GODDARD PROGRAM FOR MEASUREMENT OF CARBON DIOXIDE USING A BROADBAND LIDAR

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Abstract **In order to better understand the budget of carbon dioxide in the Earth's atmosphere it is necessary to develop a global understanding of the carbon dioxide column. In order to uncover the "missing sink" responsible for the large discrepancies in the budget a measurement accuracy on the order of 1 ppm [1] is necessary. The column average CO_2 has reached 380 ppm so this represents a precision on the order of 0.25% for these column measurements. No species has ever been measured from space at such a precision. In recognition of the importance of understanding the CO_2 budget in order to evaluate its impact on global warming the National Research Council in its decadal survey report to NASA recommended a laser based total CO_2 mapping mission in the near future [2]. The extreme measurement accuracy requirements on this mission places very strong restrictions on the laser system used for the measurement. Because atmospheric pressure and temperature change the size and shape of CO_2 absorption lines no single narrowband laser observation can meet the 0.25% precision requirement. Moreover this precision puts stringent requirements on wavelength stability for a single laser line.**

We have been examining the possibility of making precise measurements of atmospheric carbon dioxide using a broad band source of radiation. This means that many of the difficulties in wavelength control can be treated in the detector portion of the system rather than the laser source. It also greatly reduces the number of individual lasers required to make a measurement. Simplifications such as these are extremely desirable for systems designed to operate from space.

Our current system employs an OPA pumped by a small Nd:YAG laser (50 mJ at 15 Hz). We have achieved a signal to transmit that is 14 mJ in a 4 nanosecond wide pulse with a spectral width about 3 nm wide centered at ~1571 nm. CO_2 has several strong spectral lines in this region. Our receiver is sensitive in this region. It consists of an 8 inch telescope coupled to our two channel detector system. One channel contains only a broad band filter while the second channel employs a Fabry-Perot etalon to select regions of strong CO_2 absorption. Both channels use avalanche photodiode detectors. We have not field tested the complete system yet but expect to have early test results by the time of the conference.

Instrumentation; measurement; metrology; remote sensing; atmospheric composition; optical instruments; absorption; interferometry; Fabry-Perot.

I. INTRODUCTION

This paper describes the development, initial testing and preliminary experimental results for our novel CO_2 lidar sensor for 1.57 microns. In our initial setup we are using superluminescent light emitting diode (SLED) as a source and our previously developed Fabry-Perot interferometer subsystem as a detector part [3], [4], [5].

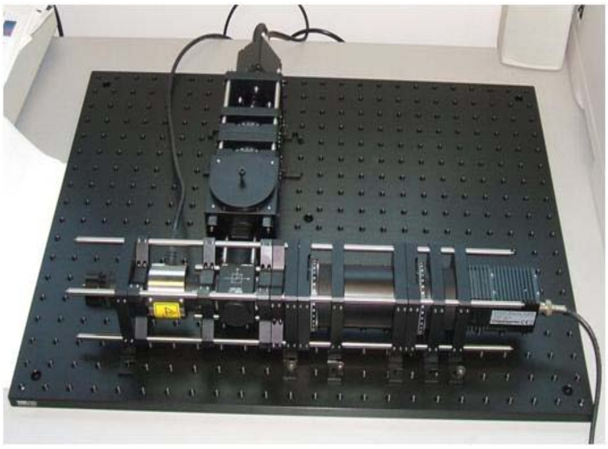

Figure1. This shows the mechanical setup of the improved Fabry-Perot detector for the broad band lidar. Light enters the system at the upper left and passes through the band pass filter. Some of it is then split off and passes through a polarization compensator and onto a detector. The unsplit component continues toward the right through a Fabry-Perot etalon and is detected.

The detector part (Figure 1) has been developed over the last five years at Goddard as a passive sensor to measure CO_2 column using scattered solar flux and was tested at two flight campaigns [3], [6]. This system employs Fabry-Perot etalons to create a differential response to the absorption of sunlight by carbon dioxide lines near 1.57 microns. Over time the sensor has been improved by changing the detectors, downsizing and advancing the design in order to permit prompt and easy alignment. The new smaller design for the receiver makes more efficient use of light from a collimated source than the original passive system did which was optimized for sunlight.

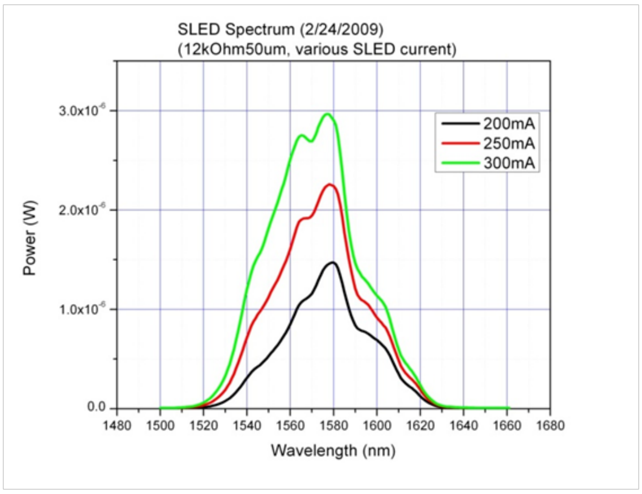

Figure2. The output of the SLED increases with increasing the drive current. The spectral output is quite broad covering almost 100 nm. We only use a narrow region 2-3 nm wide centered on 1571 nm. The OPA is designed to amplify this region in particular.

By modifying the composition and geometry of the SLED its output can be tailored to some extent to meet specific requirements for operating wavelength and bandwidth. The output of a commercially available off the

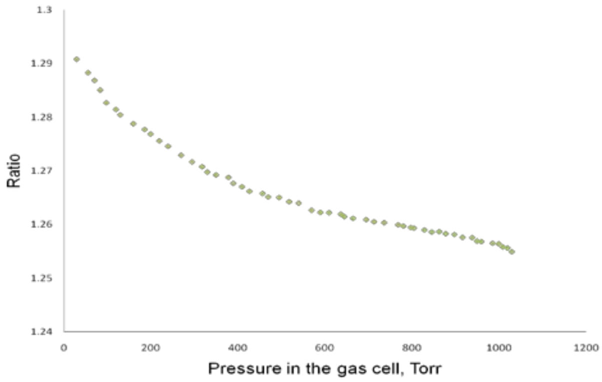

Figure3 Change in ratio as a function of CO_2 pressure in an absorption cell.

shelf SLED manufactured by EXALOS has ~70% of the output power between 1540nm and 1600 nm and is almost centered over the 1567nm to 1574 nm region used by the Fabry-Perot detector. The total output power for the device can be on the order of 20 mW. Figure 2 shows the SLED output at different drive currents. This is not enough output for a measurement from space, but it is satisfying for initial laboratory work on the feasibility of the technique.

II. Experimental

A. Observation of CO_2 absorption in the lab using SLED source

The Fabry–Perot etalon in the detector part of the sensor is solid fused silica with a free spectral range (FSR) of 0.306 nm and a refractive index of 1.443 at λ = 1571 nm. The spacing between etalon fringes is approximately matched to the spacing of CO_2 lines through etalon thickness. Similarly, the width of fringes is approximately matched to CO_2 line

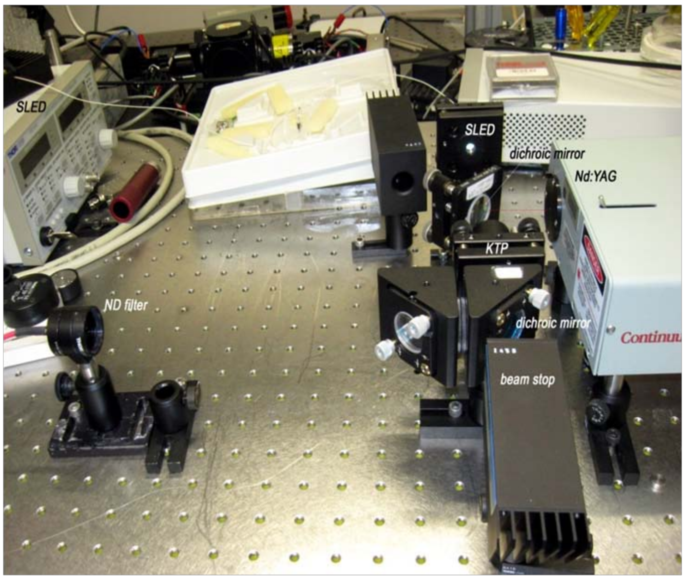

Figure 4. This shows the layout of the Optical Parametric Amplifier (OPA) set-up in the lab.

width by appropriate choice of reflectance of the etalon surfaces. Alignment between etalon fringes and CO_2 absorption lines can be further adjusted by temperature tuning the Fabry–Perot [3], [4], [5], [6]. To validate in the laboratory that the broadband technique is feasible the changes in the ratio of Fabry–Perot to reference signals were monitored for different CO_2 pressures using input SLED light (Figure 3) and miltipass gas cell filled with carbon dioxide at different pressures. The pressure experiment was done with modulated SLED output using a pulse generator.

B. Coupling a SLED source to an amplifier

It is necessary to boost the output power up to the tens or hundreds of Watts for longer range measurements from space platforms. There are several approaches to accomplishing this. The most common one is to use a fiber amplifier device known as an EDFA (Erbium Doped Fiber Amplifier) for this purpose [7], [8], [9], [10], [11]. EDFA's have been developed for use in fiber optical communications system so they are rugged and reliable. Our more recent efforts have indicated that the pulse width obtainable with an EDFA is not optimal for the broadband lidar approach. An Optical Parametric Amplifier (OPA) offers higher conversion efficiency, broad tuning range and shorter pulse width (~10 ns). We have therefore decided to use an Optical Parametric Amplifier (OPA) instead of the EDFA for this amplification process. Figures 4 and 5 show the OPA setup.

In the OPA cw light from the SLED at 1570 nm is focused into a crystal of KTP ($KTiOPO_4$, potassium titanyl phosphate) and pulses from the Nd:YAG are overlapped in the same crystal (Figure 4). Non-linear processes in the KTP crystal split the Nd:YAG photons whose combined energy is equal to that of the single Nd:YAG photon. One of these two photons will be at the SLED wavelength so the light coming out of the KTP crystal contains an amplified signal at 1570 nm. The residual photons at 1.06 from the

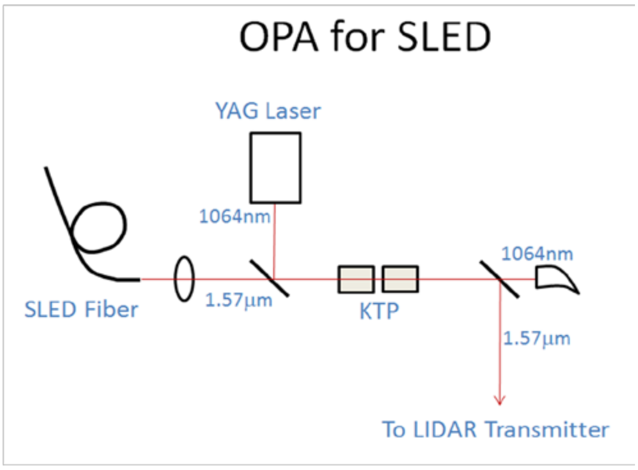

Figure5. This is a diagram of the operation of the Optical Parametric Amplifier (OPA).

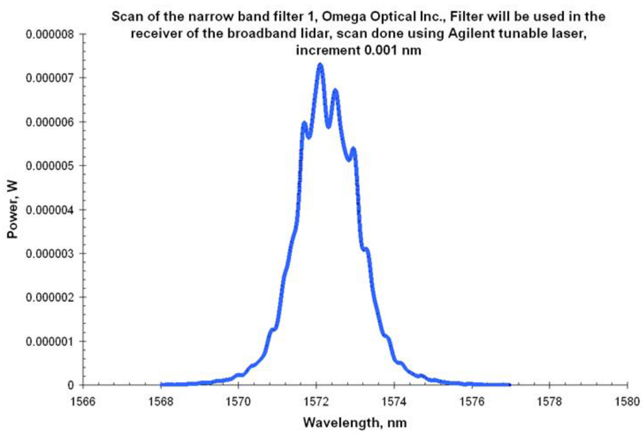

Figure6. Laser scan of one of our bandpass filters. These filters are used in the receiver to confine the range of wavelengths observed to those over which a good alignment between the CO_2 absorption lines and the Fabry-Perot transmission peaks can be maintained.

Nd:YAG and the “idler” photons at 3.3 microns are separated and discarded. The amplified 1570nm is transmitted for the broadband lidar.

We had reported an amplified output of 2 mJ per pulse from the OPA from the Nd:YAG laser with power of 42 mJ per pulse. Improvements in the beam quality of the Nd:YAG and in the alignment of this system have resulted in an increase in the OPA energy to 14.6 mJ per pulse.

Figure 6 shows a laser scan of one of our bandpass filters (Barr Associates). One of those filters will be used in the lidar receiver and another will be used between the SLED output and the OPA to restrict the range of amplified wavelengths to those that our receiver can detect. Ideally the OPA output would exactly match the bandpass of this filter.

The output of the OPA was measured using an ORIEL grating monochromator. The spectral width has been reduced to about 2 nm. All of the photons coming out of the OPA are within the bandpass of our lidar receiver. We would like to increase the output bandwidth of the OPA slightly to match the filter in the receiver. We have also operated the system as an OPO without using the SLED to inject the desired wavelength. This has shown that the output wavelength is controlled more by properties of the KTP crystal than by the injected wavelength.

As the power of the energy output increase the difference between OPO/OPA decreases due to the saturation effect. For this measurement the KTP crystal was at room temperature. By placing the KTP crystal in an oven we were able to study its temperature dependence which is important for the system performance. If we increase the temperature of the crystal from 25 to 55 degrees C, the peak of the OPO/OPA output shifts to shorter wavelengths and the shift is on the order of one nm which agrees with reports in the literature [12]. We may be able to use a pair of crystals operating at slightly different temperatures to broaden the OPA output.

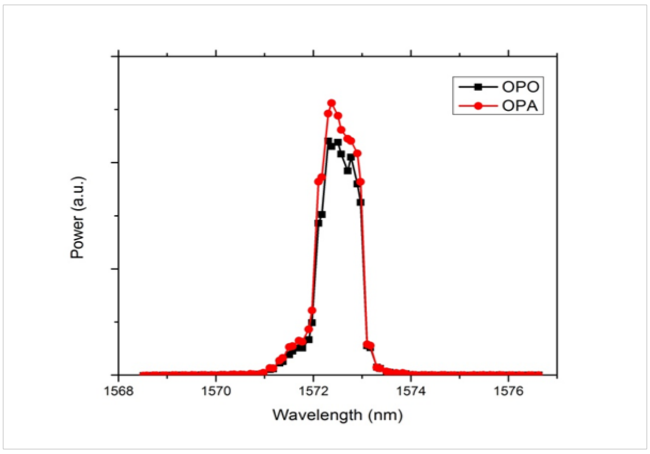

Figure7. OPA output

There are CO_2 absorption lines located at 1571.7, 1572.0, 1572.3, 1572.65, and 1573.0 nm that will absorb light from this transmitter with the limited bandpass that we have at present.

The output of the SLED alone is a continuous laser beam with an average power on the order of 20 mW. The output of the OPA are14mJ pulses at15 Hz.

If the output of the transmitter could be modified to put more energy on the CO_2 lines and less in between the lines the overall efficiency of the measuring system will be improved. We can spectrally modulate the output of the transmitter by inserting a Fabry-Perot etalon identical with the one used in the receiver into the transmitter located between the SLED output and the OPA. By angle tuning this Fabry-Perot we can align the transmitter output peaks with the CO_2 absorption features using a photoacoustic cell.

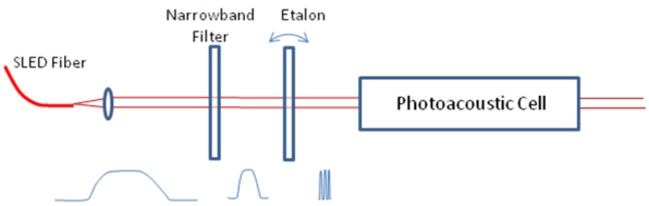

Figure 8. This is the experimental setup to modulate the output of the SLED in order to put more transmitter power on the CO_2 absorption lines. The photo acoustic cell is filled with CO_2. The acoustic signal from the cell increases when the laser light focused into the cell is correctly tuned to one (or in our case several) of the CO_2 lines.

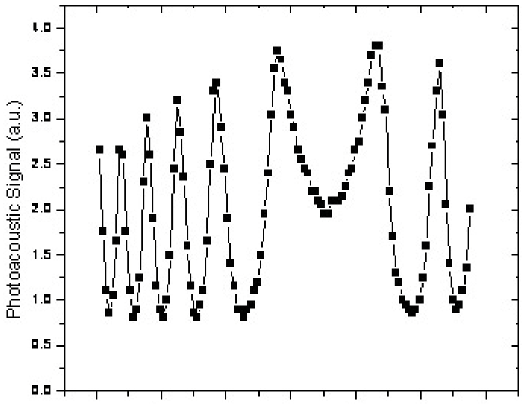

Figure 9. This shows the results of the experiment illustrated in Figure 8. The Fabry-Perot transmission lines and the output wavelengths from the SLED align and then misalign with the CO_2 absorption features.

Wavelength of the Fabry-Perot varies as the cosine of the angle of incidence. This means that normal incidence occurred when our rotator mount was set at about 3.5 degrees. In practice we would set the etalon at an indicated angle of about 2.8 degrees.

In figure 10 we show a schematic of the field lidar system. The collimated beam from the OPA will be sent to a transmitter, light with frequency 2 pulses per second will be used to gather information about the CO_2 absorption in 200 m atmospheric column. For the detection we will use avalanche photodiodes (APD's).

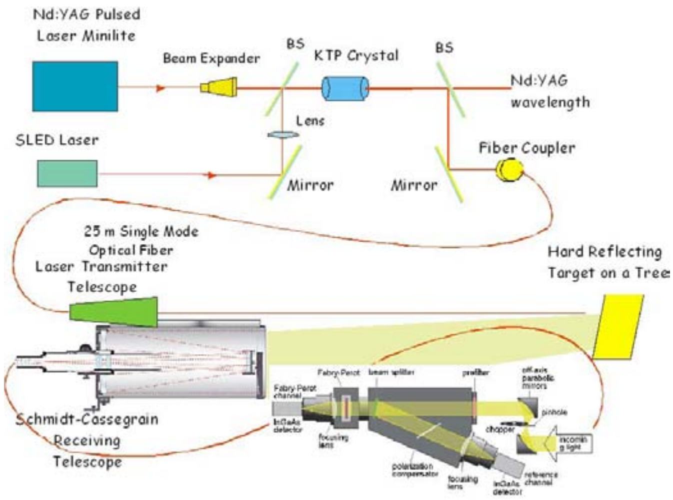

Figure10. Schematic of the initial broadband lidar system using SLED, Nd:YAG and OPA.

C. Broadband 2 micron lidar for CO_2 column measurements

The broadband approach could be implemented at 2 micron spectral region.

Figure11. Lidar system assembly in the lab. The Vixen telescope is the receiver and the Orion is the transmitter beam expander. The Nd:YAG pump laser for the OPA is in the left foreground.

The strong CO_2 band with wavelengths in the vicinity of 2 µm provides a second and totally independent measure of the CO_2 abundance. The 2 µm band measurements are also sensitive to variations in atmospheric pressure and humidity along the optical path. The 2 µm band spectra are very sensitive to the presence of aerosols which will tremendously enhance the measurement accuracy.

Northrop Grumman (NGST) has developed a broadband 2.0 micron laser source employing thulium-doped fibers that may prove ideal for broadband lidar for 2 micron spectral region. Our group was working on the 2 micron receiver development using IRAD funds.

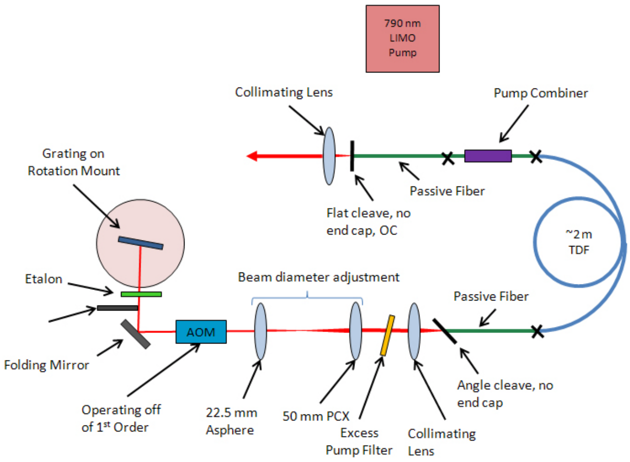

Figure 12. Current Laser Layout for the 2 micron lidar development (NGST)

The performance of a lidar for measuring CO_2 at 2 µm has been simulated assuming a 500 km orbit with a sampling scale footprint 100m. The telescope diameter is 1.5 m and the Field of View (FOV) of the sensor is 200 µrad. The laser output of 100nsec pulses at 10 kHz will have an average power of 22 Watts. The laser beam will be passing through a prefilter (FWHM = 5nm) with the same design as the prefilter that will be used in the receiver so the output light is at 2. 054 µm.

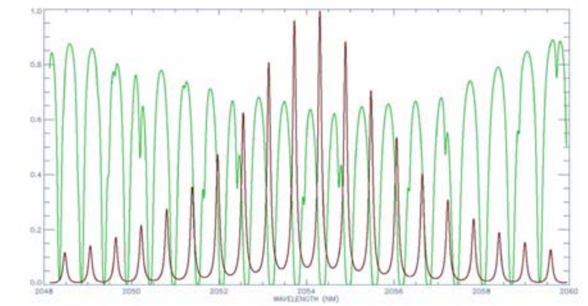

Figure13. Generated synthetic spectrum for the two micron laser

The Fabry-Perot etalon for the receiver will be a 2.5 mm fused silica etalon with finesse = 17. A second Fabry-Perot is used for the prefilter and this one has a gap of 14 microns with a finesse of 25. Assuming 18 Watts transmitted laser power, an Earth albedo of 10%, a 1.5 meter diameter receiver telescope the model showed a one second SNR of 240:1. Since we require a SNR in excess of 400:1 over a p;ath that is 100 km long (~14 seconds of averaging this simulation implies that the 2.0 micron system should be scalable to meet the CO2 column measurement requirement. However, the simulation also indicates some sensitivity to water vapor interference. Additional work will be required to achieve a final workable design. The generated synthetic spectrum with the prefilter shape, the Fabry-Perot passbands and the CO_2 absorption lines at that spectral region are shown in the Figure 13.

III. CONCLUSIONS

We presented here a prototype active Fabry-Perot based sensor for absorption measurements of total column carbon dioxide using broadband laser sources for 1.57µm and 2 µm. The sensitivity and feasibility of the technique has been demonstrated in the laboratory when used with an absorption cell filled with carbon dioxide. Additionally, more laboratory experiments, field measurements and airborne tests will validate the instrument's sensitivity to measure atmospheric CO_2.

The sensor described here has the potential for providing relatively simple optical detection for carbon dioxide. The future technology to study the Earth system and climate will more and more shift toward spaceborne lidars instead of passive sensors. The advantage of lasers is that they can determine the optical path length for the measurement process very precisely eliminating a serious source of error that may affect passive systems. Lasers can also operate without the need for sunlight and so can make measurements of the full diurnal cycle of CO_2 around the whole earth. Therefore the broadband approach for accurate CO_2 measurement from space is very important to be fully developed and implemented.

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