Fiber Raman Amplifier Development for Laser Absorption Spectroscopy Measurements of Atmospheric Oxygen near 1.26 Micron

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Abstract – **We report on the latest development of a high power narrow linewidth fiber Raman amplifier for the measurement of atmospheric oxygen. This technology is focused on advancing engineered fibers to overcome the limitations imposed on this type of amplifier by the nonlinear effect of stimulated Brillouin scattering (SBS), and applying this to the laser absorption spectroscopy (LAS) of atmospheric oxygen. Our work has focused on using P_2O_5 as the primary fiber dopant to take advantage of the large (~1330 cm^{-1}) stokes shift which allows amplification in the 1.26 micron region using a commercially available Yb pump laser and a single amplification stage. Output powers of > 13 W continuous wave (CW) have been demonstrated with these fibers, but with reduced spectral purity. The latest implementation of the amplifier has demonstrated 3 W of CW output power and the ability to maintain the narrow spectral characteristics of the 1.26 micron distributed feedback (DFB) seed laser. In addition the current amplifier has been shown to produce clean modulation waveforms in the 50 KHz frequency range that are compatible with ITT's unique LAS technique. This paper will focus on the amplifier development, integration with the ITT engineering development unit (EDU), which has demonstrated high precision CO_2 measurements through multiple flight validation campaigns, evaluation of measurements of atmospheric oxygen and recent developments with the ongoing fiber work.**

INTRODUCTION

The need for a co-aligned atmospheric oxygen measurement is called out in the NRC Decadal Survey [1], in support of the Active Sensing of CO_2 Emissions over Nights, Days and all Seasons (ASCENDS) mission. The O_2 measurement will permit column integrated CO_2 measurements to be converted into ppm CO_2 measurements, by exploiting the fact that O_2 is a well mixed gas who's fraction of the atmosphere is well known. Achieving an active measurement of O_2 from space requires reliable high-power narrow-linewidth lasers at appropriate wavelengths. No commercially available solution currently exists for either the 765 nm or 1262 nm absorption bands which can meet the requirements for this mission. On the other hand robust rare earth doped fiber lasers are commercially available such as Erbium doped fiber amplifiers (EDFA's) in the 1570 nm range for CO_2 measurements. Other rare earth fiber lasers and amplifiers, using ytterbium are available commercially for wavelengths in the range of 1060 and 1090 nm. Over the past two years we have been working on developing a Raman amplifier using phosphosilicate doped glasses and a commercially available Yb laser to achieve high power narrow line-width source at 1260 nm which is compatible with ITT's LAS approach. Phosphosilicate glass is of key interest due to the large Stokes shift of approximately 1330 cm^{-1} which will enable single stage amplification from the commercially available pump lasers to the seed wavelengths in the 1262 nm wavelength range. In the following sections we will provide an overview of the ITT LAS instrument and measurement concept, an update on our amplifier development to date and a discussion of fiber design and manufacturing process's which are approaching an ideal fiber design to scale the Raman amplifier to the powers and efficiency required for the space-based measurement of O_2.

LAS INSTRUMENT OVERVIEW

The architecture for ITT's CO_2 LAS EDU for ASCENDS is illustrated in Figure 1. The all-fiber-coupled transmitter

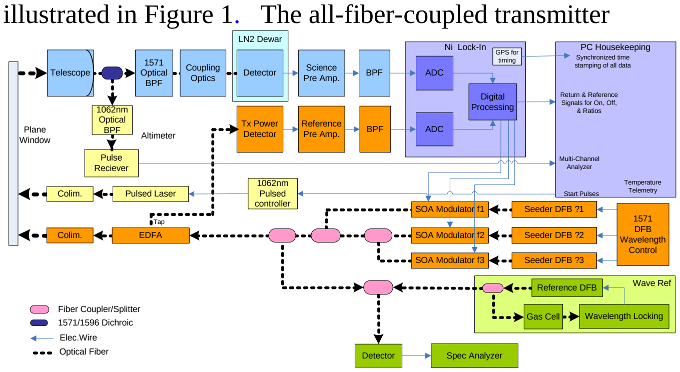

Figure 1: ITT's CO2 LAS has been operationally validated via extensive ground and aircraft campaigns

consists of a set of distributed feedback lasers (DFB's), each paired with a modulator or semi conductor amplifier (SOA), and one or more erbium doped fiber amplifiers. Each continuous wave (CW) laser wavelength is amplitude-modulated with its own RF frequency and all are transmitted simultaneously. A lock-in method is used to separate the wavelengths in the return measurement signal as well as the transmitted energy reference signal.

This instrument has undergone multiple ground and airborne field validation tests in cooperation with NASA Langley Research Center (LaRC), since 2004[2-5]. The instrument was built largely with off-the-shelf components and uses high reliability telecom components, including lasers, modulators and fiber amplifiers as the transmitter. All wavelengths are transmitted simultaneously from a single fiber collimator and the return signal is collected by a simple 8" telescope fiber coupled to a HgCdTe APD. This eliminates sensitivity to common electronics noise and highly varying surface reflectance, and also minimizes the effects of atmospheric turbulence and speckle by making them common mode. The analog signal is sampled with a high resolution scope card housed in a National Instruments PXI chassis and the digitized signal is passed through our custom-built software-based lock-in processing system which allows separation of the signals from the individual wavelengths. The separated signals are then used in the standard differential absorption lidar (DIAL) relations to determine the integrated column differential optical depth. The O2 function is identical except a Raman amplifier rather than and EDFA is used as the transmitter.

RAMAN AMPLIFIER DEVELOPMENT

The main focus of the Raman amplifier development has been to manufacture specialty fibers which either 1) broaden the Brillioun gain spectrum thus increasing the threshold power for SBS to occur, or 2) have a material profile that separates the acoustic and optical mode overlap to limit the interaction between these modes, which is the physical mechanism for generating SBS. The first approach can be accomplished by varying the mode field diameter longitudinally along the fiber during the drawing process. The second approach is accomplished through fiber design and developing manufacturing processes to meet the design.

Two fiber amplifiers have been built to date using P_2O_5 as the primary fiber dopant and a commercially available Yb fiber laser as the pump source. The first amplifier was completed in Jan 2010 and is shown in Figure 3. Details on this amplifier are given by Nagel et al., in 5 and 6.

This amplifier produced 1.8 W of average output power and a 3 dB linewidth of 3 MHz. This amplifier was integrated with the ITT LAS Engineering development Unit (EDU) and horizontal measurements of O_2 were made to targets ranging from 500 – 2600 m at the ITT lidar ground test facility in New Haven, Indiana. The measurements showed good correlation with modeled results [7-9]. The first generation amplifier used a separate stage for the on and the offline wavelengths to prevent degenerate 4 wave mixing due to the close proximity of the wavelengths (~50 pm).

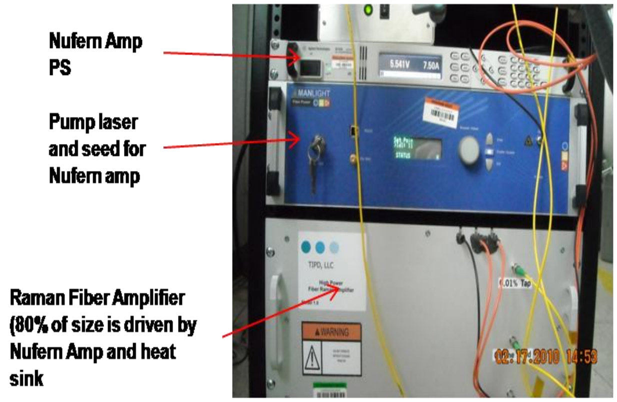

Figure 2: Raman amplifier components for O2 LAS demonstration.

The amplifier layout is shown in Figure 4. A 10 W Yb pump laser operating at 1088 nm was used as the primary pump source, but the separate amplifier stage required the additional use of a Nufern amplifier to pump the second stage, which drove a large part of the size and weight for the first amplifier.

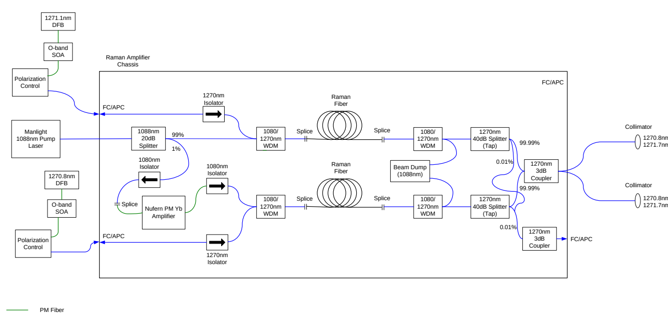

Figure 3: Generation I FRA design schematic based on P_2O_5 as primary dopant in the gain fiber.

The second year amplifier has a similar layout in terms of using two separate gain stages for the on and off lines, but we are pumping the fibers in a backward (relative to the seed) configuration. The result of this is a significant increase in spectral purity, with the cost being decreased efficiency. Improvements in the fiber design and implementation of a backward pumping scheme resulted in the second year amplifier being capable of producing 1.5 W average modulated power with > 45 dB side-mode suppression. In addition we have implemented a high power (50W) pump source and eliminated the need for the second amplifier. This has allowed us to reduce the size of the amplifier to approximately 2 X the size of the EDFA used for the CO_2 instrument. The second year amplifier is shown in Figure 5 and is half the size of the first year amplifier. Figure 6 shows the spectral properties of the second generation amplifier.

Figure 4: 2nd generation backward pumped 1262 nm Raman amplifier with seeds and modulators.

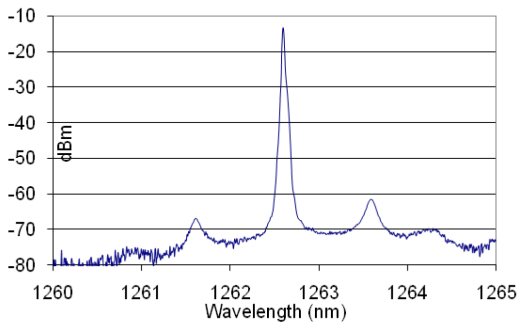

Figure 5: Spectrum of backward pumped 2nd generation Raman amplifier.

We are currently in the process of integrating with the CO_2 instrument, will begin ground testing the 2nd year amplifier in June, and are planning to take advantage of a flight of opportunity on the NASA DC-8 in July and August 2011. This would represent the first high power O_2 airborne measurement in this wavelength region, and is a critical risk reduction step for the ASCENDS mission.

FIBER DEVELOPMENT

In parallel with the fiber amplifier development using the varying mode field diameter fiber we have been working with the Fiber Optics Research Center (FORC) to develop a fiber for separating the acoustic and optical modes. The first P_2O_5/F fiber delivered had an irregular shaped core and was guiding light in the inner cladding as can be seen in the left panel of Figure 6. Since February 2011, 3 additional fiber runs have been complete and delivered to TIPD. During the past several months FORC has improved their processes for manufacturing these fibers and all of the last three fibers have circular core geometry as shown on the right panel of Figure 6. In addition, each iteration has gotten closer to matching the design doping concentrations and reducing diffusion of Fluorine into the core. An example of the latest design is illustrated in Figure 7. This design has a lower than desired P_2O_5 concentration in the core for optimal Raman amplification, but would provide decoupling of the Acoustic and optical mode. The trade for less Raman gain but increased SBS suppression can allow longer fibers to be utilized in the amplifier to improve overall efficiency and increase the total output power.

Figure 6: First P_2O_5/F doped fiber (left) showing triangular core shape and coupling into the inner cladding. Latest P_2O_5/F fiber deonstrated ciruclar core and singlemode operation.

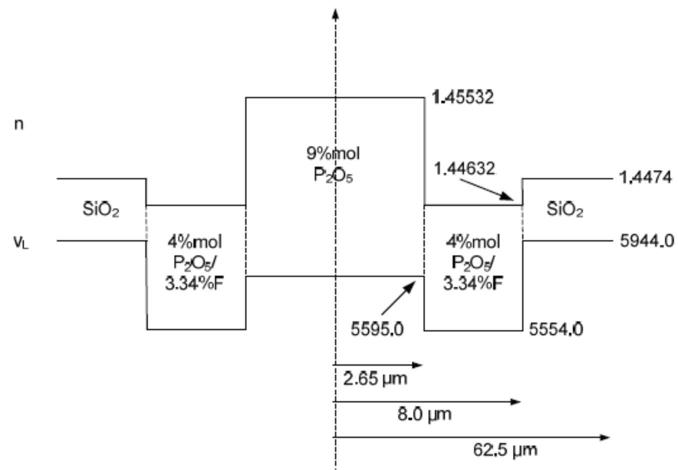

Figure 7: Latest iteration of a P_2O_5/F fiber design

Modeling has shown that the design in Figure 7 would result in reducing the overlap between the first order acoustic mode and the optical mode to only 3.85%. The result would be ~14.2dB of SBS suppression, neglecting higher order modes, which would allow 5 W average power and close to 50% optical to optical efficiency to be achieved. We still have work to do in controlling the relative concentrations of P_2O_5 and F, and have been working that through an iterative process which involves small variations to the design to improve manufacturability while also improving the manufacturing processes to better match the model design. Figure 8 shows the latest fiber refractive index profile relative to the design. As can be seen the actual index profile has a lower peak than the design and deeper depressions for the inner cladding. Based on the index profiles it appears that the core was slightly under doped with P_2O_5 and the inner cladding was either over doped with F or also under doped with P_2O_5. Tests are currently being conducted to quantify the Mol% of each of the primary dopants and correct this difference for future runs.

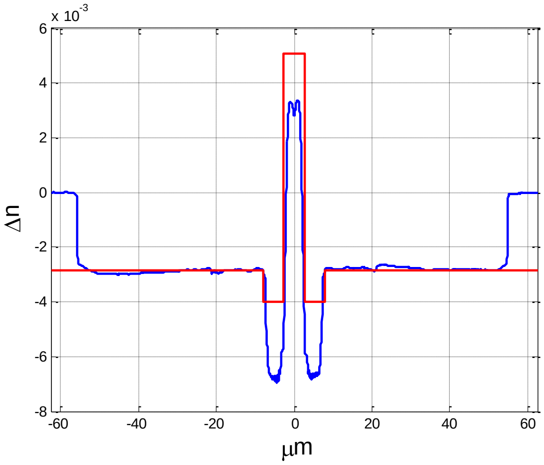

Figure 8: Refractive index profile deviation from SiO_2 fiber as a function of distance from the center; actual (blue); design (red).

Although this latest fiber is not perfectly matched it has shown single mode operation at both the pump and seed wavelengths. The loss of the fiber was ~6 dB/km which is higher than expected, but the fiber still showed pump-limited Raman gain in recent experiments with a 10 W pump laser.

CONCLUSION AND FURTHER WORK

We completed an amplifier in the first year that produced 1.8 W of average output power, with a 3 db linewidth of 3 Mz, and we integrated it into the ITT EDU and conducted field measurements over a range of horizontal paths. These represented the first known high power narrow linewidth measurements of Atmospheric O_2 in this wavelength region. The data was compared to model predictions using independent data and showed good correlation. Evaluation of the measurements and the amplifier performance revealed some instability in the energy monitoring tap and a broad spectral base that was ~ 25dB below the peak output but contained nearly 60% of the total energy. Using the lessons learned in the first year, both of these issues were addressed in the second generation amplifier, which has demonstrated it can maintain the spectral purity of the seed source while producing 1.5 W of clean modulated average power.

The second amplifier is currently being integrated into the EDU and will be ground tested in June, prior to being deployed on the NASA DC-8 in July and August. We are currently seeking funding to continue the work with FORC and exploit the progress we have made to realize the additional SBS suppression predicted by theory. With a little refinement of the manufacturing processes and the designs, we are confident we can achieve the SBS suppression required to achieve 5 W average power with 10% WPE.

AKNOWLEDGEMENTS

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