

2-micron Laser Developments for Wind and CO₂ Lidar Applications

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Abstract—Significant advancements in the 2-micron laser development have been made recently. The world record 2-micron laser energy is demonstrated with an oscillator and two amplifiers system. In addition to technology development and demonstration, a compact and engineering hardened 2-micron laser is under development. It is capable to produce 250 mJ at 10 Hz by an oscillator and one amplifier. This compact laser is expected to be integrated to a lidar system, and take field measurements. The recent achievements push forward the readiness of such a laser system for space lidar applications. This paper will review the developments of the state-of-the-art solid-state 2-micron laser.

I. INTRODUCTION

Solid-state 2-micron laser is a key subsystem for a coherent Doppler lidar that measures the horizontal and vertical wind velocities with high precision and resolution. The same laser, after a few modifications, can also be used in a Differential Absorption Lidar (DIAL) system for measuring atmospheric CO₂ concentration profiles. Development of a high energy, high efficiency, high beam quality, single frequency, compact and reliable solid state 2-micron laser is critically needed for such lidar systems. The recent achievements push forward the readiness of such a laser system for space lidar applications. This paper reviews the developments of the state-of-the-art solid-state 2-micron laser.

II. ONE-JOULE PER PULSE Q-SWITCHED 2- μ m SOLID-STATE LASER

Recently, significant advancements in the 2-micron laser development have been made in terms of high energy demonstrations. A 125 mJ injection seeded 2-micron Ho:Tm:YLF oscillator at room temperature was developed in 1998 [1]. A 400mJ Q-switched 2-micron laser system using a conductively cooled laser pump module was reported in 2004 [2]. A 600 mJ Q-switched diode-pumped Tm:Ho:LuLF using a MOPA system at double pulse format was published in 2003 [3]. A Joule level 2-micron laser MOPA system was reported in 2004, but it was operated in double-pulse format [4]. Here we describe a one-joule-per-pulse Q-switched 2-micron laser system.

The MOPA 2-micron laser system comprises an oscillator, a preamplifier and two power amplifiers. The MOPA system is a typical way to achieve high energy, and at the same time to preserve good beam quality required by the nature of

coherent lidars. The laser and amplifiers are all designed in side-pumped rod configuration, pumped by back-cooled conductive packaged GaAlAs diode laser arrays. The efficiency of the diode laser arrays is in the range of 38% to 44%. The symmetry afforded with side-pumped rod geometry helps to produce a high quality, circularly symmetric Gaussian beam output. The laser oscillator was pumped by two banks of three, radially arranged, 792nm laser diode arrays, each capable of producing 600 mJ of optical power for a nominal total of 3.6 J of 1 ms pulses. The laser oscillator and amplifier modules are in monolithic design. The diode arrays were directly mounted on aluminum modules, cooled by flowing water at 15°C. The amplifier modules are similar to the oscillator module design, except using four banks of three, radially arranged laser pump diode arrays with total nominal pump energy of 7.2J of 1ms pulses. The preamplifier module is exactly the same as the oscillator module. The gain medium of the laser system is Tm:Ho:LuLF crystal with 6% Thulium and 0.5% Holmium doping concentration. A detail study of the Tm:Ho codoped crystals of YLF and the isomorphs LuLF and GdLF revealed that small changes in the thermal population of the lower laser level in ground state terminated lasers can significantly alter the laser performance [5]. The larger host ion size of Lu leads to larger crystal fields and, as a result, larger crystal field splitting of lanthanide series ions. Thus, the LuLF host crystals provide better laser performance compared with YLF or GdLF based lasers [6]. The pump diode arrays and the laser crystal rods are cooled in different chiller loop, so the temperatures of diodes and rods can be independently controlled.

The oscillator uses a stable ring resonator configuration to obtain a near Gaussian spatial profile beam. A stable resonator design is less sensitive to external vibrations and other mechanical perturbations in terms of laser performance. This is clearly desirable in an unintended vibration and temperature-cycle prone environment. The total resonator length for this laser is 2.8 meters. The large resonator length is a simple way to obtain long laser pulse width that is desirable to achieve a Fourier transform limited narrow linewidth. An acoustic-optic Q-switch provides single or double Q-switched pulses. To obtain single longitudinal mode oscillation, injection seeding is required [7]. By injection seeding, not only a single longitudinal mode oscillator was obtained, unidirectional output of the ring resonator was achieved as well. However, for simplifying

this experiment, the injection seeding is not implemented. A retro reflector is used to obtain unidirectional output.

Two-micron Ho lasers are quasi four level lasers, so low temperature of the laser gain medium helps to reduce the threshold and to increase the slope efficiency. The coolant temperature can not be lower than 8°C in the experiment, limited by the dew point constraint. Fig.1 depicts the oscillator performances for long pulse, single Q-switch and double Q-switch operations at a laser rod coolant temperature of 8°C. Long pulse is obtained at the free run mode with the pulse length typically several hundred microseconds. The laser slope efficiencies for the three operation formats are 16.5%, 11.9%, and 14.3%, respectively. The oscillator is capable of producing 150 mJ. However, due to the concern of optical damage by high intracavity fluence, the output is lowered to a 100mJ level by reducing the pump diode current. The full width half maximum of the oscillator pulse width is measured at 187 ns. Derating the pump diode power helps to extend the lifetime of the pump diodes as well.

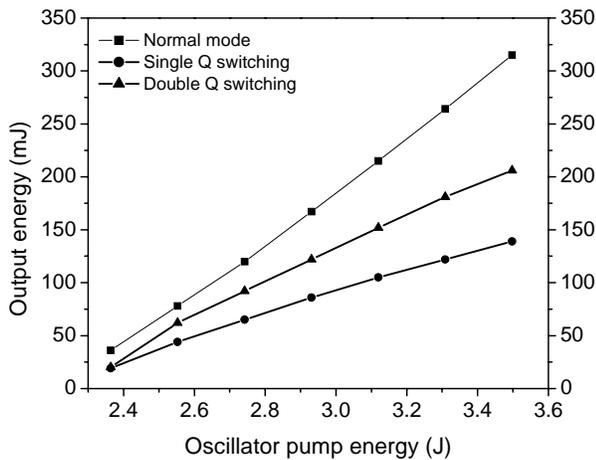


Fig. 1. Oscillator output performance for normal mode, single Q-switch, and double Q-switch pulses

The preamplifier increases the laser energy to 187 mJ. To maximize the extracted energy, the two amplifiers shall be operated near saturation. Under three-side pumping geometry, the gain profile peaked at the rod center and lower at edges. Some portion of the area around the edge of the rod where it did not directly face the diodes may not even reach the threshold of the population inversion, resulting in net loss in these areas. Thus, the optimal mode matching between the probe beam and the pump volume is an important factor. For oscillator, the optimum beam diameter at the laser rod position is ~2.2mm. Mode matching is realized by selecting the radius of curvatures of the reflect mirrors between the amplifier stages such that the beam sizes at amplifiers are little larger than 3.0mm.

The modified Frantz-Nodvik equation was used to simulate the performance of amplifier one for both the single and double pass amplification [8]

$$d(E(z, t)/E_s)/dz = g_0[1-\exp(-E(z, t)/E_s)] - \alpha_0 E(z, t) \quad (1)$$

where the g_0 is the small signal gain coefficient, E_s is the saturation intensity, and the α_0 is the unsaturable loss. The small signal gain coefficient, g_0 , and saturation intensity, E_s , may be measured and derived from the gain measurements of the amplifier. The calculated data agrees with the experiment result with a small signal gain coefficient of 0.26 cm^{-1} and saturation energy of 0.492J.

Fig. 2 shows the MOPA system performance for long pulse, single Q-switch and double pulse Q-switch output. For total MOPA system pump energy of ~21.9J, 1.1 J single Q-switched output energy is achieved. The optical to optical conversion efficiency is 5%. In the double pulse Q-switch operation, the total output energy reaches 1.35 J, representing an optical to optical conversion efficiency of ~6.2 %. In double pulse operation, the second pulse energy comes from the free repopulating energy transfer process between the Tm and Ho ions after the Ho energy extraction by the first pulse [9].

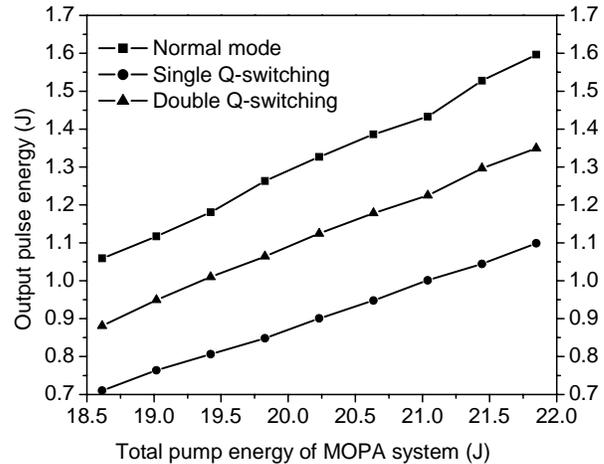


Fig. 2 Oscillator output performance for normal mode, single Q-switch, and double Q-switch pulses

This 2-micron laser system provides nearly transform limited beam quality. Table one listed the beam quality for each stage of the MOPA system. The beam quality of the MOPA system is characterized by scanning knife edge technique measuring the beam diameters at 11 planes on both sides of the focus point for a 500mm focal length lens under full power condition [10]. The curve fitting then applied to the data points with Least Squares curve fits Pearson's parameter R^2 value of at least 0.97. The beam quality is directly derived from the fitting parameters. Except the last

amplifier, the beam qualities for oscillator, preamplifier and double pass amplifier one are excellent at the value of 1.1x transform limited. Even at the last amplifier stage, the beam quality is 1.4x transform limited.

III. ENGINEERING HARDENED COMPACT 2-MICRON LASER DEVELOPMENT

Over the last few years, research in the area of the 2- μm laser technology for wind and carbon dioxide measurement has concentrated on primarily improving the efficiency, and increasing the energy. For applying this technology to ground field lidar measurements, to airborne and eventually space-borne missions, it is crucial to engineering package the state-of-the-art technology to meet the field mission requirements. We are developing a compact, engineered 2-micron coherent Doppler wind lidar transceiver to address the challenge. The packaged transceiver will certainly meet the requirements of the ground and airborne field missions, and it will be as close to perform UAV autonomous validation and to an envisioned spaced based Doppler wind lidar as possible.

The design specifications of this engineered transceiver are listed in table 1. This engineered transceiver consists of four lasers; a continue wave solid state seed laser at wave length of 2.053 μm with linewidth at kilo Hz range, a power oscillator capable producing $\sim 100\text{mJ/pulse}$ energy, an amplifier operating at double pass configuration, and a alignment laser.

TABLE 1
Design specifications of the engineered transceiver

Wave length	2.053 μm
Pulse energy	>250mJ
Pulse Repetition Rate	10 Hz
Pulse length	>100ns
Beam transversal mode	TEM ₀₀ , $M^2 < 1.3$
Beam longitudinal mode	Single frequency by injection seeding
Heterodyne frequency offset	105MHz
Transceiver size	25"x7"x10.5", LxWxH

One of the general design guidelines for space-qualifiable laser is to operating all the optical components at appropriately de-rated levels. It is particularly important for de-rating pump diode laser to have long operational lifetime. To reach the maximum population inversion of the Ho:Tm solid state lasers, the pumping duration for laser gain medium is as long as 1ms, thanks to the long life time of the laser up-level. Thus, even though the duty cycle of the pump diode arrays is as low as 1%, it still experiences significant heat during such a long pulse period. A pump diode array can produce 14.4w average power at 120A pump current. These diodes will be de-rated to 11w average power at lower pump current. Thus, the pump diodes are operated at 76% of their designed peak optical powers. In addition to de-rate the pump diodes operational current, the laser fluence is kept $\sim 50\%$

below the optical components damage level inside the oscillator cavity and in the amplifier optical pass. To obtain single longitudinal frequency, the power oscillator is injection seeded by a CW solid-state laser operating at 2.053 μm . The ramp and fire technique is used to lock the laser at the seed laser frequency. The electronic control system has been updated that utilizes FPGA and digital filters to improve the control flexibility and injection seeding reliability and stability. The output of the power oscillator is amplified by a laser amplifier, which operated at double pass configuration. By double pass the amplifier, it increases the amplifier extraction efficiency, thus the entire transceiver efficiency.

Part of receiver is also included in this transceiver. Among them are the transmit/receive (TR) switch, a quarter wave plate, a frequency modulator to shift the seed frequency by 105MHz and a dual channel signal receiver. The atmospheric returning signal is fiber coupled into the dual channel receiver, where it mixes with local oscillator, which is partially splitted from the seed laser. This transceiver did not include telescope and associated scanner. The transceiver size is 25 by 7 by 10.5 inches, and it is sealed and purged with nitrogen. This size of transceiver can be adapted to an airborne system in an airplane such as WB57.

Table 2 summarizes the transceiver system level operation requirements. For practical and economical reasons, the transceiver does not adapt the fully conductive cooled 2-micron laser technique, which is developed at separate task [11]. In stead, a partially conductive cooled laser and amplifier are utilized in the transceiver. The laser bench is temperature controlled to maintain the laser energy stability. To achieve high laser efficiency, the laser is designed to operate at 5 $^{\circ}\text{C}$, but it will work at the temperature range between 0 $^{\circ}\text{C}$ and 30 $^{\circ}\text{C}$. The power consumption is less than 600W without considering the chiller power. Half of the power is used by pump diodes. The rest of the power is shared between the seed laser, Q-switch driver, frequency modulator, PZT mirror driver and electrical control system.

TABLE 2
System Level Requirements

Operational Temperature	0 $^{\circ}\text{C}$ - 30 $^{\circ}\text{C}$
Storage temperature	-25 $^{\circ}\text{C}$ - +50 $^{\circ}\text{C}$
Humidity	<50% RH@25 $^{\circ}\text{C}$
Vibration	2.0 g-rms
Cooling method	Partially conductive cooling
Optical bench	Temperature controlled
Cooling temperature	5 $^{\circ}\text{C}$
Power consumption	600w (not include Chiller power requirement)

The mechanical design of the transceiver is depicted in the Figure 3. Both side of the optical bench are designed to hold optical components. The power oscillator, laser amplifier and alignment laser are mounted at one side of the optical bench. The seed laser, isolators, receiver detectors and fiber couplers

are at the other side of the optical bench. The two sides are optically coupled through a hole in the optical bench. All the optical mounts are custom designed to withstand at least 2.0 g-rms vibration, sufficient for an airborne field missions.

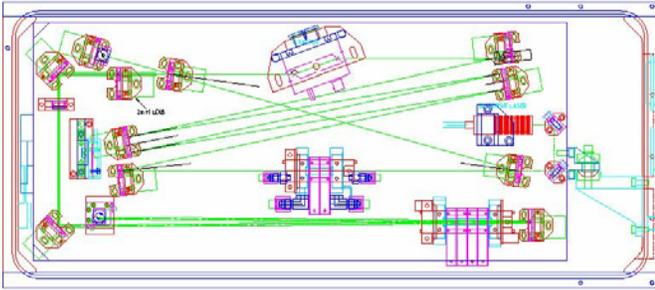


Fig. 3a Power oscillator and amplifier

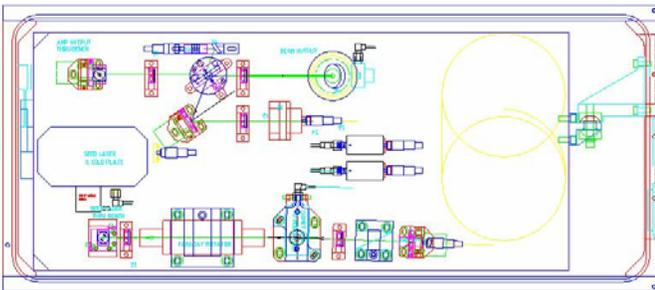


Fig. 3b Seed laser and receiver components

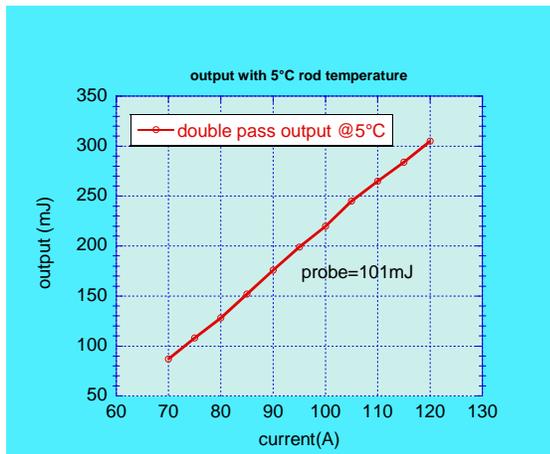


Fig. 4 test-bed laser output energy performance

A test bed laser that is at exactly the same dimension of the designed compact laser is developed. The compact performance such as energy, pulse width, longitudinal and transversal beam quality, is characterized and validated by

this test bed laser. This test bed laser is nearly perfect seeded to produce single frequency output. Figure 4 shows the laser energy output characteristics. At the probe energy of 101mJ, the double passed amplifier produces more than 300mJ/pulse energy, exceeding the design specifications. The beam quality of the power oscillator, single pass amplifier and double amplifier are also characterized, and they are all at M^2 value of better than 1.2.

IV. CONCLUSION

In summary, a larger than one-joule-per-pulse, diode pumped, Q-switched 2-micron MOPA system has been successfully demonstrated with excellent beam quality. This high energy 2-micron laser demonstration is one step closer for developing a space-borne coherent Doppler wind lidar with the required energy.

An engineering hardened, compact 2-micron transceiver, specifically designed for coherent wind lidar, is also designed. Its performance has been characterized and validated by a test-bed laser. This development advances the TRL of the coherent wind lidar, and makes significant milestone towards the space wind lidar mission.

ACKNOWLEDGMENT

This work was supported by Laser Risk Reduction Program, funded by NASA Science Mission Directorates.

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