# Thulium-Doped Fiber Amplifier Development for Power Scaling the 2 Micron Coherent Laser Absorption Instrument for ASCENDS

Dr. Mark W Phillips
Lockheed Martin Coherent Technologies
135 South Taylor Avenue, Louisville CO 80027
Email: mark.w.phillips@lmco.com

*Abstract-* **We describe the development and testing of a 2 micron Tm:glass fiber amplifier that scales the output power of a single frequency Tm,Ho:YLF seed laser from 30 mW to >5 W while maintaining an absolute frequency excursion of less than 1 MHz. The demonstrated fiber amplifier performance provides a path for power-scaling the coherent 2 micron sensor solution to the National Aeronautics and Space Administration (NASA) Active Sensing of $CO_2$ Emissions Over Nights, Days, and Seasons (ASCENDS) mission for measuring and mapping global $CO_2$ concentrations through measurement of integrated path differential absorption (IPDA). The 2 micron sensor solution for ASCENDS is based on column-content absorption measurement biased to the Planetary Boundary Layer through measurement in the wing of a $CO_2$ absorption feature in the vicinity of 2051 nm. Coherent detection combined with speckle averaging offers a reduced power-aperture product compared with alternative optical depth measurement methods. This approach is currently being evaluated via airborne sensor tests by Jet Propulsion Lab (JPL), with the output power per sensor channel limited to about 100 mW. Operating single frequency at the wavelength of 2051 nm with a single channel output power of 5 W meets the on-orbit laser transmit power flow-down requirement for ASCENDS, assuming a 0.7 m telescope aperture size and an along-orbit axis spatial resolution of 80 km. The power-derated fiber amplifier is also compatible with dual channel amplification to >10 W, allowing both on-line and off-line channels of the IPDA sensor to use a single power amplifier stage.**

## I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) Active Sensing of $CO_2$ Emissions Over Nights, Days, and Seasons (ASCENDS) mission requires very accurate column content measurement of atmospheric $CO_2$ concentration (<2 ppmV precision over the total column) from an active sensor in low earth orbit. There is ongoing debate with regard to the along-orbit track spatial resolution requirement for the ASCENDS data set. Initially this resolution requirement was set at about 100 km integrated distance, but there is a growing desire to reduce this to 5-20 km, in order to better resolve small scale $CO_2$ "plumes", especially those related to anthropogenic sources. Several candidate sensor solutions are currently being evaluated via concurrent airborne tests, involving sensors with continuous wave (CW) and pulsed waveforms at both 1.5 and 2 micron wavelengths. While both wavelength choices have their benefits and disadvantages, there is a growing trend to favor the 2 micron solution in order to have a column content measurement that is strongly biased to the planetary boundary layer (PBL) where concentration variation due to the presence of underlying sources and sinks is most measurable.

In this paper, we describe an effective means for power scaling the 2 micron CW sensor solution for the ASCENDS mission. Under a previous Earth Science Technology Office (ESTO)-funded Instrument Incubator Program (IIP), the Jet Propulsion Lab's (JPL) laser-based remote sensing group led by Bob Menzies and Gary Spiers developed a CW 2 micron integrated path differential absorption (IPDA) instrument for measuring column content $CO_2$ from an airborne platform. The instrument, referred to as the $CO_2$ Laser Absorption Spectrometer (or $CO_2$ LAS) was initially flown on a Twin Otter aircraft to obtain initial proof of performance data, and has since flown in 2010 with other potential ASCENDS mission sensors aboard the NASA DC-8 Experimental Aircraft [1]. Lockheed Martin developed the laser-based transceiver for the $CO_2$ LAS instrument [2] and continues to support JPL in its efforts to propose a CW (or pulsed) 2 micron sensor solution for the ASCENDS mission.

Under an ESTO Advanced Component Technology (ACT) Grant, Lockheed Martin is currently evaluating the ability to power scale the $CO_2$ LAS instrument performance from 100 mW per transmit channel to >5 W per channel. This is to be done while maintaining the existing key performance characteristics of the $CO_2$ LAS instrument, including an uncertainty in the absolute frequency content of the transmit light of <1 MHz total linewidth. The demonstration set-up and results obtained under the ACT Grant activity are described below.

## II. POWER SCALING ARCHITECTURE

The 5 W output power requirement for ASCENDS was determined from a Lockheed Martin anchored ladar model assuming a 500 km ASCENDS orbit height, a telescope aperture diameter of 75 cm, and a 0.2% error budget allocated to the optical depth uncertainty of the $CO_2$ measurement. The integrated path length (ground footprint) was set at 80 km, slightly less than the original spatial resolution requirement for ASCENDS. The current $CO_2$ LAS instrument uses a modified version of Lockheed Martin's 2 micron single frequency laser product METEOR®. The instrument has three near identical single frequency lasers onboard, a reference laser that is locked to an onboard $CO_2$ gas cell absorption line, and two transmit lasers (online and offline) that are both transmitted from the instrument and are used for heterodyne return signal detection. In each case, the Tm,Ho:YLF laser gain material provides laser operation at 2051 nm, providing excellent overlap with a suitably strong absorption line for the ASCENDS $CO_2$ measurement. The METEOR® laser emits just over 100 mW of single frequency light, and can be tuned in frequency over a range of about 20 GHz by either adjusting the laser resonator temperature (slow thermal tuning) or by applying a control voltage to a piezo-electric (PZT) element attached to the laser resonator output coupling mirror. PZT-controlled frequency tuning is the method selected for high accuracy and fast response frequency control as utilized in the $CO_2$ LAS instrument.

Both amplifier and seeded power oscillator options were originally considered to address this power scaling requirement for ASCENDS. However, advances in 2 micron fiber amplifier performance over the past 2-3 years made the down-selection to a fiber amplifier solution relatively straight-forward. Indeed, a key to this demonstration was not how much power could be obtained using a 2 micron fiber amplifier regardless of hardware configuration, but rather what was possible while maintaining an all-fiber network (no free-space pump launching, all fibers spliced throughout the assembly) and providing a design that offered major pump diode power derating and redundancy. Based on a competitive bid process, Nufern was selected as the fiber amplifier supplier.

Fig. 1 shows the overall concept for the power-scaling demonstration under the ACT Grant. A 2-step plan was established whereby the key performance characteristics (output power, linewidth maintenance, beam quality, polarization state, etc.) of the single frequency fiber-amplifier could be demonstrated using a free-running METEOR® laser (with short term linewidth jitter of

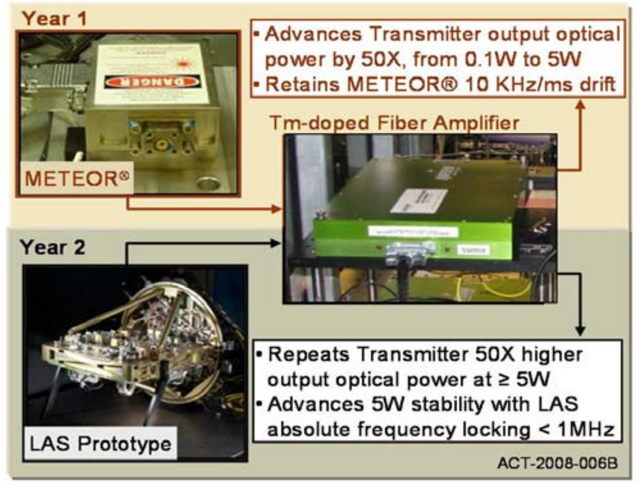


Fig. 1. 2-Step Demonstration Plan for ACT Grant

~10 kHz/ms but no absolute frequency control). The second step was to repeat the same demonstration using the lasers and frequency lock controls of the $CO_2$ LAS instrument to show that the same 5 W output power performance was achievable while maintaining the absolute frequency control and knowledge of <1 MHz demonstrated at the 100 mW power level in the $CO_2$ LAS instrument.

The Tm:glass fiber amplifier supplied by Nufern is based on a 2-stage amplifier configuration with optical isolation between stages and at the input and output ports of the assembly. The amplifier is polarization-maintaining, combining pump light and signal light using polarization-maintaining 7-into-1 couplers. The coupler configuration supports multiple pump diode redundancy and significant pump diode derating at the demonstrated 5 W output power level.

## III. EXPERIMENTAL SETUP

The experimental set-up for the first phase of the demonstration (using a stand-alone METEOR® single frequency laser) is shown in Fig. 2. The Tm:glass fiber

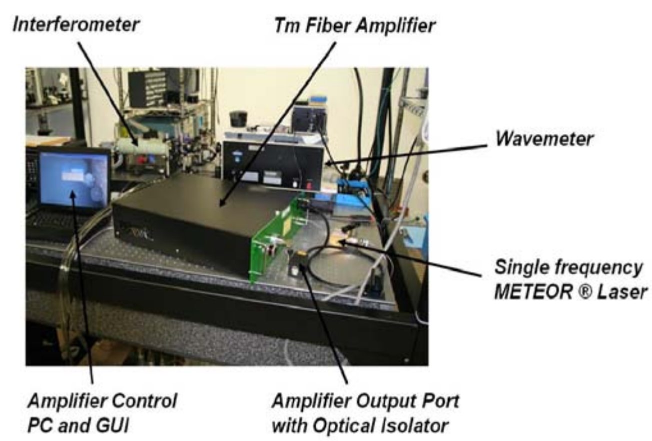


Fig. 2. Amplifier Test Configuration using Stand-Alone METEOR® Laser

amplifier is shown configured as a 19-inch rack mount unit containing both the optics and electronics sub-assemblies, with an output fiber lead with attached optical isolator. This was deemed sufficient for the lab-based demonstration, but the sub-assembly designs are also compatible with separate optics and electronics packaging as likely required for implementation in an airborne sensor or a space based mission such as ASCENDS. The amplifier comes with a dedicated PC and graphical user interface based on LabView control software. Single frequency operation of the amplifier at 2051 nm was characterized using a combination of scanning confocal interferometers, wavemeters, and optical spectrum analyzers, allowing detection of the output at varying levels of frequency resolution. Fig. 3 shows the equivalent experimental set-up using the $CO_2$ LAS instrument for the input single frequency light source and for absolute frequency lock control during the second phase of the amplifier demonstration. In this latter case, the $CO_2$ LAS online laser was amplified from 100 mW to >5 W and a 100 mW fraction of this output was fed back into the $CO_2$ LAS instrument to enable absolute frequency lock control.

## IV. EXPERIMENTAL RESULTS

Figs. 4, 5 and 6 show images capturing the overall results of the 2-step amplifier testing. A more detailed description of the specific performance characteristics will be discussed at the meeting.

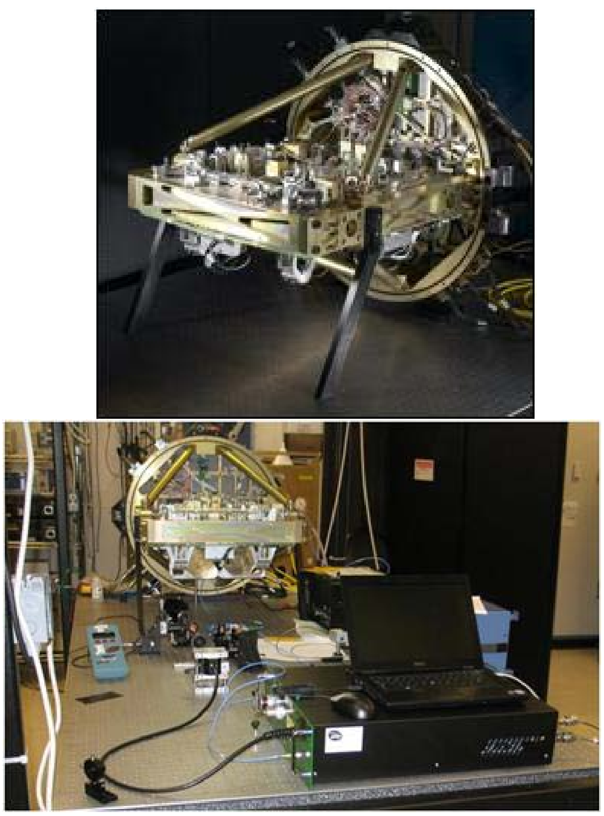

Fig. 3. Amplifier Test Configuration using $CO_2$ LAS Instrument

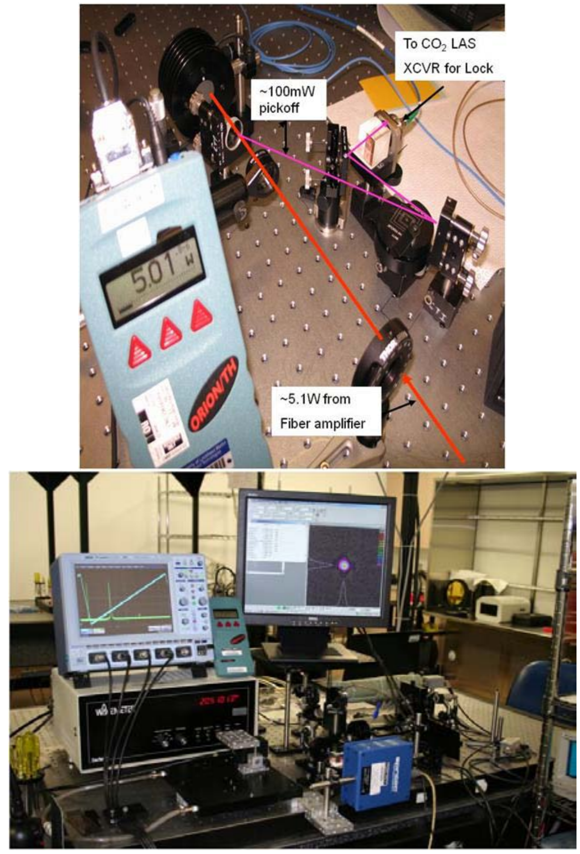


Fig. 4. Images of Experimental Results.

The upper image of Fig. 4 indicates the 5 W fiber amplifier output measured with a power meter, with ~100 mW being fed back into the $CO_2$ LAS instrument for absolute frequency lock control. The lower image of Fig. 4 shows the simultaneous measurement of multiple performance features including single frequency operation as indicated by the scanning confocal interferometer trace (left hand scope trace), near diffraction-limited output beam quality (beam profiler trace on right hand side of image, $M^2$ measured as <1.1), the correct output wavelength of 2051 nm, and a power meter reading in the ~7 W range in this case. There is still the possibility of out-of-band ASE power contributing at a non-negligible fraction to the measured fiber amplifier output power (much broader band than the single frequency tone being amplified). However, measurements with an optical spectrum analyzer (OSA) with a 0.05 nm resolution bandwidth indicate ASE is not measurable above the OSA noise floor, which is 30 dB down from the in-band amplified signal, over a 30 nm range around the signal peak.

The images in Figs. 5 and 6 are plots generated when using the $CO_2$ LAS instrument for absolute frequency control. The images in Fig. 5 show the absolute frequency lock servo error signal generated by sending a fraction of

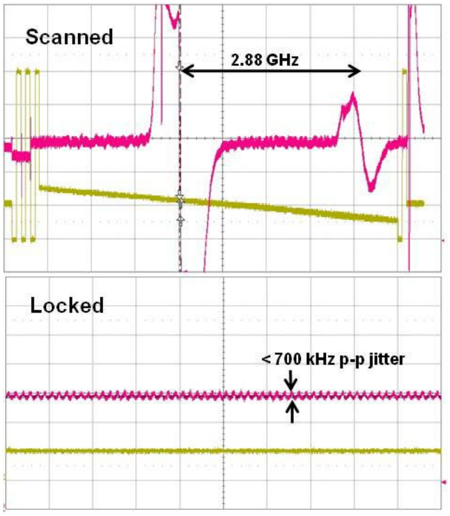


Fig. 5. Images showing < 700kHz frequency uncertainty maintenance of CO2 LAS reference laser.

the reference laser light through the onboard $CO_2$ gas cell with phase modulation sidebands applied. The resulting output is demodulated against a phase delayed copy of the phase modulation frequency signal. The upper trace shows the error signal when not locked (swept through the selected $CO_2$ absorption feature). A second weaker feature is observed to the right of the trace which corresponds to a $^{13}C^{16}O_2$ absorption line: the instrument is locked to the stronger $^{12}C^{16}O_2$ absorption line, associated with the primary isotopic component of $CO_2$ in the atmosphere. The separation of these two absorption lines is well characterized as being 2.88 GHz and is used to calibrate the error signal discriminant slope. The lower trace shows the equivalent signal when in locked mode. The amplitude fluctuations are a direct measure of frequency jitter as measured by movement up and down the error signal discriminant slope. Using the isotopic calibration, the plot indicates an absolute frequency uncertainty of about 700 kHz.

The absolute frequency knowledge of the reference laser is transferred to the two transmit lasers by means of a method referred to as frequency offset locking (FOL). The frequency offset between the two lasers is controlled using a phase locked loop configuration which compares the heterodyne beat frequency with a user-commanded frequency tone generated by a digital synthesizer. The images of Fig. 6 shows traces of the heterodyne beat signals between the reference laser and the non-amplified online laser ($CO_2$ LAS) compared with the equivalent heterodyne beat signals between the reference laser and the amplified online laser (Amplified $CO_2$ LAS). The traces indicate no discernable change in heterodyne beat signal width (combined uncertainty of <400 kHz at -3 dB point, with an equivalent de-convolved output linewidth of ~275 kHz) and no discernable change in background noise level (at the -100 dB level within the receiver bandwidth). Taking this value for the output linewidth due to the FOL process

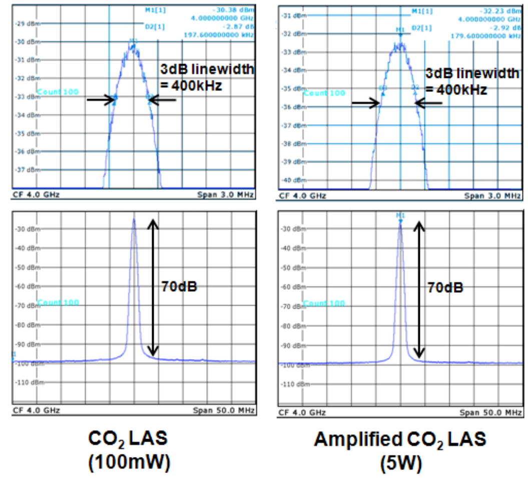


Fig. 6. Images showing <400kHz frequency uncertainty maintenance between reference laser and offset-locked laser (before and after fiber amplification). De-convolved amplifier output linewidth ~ 275 kHz.

and adding it to the reference laser lock frequency uncertainty, the total absolute frequency uncertainty for the transmit lasers (online demonstrated only but expected equivalent for both transmit lasers) meets the $\leq$ 1 MHz requirement.

## V. SUMMARY

In summary we have demonstrated a reliable means of power scaling the CW 2 micron sensor solution to the ASCENDS mission from 100 mW to >5 W while maintaining an absolute frequency uncertainty for the transmit lasers of <1 MHz total linewidth. This demonstration was identified in the 2008 Bar Harbor ASCENDS Workshop as the highest priority activity needed to mitigate technical risk associated with the CW 2 micron sensor solution to the ASCENDS mission.

## ACKNOWLEDGMENTS

We would like to acknowledge Gary Spiers and Robert Menzies of JPL for providing the CO2 LAS instrument used during part of the fiber amplifier power-scaling evaluation.

## REFERENCES

[1] G. Spiers, R. Menzies, J. Jacob, L. Christensen, M. Phillips, Y. Choi, and E. Browell, “Atmospheric CO2 Measurements with a 2-micrometer Airborne Laser Absorption Spectrometer Employing Coherent Detection,” accepted for publication in *Applied Optics*, Vol. 50, Iss. 14, pp 2098–2111, 2011.

[2] M. Phillips, G. Spiers, and R. Menzies, “Coherent Laser Radar Transceiver for the NASA CO2 Laser Absorption Spectrometer Instrument,” Proceedings of the 13th Coherent Laser Radar Conference, Kamakura, Japan , pp 118-121,October 2005.