

Fiber Lasers and Amplifiers for Space-based Science and Exploration

Anthony W. Yu,⁺ Michael A. Krainak, Mark A. Stephen, Jeffrey R. Chen, Barry Coyle,
Kenji Numata, Jordan Camp, James B. Abshire, Graham R. Allan, Steven X. Li, Haris Riris

NASA Goddard Space Flight Center, Greenbelt, Maryland USA 20771

ABSTRACT

We present current and near-term uses of high-power fiber lasers and amplifiers for NASA science and spacecraft applications. Fiber lasers and amplifiers offer numerous advantages for the deployment of instruments on exploration and science remote sensing satellites. Ground-based and airborne systems provide an evolutionary path to space and a means for calibration and verification of space-borne systems. NASA fiber-laser-based instruments include laser sounders and lidars for measuring atmospheric carbon dioxide, oxygen, water vapor and methane and a pulsed or pseudo-noise (PN) code laser ranging system in the near infrared (NIR) wavelength band. The associated fiber transmitters include high-power erbium, ytterbium, and neodymium systems and a fiber laser pumped optical parametric oscillator. We discuss recent experimental progress on these systems and instrument prototypes for ongoing development efforts.

Keywords: Fiber laser, Fiber amplifier, Lidar, Remote Sensing

1. INTRODUCTION

One of NASA's primary objectives is to provide scientific measurements on a global scale. Our recent space-based laser instruments include the Mars Orbiter Laser Altimeter (MOLA), Geoscience Laser Altimeter System (GLAS), Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument, launched in 2006 as a part of CALIPSO mission, Mercury Laser Altimeter (MLA), Lunar Orbiter Laser Altimeter (LOLA) and the most recently launched Sample Analysis at Mars (SAM) on the Mars Science Laboratory (MLS).[1, 2, 3, 4, 5, 6] Five of the six active instruments (MOLA, GLAS, CALIPSO, MLA, LOLA) are designed for global scale measurements from orbits and they all used short high-peak-power pulses of Q-switched Nd:YAG lasers for time-of-flight based laser altimetry. The sixth and just launched active instrument is SAM, which is the first in-space Laser Induced Breakdown Spectroscopy (LIBS), this will be deployed as part of a suite of instruments on the MLS Rover.[7] For space-based lasers, in addition to the numerous electro-optic requirements, ruggedness, reliability and long term operational stability are particularly important since these instruments are designed to monitor global changes of measurable parameters (e.g. ice sheet thickness, atmospheric composition, etc.) over long periods of time (over mission life).

Traditionally NASA has been interested in bulk, diode pumped solid-state lasers (DPSSL) to generate mJ-class laser pulses for scientific measurements.[8] These types of laser system designs have space heritage, can be easily scaled for specific use and can be ruggedized for space deployment. At the same time as we develop DPSSL for space, we are also investing in fiber laser and amplifier technologies. Fiber laser and amplifier systems have captured a large market share in recent years due to the ever increasing demands on materials processing applications, which include automobile, shipbuilding, pipeline laying, construction, electronics and aerospace. Fiber lasers and amplifiers have the potential for superior beam quality (TEM₀₀), high electrical efficiency (>30% wall-plug), lower maintenance, higher reliability, smaller footprint, ruggedness and easier transportability when compared to traditional DPSSL systems. All these attributes are most relevant to NASA's future missions. These attributes make fiber lasers and amplifiers excellent candidates for future space-based applications with benefits including

- low susceptibility to optical misalignment and contamination (fusion splices);
- strong leverage from the laser and telecommunications industries;
- high-reliability pump laser diodes [leveraged from telecommunications];

⁺ anthony.w.yu@nasa.gov; phone 1(301)614-6248; fax 1(301)614-6819

- numerous pump laser diode and fiber laser/amplifier suppliers;
- upsurge in performance - including orders of magnitude power increases over the last several years with predicted future increases (recently 2 kW single-mode average power [9], 1 MW peak power [10] have been achieved);
- distributed thermal load;
- low parts count;
- radiation-tolerant devices available;
- space-qualified CW version (low peak power) available;
- large wavelength range availability;
- tunable, diverse-wavelength reliable, low-cost, space-qualified single-frequency laser diode seed sources available for Master Oscillator Power Amplifier architecture;
- scalable to very high powers with both single-device and multi-device architectures;
- eye-safe (wavelengths longer than retinal thermal damage) versions available;
- Er and Nd have wavelength compatibility with scientifically important atmospheric trace gas (e.g. H₂O, CO₂, CH₄, O₂) spectral features;
- high wall-plug efficiency (> 20%);
- pump diodes are physically separated from active laser region allowing better thermal management.

Although mJ level pulse energies have been reported in fiber lasers,[11] in general the pulsed fiber-laser/amplifier optical-peak-power is much lower than what is available from bulk solid-state lasers and new and optimized system architectures and measurement approaches are required to exploit and optimize the device capabilities. Rather than low-repetition-rate (1-100 Hz) high-peak-power systems, we are investigating both high-repetition-rate modest peak-power instruments and pseudo-noise code systems for laser ranging [12]. Further, fiber-based laser systems enable us to consider the use of multiple lasers for continuous wide-swath high-spatial-resolution mapping.

The situation is similar for global atmospheric gas composition profiling. Rather than a high-energy pulsed Differential Absorption Lidar (DIAL) instrument we are investigating an instrument approach using differential absorption optical spectroscopy that we refer to as a “laser sounder” [13]. We use the term “sounder” for two reasons: 1) the instrument relies on the optical surface return (“echo” - similar to an ocean depth sounding instrument) rather than atmospheric backscatter and 2) the dictionary definition of sounding (“measurement of atmospheric conditions at various heights”). At first glance, it appears that this instrument can only be used to integrate over the entire atmospheric column (from the spacecraft to ground). However, some height profile information may be obtained by sampling across a spectral line at multiple optical wavelengths. Pressure broadening of the spectral line provides enhanced sensitivity to lower altitudes (i.e. higher pressure) in the line wings. This property can be exploited to isolate the gas variability in the lower atmosphere.

2. SYSTEM ENGINEERING

Size, weight and power (SWaP) requirements are strong factors in determining the viability of a space-based instrument. Although each application has numerous factors that influence technology decisions, when considering only the electrical efficiency, the present fiber and pump diode technology favors the Yb-fiber-based laser transmitters. In addition, high electrical-efficiency also means that fewer pump diodes are required for a given optical output power, reducing the required weight.

Laser optical (and electrical) power requirements are determined from system “link” budgets. The cost and performance of the optical receiver components directly impact the required laser power. Even with state-of-the-art lightweight one-meter diameter receiver telescopes, these low-peak-power fiber-laser-based instruments still usually require photon-counting detectors. Depending on the application, we consider both time-resolved and integrating single-photon sensitive detectors. Some NASA application-specific considerations for time-resolved near-infrared photon-counting detectors have been recently published [14].

3. FIBER LASER SYSTEMS

3.1 ERBIUM FIBER MOPA AT 1571 NM

We are conducting research on a laser sounder instrument for global (Earth and Mars) measurements and profiling of atmospheric CO₂ in support of the future Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS) mission. Although increasing atmospheric CO₂ is widely accepted as the largest anthropogenic factor causing climate change, there is considerable uncertainty about its global budget. Accurate measurements of tropospheric CO₂ mixing ratios are needed to study CO₂ emissions and CO₂ exchange with the land and oceans. To be useful in reducing uncertainties about carbon sources and sinks the atmospheric CO₂ measurements need degree-level spatial resolution and ~ 0.3% precision. Our group has developed a pulsed lidar approach as a candidate for the ASCENDS mission (Figure 1). Our approach uses an erbium fiber amplifier based transmitter for atmospheric CO₂ measurements in an overtone band near 1.57 μm [15]. It uses a dual band pulsed laser absorption spectrometer and the integrated path differential absorption (IPDA) or the laser sounder technique. The approach uses two tunable pulsed laser transmitters allowing simultaneous measurement of the absorption from a CO₂ absorption line in the 1570 nm band, O₂ absorption in the oxygen A-band (765 nm), and surface height and atmospheric backscatter in the same path. A tunable laser is stepped in wavelength across a single CO₂ line for the CO₂ column measurement, while simultaneously a laser is stepped across a line doublet near 765 nm in the Oxygen A-band for an atmospheric pressure measurement [16, 17]. Both lasers are pulsed at a ~8kHz rate, and the two absorption line regions are sampled at each wavelength step at typically ~1 kHz. The direct detection receiver measures the time resolved laser backscatter from the atmosphere along with the energies of the laser echoes from the surface. After suitable averaging the gas extinction and column densities for the CO₂ and O₂ gases are calculated from the sampled wavelengths of the surface reflected line shapes via the IPDA Lidar technique.[18]

For the ASCENDS instrument, the wavelength stability and tunability requirement for sampling the absorption feature of the CO₂ and O₂ gases drove the laser transmitter to a MOPA architecture. We have recently demonstrated a wavelength-locked laser source that rapidly steps through six wavelengths distributed across a 1572.335 nm CO₂ absorption line to allow precise measurements of atmospheric CO₂ absorption. A distributed-feedback laser diode (DFB-LD) was frequency-locked to the CO₂ line center by using a frequency modulation technique, limiting its peak-to-peak frequency drift to 0.3MHz at 0.8 s averaging time over 72 hours. Four online DFB-LDs were then offset locked to this laser using phase-locked loops, retaining virtually the same absolute frequency stability. These online and two offline DFB-LDs were subsequently amplitude switched and combined. This produced a precise wavelength stepped laser pulse train, to be amplified for CO₂ measurements.[19] Figure 1 shows a conceptual master oscillator approach. A similar approach will be used for the 1529 nm wavelength band and then frequency doubled to generate the 764.5 nm for oxygen sensing.

To scale for space, the energy per pulse in each of these wavelengths (1.53 and 1.57 μm) needs to be increased to appropriate levels. A space-based version of this lidar must have a much larger lidar power-area product due to the ~x40 longer range and faster along track velocity compared to airborne instrument. We have developed receiver SNR models for both the CO₂ and O₂ channels and applied them to estimate lidar parameters needed for the space measurement. Initial calculations indicated that for a 500 km orbit, a 1.5 m diameter telescope and a 10 second integration time, which allows a 70 km along track integration in low earth orbit, a ~3 mJ laser energy is required to attain the precision needed for each measurement. The instrument power consumption is between 600 and 900W depending on the detector sensitivity. An initial mass estimate is 400 kg, and the uncompressed data rate is < 2 Mbits/sec. Although more work is needed using better-defined measurement requirements and lidar components, the studies found that fiber based laser amplifier provide a good design base for the ASCEDSN space based instrument.

The laser sounder for Earth atmospheric CO₂ requires measurements of atmospheric O₂ (pressure and temperature). The ratio of CO₂ to O₂ will provide a measurement of the dry-air mixing ratio of CO₂. This quantity should be insensitive to fluctuations in surface pressure resulting from changing topography or weather systems and to fluctuations in temperature and humidity. For O₂ (at 770 nm), the most straightforward approach is a 1540 nm DFB-laser-diode oscillator frequency-doubled erbium-fiber-amplifier (1540nm/770nm) MOPA transmitter (see Figure 2).[20] Our experimental results are shown in Figure 3. More recently we have achieved over 1 kW peak power from a 1530 nm fiber amplifier [21].

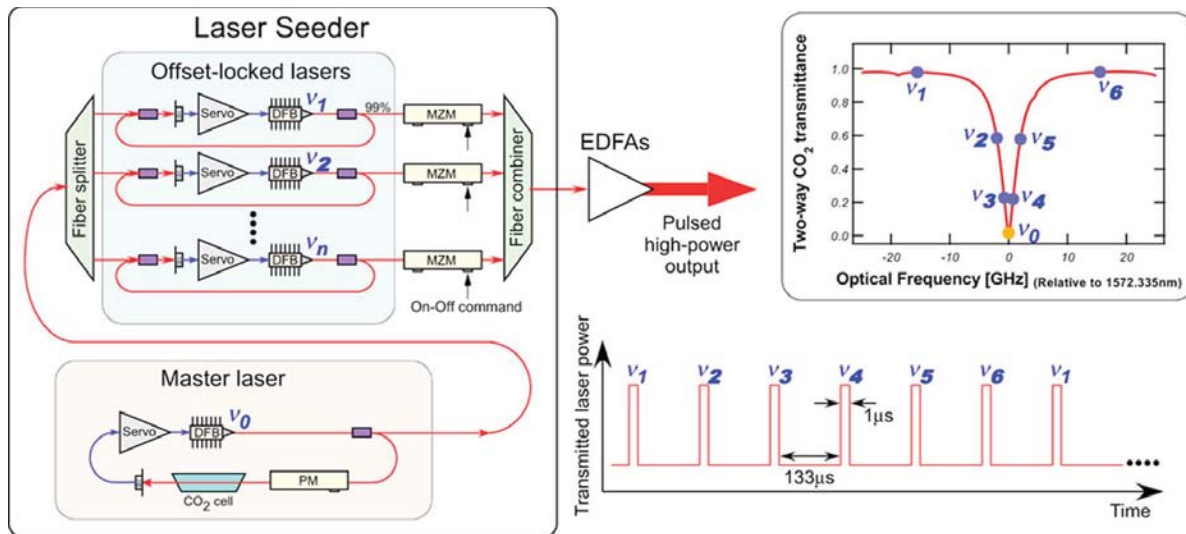


Figure 1. Basic design concept for our CO₂ sounder transmitter. The laser seeder (left) is rapidly pulsed and switched among the six measurement laser frequencies to provide the wavelength-stepped pulse train (lower right) that is subsequently amplified by EDFAs. The amplified pulse-train is used to repeatedly measure at six points across the 1572.335nm CO₂ absorption line (upper right).

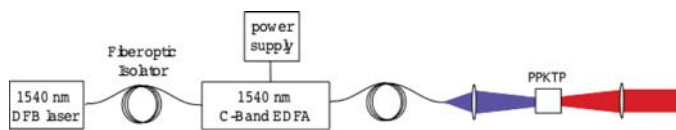


Figure 2. Frequency-doubled MOPA with Er fiber amplifier and PPKTP doubler.

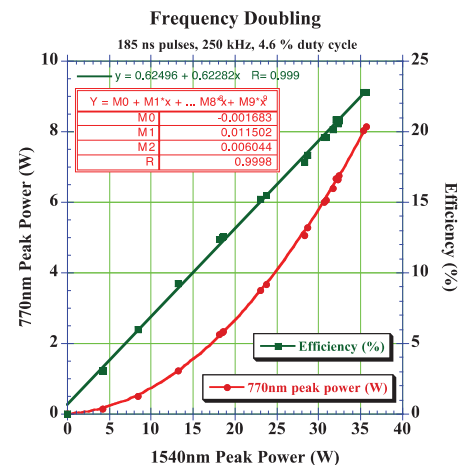


Figure 3. Experimental results from frequency-doubled MOPA with Er fiber amplifier and PPKTP doubler.

3.2 ND FIBER MOPA AT ~1000 NM

One of the NASA mantras for Martian exploration is “follow the water”. We developed a prototype atmospheric water vapor instrument for higher-precision global measurements that can be used in both Mars and Earth orbit [22]. For water vapor, the combination of a suitable optical absorption feature and the availability of both an efficient, reliable space-qualified fiber-based transmitter and a photon-counting detector (Perkin-Elmer SPCM) currently favors the choice of a 920-940 nm (strongest line at 935.68 nm) wavelength DFB-laser-diode (Eagleyard Photonics) neodymium-fiber-amplifier MOPA transmitter. The measured output spectrum is shown in Figure 4.

The future Lidar Surface Topography (LIST) mission will allow topographic mapping from space to provide precise elevation images for global measurements of ice sheets, sea ice glaciers and land topography. It uses contiguous 10m laser footprints in a swath width of 250m or greater. In addition to crossovers, the width of the measurement swath, in combination with precise spacecraft pointing, allows continuous overlapped repeat coverage of surface elevation along the measurement track, which provides improved repeatable coverage and the capability to determine trends in elevation changes. Our objective is to measure surface heights to <10 cm within 10 m diameter spots with a mission lifetime of >7 years. The individual surface height measurements can be aggregated and/or sampled to allow comparing to existing space measurements. [26]

We have selected a highly redundant push-broom measurement configuration, which uses multiple lasers and detectors operating in parallel. The instrument uses lasers with nanosecond pulse widths, along with sensitive photon-counting detectors and high-resolution timers to accumulate an echo pulse waveform for each spot. We are working with industry to develop an Yb fiber laser that pushes the highest possible reliable peak-power for this application. [27]

3.4 LOW-REPETITION-RATE PULSE-PUMPED YB-FIBER MOPA

In-house efforts have also been underway to produce Yb doped systems at 1045nm and 1064nm for terrain mapping and imaging altimetry with complete pulse return digitization. This requires non-CW pumped repetition rates (0 – 5 kHz) and discrete optical pulse shaping control. For example, our Laser Vegetation Imaging System (LVIS) is an aircraft-based laser altimeter with an active 2-axis scanning mechanism, used for 3-dimensional volumetric biomass measurements of the Earth.[28] Its on-board, diode-pumped Nd:YAG laser is an excellent target for replacement with such a pulsed, master oscillator Yb power amplifier system (MOPA). The current LVIS laser operates well, but its significant size and requisite liquid cooling system will eventually be replaced with a much smaller, conductively cooled, seeded fiber system with excellent beam quality and stability over a wide range of operating parameters. We will have complete control over repetition rate, pulse energy, pulse width and shape. To date, we have produced over 150 μ J pulses at 1064nm in our laboratory fiber system. More energy is possible, and planned, but we are simply limited in the diameter of our current output end cap. The seed laser is a pulsed, narrow frequency, diode laser, externally tuned with a KTP-Bragg grating. More optimization is needed for the complete pulse-pumped Yb fiber system, but we have demonstrated several repetition rates between 100 Hz and 3 kHz with pulse widths between 2 – 10 ns, and >100 μ J energies. We've achieved more than 50 dB of gain where a seed pulse of ~1nJ was amplified to over 100 μ J, with excellent ASE control and little SBS effects. Current efforts underway include improving the efficiency by optimizing the pumping parameters (pulse width, current, temperature, etc.) over repetition rate and improving the packaging such that the laser can confidently move from the laboratory to an aircraft environment.

3.5 FREE SPACE OPTICAL COMMUNICATION FIBER MOPAS

Free space communications is another important optical fiber transmitter application. The Lunar Laser Communication Demonstration (LLCD) is managed by GSFC and the instrument built by MIT/LL. LLCD (2013 launch) will use a 0.5W erbium fiber laser amplifier in a MOPA configuration.[29]

We have recently initiated the Laser Communication Relay Demonstration (LCRD) program (late 2016 launch). The LCRD plans to use a telecommunication laser diode master oscillator seeding an Er-doped fiber amplifier. The wavelength of the LCRD system will be in the 1.55 μ m band. LCRD will fly two optical communications terminals on a geosynchronous commercial communications satellite. Each LCRD space terminal will consist of an optical module beam director, controller electronics, and two separate modems 1) an LLCD modem for Pulse Position Modulation and a multi-rate Differential Phase Shift Keying (DPSK) modem. There will also be a controller / data processor between the two space terminals. Each space terminal will be communicating bi-directionally with optical communications ground stations. [30]

3.6 YB-FIBER-PUMPED OPTICAL-PARAMETRIC-OSCILLATOR

In the past few years, we have engaged in a research effort for measuring atmospheric methane. This has importance for both Earth and Martian science. Methane has strong absorption lines near 3.4 microns and an overtone band near 1650 nm. A Raman-shifted erbium-fiber-laser pumped source was an early candidate. However, we were concerned that stimulated Brillouin scattering (SBS) effects may severely limit the achievable output power. Instead, we built an Yb MOPA pumped OPO system.[31] This system appears to offer the promise of a fiber laser pump based laser transmitter

that can be modified to operate anywhere in the 1-10 micron wavelength range without the requirement for gas-absorption-wavelength-specific seed lasers.

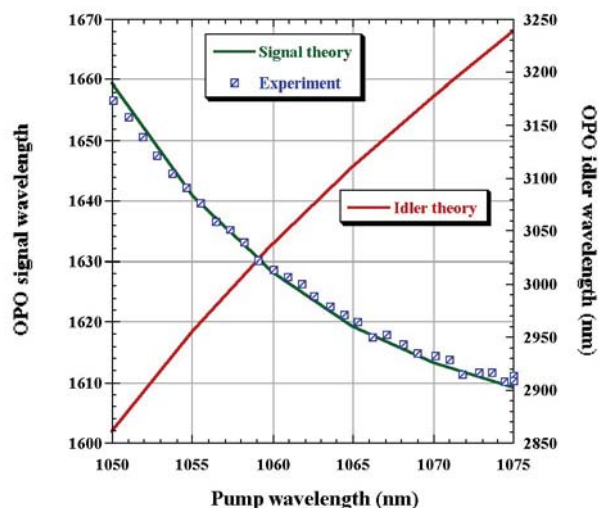


Figure 6. Optical-parametric-oscillator (OPO) consisting of a two-mirror cavity and a temperature-controlled periodically-poled lithium-niobate crystal for nonlinear optical-wavelength conversion.

Our approach is a MOPA pumped optical-parametric-oscillator (OPO). The master oscillator is an external cavity tunable semiconductor diode laser. The power amplifier is a diode-pumped ytterbium (Yb) fiber optic amplifier. The OPO is a simple two-mirror cavity laser with a high-temperature-controlled oven containing a periodically-poled lithium-niobate crystal (Figure 6) for nonlinear optical wavelength conversion.

The wavelength of the OPO light output is a function of several parameters including the pump wavelength (tunable by the master oscillator), the grating period of the PPLN – which can be fine-tuned with the oven temperature and the mirror reflectivity and absorption. Our preliminary experimental set-up is shown in Figure 7. With the proper non-absorbing mirrors (not yet purchased), light output can be achieved at both near-infrared (near 1650 nm) and mid-infrared (3250 nm) wavelengths. Using the low-cost readily available mirrors we purchased, we could only measure light output near 1650 nm. Since methane concentrations are very low on both Earth and Mars, the use of 3.25 micron wavelength light would allow improved detection sensitivity because the methane absorption line strength is 100 times larger at 3.25 microns compared to 1.65 microns. A similar OPO effort with a solid-state laser pump is being developed for a European space mission [32].

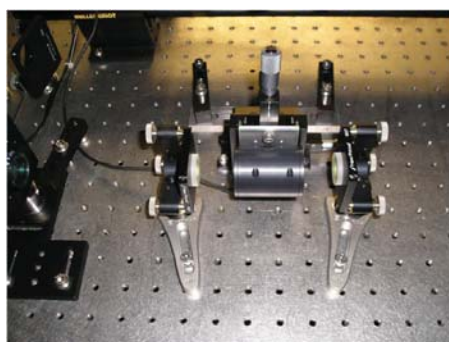


Figure 7. Yb-fiber MOPA pumped OPO output wavelengths (experiment and theory) as a function of master oscillator wavelength for the 30.0 micron periodically-poled lithium-niobate crystal grating spacing. At this writing we did not have an instrument to measure the long wavelength output.

4. FIBER-BASED LASER TRANSMITTER ISSUES

In spite of the numerous advantages of fiber-based laser transmitters there are still issues to be resolved for some NASA applications. The principle issue for many of the high-peak-power transmitters, (in particular those that require narrow bandwidth and in some cases single-frequency operation), are nonlinear effects. Probably the most prominent deleterious nonlinear effect is SBS. Fortunately, there has been some recent work [33] on methods to mitigate the SBS effects.

5. CONCLUSION

Fiber-based laser transmitters appear to have a strong future for numerous NASA space-based instrument applications.

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