Fiber lasers and amplifiers for Earth/planetary science and exploration at NASA Goddard Space Flight Center

Michael A. Krainak, Hossin Abdeldayem, James Abshire,
Graham R. Allan, John Burris, Jeffrey Chen, Barry Coyle, Steven Li,
Haris Riris, Antonios Seas, Mark Stephen, Emily Wilson, Anthony Yu

NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

Abstract-**We discuss present and near-term uses for high-power fiber lasers and amplifiers for NASA-specific applications including planetary topography and atmospheric spectroscopy. Fiber lasers and amplifiers offer numerous advantages for both near-term and future deployment of instruments on exploration and science remote sensing orbiting satellites. Ground-based and airborne systems provide an evolutionary path to space and a means for calibration and verification of space-borne systems. We present experimental progress on both the fiber transmitters and instrument prototypes for ongoing development efforts. These near-infrared instruments are 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. The associated fiber transmitters include high-power erbium, ytterbium, and neodymium systems and a fiber laser pumped optical parametric oscillator.**

I. INTRODUCTION

One of NASA's primary objectives is to provide scientific measurements on a global scale. Recent space-based laser instruments examples include MOLA[1], ICESat/GLAS[2] and MLA[3]. These active instruments for global scale measurements all use short high-peak-power pulses of Q-switched Nd:YAG lasers for time-of-flight based laser altimetry. For space-based lasers, in addition to the numerous electro-optic requirements, ruggedness and reliability are particularly important to global-change, science needs – the observation of small changes of a parameter (e.g. ice sheet thickness, atmospheric composition) over long periods of time.[-]

Fiber laser and amplifiers are exciting candidates for these space-based laser applications. Advantages include: 1) low susceptibility to optical misalignment (fusion splices) 2) strong leverage from the laser and telecommunications industries 3) high-reliability pump laser diodes [leveraged from telecommunications] 4) numerous pump laser diode and fiber laser/amplifier suppliers 5) upsurge in performance - including orders of magnitude power increases over the last few years with predicted future increases (recently 2 kW average power [4], 1 MW peak power[5] have been achieved) 6) distributed thermal load 7) low parts count 8) radiation-tolerant devices available 9) space-qualified CW version (low peak power) available 10) large wavelength range available 11) tunable, diverse-wavelength reliable, low-cost, space-qualified single-frequency laser diode seed sources available for Master Oscillator Power Amplifier architecture 12) scalable to very high powers with both single-device and multi-device architectures 13) eye-safe (wavelengths longer than retinal thermal damage) versions available 14) Er and Nd have wavelength compatibility with scientifically important atmospheric trace gas (e.g. H_2O, CO_2, CH_4, O_2) spectral features 15) high wall-plug efficiency (> 20%) 16) much less susceptibility to contamination (since there is no open cavity) 17) pump diodes are physically separated from active laser region allowing better thermal management.

New or modified instrument system architectures are required to exploit and optimize the device capabilities. Pulsed fiber-laser/amplifier optical-peak-power is much lower than what is available from bulk solid-state lasers. 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[6]. 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 a quasi-CW instrument that uses differential absorption optical spectroscopy that we refer to as a "laser sounder" [7]. 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

[-] *We acknowledge the support of the NASA Laser Risk Reduction Program, ESTO Advanced Technology Program, GSFC Director's Discretionary Fund and Internal Research and Development (IRAD) programs.*

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.

II. System Engineering

The total weight and power 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 (borrowing the communications terminology). 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 photon-counting detectors. Some NASA application-specific considerations for time-resolved near-infrared photon-counting detectors have been recently published[8].

III. Er fiber MOPA at 1571 nm

We are conducting research on a laser sounder instrument for global (Earth and Mars) measurements and profiling of atmospheric CO_2. We are also developing a short-range (2 km) ground-based DIAL instrument [9]. At present, the combination of a suitable optical absorption feature (proper line strength and free from other gas absorption line interference) and the projected availability of both an efficient, reliable space-qualified fiber-based transmitter and a photon-counting detector (Hamamatsu photomultiplier) favors the choice of an L-band (1571 nm) DFB-laser-diode erbium-fiber-amplifier MOPA transmitter. Our present single-frequency 500-ns pulse-width large-mode-area custom Er amplifier is Stimulated Brillouin Scattering (SBS) limited to 35 W peak power at 1571 nm. We are working with industry to develop an Er amplifier that supports much higher peak power under similar operating conditions.

III. Nd fiber MOPA at 920 – 940 nm.

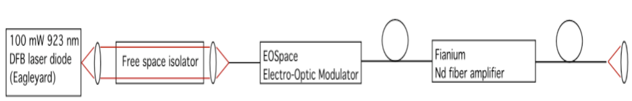

Fig. 1. MOPA with Nd fiber amplifier

One of the NASA mantras for Martian exploration is "follow the water". We are developing a prototype atmospheric water vapor instrument for higher-precision global measurements that can be used in both Mars and Earth orbit [10]. 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 (Fig.1). The measured output spectrum is shown in Fig. 2. We continue to collaborate with researchers at NOAA on a short-range DIAL system[11].

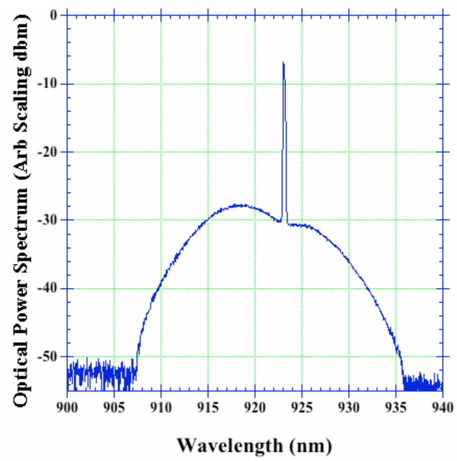

Fig. 2. Optical spectrum of MOPA with Nd fiber amplifier

III. Frequency-doubled erbium fiber MOPA

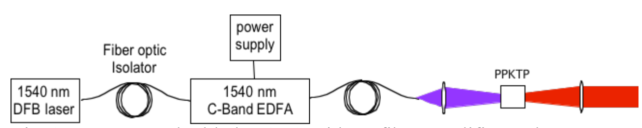

Fig. 3. Frequency-doubled MOPA with Er fiber amplifier and PPKTP doubler.

The laser sounder for Earth atmospheric CO_2 requires measurements of atmospheric O_2 (pressure and temperature) as well. The ratio of CO_2 to O_2 will provide a measurement of the dry-air mixing ratio of CO_2. 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 O_2 (at 770 nm), the most straightforward approach is a 1540 nm DFB-laser-diode oscillator frequency-doubled erbium-fiber-amplifier (1540nm/770nm) MOPA transmitter (Fig. 3) [12]. Our recent experiment results our shown in Fig. 4.

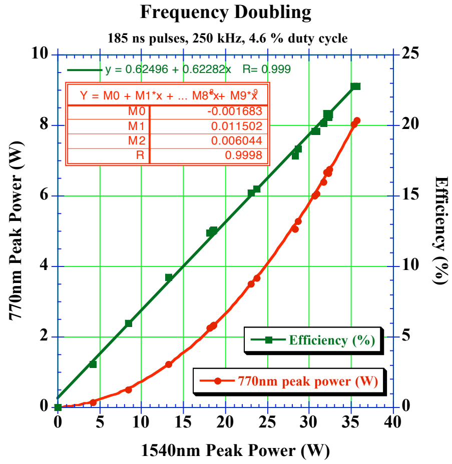

Fig. 4. Experimental results from frequency-doubled MOPA with Er fiber amplifier and PPKTP doubler.

VI. HIGH-REPETITION-RATE YB-FIBER MOPA

We are developing an new approach enabled by new technology for a next-generation space-based laser altimeter. This is a swath imaging laser altimeter mission will allow topographic mapping from space to provide precise elevation images for global measurements of ice sheets, sea ice glaciers and land topography, glaciers. 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 much greater repeatable coverage and 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, such as those from ICESat.

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 time 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.

V. LOW-REPETITION-RATE PULSED-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.[13] It's 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 unchanging excellent beam quality 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 uJ pulses at 1064nm in our laboratory pulsed 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, from AdvR Inc. of Bozeman, Montana. More optimization is needed for the complete pulsed-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 uJ energies. We've achieved more than 30dB of gain where a seed pulse of ~ 1nJ was amplified to over 100 uJ, with excellent ASE control and little SBS effects. Current efforts underway include improving the efficiency with optimizing the pumping parameters (pulse width, current, temperature…) over repetition rate and improving the packaging such that the laser can confidently move from the laboratory to an aircraft environment.

VI. FREE SPACE OPTICAL COMMUNICATION FIBER MOPAS

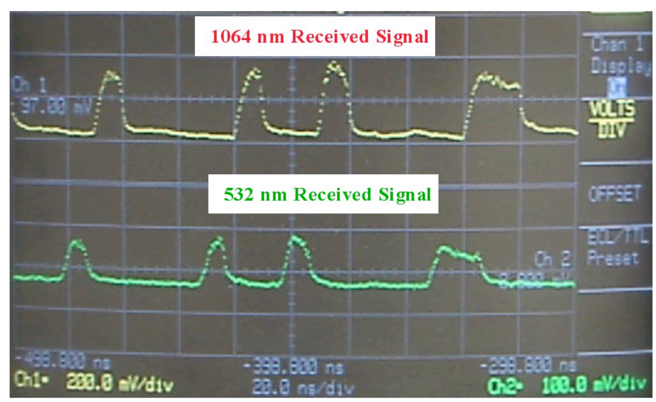

Fig. 5. Experimental results showing free space 50 Mbps Q-PPM received data from Yb fiber amplifier MOPA transmitter 1064 nm and 532 nm (frequency-doubled).

Free space communications is another important optical fiber transmitter application. Details of NASA's recently cancelled laser communications pathfinder project - Mars Laser Communication Demonstration (MLCD) are available[14]. The MLCD planned to use an Yb fiber laser/amplifier master oscillator power amplifier (MOPA) system. We have been developing several laser transmitter options including 1) an Yb fiber amp MOPA 2) a frequency doubled Yb fiber amp MOPA and an 3) Er fiber amp MOPA. The communications system engineering is still dominated by the availability of high-efficiency single-photon counting detectors. Cost-effective detectors still favor the visible wavelengths. Our preliminary 50 Mbps Quaternary Pulse Position Modulation (Q-PPM) communication system results at both 1064 and 532 nm are shown in Fig. 5.

VII. Yb-FIBER-PUMPED OPTICAL-PARAMETRIC-OSCILLATOR

We have recently initiated 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 [15]. 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.

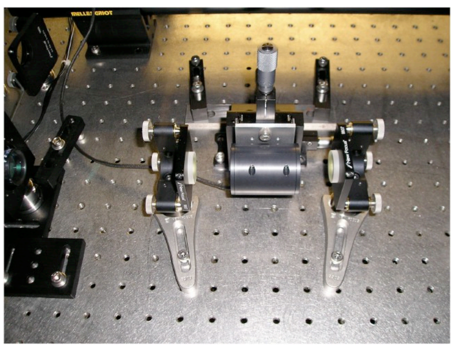

Fig. 6. Optical-parametric-oscillator (OPO) consisting of a two-mirror cavity and a temperature-controlled periodically-poled lithium-niobate crystal for nonlinear optical-wavelength conversion.

Our approach is a master-oscillator power-amplifier (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 (Fig. 6) for the 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 fined tuned with the oven temperature and the mirror reflectivity and absorption. Our preliminary experimental results are shown in Fig. 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 achieve 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.

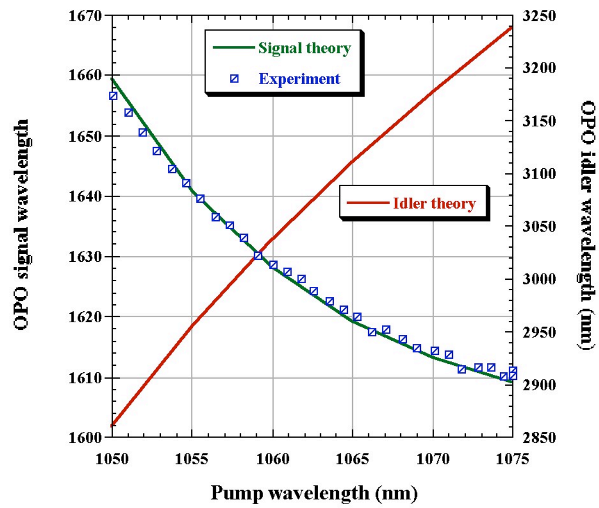

Fig. 7. Yb-fiber MOPA pumped OPO output wavelengths (experiment and theory) as a function of master oscillator wavelength for the 30.0 micron periodically-poled lithium-niobate crystal grating spacing. At this writing we did not have an instrument to measure the long wavelength output.

VIII. 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[16] on methods to mitigate the SBS effects.

IX. CONCLUSION

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

REFERENCES

1. D.E. Smith *et al.,* "Mars Orbiter Laser Altimeter: Experiment summary after the first year of global mapping of Mars" *Journal Of Geophysical Research-Planets* 106 (E10): 23689-23722, 2001.

2. B.E. Schutz. H.J. Zwally, C.A. Shuman , *et al.* "Overview of the ICESat Mission" *Geophysical Research Letters* 32 (21): Art. No. L21S01, 2005.

3. D. J. Krebs *et al.,* “Compact, passively Q-switched Nd : YAG laser for the MESSENGER mission to Mercury” *Applied Optics* 44 (9): pp. 1715-1718, 2005.

4. V. Gapontsev *et al.,* "2 kW CW ytterbium fiber laser with record diffraction-limited brightness" *CLEO/Europe.* Page(s):508 June 12-17 2005.

5. F. DiTeodoro and C.D. Brooks. "MW peak-power, mJ pulse energy, multi-kHz repetition rate pulses from Yb-doped fiber amplifiers" *Proceedings of SPIE* -- Volume 6102 Feb. 23, 2006.

6. J.B. Abshire *et al.* “Laser Altimetry Using Pseudo-Noise Code Modulated Fiber Lasers and Photon Counting Detectors”, *Conference on Lasers and Electro-Optics* Paper JThI4 Baltimore, MD 2005.

7. J.B. Abshire *et al.,* "Laser sounder approach for measuring atmospheric CO_2 from orbit" *Proceedings of the Third Annual Earth Science Technology Conference* pp. 6569-6577, 2003.

8. M.A. Krainak, “Photon counting detectors for the 1.0 - 2.0 micron wavelength range”, *NASA 2004 Earth Science Technology Conference* Paper B3P1 Palo Alto, CA, 2004.

9. H. Riris *et al.,* "A 1.57µm DIAL Lidar System for Range Resolved Measurements of Atmospheric CO2" *CLEO* May 2006.

10. G.R. Allan *et al.,* "Small lidar for remote measurements from orbit of water-vapor, cloud, and aerosol profiles", *Proc. SPIE Int. Soc. Opt. Eng.* 5653, 228, 2005.

11. J.L. Machol, *et al.,* “Preliminary measurements with an automated compact differential absorption lidar for the profiling of water vapor” *Applied Optics* Vol. 43, No. 15 pp. 3110-3121 (2004)

12. P.A. Champert, S.V. Popov, J.R. Taylor "Power scalability to 6 W of 770 nm source based on seeded fibre amplifier and PPKTP" *Electronics Letters* 37 (18): 1127-1129 Aug. 30 2001.

13. J. B. Blair, D. L. Rabine, and M. A. Hofton, "The Laser Vegetation Imaging Sensor (LVIS): A medium-altitude, digitization-only, airborne laser altimeter for mapping vegetation and topography", *ISPRS Journal of Photogrammetry and Remote Sensing*, 54, 115-122, 1999.

14. D.M. Boroson, C.-C. Chen, B. Edwards, "The Mars laser communications demonstration project: truly ultralong-haul optical transport" *Optical Fiber Communication Conference*, 2005.

15. I.D. Lindsay *et al.,* "110GHz rapid, continuous tuning from an optical parametric oscillator pumped by a fiber-amplified DBR diode laser" *Optics Express* 13 (4): 1234-1239 (2005)

16. A. Liu "Novel SBS suppression scheme for high-power fiber amplifiers" *Proc. SPIE* 6102 Feb. 23, 2006