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

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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 pseudo-noise (PN) code laser ranging system. The associated fiber transmitters include high-power erbium, ytterbium, neodymium and Raman fiber amplifiers.

In addition, we will discuss near-term fiber laser and amplifier requirements and programs for NASA free space optical communications, planetary topography and atmospheric spectroscopy.

Introduction

One of NASA's primary objectives is to provide scientific measurements on a global scale. Recent space-based laser instruments examples include MOLA[Smith], ICESat/GLAS[Kwok] and MLA[Krebs]. 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, 1 MW peak power 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. H₂O, CO₂, CH₄, O₂) 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[Abshire-2005]. 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”. 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.

Deep space communications is another important optical fiber transmitter application. Details of NASA’s present laser communications pathfinder project - Mars Laser Communication Demonstration (MLCD) are available[Boroson]. The MLCD will use an Yb fiber laser/amplifier master oscillator power amplifier (MOPA) system targeted for a 2009 launch.

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 light-weight

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[Krainak].

Fiber laser transmitters for specific instruments

We are conducting research on a laser sounder instrument for global (Earth and Mars) measurements and profiling of atmospheric CO₂[Abshire-2003]. We are also developing a short-range (2 km) ground-based DIAL instrument [Andrews]. 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.

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 [Allan]. 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. However, due to the rapid development of Yb fiber MOPA pumped OPOs [Lindsay] we are also evaluating developing a system at 1390 nm. We continue to collaborate with researchers at NOAA on a short-range DIAL system[Machol].

The laser sounder for Earth atmospheric CO₂ requires measurements of atmospheric O₂ (pressure and temperature) as well. 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.

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 plan to mimic the Yb MOPA pumped OPO system that was recently demonstrated[Lindsay]. 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.

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[Hansryd, Marconi] on methods to mitigate the SBS effects.

Conclusion

Fiber-based laser transmitters appear to have a strong future for numerous NASA space-based instrument applications. As a footnote we add that an Yb-fiber amplifier has recently been considered as a possible candidate for the NASA LISA mission[Trobs].

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