

A BROAD BAND LIDAR FOR PRECISE ATMOSPHERIC CO₂ COLUMN ABSORPTION MEASUREMENT FROM SPACE

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Abstract Accurate global measurement of carbon dioxide column with the aim of discovering and quantifying unknown sources and sinks has been a high priority for the last decade. In order to uncover the “missing sink” that is responsible for the large discrepancies in the budget the critical precision for a measurement from space needs to be on the order of 1ppm [1]. To better understand the CO₂ budget and to evaluate its impact on global warming the National Research Council (NRC) in its recent decadal survey report (NACP) to NASA recommended a laser based total CO₂ mapping mission in the near future [2]. That’s the goal of Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS) mission -to significantly enhance the understanding of the role of CO₂ in the global carbon cycle. Our current goal is to develop an ultra precise, inexpensive new lidar system for column measurements of CO₂ changes in the lower atmosphere that uses a Fabry-Perot interferometer based system as the detector portion of the instrument and replaces the narrow band laser commonly used in lidars with a high power broadband source. This approach reduces the number of individual lasers used in the system and considerably reduces the risk of failure. It also tremendously reduces the requirement for wavelength stability in the source putting this responsibility instead on the Fabry-Perot subsystem.

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 CO₂ lidar sensor for 1.57 microns under development. 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].

The detector part (Figure 1) has been developed over the last few years at Goddard as a passive sensor to measure CO₂ 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 absorption lines near 1.57 microns. The sensor was further improved by

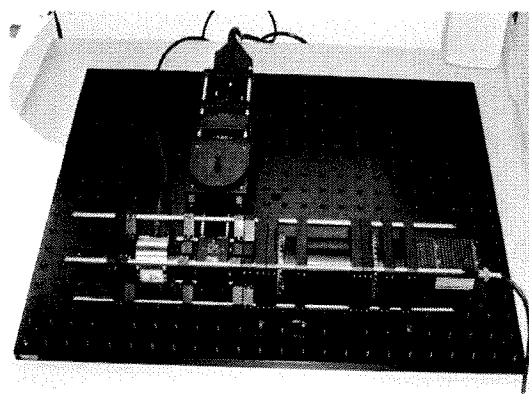


Figure 1. This shows the mechanical setup of the improved Fabry-Perot detector for the broad band lidar. Light enters the system at the upper left and passes through the narrow band filter. Some of it is then split off and passes through a polarization compensator and onto a detector (Reference). The unsplit component continues toward the right through a Fabry-Perot etalon and is detected (Fabry-Perot signal).

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. 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 shelf SLED manufactured by EXALOS has ~70% of the output power between 1540nm and 1600 nm and is almost centered over the 1567 nm 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 measured SLED output

at different drive currents. This is not enough output for a

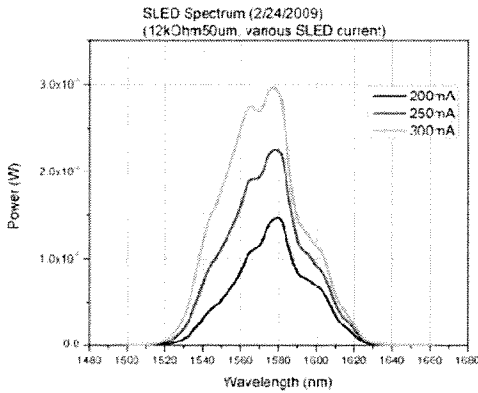


Figure 2. The output of the SLED increases with increasing the drive current. The spectral output is quite broad covering almost 100 nm. We only use a narrow region 2-3 nm wide centered on 1571 nm. The OPA is designed to amplify this region in particular.

measurement from space, but it is satisfying for initial laboratory work on the feasibility of the technique.

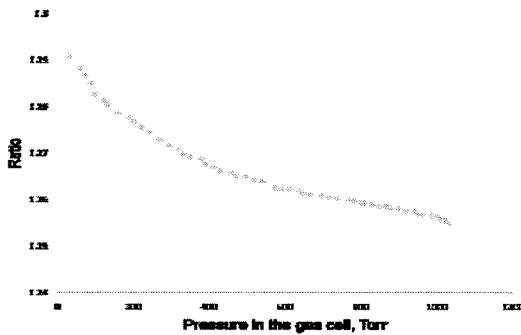


Figure 3 Change in ratio (FP signal/Reference signal) as a function of CO₂ pressure in an absorption cell.

II. EXPERIMENTAL

A. Observation of CO₂ 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 $\lambda = 1571$ nm. The spacing between etalon fringes is matched to the spacing of CO₂ lines through etalon thickness. Similarly, the width of fringes is approximately matched to CO₂ line width by appropriate choice of the reflecting coatings on the etalon surfaces. Alignment between etalon fringes and CO₂ absorption lines can be further adjusted by temperature tuning the Fabry-Perot [3], [4], [5], [6]. To validate in the

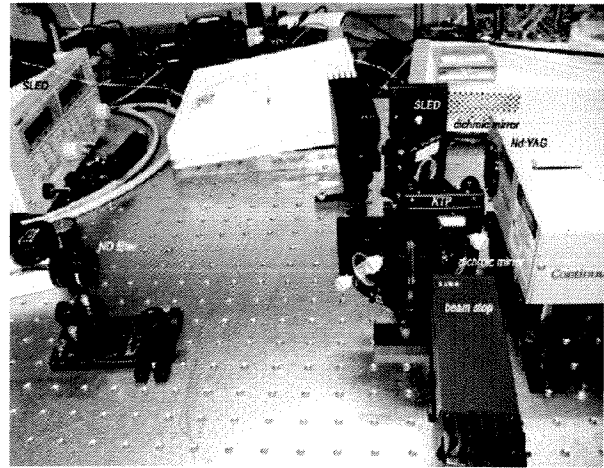


Figure 4. This shows the layout of the Optical Parametric Amplifier (OPA) set-up in the lab.

laboratory that the broadband technique is feasible the changes in the ratio of Fabry-Perot to reference signals were monitored for different CO₂ pressures using input SLED light (Figure 3) and multipass 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.

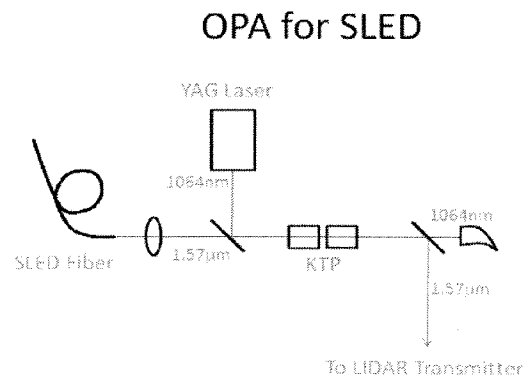


Figure 5. This is a diagram of the operation of the Optical Parametric Amplifier (OPA).

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. We have therefore decided to use an Optical Parametric Amplifier (OPA) instead of the EDFA for this amplification process.

In the OPA cw light from the SLED at 1570 nm is focused into a crystal of KTP and pulses from the Nd:YAG are overlapped in the same crystal (Figure 4, Figure 5). 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 Nd:YAG and the "idler" photons at 3.3 microns are separated and the latter are discarded. The amplified 1570 is transmitted for the broadband lidar. The spectral region 1571-1573 nm for the CO₂ band is well suited for this measurement because there is no interference from other trace gases. Also there are better detectors than for 2 micron region.

Figure 6 shows a laser scan of one of our bandpass filters. One of these 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 actually detect. The prefilters and Fabry-Perot interferometer optics are mounted in ovens and temperature controlled.

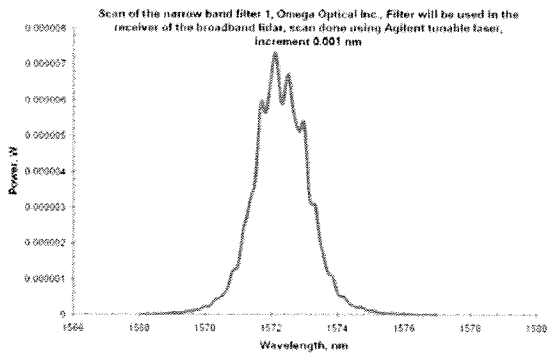


Figure 6. Laser scan of one of our bandpass filters. These filters are used in the receiver to confine the range of wavelengths observed to those over which a good alignment between the CO₂ absorption lines and the Fabry-Perot transmission peaks can be maintained.

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.

The output of the OPA was measured using an ORIEL grating monochromator. 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].

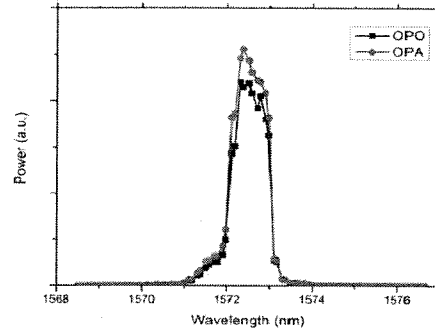


Figure 7. OPA output

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.

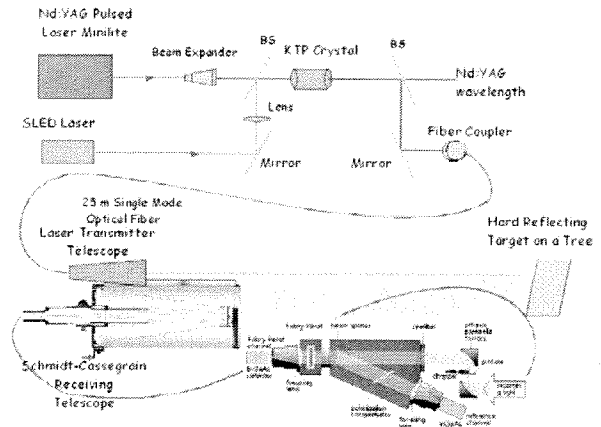


Figure 8. Schematic of the broadband lidar system using SLED, Nd:YAG and OPA.

In Figure 8 we show a schematic of the field lidar system. There are CO₂ absorption lines located at 1571.7, 1572.0, 1572.3, 1572.65, and 1573.0 nm that will absorb light from this transmitter.

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 are 14mJ pulses at 15 Hz.

C. Broadband two micron lidar for CO₂ column measurements

We are interested to develop a similar lidar for the 2 micron spectral region. The strong CO₂ band with wavelengths in the vicinity of 2 μm provides a second and totally independent measure of the CO₂ 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.

The performance of a lidar for measuring CO₂ 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.

We did an etalon study and the Fabry-Perot etalon for the receiver will be a 2.5 mm fused silica etalon with finesse =

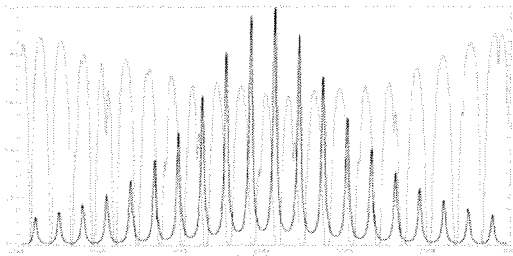


Figure 9. Generated synthetic spectrum for the two micron laser

17. For the narrow band prefilter the specifications are: thickness 14.2 μm and 25finesse. In the simulations we assume an Earth albedo of 10%. The generated synthetic spectrum with the prefilter shape, the Fabry-Perot passbands and the CO₂ absorption lines at that spectral region is shown in the Figure 9.

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 1.58μm 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 CO₂.

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 CO₂ around the whole earth. Therefore the broadband approach for accurate CO₂ measurement from space is very important to be fully developed and implemented.

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