Fiber-based Laser MOPA Transmitter Packaging for Space Environment

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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. The ultimate goal is to make space-based satellite measurements with global coverage. We are working on maturing the technology readiness of a fiber-based, 1.57-micron wavelength laser transmitter designed for use in atmospheric CO_2 remote-sensing. To this end, we are building a ruggedized prototype to demonstrate the required power and performance and survive the required environment.

We are building a fiber-based master oscillator power amplifier (MOPA) laser transmitter architecture. The laser is a wavelength-locked, single frequency, externally modulated DBR operating at 1.57-micron followed by erbium-doped fiber amplifiers. The last amplifier stage is a polarization-maintaining, very-large-mode-area fiber with ~1000 μm^2 effective area pumped by a Raman fiber laser. The optical output is single-frequency, one microsecond pulses with >450 μJ pulse energy, 7.5 KHz repetition rate, single spatial mode, and > 20 dB polarization extinction.

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

1. 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 CH_4 fluxes and processes.

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 and ~ 2.5 millijoules pulse energy. Each laser pulse must be wavelength locked and the seed laser needs to be rapidly tuned and locked to a new wavelength for the next pulse. 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. The pulse format is illustrated in Fig. 1 and the laser architecture is shown in Figure 2.

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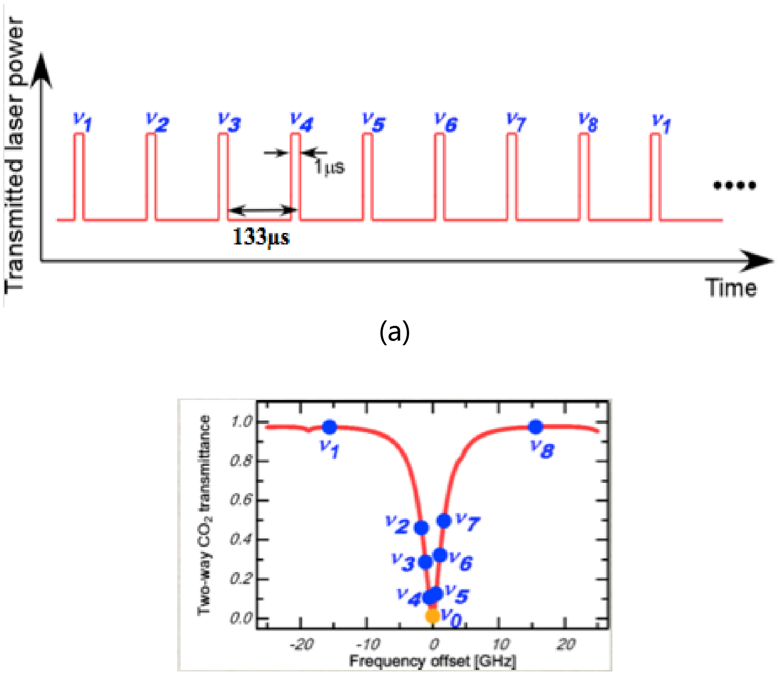

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Figure 1. (a) Pulse configuration illustrating wavelength tuning on consecutive pulses that scan through (b) the relevant CO_2 absorption line. The 133-µs pulse period corresponds to 7.5 KHz.

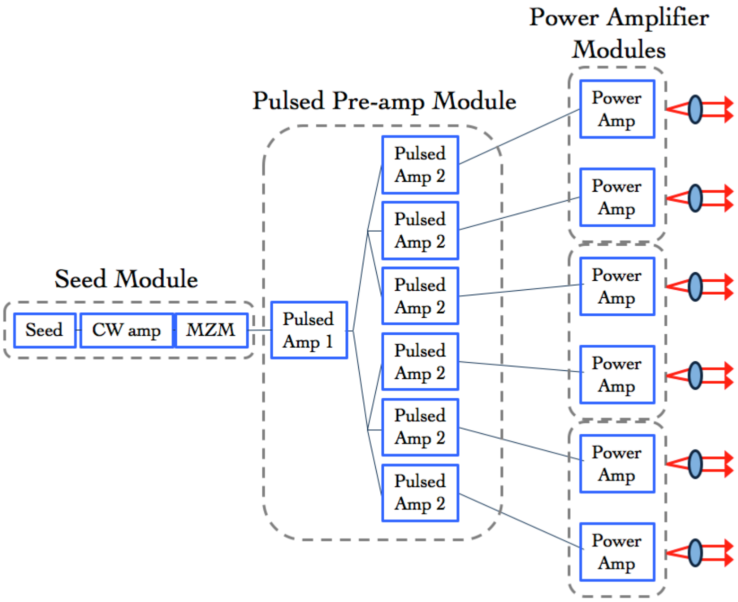


Figure 2. MOPA laser architecture illustrating multiple fiber laser amplification stages and parallel free-space optical output beams to reach required optical power.

2. LASER

We are working on 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 optical performance of 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. This modular design also helps with packaging. The wavelength tuning and locking are accomplished inside the seed laser module. The seed laser is then (pre)amplified by diode-pumped, erbium-ytterbium co-doped fiber. The final amplification stage employs a polarization-maintaining very large mode area (PM-VLMA) erbium (Er) fiber that enables high peak optical power. Despite this design, the peak power in the VLMA is limited to ~700 W, 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 are then amplified again. These six signals are then amplified by the power amplifiers 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. The first is a distributed feedback (DFB) laser used as a wavelength reference 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. The DBR is quickly tunable and can be tuned and locked to an absolute wavelength in under 100 microseconds. We then use a 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 a known 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.

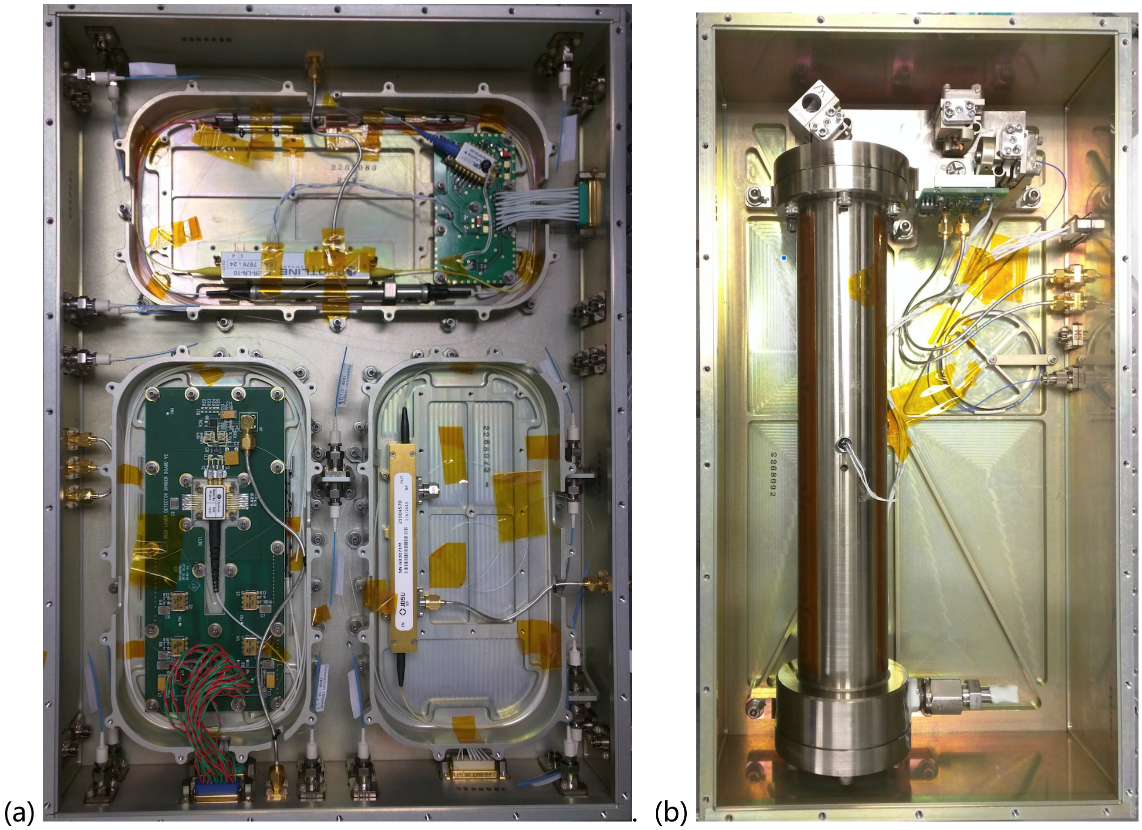


Figure 3. (a) Completed seed laser module with reference laser, tunable laser and Mach-Zehnder modulator shown. Module Dimensions: 44-cm x 32-cm x 8-cm. (b) Herriot cell filled with CO_2 gas with integration optics in a ruggedized package to lock the reference laser to an absolute wavelength. Module Dimensions: 42-cm x 24-cm x 10-cm.

The pre-amplifier module was purchased from NuPhoton, Inc. It has a single input and six parallel output 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 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 promising sign that the unit will survive later, more rigorous thermal vacuum testing.

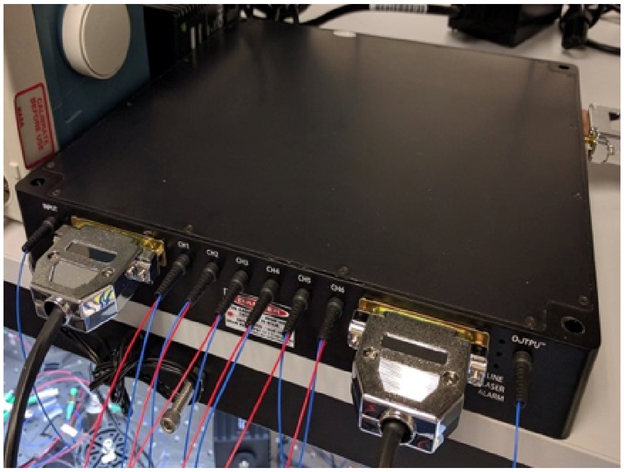
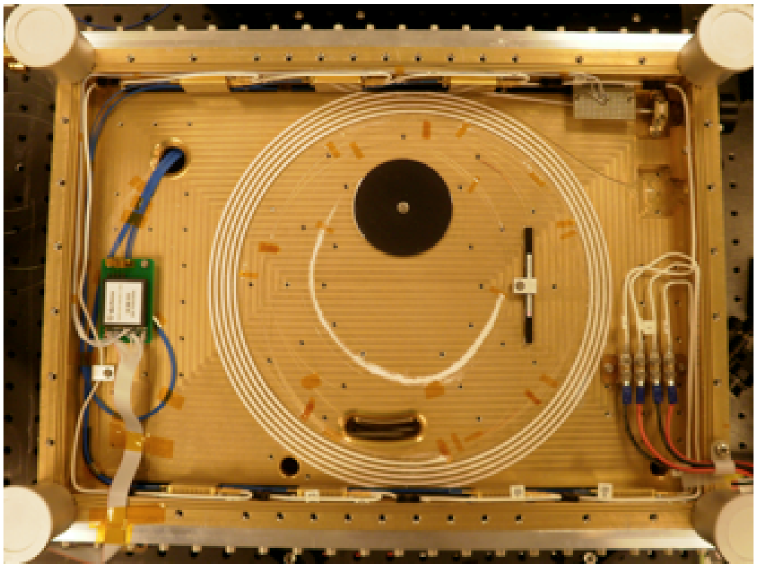


Figure 4. (a) Photos of VLMA power amplifier prototype. The top photo shows the top half of the box with the VLMA fiber spiral. The bottom photo shows the Raman pump system. Module dimensions: 28-cm x 28-cm x 5-cm.

The power amplifier (PA) modules produce the pulse energy needed for space. Due to combination 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 Raman fiber 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 transmitter to fail) with efficiency (which leads to using fewer Raman lasers.) The power amplifiers use PM-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 at 1572 nm. The PM-VLMA fiber does impose a packaging limitation. In order for the single 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.



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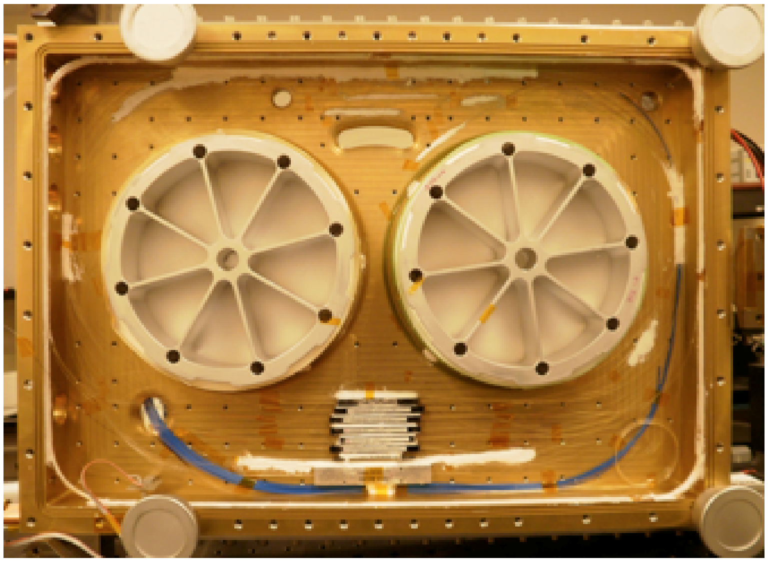

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Figure 5. (a) Photos of VLMA power amplifier prototype. The top photo shows the top half of the box with the VLMA fiber spiral. The white fiber potting material makes the spiral groove easy to visualize. The bottom photo shows the Raman pump system. There are two spools and the fiber components are in the lower center of the photo. Module dimensions: 44-cm x 32-cm x 9-cm.

3. 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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