# Advanced 2-micron Solid State Laser Developments

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***Abstract*- The development of a space-qualifiable 2-micron laser is beneficial to both the Exploration and Earth science technology goals. Recently, significant advancements in the laser development have been made under the Laser Risk Reduction Program. One Joule per pulse energy was achieved by a Master-Oscillator-Power-Amplifier (MOPA) system. To our knowledge, it is the highest recorded energy at this wavelength. Fully conductive cooled 2-micron laser was demonstrated by the use of heat pipe technique. It enhanced the laser thermal management, and virtually eliminated the running coolant to increase the overall system efficiency and reliability. Direct pumped Ho laser, by taking the advantage of the commercial Tm fiber laser, is explored. It significantly increases the laser system efficiency and thermal performance. All these technical development efforts push forward the readiness of the space-borne coherent Doppler lidar. This paper will review the current state-of-the-art developments and the future technology challenges in the 2-micron solid-state lasers.**

## I. INTRODUCTION

Earth atmospheric carbon dioxide vertical profiles and tropospheric wind database are critically needed measurements for global climate change studies and for predicting the evolution of the atmospheric process that influences life on Earth. Mars atmospheric density and winds data are also critical to aerocapture, and entry, descent, and landing (EDL) of future robotic and human Mars missions. Two-micron, pulsed, coherent-detection lidar system measures horizontal wind velocity with a high measurement precision. The same lidar system can also measure atmospheric $CO_2$ concentration profiles, and therefore density. Ground based 2-µm coherent Doppler wind lidars and $CO_2$ Differential Absorption Lidars (DIALs) by using 2-micron laser transmitters at output energy of 100 mJ level have been successfully demonstrated [1, 2]. It enables better measurement accuracy with higher range resolution and distance coverage.

Space based wind sensing coherent Doppler lidar requires eye-safe, high energy, high efficiency, high beam quality, and single frequency laser transmitter. It shall also meet the requirements of the space operation environments. Thus, the efficient thermal management, the size and weight of the laser transmitter, the ruggedness of the laser design, the healthy of the laser operation under extreme space environment need be considered seriously. Under the Laser Risk Reduction Program, we develop technologies to address these issues simultaneously. This paper reports the significant advances in the 2-micron laser technology developments.

## II. ONE-JOULE DOUBLE-PULSED HO:TM:LuLF MASTER-OSCILLATOR-POWER-AMPLIFIER (MOPA)

Development of a laser transmitter is always the most critical technology among the three key factors for a typical lidar system, namely the laser transmitter, detector, and data-acquisition systems. The critical parameters for a transmitter include laser pulse energy, laser pulse duration, laser wavelengths for both absorption on-line and off-lines, laser linewidth, frequency stability, spectral purity, laser beam profile and quality [3-6]. To qualify the spaceborne coherent Doppler wind lidar and $CO_2$ Differential Absorption Lidar (DIAL) for the accurate profiling of wind and $CO_2$ concentration, a multi-Joule high efficient 2-µm Master-Oscillator-Power-Amplifier (MOPA) laser system is required.

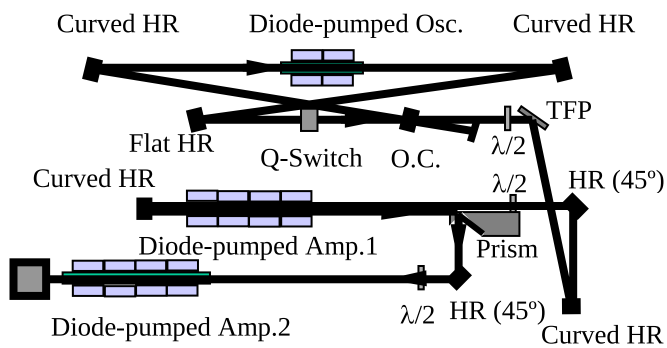


Fig. 1. Schematic diagram of the experimental setup for laser Master-Oscillator-Power-Amplifier (MOPA)

The schematic diagram of the experimental setup for the MOPA laser system is shown in Figure 1. The laser resonant cavity consists of two curved high reflectors, one flat reflector and one flat output coupler and was symmetrically configured for the stable operation. Two curved high reflectors made two Gaussian beam waists inside the cavity and the laser beam more parallel within the resonator, so the utilization of the active mode volume inside the resonator and the Q-switch was more efficient when the laser crystal rod and a Brewster-angle-cut fused-silica acousto-optical Q-switch were located at these two Gaussian beam waists respectively. A flat high reflector was used to force the one direction operation of the laser in the ring cavity configuration. The first amplifier was set in a double-pass configuration. Although the amplifier was originally designed in collinear configuration with a combination of a Thin Film Polarizer (TFP), a 45° Faraday rotator, and a half-wave plate

[7], the final experiment was completed in off-linear configuration due to the damage of the Faraday rotator. The second amplifier was setup in single-pass configuration due to the limitation of the damage threshold of the laser crystal rod. The curved high reflectors are used to direct the laser beam in to the amplifiers for the compensation of the beam divergence.

The designed laser MOPA system could operate at normal mode, single pulse Q-switched mode, and double pulse Q-switched mode based on the laser oscillator. The pumping diodes of the laser oscillator and laser amplifiers were triggered by electronic pulses with a width of 1 ms at a repetition rate of 2 Hz. The Q-switch inside the laser oscillator was triggered once for single pulse operation and twice for double pulse operation during one cycle of the diode-pumping period. The first Q-switch trigger started 1.1 ms after the beginning of the diode-pumping trigger pulse and the time interval between two Q-switch triggers was 200 μs. The total output pulse energy was measured as a function of total optical pump pulse energy for three operation modes, and they are shown in Fig. 2. The maximum output pulse energy at the total optical pump pulse energy of about 15 J was 1.4 J, 626 mJ, and 1.05 J when output pulse energy of the laser oscillator was 280 mJ, 115 mJ and 186 mJ and the output pulse energy of the first amplifier was 830 mJ, 380 mJ and 630 mJ for normal mode, single Q-switch pulse and double Q-switch pulse, respectively.

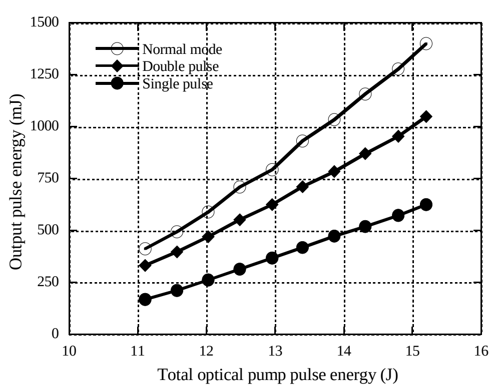


Fig. 2. MOPA output pulse energy as a function of the total optical pump pulse energy

Double-pass or multiple-pass amplifier helps to extract more pulse energy from the amplifiers in order to increase the output pulse energy and to improve the efficiency of the amplifiers, so the first amplifier was setup in a double-pass configuration. Figure 3 shows the total pulse energy extraction efficiencies of two amplifers, defined as $\eta$ = (total output pulse energy – input pulse energy)/(total optical pump pulse energy), as a function of the total optical pump pulse energy of two amplifiers for both single-pulse and double-pulse operation modes.

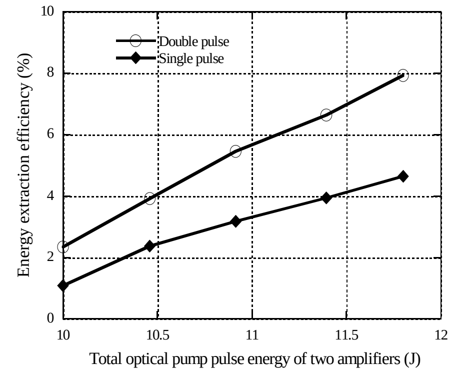


Fig. 3. Total pulse energy extraction efficiency as a function of the total optical pump pulse energy of two amplifiers

## III. Conductive cooled 2-micron laser development

Over the last few years, research in the area of the 2-μm laser technology has concentrated on primarily improving the efficiency, and increasing the energy. In most of the 2-μm laser developments, simple traditional method of circulating refrigerated water to remove the heat satisfies the cooling requirements. However, it is not cost effective or practical if the laser system is to be used in an environment where there are power and weight constraints and the use of water is not acceptable. The primary motivations for designing a total conductively cooled laser are to demonstrate the technologies leading to space laser application, and to enhance the overall wall plug efficiency of the laser by passively cooling the laser [8]. The reduction of weight and volume of any space-borne system translates into savings of tens of thousands of dollars per pound. This system is designed with heat pipes capable of removing heat both from the diode lasers and the rod using capillary action and transferring to a radiator. In space operation, a radiator can dissipate the heat by merely facing deep space.

TABLE 1
Physical parameters of the laser crystal and the pump diode laser

| | |
|---|---|
| Laser crystal material | Ho:Tm:LuLF |
| Crystal size | 4mm diameter, 21mm long |
| Thermal conductivity | 4.3 W/mK |
| LuLF coefficient of thermal expansion | 14ppm/K a-axis and 11ppm/K c-axis |
| Pump diode laser | Conductive cooling configured 6 bar array |
| Diode laser array per oscillator head | 6 |
| Output divergence | 40° and 10° in x, y axis |
| Output power | 6 watt average per diode at 1ms pulse width at 10pps |
| Diode laser Efficiency | 42% |

The physical descriptions of the laser crystal and the pump diode lasers are shown in table 1. The total pump energy required for producing a 100mJ class oscillator is in the order of 3.6 joules. The laser crystal length is defined by the size of two staggered diode lasers and the diameter is determined by the Thulium doping concentration and the pump absorption depth.

Fig. 4 depicts the totally conductive cooled laser head module. The six pump diode lasers are placed 10 mm away from the laser crystal. They are arranged 120° apart around the rod. A systematic illumination analysis by using ray tracing was performed to determine the optimum design with maximum coupling efficiency for various coupling methods such as lens duct, cylindrical lenses, cylindrical reflector, conic parabolic concentrator and plane mirror reflector. The result of the study showed that plane mirrors can form a light guide superior than any of the other schemes examined. Up to 97% of the light is delivered to the rod.

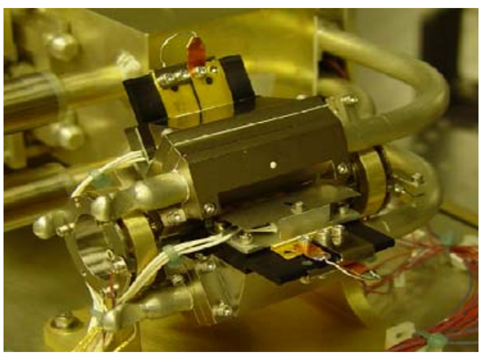

Fig. 4. Totally conductively cooled laser head assembly

Given the poor thermal conductivity of the laser material and the limited contact surface area, it is extremely technically challenging to effectively remove heat from the laser rod. The Ho:Tm:LuLF crystal, which is 4mm in diameter, has only 1.52cm$^2$ accessible for heat removal and the rest is used for optical pumping. The laser rod is clamped between Thermkon heat sink using Nusil as interface. In addition to high thermal conductivity of thermkon, its thermal expansion coefficient is close to that of the laser crystal which helps minimize the additional mechanical stress.

The pump diodes are mounted on a heat sink made of thermkon 83 as well. To keep the diode output wavelength at the peak of the absorption of the laser crystal the diode laser temperature shall be maintained at ~15°C, while the laser rod temperature shall be maintained at as low as possible. Thus, a thermal spacer acting as thermal buffer is designed, which is placed between the diode laser and thermkon heat sink. In addition to the thermal spacer, a trim heater is incorporated to actively control the diode lasers operating temperature.

The laser rod sub-assembly and the laser diodes sub-assembly are connected a to heat pipe. The heat generated from both laser diodes and laser rod was dissipated through the same heat pipe to a heat sink, from which the heat will be removed. For space application, this heat sink can be eliminated. The heat pipe will be directly connected to radiator, where the heat is dissipated into deep space. The heat load determines the size of the heat pipes while the minimum temperature determines the type of fluid used. Three heat pipes are used with total heat transfer capability of 150W at –50°C at 0.001-inch adverse elevation. The heat pipes are attached to a chiller block that is cooled down to –34°C.

The laser head is sealed in a box made of aluminum. The box is purged with dry nitrogen to avoid condensation. To better understand the thermal dynamics of the system, a total 18 temperature and humidity sensors are installed to monitor temperatures at various locations. In addition, three fiber temperature sensors are used to measure the diode laser temperature directly. The chiller coolant, thermocouple, fiber sensor, humidity sensor, and diode laser drive power are all interfaced through the box. Two optical windows with high transmission coating are also placed along the axis of the crystal for optical access.

To meet the long pulse width, single transverse and longitudinal mode requirements specifically for wind lidar application, 2.65m resonator with two 5m radius of curvature mirrors and two flat mirrors form the ring cavity. This resonator creates two minimum waists where the laser crystal is placed at one of the minimum waist and the Q-switch is placed on the other. A relatively large TEMoo mode helps to extract maximum energy. Using ABCD matrix the resonator mode is calculated to have a 1.18 mm radius at the rod. This size is also adequate to avoid laser induced damage in the crystal.

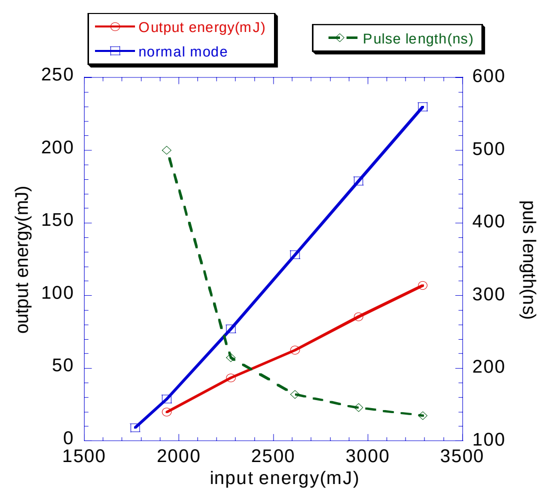


Fig. 5. Totally conductive cooled laser performance

As shown in Fig. 5, maximum energy of 230mJ at normal mode and 107mJ at Q-switch mode is achieved with slope efficiency of 14.5% and 6.4%, respectively. Nearly half of the normal mode energy is converted to Q-switched energy. At maximum output, the pulse width is 140 ns. The laser is operated very well for the entire repetition rate range and various heat loads.

## IV. Conclusion

In summary, we have developed a Tm:Ho:LuLF laser Master-Oscillator-Power-Amplifier (MOPA) with one Q-switched laser oscillator and two Tm:Ho:LuLF laser amplifiers. The first amplifier was operated in double-pass configuration and the second in single-pass configuration. The laser oscillator was operated at a repetition frequency of 2 Hz and provided 115 mJ output pulse energy at a single pulse operation and 186 mJ output pulse energy at a double pulse operation. The total output pulse energy of 636 mJ for the single pulse operation at input pulse energy of 115 mJ or 1.05 J for the double pulse operation at input pulse energy of 186 mJ has been demonstrated with the laser Master-Oscillator-Power-Amplifier (MOPA). The efficiency of the laser oscillator is 3.1% at the single pulse operation and 5.0% at the double pulse operation respectively. The total efficiency of the laser MOPA system is 4.1% and 6.9% for the single pulse and double pulse, respectively.

A totally conductive cooled 2-micron laser has been successfully demonstrated. This marks a significant milestone for developing a space-qualified laser. Despite the thermal gradient that was created in the Ho:Tm:LuLF crystal due to the cooling method and geometry, near diffraction limited beam and up to 107 mJ of Q-switched output with a pulse length of 135ns was obtained. This endeavor is deemed beneficial in a system where the power consumption and weight of a system is to be kept at a minimum without compromising performance.

## Ackowledgment

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