Fiber-based Laser Transmitter Technology Maturation for Spectroscopic Measurements from Space

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***Abstract*— NASA's Goddard Space Flight Center has been developing lidar to remotely measure CO_2 and CH_4 in the Earth's atmosphere. We have advanced the tunable laser technology to enable high-fidelity measurements from space. In this paper, we will report on the progress of fiber-based, 1.57-micron wavelength, laser transmitter that has demonstrated the optical performance required for a low earth orbiting instrument. The Laser transmitter has been packaged and is undergoing environmental testing to demonstrate its technology readiness for space.**

Keywords—Laser, spectroscopy, lidar, carbon cycle, atmosphere, carbon dioxide (CO_2), satellite instrument

I. INTRODUCTION

Despite decades of research of the Earth's carbon cycle, modeling and in situ observations, the processes governing land and ocean carbon uptake, their spatial distributions, and relative magnitudes, remain poorly understood [1, 2]. New observations of atmospheric CO_2 that can characterize oceanic and terrestrial fluxes globally and capture the scales of variability required for attribution to underlying mechanisms are required to reduce these uncertainties and reliably project the future trajectory of carbon and climate [3, 4]. A similar need exists , for understanding global CH4 fluxes and processes.

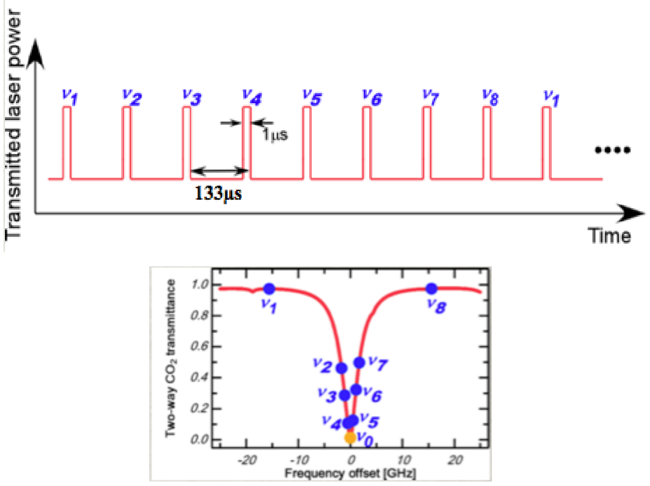

Fig. 1. Pulse configuration illustrating wavelength tuning on consecutive pulses that scan through the relevant CO_2 absorption line.

NASA's Goddard Space Flight Center (GSFC) has developed and demonstrated airborne integrated path differential absorption (IPDA) lidar to measure the column concentrations of atmospheric methane (CH_4) and carbon dioxide (CO_2) [5-7]. To make the transition from a lidar for airborne demonstration measurements to an operational satellite requires a significant increase in laser power as well as a significant increase in ruggedness and lifetime. The design for our space-based CO_2 IPDA lidar requires a wavelength-tunable, pulsed laser operating at 7.5 kilohertz pulse rate and 1 microsecond pulse width. The pulse format illustrated in Fig. 1 and the laser architecture is shown in Figure 2. The measurement requires ~ 2.5 millijoules pulse energy and the laser pulses need to be locked and rapidly tunable in wavelength. The final product must be compact and survive the rigors of launch and satellite operation. We have been designing and building a packaged engineering model laser that meets these requirements.

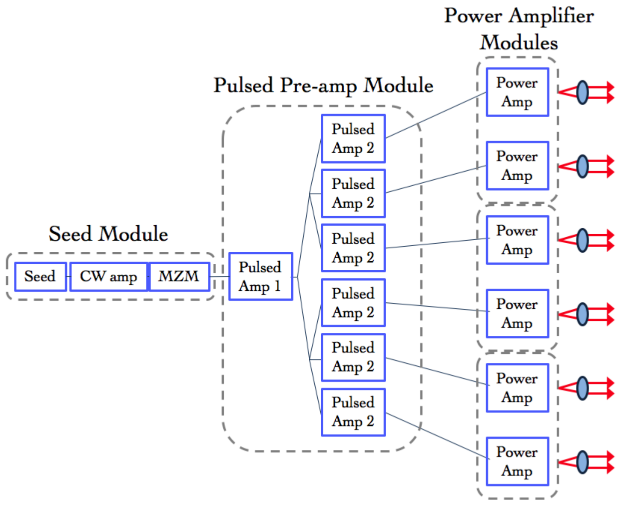

Fig. 2. MOPA laser architecture illustrating multiple fiber laser amplification stages and parallel free-space optical output beams to reach required optical power.

II. LASER

We are developing the flight laser technology required for this and other spectroscopic measurements. We have developed a high-fidelity wavelength locking and tuning approach as well as fiber amplifier technology to allow optical power scaling. More details on the technology can be found in [8-11]. We chose a master oscillator power amplifier (MOPA) architecture to separate the issues associated with wavelength control from those of power scaling. The wavelength tuning and locking is accomplished inside the seed laser module. The seed laser is then (pre)amplified by diode-pumped, erbium-yterbium co-doped fiber. The final amplification stage employs a very large mode area (VLMA) erbium (Er) fiber that enables high peak optical power. Despite this design, the peak power in the VLMA is limited to ~700 W (at 1.57 microns), so we also employ parallel amplifier stages to further increase the overall optical power directed to the target. This architecture is shown in Fig. 2. Low power, wavelength-tuned laser pulses are produced in the seed module. Once they enter the pre-amplifier module, they are amplified by the first stage, split into six different fibers and then amplified again. These six signals are then amplified by the power amplifier using the VLMA fiber. From the fiber-coupled seed lasers (butterfly-type packages) through the VLMA amplifiers, the system is fiber-coupled. The light is collimated as it exits the fiber and all six beams are co-aligned to illuminate the same spot on the Earth's surface.

The seed module uses two diode lasers. One is a distributed feedback (DFB) laser wavelength reference that is locked to the absorption peak of a CO_2 line, which is currently at 1572.335 nanometers. A distributed Bragg reflector (DBR) laser is offset-locked to the reference laser using high-speed electronics. In this way, we achieve a quickly tunable laser source that can be locked to an absolute wavelength in under 100 microseconds. We then use an external Mach-Zehnder modulator (MZM) to carve out 1 microsecond pulses at the 7.5 kilohertz rate. This modulator also enables us to shape the power of the pulses. This shaping is important to allow optimization of the shape and energy of the final output pulse. The seed module produces low energy pulses – around 50 nanojoules. Using this technique, we scan the laser across the CO_2 absorption line to make a high-fidelity spectroscopic measurement, where each laser pulse in a series is locked to an absolute wavelength across the absorption.

The optical signal from the reference laser passes through a Herriott cell filled with CO_2 gas used as an absolute wavelength standard. The Herriott cell has been ruggedized to meet the environmental requirements for space. The completed package is shown in Fig. 3. The optical path length inside the cell is ~10 meters. Maintaining alignment to ensure stable operation is critical to the laser wavelength performance.

The pre-amplifier module was purchased from NuPhoton, Inc. It has a single input and six parallel ouput signals. The pre-amplifier module increases the pulse energy in each of the six channels to ~2.5 microjoules with greater than 50% derating – meaning if there were degradation on orbit, it could

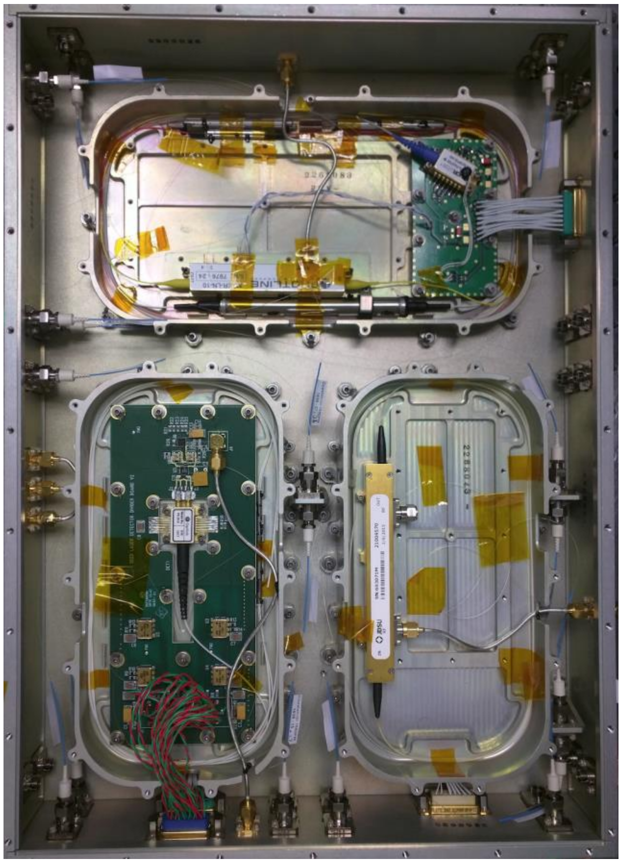

Fig. 3. Completed seed laser module with reference laser, tunable laser and Mach-Zehnder modulator shown.

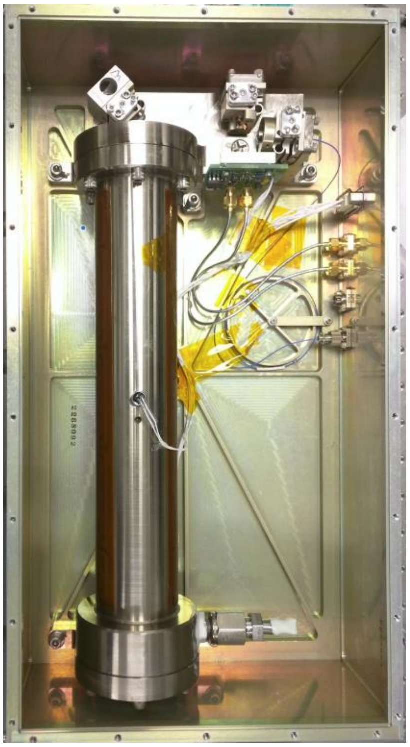

Fig. 4. Herriot cell filled with CO_2 gas with integration optics in a ruggedized package to lock the reference laser to an absolute wavelength standard. Module Dimensions: 25.5-cm x 12.5-cm x 10-cm

be compensated. Although there is some minor distortion of the temporal pulse shape, the amplifier otherwise preserves all the key performance criteria of the seed. The temporal pulse distortion can be compensated by pre-shaping the pulses with the MZM.

The packaging is compact and includes drive and control electronics. It has undergone preliminary vacuum bake-out as a cleaning procedure with no changes in performance. This is a promisng sign that the unit will survive later more rigorous thermal vacuum testing.

The power amplifier (PA) modules produce the pulse energy needed for space. Due to a combination of factors including reliability, modularity, efficiency and size, two power amplifiers are packaged in each module. The power amplifier fiber is pumped at 1480 nm using a fiber Raman laser. Each PA module has a single Raman laser that pumps two amplifiers. The Raman lasers operate more efficiently at higher average power. Using one Raman pump for every two amplifiers balanced reliability (avoiding a possible Raman laser failure causing the entire laser to fail) with efficiency (which leads to using fewer Raman lasers.) The power amplifiers use VLMA fiber that has a mode field area of 1,100 square microns as a gain stage. This large mode field is what enables this amplifier to exceed the peak optical power performance of other fiber systems. The characteristics of the VLMA fiber impose a packaging limitation. In order for the spatial mode performance to be preserved, it is important to maintain a large bend radius. Stresses in the fiber coil must also be avoided. As a result we mounted the fiber in a carefully controlled spiral pattern. This is shown in Fig. 6. (top). Fig. 6 (bottom) shows the fiber spools for the Raman pump system.

For the initial packaging activity we chose to populate the module with only one amplifier. We demonstrated the same optical performance on this packaged prototype as was achieved in the initial breadboard design. Three complete modules capable of the full power-scaling required for space operation are now under development.

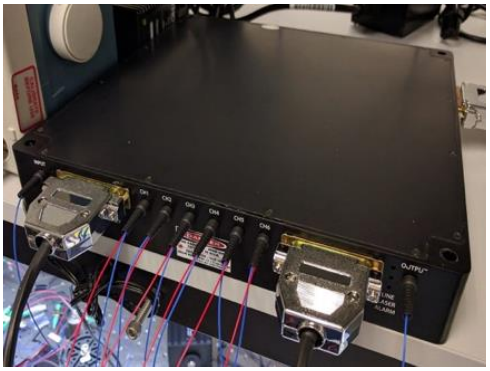

Fig. 5. Photos of VLMA power amplifier prototype. The top photo shows the top half of the box with the VLMA fiber spiral. The bottom photo shows the Raman pump system.. Module dimensions:. 28-cm x 28-cm x 5-cm

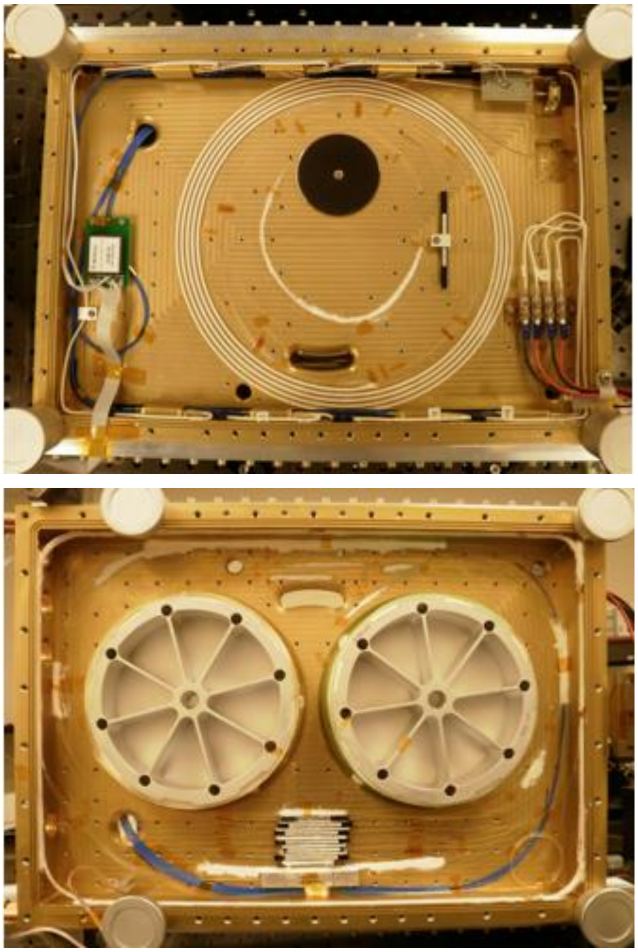

Fig. 6. Photos of VLMA power amplifier prototype. The top photo shows the top half of the box with the VLMA fiber spiral. The white fiber potting material makes the spiral groove easy to visualize. The bottom photo shows the Raman pump system.. There are two spools and the fiber components are in the lowower center of the photo. Module dimensions:. 44-cm x 32-cm x 9-cm.

III. SUMMARY

The three laser transmitter components, seed module (including Herriott cell), pre-amplifier module and the power amplifier module have all been built. The optical performance achieved meets the requirements needed for a space-borne CO_2-sensing instrument. The prototypes will now undergo environmental testing of vibration, thermal vacuum and radiation. This laser development should remove the final technology hurdle to continuous monitoring of atmospheric CO_2 from space and assist other programs with similar technology requirements.

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