Development of a Pulsed 2-micron Laser Transmitter for CO_2 Sensing from Space

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***Abstract* – NASA Langley Research Center (LaRC), in collaboration with NASA Jet Propulsion Laboratory (JPL), is engaged in the development and demonstration of a highly efficient, versatile, 2-micron pulsed laser that can be used in a pulsed Differential Absorption Lidar (DIAL) / Integrated Path Differential Absorption (IPDA) instrument to make precise, high-resolution CO_2 measurements to investigate sources, sinks, and fluxes of CO_2. This laser transmitter will feature performance characteristics needed for an ASCENDS system that will be capable of delivering the CO_2 measurement precision required by the Earth Science Decadal Survey (DS).**

I. INTRODUCTION

The National Research Council (NRC) Decadal Survey (DS) recommended - an active laser-based CO_2 mission, Active Sensing of CO_2 Emissions over Night, Days, and Seasons (ASCENDS), to dramatically increase our understanding of CO_2 sources, sinks, and fluxes worldwide [1]. ASCENDS provides 1) full seasonal sampling to high latitudes, 2) day/night sampling, and 3) ability to resolve the altitude distribution of CO_2 column measurement, particularly across the mid to lower troposphere. According to the DS the measurement accuracy should be 0.5% of the background (i.e., <2 ppm) at 100 km horizontal length scale over land and 200 km over open oceans. An important outcome of the 3-day ASCENDS community workshop held in July 2008 was a priority list of technology development recommendations needed to advance the readiness of the ASCENDS mission. Included was a strong recommendation to scale the 2.05 µm laser transmitter to higher output power levels in a robust prototype with long-lifetime design features.

Our current laser development addresses the ASCENDS workshop recommendation on transmitter needs. It will operate in a favored wavelength region selected for optimum sounding for high-precision measurements [5], with pulse energy and repetition frequency matching the performance parameters of comprehensive system performance studies [2-4]. The pulsed 2µm lidar approach possesses advantages over passive and CW active sensors. ***First***, using time-of-flight determination, the pulsed format provides a built-in means for determining range to the scattering target. With pulses of sufficiently short duration, and appropriate receiver bandwidth, it eliminates the need for the ancillary laser altimeter in the payload, for accurate measurement of scattering surface elevation. More importantly, in a scattering atmosphere containing thin clouds and aerosol layers, the reflected signals from the surface for the lower tropospheric column CO_2 IPDA measurement can be resolved from those due to intervening thin cloud and aerosol backscattering. Therefore, it easily, efficiently, and unambiguously eliminates the contamination from aerosols and clouds that can bias the IPDA measurement and reduce measurement accuracy. ***Second***, by concentrating the laser energy into high-energy (50-100 mJ or greater) pulses, sufficient backscatter signal strength can often be obtained from boundary layer aerosol scattering as well as the surface. This provides added flexibility to retrieve the CO_2 structure near the surface. ***Third***, the higher per-pulse SNR (signal-to-noise ratio) obtainable with high energy pulsed backscatter means less reliance on multi-pulse averaging, providing potential for higher along-track spatial resolution and better measurement capability in regions of partial cloud coverage, benefiting high precision measurements. ***Fourth***, as mentioned above, the chosen absorption line at the 2.05 µm band is ideally suited for the IPDA measurement of CO_2 weighted column mixing ratios. In particular, with operation at the R(30) line in the 2.05 µm band, weighting functions can be obtained that maximize the interaction with CO_2 in the lower troposphere (lowest 5 km), while still maintaining the differential absorption optical depth near the optimum value of ~1 [5, 6].

II. DESCRIPTION OF TECHNOLOGY CONCEPT AND RATIONALE

This technology development was initiated during NASA Earth Science Technology Office (ESTO) funded Laser Risk Reduction Program (LRRP) with the objective to develop a Thulium (Tm) fiber laser pumped Holmium (Ho) solid-state laser that generates laser pulses in the 2µm wavelength for pulsed CO_2 DIAL/IPDA instrument. The key performance characteristics of this laser, such as energy, pulse repetition rate, pulse width, efficiency, frequency accuracy and stability, will meet or exceed the needs of the ASCENDS transmitter as currently envisioned. This space qualifiable laser architecture utilizes fiber laser and solid-state crystal laser technologies. One of the outstanding properties of the fiber laser is its efficiency. However, it inherently has low damage threshold at high energy pulses. On the other hand, the solid state laser has the capability to produce Joule-level energy at 2µm wavelength [7]. The proposed laser combines the advantages of both lasers to provide the desired energy with high efficiency.

There are excellent absorption lines for the measurements of CO_2 in 2µm wavelength region with regard to the strength of the absorption lines, low susceptibility to atmospheric temperature variability, and freedom from problematic interference with other absorption lines [5, 8]. We have chosen to operate on the short wavelength wing of R (30) CO_2 line at 2050.967 nm (4875.766 cm^{-1}) in the side-line operation mode which is required for low troposphere CO_2 measurement. The side-line operation was demonstrated for Lidar Atmospheric Sensing Experiment (LASE) at near-infrared wavelength [9]. The exact wavelengths of the Ho laser are controlled by injection seeding technique to provide the required on-and-off line wavelength pulses sequentially. This laser transmitter has the advantages of high electrical efficiency, compact size and low mass.

III. GENERAL DESCRIPTION OF THE 2-µM PULSED LASER TRANSMITTER

Figure 1 illustrates a conceptual block diagram of the proposed Ho 2µm pulsed laser. The Tm fiber laser pumped Ho laser provides several significant advantages including low thermal load; long energy storage lifetime; high system efficiency; simpler laser architecture; and in a more compact and rugged package. It uses a Thulium (Tm) fiber laser to pump a Q-switched Holmium (Ho) solid-state laser to produce defined wavelength, line width, pulse width, beam quality and pulse repetition rate. The following amplifier scales the energy to the desired energy level. The repetition rate of the laser is controlled by the rate of the Q-switch; effectively, it is a variable rate laser transmitter. This is a valuable feature for multiple lidar applications. The intended design for the Ho laser will be optimized for CO_2 DIAL/IPDA via direct detection method, where relatively high energy at modest repetition rate is required.

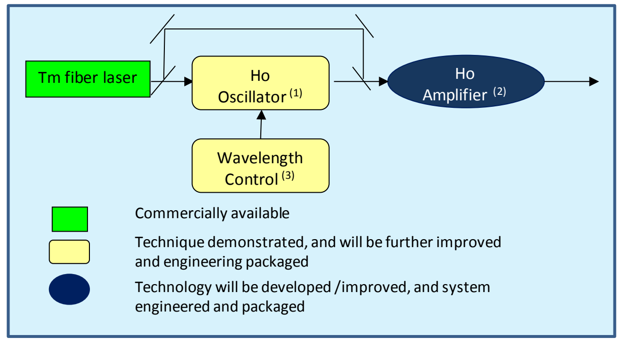

Figure 1: Block diagram of proposed 2µm laser transmitter, illustrates the focus of the development approach

High efficiency of this laser design architecture has been obtained experimentally from a laser pumped Ho:YLF laser in our laboratory [10]. It produced 33mJ of pulse energy with a quantum efficiency of 88%. Recent great advancement in fiber laser made it possible to replace the Tm:$YAlO_3$ laser with commercially available Tm:fiber laser as the pump source. The following subsections (III.1-5) provide a detailed description of each subsystem in Figure 1.

III.1 THULIUM-FIBER PUMP LASER

Figure 2 illustrates a commercially available Tm:fiber laser made by *IPG* Photonics which operates in a tandem pumping scheme. The best wall plug efficiency for this type of Tm:fiber laser was about 9%. The Tm:fiber lasers can also be pumped directly through the 800nm band. By using a heavily doped Tm concentration, the laser efficiency can be significantly enhanced by the well-known cross-relaxation process, where one pump photon can excite two Tm ions in to $^3H_4$ level. *Q-peak* has reported that 300W of power at ~1.9µm has been generated with 62% optical-to-optical efficiency in a Tm doped silica fiber laser [11]. *NP Photonics* took a different approach, and has developed Tm-doped germinate glass double-cladding single-mode fiber laser. Output power of 64 W at 1.9 µm with a slope efficiency of 68% was demonstrated [12]. The efficiencies in both of these approaches are significantly higher than the Stokes limit of 42%. Taking a conservative estimate of 60% optical-to-optical conversion efficiency for Tm:fiber lasers and assuming 45% of electrical-to-optical conversion efficiency for pumping diodes, the Tm:fiber lasers would have 27% electrical efficiency.

Figure 2: A commercially available *IPG* Tm:fiber laser being used in the experimental setup

Commercially available (IPG) Tm:FLs have been repackaged to MIL spec standards. Consequently, utilizing a commercially available, efficient fiber laser as a pump source significantly increases the system efficiency and reduces the risk.

III.2 HOLMIUM SOLID-STATE LASER

Table 1 lists specifications for the planned laser development and current development status. They are designed to meet the stringent laser transmitter requirements as imposed by high-precision and accuracy of the CO_2 measurements defined in the DS. The target objective for space-based system as listed are based on the results of a comprehensive study conducted by ESA under contract No. 10880/03/NL/FF [3].

Table 1: 2-micron Laser Transmitter Specifications.

Parameter	Development Objectives for Current System	Target Objectives for Space-based System
Wavelength (µm)	2.051	2.051
Energy(mJ)/ Rep. Rate (Hz)	>65mJ / 50Hz	65mJ / 50Hz
Pulse width (ns)	<= 50ns	<= 50ns
Transverse Mode	TEMoo	TEMoo
Longitudinal mode	Single frequency	Single frequency
Frequency control accuracy	<2MHz	2MHz

III.3 HO LASER OSCILLATOR

A Ho solid-state pulsed laser was successfully demonstrated under a LRRP task funded by Earth Science Technology Office (ESTO) [14]. Ring cavity design was used for this pulsed Ho laser. It eliminates the effect of "spatial hole burning" in the laser gain medium to obtain higher beam quality. This laser is injection seeded by a well-behaved seed laser source. The injection seeding is based on the ramp-and-fire technique. The demonstrated successful injection seeding rate is >99.9% [15]. This injection seeded ring cavity laser architecture has been successfully applied to operational coherent wind lidar and CO_2 DIAL, and the wind lidar has been successfully flown in NASA DC8 platform recently [16].

At NASA LaRC, we have demonstrated a Ho:YLF laser pumped by a Tm:fiber laser as part of LRRP. 31mJ at 100Hz repetition rate was achieved in a ring cavity configuration with pump power of 13 W as shown in Figure 3 [17]. One stage of amplifier is needed to scale the energy to meet the energy requirement of space IPDA instrument.

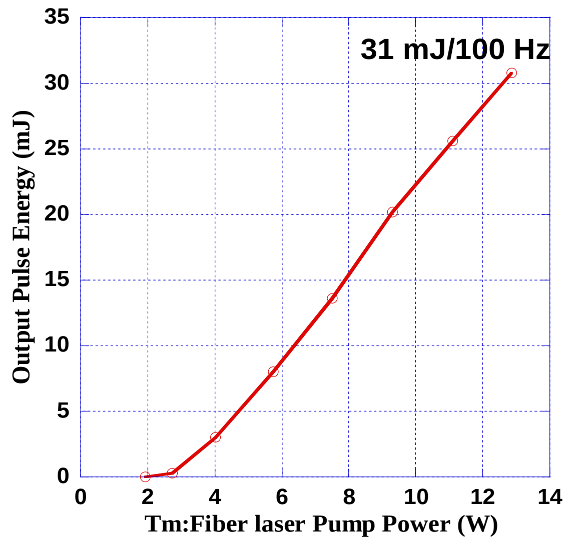

Figure 3: Demonstrated performance for a similar Tm fiber laser pumped Ho laser.

III.4 HO LASER AMPLIFIER

A Ho laser amplifier in a double-pass, straight through slab configuration is envisioned to provide scaling to a high energy of at least 65mJ due to the better thermal management arrangement. The advantages of longitudinal pumping scheme are better pump/probe beam overlap and a simple geometry of the slab amplifier. The 1.94 laser pumps the Ho:YLF crystal through beam shaping optics and a dichroic. The probe beam from the output of the oscillator is introduced into the amplifier from the other end. It double passes the amplifier gain medium by the slightly tilted dichroic mirror. The key to obtain high amplifier efficiency with good beam quality is to effectively dissipate the heat generated in the amplifier gain medium. Due to the resonant pumping, the small quantum defect of the amplifier indicated only ~5% of the pump power is generated as heat. The study of Ho:Ho interactions in YLF [18] suggests that the up conversion loss in this material is much lower than that of YAG material.

III.5 INJECTION-SEED LASER AND WAVELENGTH CONTROL

Tuning and stability of the laser transmitter are critical for making precise and accurate CO_2 measurements. The laser wavelength control technology described here has been previously built and integrated into a complete breadboard prototype lidar used in ground-based field experiments [19, 20]. Three CW seed lasers are being planned to be integrated and optimized in an optical switch design to meet the required wavelength control and tunability. The CW lasers are commercially available devices originally developed for the NASA Space Readiness Coherent Lidar Experiment (SPARCLE**)** [21]**.** We have developed a technology for establishing wavelength knowledge to well under 0.05 pm (3.75 MHz) [22]. Furthermore, a capability has been added to tune and lock anywhere on the side of the absorption line, so that the amount of absorption to a desired range can be optimized. Tailoring the level of absorption further improves precision and accuracy of the DIAL/IPDA results.

IV. SUMMARY AND CONCLUSIONS

The mid-IR wavelength regions at 1.57µm and 2.05µm are considered suitable for CO_2 IPDA measurements. Two instruments operating at 1.57µm have been developed and deployed as airborne systems for atmospheric CO_2 column measurements [23, 24]. One instrument is based on an intensity modulated CW approach, the other on a high PRF, low pulse-energy approach. These airborne CO_2 lidar systems operating at 1.57µm utilize mature laser and detector technologies by taking advantage of the technology development outcomes in the telecom industry. However, significant challenges remain for scaling from airborne to space-borne mission prototype. For example, in the case of the high PRF pulsed system, two orders of magnitude average power scaling is needed [23, 25]. On the other hand, lidars operating in the 2µm band offer better near-surface CO_2 measurement sensitivity due to the intrinsically stronger absorption lines. The 2µm pulsed laser needs a factor 2 scaling to meet laser transmitter pulse energy and PRF requirements for a CO_2 space mission [3], which can be achieved by adding single stage amplifier as envisioned in this paper. In addition recent work documents the capability to precisely control and stabilize the output frequency of this type of Ho laser [19, 20], and demonstrated a higher than 0.7% measurement precision via a ground based CO_2 lidar instrument [22]. The recent emergence of new 2µm detector capabilities makes direct detection at the 2µm wavelength from space very attractive [26, 27]. The pulsed 2µm laser provides a viable approach for space based CO_2 column density measurement.

Although both the wavelengths at 1.57µm or 2.05 µm are suitable for the CO_2 concentration measurement, the weighting function at 2.05 µm is more favorable for measurements in the lower troposphere, including the boundary layer. This is important since this is where the CO_2 sources and sinks reside [5]. In theory, the 1.57µm sounding can be done with a similar weighting function, by displacing the on-line laser frequency ~ 2 half widths from the line center of the pressure-broadened absorption line. However when doing that at 1.57µm, the differential absorption optical depth (DAOD) becomes very small (~0.1, or 10%) [5], requiring extremely high on-line and off-line SNR to achieve the required measurement precision. In addition, it becomes more difficult to control the influence of sources of bias when the differential absorption "signal" is so small. The DAOD at 2µm is closer to ideal DAOD of ~1 [6]. The inherent spectroscopic factors result in a significantly larger measurement precision and bias reduction challenge when operating at 1.57 µm, compared with 2.05µm.

In addition, high energy pulse approach at 2µm provides higher measurement accuracy. Given a fixed transmitter average power, high pulse energy is preferred when striving for high signal-to-noise level in a direct-detection lidar system when dark current and/or background-induced photocurrent are not insignificant, as is the case for ASCENDS. The currently envisioned 1.57µm concepts employ much lower pulse energy (~ 1 mJ) or operate CW.

In summary, the ESTO funded 2-micron laser technology under LRRP provides a clear technology development path to spaceflight application. The NASA LaRC developed Ho pulse laser meets or exceeds the generally accepted requirements of a direct detection 2µm IPDA system, which can provide adequate CO_2 column density measurements from space. The pulsed lidar transmitter architecture, energy, repetition rate, line width, frequency control are all suitable for space application without major scale up requirements.

V. ACKNOWLEDGEMENTS

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