CO_2 over continents are typically 2 - 10 ppmv. Contrasts of this magnitude develop daily between the Planetary Boundary Layer and the free troposphere, as a direct consequence of anthropogenic and biospheric activity. Contrasts between the ocean and the land, and across the landscape, are comparable. While a large number of local and regional scale CO_2 *in-situ* measurements can be found in the literature, a network [2] of 70 ground stations involving *in-situ* observations from towers located over land has been developed only recently to monitor long-range variations of CO_2 near the surface. Although the quality of these *in-situ* tower measurements is high, the measurements only represent the small footprint of the tower which may be subject to systematic effects due to localized influences of terrain, wind patterns, and meteorological factors and currently do not provide coverage over the oceans. Only high-precision, high-resolution measurements of atmospheric CO_2 profiles from space can afford the representative sampling of large geographical regions over land and ocean thus providing a strong constraint for inverse models of the global CO_2 budget.

Emerging active and passive satellite remote sensing techniques have the potential for providing global scale CO_2 distributions and for monitoring their variations. The advantages of DIAL measurements are their relatively high spatial resolution, high measurement specificity (avoiding interference from other gases), lack of dependence on external light sources, and relatively simple inversion methods compared to retrieval methods used in passive remote sensing. Because of the potential for providing high quality measurements, a number of ground- and aircraft-based DIAL systems are currently under development [3 and references therein]. In this paper we discuss laser and detector developments at NASA Langley Research Center (LaRC) in the 2 μm region to enable DIAL CO_2 profiling capability. Observations of the diurnal variations of boundary layer CO_2 using a ground-based coherent heterodyne detection DIAL system [3,4] are presented in this paper along with an evaluation of its precision. Comparison of DIAL measurements with high accuracy *in-situ* measurements is reported. Performance of an advanced direct detection DIAL system using a novel phototransistor and a large collection area receiver to improve free tropospheric profiling capability is also presented.

2. 2-μm LASER DEVELOPMENT

Solid-state lasers based on holmium offer several advantages as a transmitter for DIAL measurements of CO_2. First, they are tunable in a spectral region containing strong CO_2 absorption lines that are suitable for high sensitivity CO_2 measurements. Second, there has been considerable development in this laser technology for application in coherent lidar measurements of wind. As much as 600 mJ energy per pulse with a single-frequency spectrum has been demonstrated with diode-pumped Ho:Tm:YLF [5]. This capability for high pulse energy, and parallel NASA research efforts for further increase in energy, provides a framework for evolution of the lidar application described here toward ground, aircraft and, ultimately, space platforms. Third, the 2-μm wavelength offers a high level of eye safety—a maximum permissible exposure of 100 mJ/cm^2 [6]. For developing a successful DIAL profiling system the following laser characteristics are needed:

- Pulsed laser for range resolved profiling

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- Double pulsed operation to sample the same air mass by on- and off-line laser pulses
- Wavelength stability and spectrally narrow output
- Line-locking with respect to a selected CO_2 line
- Operation on a side of the line for optimum absorption cross-section selection

To accomplish these objectives specific laser developments have already been demonstrated at 2-μm: 1) high energy pulsed laser operation [5], 2) tunability across a number of temperature insensitive lines [7,8], 3) line-locking on a selected absorption line using an absorption cell [7,8], 4) line narrowing and fine frequency control by injection seeding with a single-frequency continuous wave laser matched to the pulsed laser cavity by ramp-and-fire technique [3], 5) side-line operation [3], and 6) double pulsed operation for on and off wavelength generation [9]. The unique feature of the double pulse operation is that it provides on-and-off line wavelength pulse pair with a single pump pulse.

3. 2-μm DETECTOR DEVELOPMENT

Development of 2-μm detectors is critical for the development of CO_2 DIAL systems for ground, aircraft, and ultimately space-based measurements of CO_2 at this extremely useful wavelength region. High spectral responsivity, low noise, high gain, large dynamic range, short impulse response time, and linearity are the characteristics needed to meet the requirements of CO_2 DIAL systems. InGaAs and HgCdTe detectors with good spectral sensitivity are available but they are not suitable because of lack of sufficient responsivity due to the absence of internal gain. Although AlGaAsSb/InGaAsSb (AIGAS) avalanche photodiodes (APD) with separate absorption and multiplication structure were developed and tested with gains up to 500 [10], at a operating temperature of 78 K, these APDs are not commercially available. To meet the requirements of a direct detection CO_2 DIAL system, a novel AIGAS phototransistsor has been developed by AstroPower, Inc. These devices provide high gain at low bias voltage and are free from the excess noise factor effects associated with APDs. LaRC has procured several AIGAS devices and conducted optical characterization in the laboratory [11].

Optical characterization of an AIGAS phototransistor was performed by measuring the spectral response at different operating conditions. Figure 1 shows the spectral response of the detector at 20°C with different bias voltages up to 3 V. For higher bias voltages the detector was cooled to -20°C to reduce the dark current to avoid excess current damage. At this temperature the cut-off wavelength shifts to shorter values corresponding to the energy band gap increase at a lower temperature. The highest responsivity of 2650 A/W was observed with this device at 2 μm that corresponds to an internal gain of 2737. This is the highest reported responsivity at this particular wavelength.

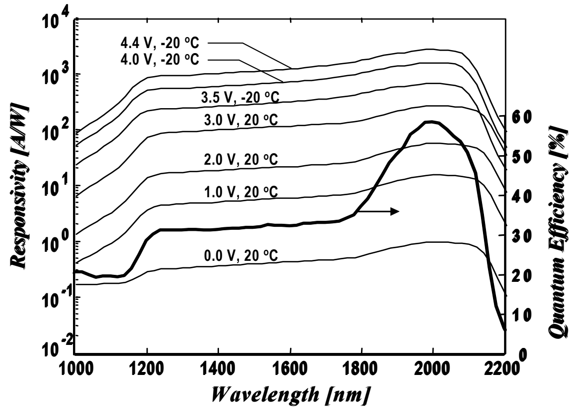

Figure 1: Responsivity and quantum efficiency measurements of AIGAS phototansistor.

Also shown in Figure 1 is the variation of the quantum efficiency with wavelength. The quantum efficiency was calculated from the 0-V bias voltage using measurements at 20°C temperature. Two distinctive regions appear in the quantum efficiency curve. A peak optimized around the 2-μm wavelength corresponds to the absorption of the InGaAsSb region and another flat region between 1.2 and 1.8 μm that corresponds to the absorption in the AlGaAsSb region. A maximum quantum efficiency of 58.4% occurs at 2 μm. Although slightly higher quantum efficiency can be obtained from other devices, its value peaks around 2 μm for this structure, with sharp edges at 1.9 and 2.1 μm, which limits the background signals. From these characterizations a detectivity of 3.9E11 cmHz$^{1/2}$/W was obtained which corresponds to a noise-equivalent-power of 4.6E-14 W/Hz$^{1/2}$. We plan to use these promising devices in a ground-based DIAL system for CO_2 profiling in the troposphere.

4. HIGH SENSITIVITY GROUND-BASED DIAL SYSTEM TO OBSERVE DIURNAL VARIATIONS OF CO_2

A high sensitivity ground-based coherent detection DIAL system has been developed and was used to observe the diurnal variability of atmospheric CO_2 [3]. It uses a Ho:Tm:YLF laser transmitter and an existing InGaAs photodiode detector. The diode-pumped Ho:Tm:YLF pulsed laser is in a ring configuration with an acousto-optic Q switch. The laser rod is pumped by 6 conductively-cooled AlGaAs diode arrays, each array is composed of six bars that can provide a total of up to 600 mJ near 792 nm in a 1-ms long pulse. Three sets of two diode arrays, side by side, are arranged 120^o apart around the laser rod circumference. The laser rod has a diameter of 4 mm and is encased in a 6-mm outer-diameter fused-silica glass tube for water-cooling of the laser rod; the coolant temperature is kept at 15 C. The 20-mm long laser rod is doped with 6% Tm and 0.4% Ho. Line narrowing and fine frequency control are accomplished by injection seeding with a single-frequency cw laser matched to the pulsed laser cavity by a ramp-and-fire technique.

In this system, coherent heterodyne detection technique is used to provide the needed sensitivity for the DIAL technique. The laser wavelength is alternated for an interleaved sampling of differential absorption, high laser pulse energies (75 mJ on/off) are transmitted, and refined algorithms are used for measuring power in a heterodyne signal. DIAL measurements were performed by operating on the temperature insensitive [12] strong CO_2 absorption line at 2050.967 nm. Using the side-line technique for selecting the optimum CO_2 absorption cross-section, optimum measurements are made in the atmosphere. Wind can also be measured with this lidar from the Doppler shift from aerosols [4]. The DIAL system parameters are given in Table 1.

Table 1. DIAL system parameters

Pulse energy = 75 mJ
Pulse width = 180 ns
Pulse repetition rate = 5 Hz
Spectrum = single frequency
On-line wavelength = 2050.967 nm
off-line wavelength = 2051.023 nm
Beam quality < 1.3 time diffraction limit
Long term (one hour) wavelength stability < 16.5 MHz
Wavelength accuracy < 15 MHz
Detector = InGaAs in heterodyne configuration
Telescope aperture = 4 inches

An atmospheric test of the DIAL system was conducted on August 22, 2003. The object of this test was to assess precision and sensitivity of this DIAL system. Experiments were conducted to see if the diurnal variations in CO_2 could be observed. To provide the 'ground-truth' of atmospheric variations of CO_2 a high sensitivity *in-situ* air sampling Li-Cor NDIR spectrometer that was used. The Li-Cor was calibrated against NOAA's Climate Monitoring and Diagnostics Laboratory standards that are directly traceable to WMO primary standards. The lidar beam was pointed horizontally such that the beam passed next to the inlet of the *in-situ* sensor. Comparison of DIAL measurements with the *in-situ* sensor observations is shown in Figure 2. The first DIAL measurement at 6:00 AM was calibrated to the Li-Cor measurement in order to compare the trend of the DIAL versus the Li-Cor. These data show that the DIAL system has the capability to observe diurnal variation of CO_2. A statistical analysis of the signal-to-noise-ratio of on- and off-signals from observations conducted under stable night conditions within a 45 minute interval was used in estimating the 1.5% precision (1-σ standard deviation) of the DIAL measurements [3].

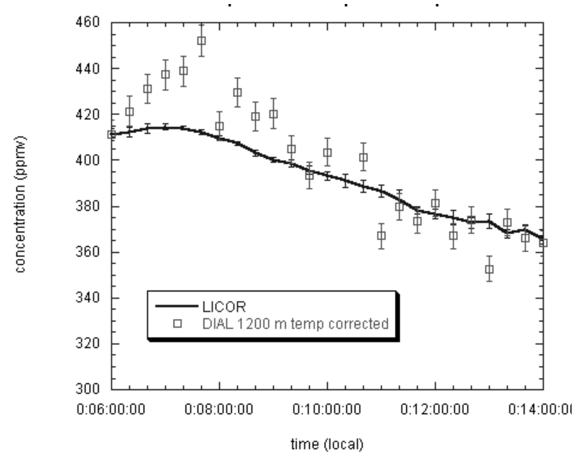

Figure 2: DIAL CO_2 measurements compared with Li-Cor

5. PERFORMANCE OF AN ADVANCED GROUND-BASED DIAL SYSTEM.

To develop the capability to profile lower tropospheric CO_2 distributions in the atmosphere a shot-noise limited direct detection DIAL system is being tested. The object is to improve the precision of the ground based system to 0.5%. This lidar will incorporate the new AIGAS cooled phototransistor and a large collection area telescope with a 15" diameter. Higher pulse energy (95 mJ on/off) is also available by using an improved laser material of Ho:Tm:LuLiF. DIAL performance calculations were done using the appropriate lidar parameters in Table 1. A mid-latitude summer atmosphere, a background aerosol model, a night background, and a CO_2 absorption line at 2050.967 nm operating with the on-line in the side-line position at 25 pm from the line center was used in these computations. Using the method described in [13] a random error or precision of the measurement is calculated using the relationship:

$$\frac{n}{n} = \frac{1}{2\Delta\sigma n\left(R_2 - R_1\right)}\left\{\sum_{i=1}^{2}\sum_{j=1}^{2}\left[\frac{\left(s_{ij}+B\right)F+D}{s_{ij}^2}\right]\right\}^{1/2}$$

Where the indices i and j refer to the ranges R_1 and R_2, respectively, B the background, F is the excess noise factor of the detector (F=1 for the phototransistor), $\Delta\sigma$ is the differential absorption cross section, D the detector dark current, and S the lidar signal. Figure 3 shows the on- and off-line lidar signals and the assumed atmospheric scattering ratio profiles. Using a 5-minute shot averaging interval and a 1 km range resolution, the calculated precision profile of CO_2 measurements of the proposed system is also shown in Figure 3. A measurement precision of 0.3% is projected up to an altitude of about 4 km. Higher vertical resolution measurements are possible at lower altitudes in the boundary layer. Information about atmospheric temperature, density, and moisture is obtained from tower in situ and/or radiosonde data for the retrieval of CO_2 mixing ratios from DIAL. This type of lidar can be used in field experiments to provide lower tropospheric profiling of CO_2 for regional flux studies and for the validation of space-based remote sensing.

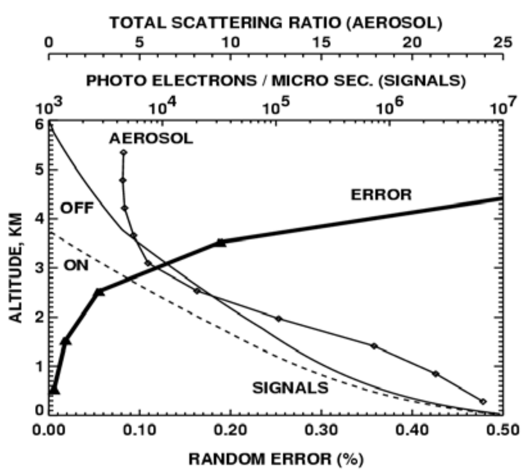

Figure 3: Performance (error) of ground-based DIAL (thick line), on/off lidar signals and assumed aerosol profile are also shown.

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