Advanced 2-µm solid-state laser for wind and CO_2 lidar applications

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ABSTRACT

Significant advancements in the 2-micron laser development have been made recently. 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 Diffrencial Absorption Lidar (DIAL) system for measuring atmospheric CO_2 concentration profiles. The world record 2-micron laser energy is demonstrated with an oscillator and two amplifiers system. It generates more than one joule per pulse energy with excellent beam quality. Based on the successful demonstration of a fully conductive cooled oscillator by using heat pipe technology, an improved fully conductively cooled 2-micron amplifier was designed, manufactured and integrated. It virtually eliminates the running coolant to increase the overall system efficiency and reliability. In addition to technology development and demonstration, a compact and engineering hardened 2-micron laser is under development. It is capable of producing 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.

Keywords: Diode-pumped lasers, solid-state lasers, Rare earth and transition metal solid-state lasers

1. 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 [1]. The same laser, after a few modifications, can also be used in a Differential Absorption Lidar (DIAL) system for measuring atmospheric CO_2 concentration profiles [2]. 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. Although the capability of producing multi-joule energy by 2-micron solid state lasers was predicted a decade ago [3], the significant advancements in the high energy 2-micron laser demonstration have not been achieved until recently. A 400mJ Q-switched 2-micron laser system using a conductively cooled laser pump module was reported in 2004 [4]. A 600 mJ Q-switched diode-pumped Tm:Ho:LuLF using a MOPA system at double pulse format was published in 2003 [5]. A Joule level 2-micron laser MOPA system was reported in 2004, but it was operated in double-pulse format [6]. Recently, a more than one-joule-per-pulse Q-switched 2-micron laser system has been demonstrated. It marked a significant milestone in the 2-micron laser development.

Space-borne lidars have not only laser transmitter energy requirements but also efficiency and advanced thermal management necessities. Space lidars using 1-micron laser as their transmitter have proven records for successfully applying fully conductively cooled laser technologies to transfer the heat from laser heads to radiator either by advanced heat pipe technology or by elegant design to directly attaching the laser head heat sink to radiator. However, it is much more difficult to apply conductively cooled technology to 2-micron laser. 2-micorn lasers, by the quasi-four level system nature, are not as efficient as 1-micron lasers.

Thus, more heat needs to be dissipated through the thermal management system under the same power requirements compared to 1µm lasers. In addition, the slab geometry that most of the 1-micron lasers are using is more suitable for applying conductively cooled technique than that of the rod geometry utilized by the current 2-micron lasers design. Conductively cooled 2-micron lasers recently have been demonstrated [7, 8,12]. One of the approaches described in these papers transfers the heat generated by both pump diode lasers and laser crystal to heat sinks by heat pipes. This advanced thermal management provides efficient heat removal that the 2-micron laser requires. By passively cooling the laser, the total efficiency of the laser system is significantly enhanced as well.

Engineering hardened coherent Doppler wind lidar using high energy 2-micron laser transmitter cannot be overlooked. Efforts are also devoted to develop a compact, rugged 2-micron lidar transceiver that will meet the stringent operational and environmental requirements. A compact 2-micron coherent wind lidar transceiver has been designed and the performance was verified in test-bed. This development advances the readiness of such a laser system for space lidar applications.

This paper reviews the recent achievements in the 2-micron laser development. The section 2 describes the high energy one-joule-per-pulse laser system. The fully conductively cooled laser development is discussed in section 3. An engineering hardened 2-micron transceiver is depicted in section 4.

2. 1.2 JOULE PER PULSE Q-SWITCHED 2-µM LASER

The Master Oscillator Power Amplifier (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. There is no single oscillator that can produce Joule energy at 2-micron wavelength without coming across the problem of optical damage. The MOPA 2-micron laser system comprises an oscillator and two power amplifiers. The laser oscillator is similar to the one described in reference [9]. The oscillator and amplifier modules are all in monolithic design in which the laser rods are side-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%. Recently, advancement of diode laser technologies led to higher than 50% efficiency for such quasi CW diode lasers. The diode arrays were directly mounted on aluminum modules, cooled by flowing water at 15°C. The pump diode arrays and the laser crystal rods are cooled in different chiller loops, so the temperatures of diodes and rods can be independently controlled.

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 symmetry afforded with side-pumped rod geometry helps to produce a high quality, circularly symmetric Gaussian beam output. The gain medium of the laser system is Tm:Ho:LuLF crystal with 6% Thulium and 0.5% Holmium doping concentration. A detailed study of the Tm:Ho co-doped 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 [10]. 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 [11].

To obtain single longitudinal mode oscillation that a coherent Doppler wind lidar requires, an injection seeding technique is applied. This injection seeding is based on a ramp and fire technique. By injection seeding, not only a single longitudinal mode oscillator was obtained, but 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.

2-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 effciency. The coolant temperature can not be lower than 8°C in the experiment, limited by the dew point constraint. The temperature is set at 8°C whenever the operation envirement allows.

To maximize the extracted energy, the two amplifiers shall be operated near saturation. Both of the amplifiers are configured at double pass to increase amplifier efficiency. 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. 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.

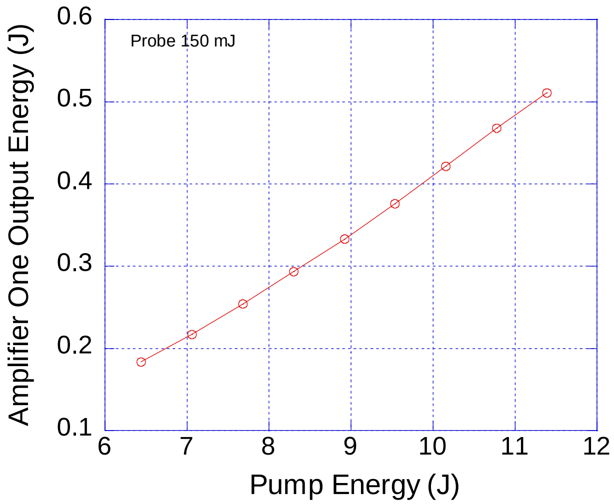

Fig. 1.Amplifier one performance

Figure 1 depicts amplifier one's performance for single Q-switch operations at a laser rod coolant temperature of 8°C. The probe energy from the oscilltor output is ~150mJ with full width half maximum of the pulse measured at 240 ns. The pump energy includes the oscillator and amplifier one's pump diode incident energy. The amplifier did not produce gain until the pump energy increased to 4.03J. At the total maximum pump energy of 11.3J, 511mJ of output energy is obtained, representing a extracted energy of 361 mJ.

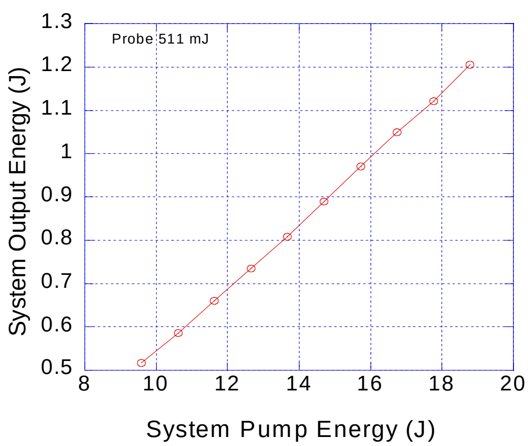

Fig. 2 .Amplifier one performance

The performance of second amplifier is shown in Fig. 2. The input energy for the amplifier two is 511 mJ. Without the pumping power, only 93mJ passes through the amplifier due to ground state absorption. The optical transparency is achieved at pump energy 3.759J, where the amplifier just overcomes the ground state absorption loss. For a total MOPA system pump energy of ~18.5J, 1.205 J of single Q-switched output energy is achieved. The optical to optical conversion efficiency is 6.5%. Amplifier two extracts more than twice as much as energy than that of the amplifier one at the similar pump conditions. Nearly 700mJ energy is extracted from the amplifier two.

Optical damage at the high energy output is a factor which needs be considered for reliable system operation. At the final beam output from amplifier two, the fluence is measured at ~26J/cm^2, which is comparable to the fluence level inside the oscillator cavity. Optical damage for the laser rod has been observed at a fluence level as low as ~30J/cm^2.

This 2-micron laser system provides nearly transform limited beam quality. 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. At the last amplifier stage, the beam quality is 1.4x transform limited.

3. CONDUCTIVELY COOLED 2-μM LASER

Circulating refrigerated water to remove the heat was used in most of the 2-μm laser developments. Although it satisfies the ground or airborne laser system cooling requirements, it is not practically to be used in space environment where there are power and weight constraints and the use of water is not acceptable. The primary motivations for designing a fully conductive cooled 2-micron 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.

Fig. 3 depicts the totally conductively cooled laser head module for the oscillator. 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 approaches 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.

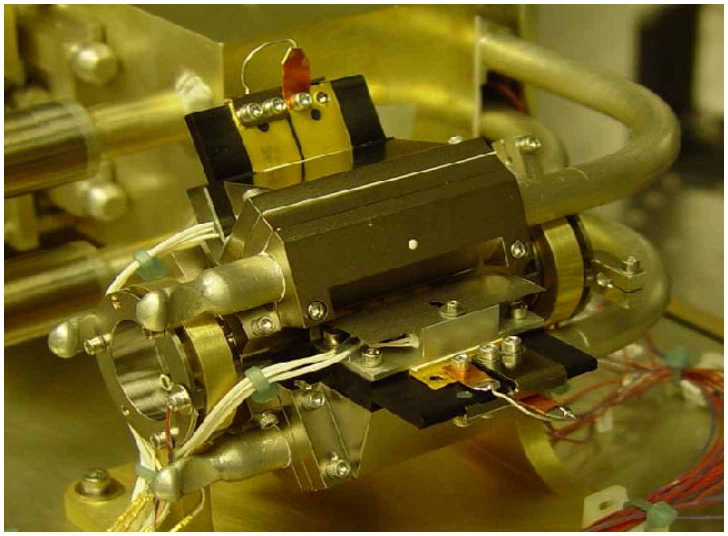

Fig. 3. Totally conductively cooled laser head assembly

Given the poor thermal conductivity of the laser material and the limited contact surface area, it is extremely challenging to effectively remove heat from the laser rod. The Ho:Tm:LuLF crystal, which is 4mm in diameter and has only 1.52cm^2 accessible for heat removal. The rest is used for optical pumping. The laser rod is clamped between Thermkon heat sink using Nusil as the 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.

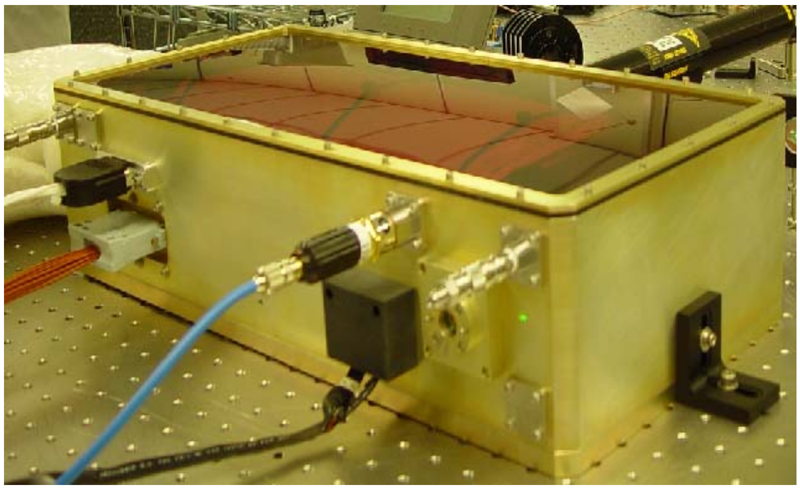

Fig.4. Totally conductively cooled laser head with enclosure

The laser rod sub-assembly and the laser diodes sub-assembly are connected to heat pipes. 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 a radiator from which 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.

Fig. 4 shows the packaged laser head. 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 of 18 temperature sensors and a humidity sensor 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.

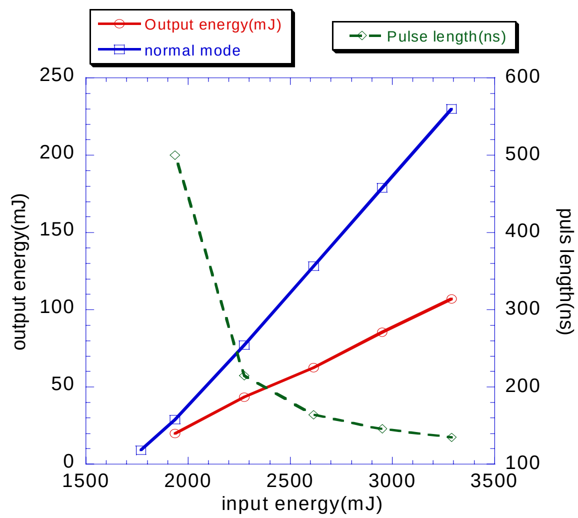

Fig. 5. Totally conductive cooled laser performance

As shown in Fig. 5, a 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.

Based on the accomplishments of the oscillator design, development of an amplifier for use in a fully conductively cooled 2-micron MOPA laser transmitter was initiated. Issues to be considered in the amplifier design include pump geometry and optical pump uniformity; higher pump energy thus higher heat load to be removed from the diodes and crystal; required lower evaporator node temperature for the heat pipes; minimize the number of thermal interfaces from the laser rod to heat pipe; and evaluate the overall added complexity for temperature control of the diode modules [8].

For the amplifier, it is not critical to have variable pulse rate control. It is designed to operate at a steady state pulse rate of 10 Hz. In turn, the power oscillator will control the amplified output pulse rate of 1, 2, 5 and 10 Hz. The steady state operation greatly simplifies the head packaging design. For a constant heat load, it is possible to select and size the appropriate thermal conductor to maintain constant diode temperature of 15 °C; therefore, diode heaters and temperature feedback controllers are not needed.

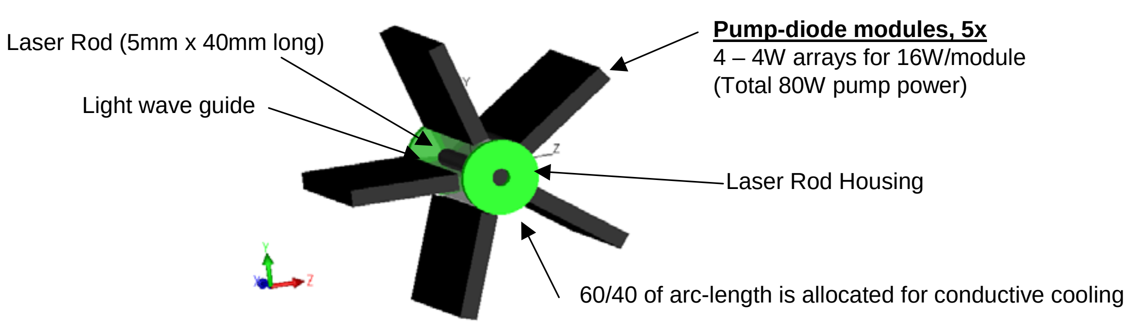

Figure 6. Conceptual design of a 5-sided, radially-pumped amplifier head

To increase the pump uniformity and utilize the maximum gain volume of the amplifier, the amplifier module uses 5-side pumping geometry instead of 3-sides pump as in the oscillator. Figure 6 shows a conceptual design of the amplifier head. The parameters for wave-guide optimization included exit aperture at the rod that is determined by the ratio of cooling to pump arc-length, the entrance aperture at the diode that is determined by the height of the diode array face, and the reflector angle and its radial length that maximizes the percent of light incident on the rod

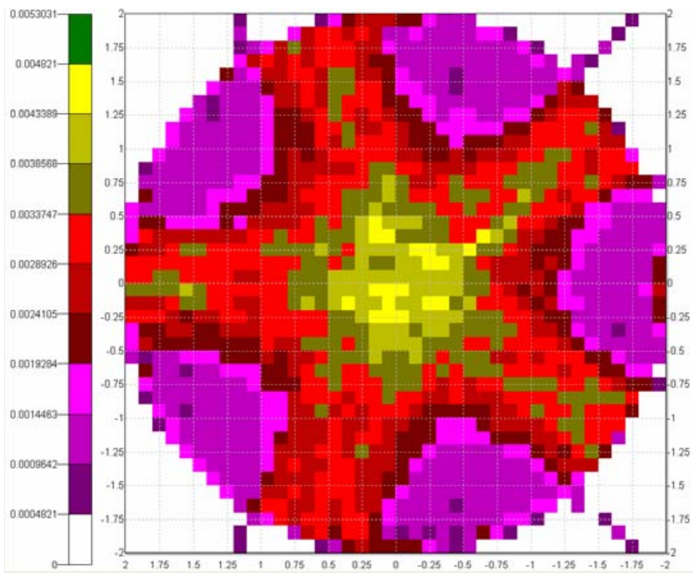

Figure 7 Cross-sectional absorbed power at mid-length of the laser crystal

Using the optimized reflector angle of 10^{o} for the conductively cooled amplifier head, TracePro simulations were performed to illustrate the absorbed power in the laser amplifier rod. The total absorbed power is 62.7W or 78.4% of the 80W available pump power. The pump uniformity is limited to within a beam diameter of approximately 2.5mm.

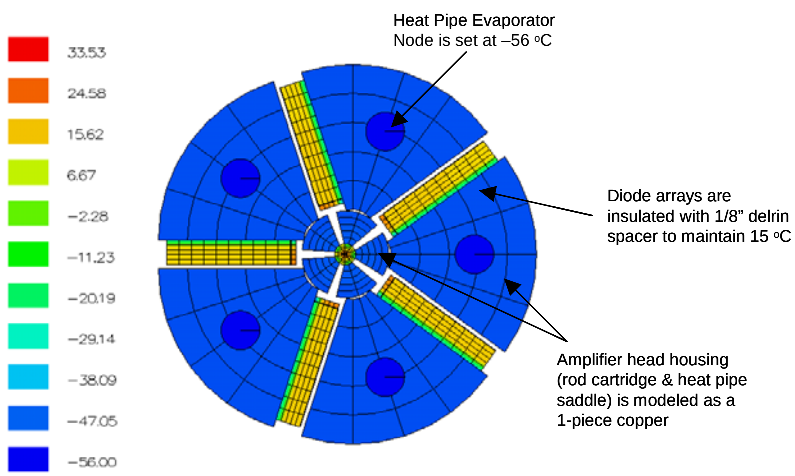

Figure 8 Thermal map of a 1-piece copper amplifier head

Thermal analyses were conducted to predict the thermal gradient in the crystal. The oscillator laser demonstrated that heat pipe is an effective thermal management technology for use in cooling the laser head. However, the amplifier head has twice the amount of heat load without much increase in volumetric space for heat conduction. The total amount of heat to be removed from the laser crystal region is 80W for the amplifier as compared to 36W for the oscillator. Improvement in the head design and better thermally conductive material is required for effective thermal control.

Figure 8 shows the overall temperature gradient in the amplifier head for the 1-piece copper housing. With a 1/8” delrin insulator, the diodes are maintained at 15^{o}C. Otherwise, the heat pipes will excessively cool the laser diodes to near evaporator node temperature. The 1-piece copper amplifier head housing lowered the peak temperature by more than 8^{o}C. The peak temperature of the laser crystal is 33.4^{o}C for heat pipe evaporator node temperature set at -56^o C. To further lower the crystal temperature to 30^{o}C, the heat pipes would have to operate with evaporator node set at -60^o C.

From the analyses in previous sections, an optimized amplifier head was designed. Figure 9 shows the overall assembled amplifier head with heat pipes. The assembled amplifier head mounted on a base plate with heat pipes attached it to it. As shown, the 1-piece amplifier head housing was achieved by combining the rod-mount cartridge with the heat pipe saddle, thus eliminating a thermal interface.

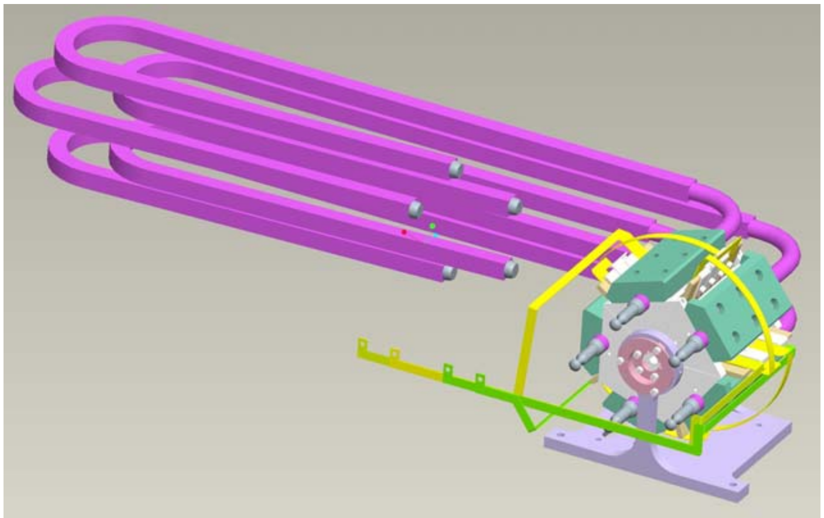

Figure 9 Final design of the amplifier head with heat pipes integrated

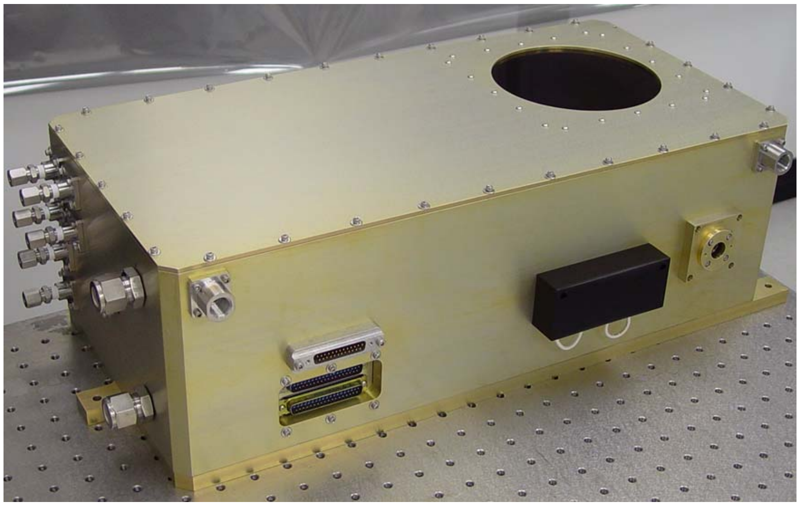

Figure 10 Completed conductively cooled 2-micron laser amplifier module

Figure 10 shows the completed conductively cooled 2-micron amplifier module. The module is sealed and purged with Nitrogen gas to reduce the dew point to as low as -80°C. There are more than 24 sensors to monitor the temperature at different locations inside the module. The most critical ones are the laser rod temperature and diode laser temperature. There is a hygrometer to measure the humidity inside the module as well. The module has been turned on. The detail characterization of this amplifier is in progress.

4. ENGINEERING HARDENED 2-μM COHERENT DOPPLER WIND LIDAR TRANSCIEVER

Over the last few years, research in the area of 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 to space-borne missions, it is crucial to ruggedly 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. It will be as close to perform UAV autonomous validation and 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 2.053μm with linewidth at kilo Hz range, a power oscillator capable producing >100mJ/pulse energy, an amplifier operating at double pass configuration, and an alignment laser.

TABLE 1
Design specifications of the engineered transceiver

Wave length	2.053μm
Pulse energy	>250mJ
Pulse Repetition Rate	10 Hz
Pulse length	100ns – 500ns
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 lasers is to operate all the optical components at appropriately de-rated levels. It is particularly important to de-rate pump diode lasers to achieve longer operational lifetime. To reach the maximum population inversion of the Ho:Tm solid state lasers, the pump duration for laser gain medium can be as long as 1ms, due to the long life time of the laser up-level. However, even though the duty cycle of the pump diode arrays is as low as 1%, they still experience 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 ~50% below the damage level of the optical components 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 2.053μm. The ramp and fire technique is used to lock the laser at the seed laser frequency. The electronic control system has been updated to utilize 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 is operated at double pass configuration. By double pass the amplifier, it increases the amplifier extraction efficiency and 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 the local oscillator, partially spitted from the seed laser. This transceiver did not include a 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.

For practical and economical reasons, the transceiver does not adapt the fully conductively cooled 2-micron laser technique, which is developed as a separate task. Instead, a partially conductively 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 °C. The power consumption is less than 600W disregarding 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.

The mechanical design of the transceiver is depicted in Figure 11. Both sides 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.

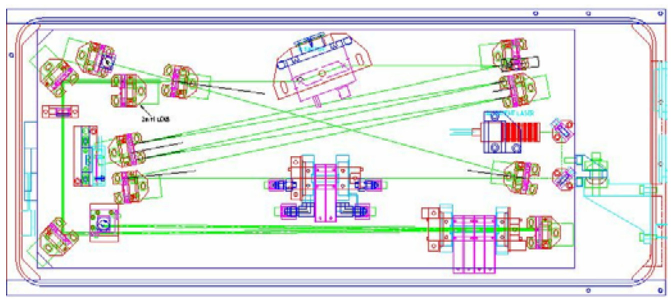

Figure 11a Power oscillator and amplifier

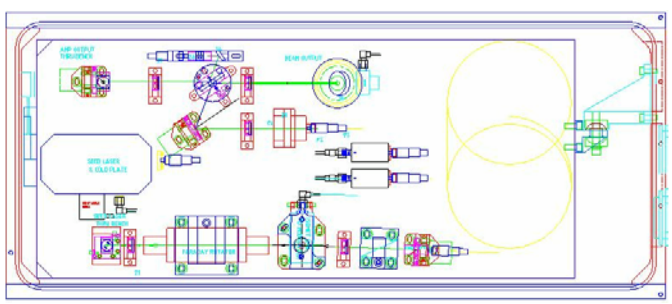

Figure 11b Seed laser and receiver components

A test bed laser that has the same dimension of the designed compact laser has been developed. The compact laser performance such as energy, pulse width, longitudinal and transversal beam quality is characterized and validated by this test bed laser. 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, and the single and double pass amplifier output are also characterized. They are all at M^2 value of better than 1.2.

5. 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.

The design of a totally conductively cooled, diode pumped 2-micron amplifier contributes to the development of a high-energy laser transmitter for spacecraft based remote sensing applications. The design of the amplifier head is complete. Optical analyses showed that a 5-sided, radially pumped laser crystal would absorb 84 percent of the available 80W pump power. The wave-guide facet angle of 10 ^{o}C would provide pump uniformity over a beam diameter of 3.0mm.

Thermal analyses show that ammonia heat pipe is sufficient for use to transport the total 200W of heat away from the laser crystal and diodes, 80 W. and 120 W. respectively. To reduce the complexity of the amplifier head packaging design, the amplifier is designed to operate at steady state pulse repetition rate of 10 Hz. The power oscillator stage within the MOPA transmitter will control the system pulse rate at 1, 2, 5 and 10 Hz.

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.

6. ACKNOWLEGEMENT

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