2-micron Coherent Doppler Lidar Instrument Advancements for Tropospheric Wind Measurement

Mulugeta Petros, U.N. Singh, J. Yu, M.J. Kavaya and G. Koch
NASA Langley Research Center, Hampton, VA. USA 23681
mulugeta.petros-1@nasa.gov

ABSTRACT

Knowledge derived from global tropospheric wind measurement is an important constituent of our overall understanding of climate behavior [1]. Accurate weather prediction saves lives and protects properties from destructions. High-energy 2-micron laser is the transmitter of choice for coherent Doppler wind detection. In addition to the eye-safety, the wavelength of the transmitter suitably matches the aerosol size in the lower troposphere. Although the technology of the 2-micron laser has been maturing steadily, lidar derived wind data is still a void in the global weather database. In the last decade, researchers at NASA Langley Research Center (LaRC) have been engaged in this endeavor, contributing to the scientific database of 2-micron lidar transmitters. As part of this effort, an in depth analysis of the physics involved in the workings of the Ho: Tm laser systems have been published. In the last few years, we have demonstrated lidar transmitter with over1Joule output energy. In addition, a large body of work has been done in characterizing new laser materials and unique crystal configurations to enhance the efficiency and output energy of the 2-micron laser systems. At present 2-micron lidar systems are measuring wind from both ground and airborne platforms. This paper will provide an overview of the advancements made in recent years and the technology maturity levels attained.

Keywords: Solid State Lasers, Coherent Doppler lidar,

1. INTRODUCTION

NASA and the global scientific community have sought-after a satellite based wind measuring lidar for improved weather prediction for over three decades. This effort required the participation of the wider scientific community to establish mission concepts which matches the technology capabilities. Laser Atmospheric Wind Sounder (LAWS), the first proposed transmitter was composed of a single CO_2 laser with output energy of 20J, operating at 10 Hz [2]. Multiple course corrections have been made since the original mission concept was introduced in the late 1980s.

1.1 Early Transmitter Development Efforts

Ever since the decision was made to implement the solid state laser material in lieu of the gas laser, NASA Langley Research Center played an essential role in researching and developing a suitable solution for the space lidar system. Since the output energy was not modified, the most important challenge was perceived to be producing such a high energy output out of a new laser material. Therefore, the problem was approached from multiple facets. On one hand new laser materials research was launched. This included finding new laser materials which can provide very high gain with the appropriate operational wavelength and efficiency and spectroscopic analysis. On the other, labs were set up to evaluate the spectroscopic findings by verifying the performances of laser crystals. Thus, a theoretical model supported by experimental verification was created.

Creating new materials for laser application is a long and arduous effort. Most of the laser industry was tuned to serving the needs of the Nd:YAG market which by then had a 30 year advance progress. As a result, the absence of industrial support for 2µm wavelength made the endeavor challenging. From finding a suitable detector to diagnose the laser output, to finding an imaging camera were all nonexistent. At the same time, researches were engaged in developing specifications for industry to provide new diagnostics and other laser components that are suitable for 2µm laser system. Additionally, through small businesses innovative research vehicle, companies were encouraged to participate in the development effort. Crystals that were studied in this process include Tm:YALO, TM:YAG, Tm:LuAg, Er:YAG, Tm: Ho: YLF, Tm:Ho:YAG are some of the Tm:Ho based lasers. In the end, Ho:Tm:YLF laser was selected and laser transmitter was build using this crystal. Although a fluoride based crystal, this material has attractive features such as low thermal lensing, long life time and high storage capability. The laser was designed with Yttrium Lithium Fluoride (YLF) as a host and is synthesized with Tm and Ho. The Tm is a convenient way to access a 792nm pump wavelength which could be achieved with an efficient semiconductor laser. It is worthwhile noting that most of the original studies were done using Alexandrite lasers tuned to the pump absorption line of 792nm. The Tm in turn pumps the Ho from which a 2µm radiation is produced. The additional attractiveness of this system is that the Tm has the unique capability to produce two photons for every pump photon in its upper level through a process of self-quenching.

The laser system would still benefit from the development of 1900 nm semiconductor laser which is still in its infantile stage. If a 1900nm efficient semiconductor laser becomes a reality, the Tm would be removed from the crystal and the Holmium will be directly pumped. This small modification to the crystal ingredients, would offer favorable quantum defect that reduces the challenge in thermal management of the present system.

2. LIDAR TECHNOLOGY DEVELOPMENT

A real step forward occurred when a 600mJ output was produced in the mid-1990. An interest was sparked to move forward and evaluate the feasibility of a space Doppler lidar. A space shuttle experiment Space Readiness Coherent Lidar Experiment (SPARCLE) was proposed. This mission was designed to use a 100mJ 2µm laser transmitter with a combination of a 250mm telescope and a wedged scanner. The primary objective of this effort was to demonstrate the technology readiness in space environment, provide data sets for validating system performance models and the selection of optimal scan patterns [3].

At the beginning of the new millennium, NASA launched an effort to reduce the risk associated with space lasers and the Laser Risk Reduction Program (LRRP) was initiated. This program played a pivotal role in addressing the risk areas of the lidar technology. At the same time a consensus was reached among the stake holders that a space wind lidar should be a hybrid of lidar systems, one operating at 2µm and the other at 0.355µm. The 2µm coherent Doppler lidar primarily uses aerosol particles for its signal and favors the lower altitudes while the direct-detection 0.355µm uses molecules to primarily extract data from higher altitudes.

Langley researchers approached the risk mitigation effort of the coherent Doppler lidar the following 5 fronts: Enhance the laser output energy, assess and improve reliability and operational lifetime of the pump laser diode array (LDA), heterodyne receiver optimization, detector development and radiation tolerance test of critical components. The cumulative actions were planned to raise the technical readiness level (TRL) of the coherent Doppler lidar instrument.

The first priority was to increase the laser energy to over one joule output. Multiple stages of improvements were implemented to the laser system. The laser crystal host was modified from Yttrium Lithium Fluoride (YLF) to Lutetium Lithium Fluoride (LuLF), this adjustment provided an additional 20% improvement in the output [4]. Pumping configurations to achieve maximum pump energy transfer to the laser crystal was improved by formulating a scheme to reflect back the unabsorbed pump energy. This effort provided with an extra 30% pump that would have been lost. Since the laser is a quasi-four level laser, it benefits from ground level population depletion. To cool the entire pumped volume efficiently, the ends of crystal used for mechanical mounting are diffusion bonded with un-doped pieces allowing the pumping of the entire doped portion of the crystal. By mid-2000, over 1 joule output was achieved with two amplifiers and an oscillator [5]. Figure 1 shows the final output of the Joule level amplifier.

A laser diode array risk and reliability group was established to look at causes of laser diode array degradation and premature failures. The team identified that a better thermo-mechanical design of high power LDA assemblies is critical to the reliable long term operation. Worked with industry for improving the operation lifetime of these critical devises and proposed various solutions [6]. With better manufacturing methods and material selection, the LDA assemblies for 2µm laser application have improved tremendously.

Heterodyne receiver optimization effort looked at the combined effects of all noise sources in the system. That included the interaction between competing control parameters of the receiver detector and the preamplifier. [7] As a result an integrated fiber coupled heterodyne detector was produced for use in the Doppler lidar.

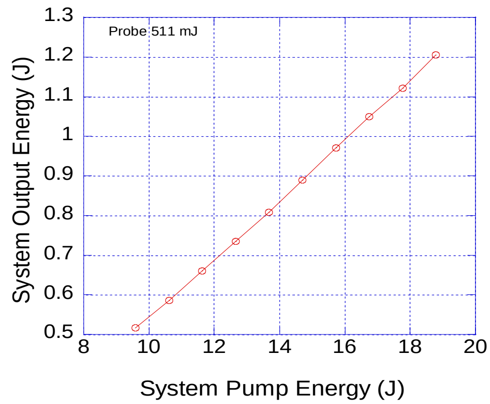

Figure 1. Final 2-moicron output from the last amplifier

Various optical detectors have been evaluated to select a suitable detection system for the 2µm lidar system. The detector group characterized commercial off the shelf detectors and custom phototransistors and documented their findings [8-9]. The product of choice for the application is extended range InGaAs pin detector.

Radiation testing was conducted and a systematic method has been developed to study the radiation effects for the 2-micron laser materials and optical components. This was done by calculating the expected amount of maximum radiation doses to the optical system during the assumed mission period. Second, based on the calculated maximum dose, radiation sources with energy levels simulating the space environment were determined and selected. Third, samples of 2-micron laser materials and optical components were prepared and manufactured. Fourth, all the test samples were characterized in the laboratory before the radiation test, which include the absorption spectroscopy and lifetime measurements for selected interested energy levels. Fifth, all the samples went for the radiation testing at chosen facilities. Sixth, the samples characterization were repeated again in the Laboratory. The characterization data before and after the radiation test were analyzed compared and documented [10].

2.1 Design for Ground and Airborne application

To augment the technical readiness level of a space based coherent Doppler wind lidar system, a laboratory system should be hardened for both on ground and airborne operation environments. This provides further opportunity to address and manage risks associated with the system and provides opportunity for the development of data processing algorithms and retrieving wind speed and direction information. The design specifications shown in table 1 are adaptable to the space requirements.

Laser wavelength	2.053 µm
Laser material	Ho:Tm:LuLF
Output energy	250mJ
Pulse length	>150 ns
Pulse repetition rate	10 Hz
Laser operating mode	Single transverse and single longitudinal mode
operating temperature	5-20 degrees Celsius
Laser output polarization	Linear polarized >100:1
Beam Quality	<1.3X Diffraction limited
Pulse laser spectral width	Transform limit <5 MHz

Table1. Design specifications of the engineered transceiver

The optical bench is populated on both sides. The front side is designed to hold power oscillator, laser amplifier and alignment laser while the back side carries, seed laser, isolators, transmit/receive switch, receiver detectors and fiber couplers. The two sides of the optical bench are optically coupled through a hole in the optical bench. All the optical mounts are custom designed to withstand high vibration, in an airborne and field missions. This transceiver is used in association with a 15cm telescope that is placed outside the enclosure.

This laser transmitter design features a conductively cooled laser and a liquid cooled rod. This was an advanced step from a totally liquid cooled head. The laser bench and the diode lasers temperatures are actively cooled to15°C while the rod temperature is kept at slightly lower temperature of 10°C to benefit from ground level population depletion in the laser crystal. This system was first tested in ground operation. Atmospheric measurements showing the lidar's capability for wind remote sensing in the atmospheric boundary layer and free troposphere were demonstrated. The lidar wind measurements were compared to a balloon radio-sonde showing agreement between the two sensors [11].

The same laser system was then reconfigured for airborne application. This required additional hardening of the laser bench and the whole instrument was enclosed in a single cylinder. A custom built telescope and a scanner are incorporated inside the enclosure. The instrument participated in the 2010 Genesis and Rapid Intensification Processes (GRIP) experiment, a NASA field campaign conducted to better understand how tropical storms evolve into hurricanes. The instrument successfully measured wind data throughout the campaign and produced invaluable sets of data to be processed for further development. [12]

2.2 Design for Space Application

In parallel to the flight activities, the development of space borne instrument has continued. The laser oscillator requirements for this transmitter are consistent with Coherent Laser Radar for Space applications. The overall design approach is to duplicate the performance of a 100-mJ level laser oscillator and an amplifier without using water as a cooling medium. The heat generated by the pump diode lasers and the rod is removed conductively using heat pipes, shown in Figure 2. Surface area is the most important parameter in removing heat conductively. The Ho:Tm:LuLF crystal, which is 4mm in diameter, has a total of 2.52cm^2 surface area out of which only 1.52cm^2 is accessible for heat-sinking and the rest is used for optical pumping. Langley researchers partnering with industry have developed a thermal configuration that uses heat pipe based thermal management which is the most efficient option for space application and has space heritage. Thermal modeling of the rod conducted for an average optical heat load of 36 watts. The design constraint was to keep the center of the rod not to exceed 25°C. Analysis revealed that there will be a thermal gradient of 30°C in the rod. Stress analysis assured that the rod can handle the thermal shock by a reasonable margin and the beam profile will not suffer from thermal-mechanical distortion. Various thermal interfaces to reduce the thermal resistance on the rod to metal interfaces have been chosen as candidate for this application. To avoid thermal expansion mismatch between the rod and the heat sink a suitable material was also chosen. To maximize the pump laser illumination on the rod, the proper beam guide geometry was determined using optical ray tracing analysis.

Figure 2. Totally conductively cooled laser head

The current state of the art 2µm lasers are capable of meeting the line-width and pulse energy, pulse repetition rate, pulse spectrum, beam quality, and electrical efficiency requirements of a space-based wind lidar, and have been ruggedized to the point of being capable of supporting airborne wind lidar missions. Although those systems represent significant progress in the development of field hardened 2 micron lasers, more remains to be done to achieve fully space-qualifiable designs. In particular, the liquid cooled heads need to be replaced by purely conductively cooled designs, and the mechanical system needs to be ruggedized to both survive the harsh vibrational environment of a launch and to operate in the vacuum environment of space with the appropriate radiation resistance.

A new laser design that can be suitable for space-bound application with Master Oscillator Power Amplifier (MOPA) configuration is proposed and funded by the Earth Science Technology Office (ESTO) at NASA. This lidar transmitter will have a form factor that has been successfully used in space lidar design. A thermal and vacuum test is scheduled for evaluating its performance in space environment. In addition to a long term lifetime evaluation test, the system will also be used as engineering verification laser.

2.3 Conclusion

Continuous 2-micron solid-state laser research at NASA Langley Research Center during the last fifteen years, primarily funded by NASA's Earth Science Technology Office, has demonstrated record pulse energy of 1200 mJ obtaining the required beam quality and pulse spectrum, demonstrated a compactly packaged 250 mJ, 10 Hz laser with the receiver. In August and September of 2010, 2012 and 1213 LaRC successfully flew the packaged liquid-cooled laser/lidar system on NASA's DC-8 and B-12 aircrafts. NASA researchers have addressed risk areas such as laser diode arrays lifetime, heterodyne efficiencies, detectors and radiation effects. For space application, NASA LaRC researchers have developed and demonstrated a fully conductive-cooled 2-micron oscillator/amplifier modules delivering 400 mJ. LaRC also teamed with industry which and was awarded an Innovative Partnership Program-2007 project. Under this, LaRC transferred the 2-micron laser design to industry. A lab version, first generation of 2-micron pulsed conductively-cooled laser has already been delivered. A transmitter with space compatible hardware is under way. This lidar component is expected to meet Technical Readiness Level, TRL 5.

REFERENCES

[1] Wayman E. Baker, Robert Atlas, Carla Cardinali, Amy Clement, George D. Emmitt, Bruce M. Gentry, R. Michael Hardesty, Erland Källén, Michael J. Kavaya, Rolf Langland, Michiko Masutani, Will McCarty, R. Bradley Pierce, Zhaoxia Pu, Lars Peter Riishojgaard, James Ryan, Sara Tucker, Martin Weissmann, and James G. Yoe, "Lidar-

Measured Wind Profiles – The Missing Link in the Global Observing System," Bulletin American Meteorological Society. 95 (4), 515-519 (April 2014) doi: http://dx.doi.org/10.1175/BAMS-D-12-00164.1
[2] Phase I Definition of the Laser Atmospheric wind Sounder (LAWS) Volume II Final Report April, 1990.
[3] George D. Emmitt, "Feasibility and science merits of a hybrid technology DWL," Proceedings 11th Coherent Laser Radar Conference, 19-22, Great Malvern, UK (1-6 July 2001)
[4] B. M. Walsh, N.P. Barnes, M. Petros, J. Yu, and U.N. Singh, "Spectroscopy and modeling of solid state lanthanide lasers: Application to trivalent Tm3+ and Ho3+ in YliF4 and LuLiF4," Journal of Applied Physics, 95, 3255-3271 (2004).
[5] J. Yu, B. C. Trieu, E. A. Modlin, U. N. Singh, M. J. Kavaya, S. Chen, Y. Bai, P. J. Petzar, and M. Petros, "1 J/pulse Q-switched 2-µm solid-state laser," Optics Letters 31(4), 462-464 (2006)
[6] Byron Meadows, Farzin Amzajerdian, Nathaniel Baker, Vikas Sudesh, Upendra N. Singh, and Michael J. Kavaya, "Thermal characteristics of high-power, long pulse width, quasi-CW laser diode arrays, "Photonic West/LASE, San Jose, California, January 24-29, 2004, Proceeding SPIE Vol. 5336
[7] F. Amzajerdian," Analysis of Optimum Heterodyne Receivers for Coherent Lidar Applications", 21th International Laser Radar Conference, Quebec, Canada, July 8-12, 2002.
[8] T. F. Refaat, M. N. Abedin, I. Bhat, P. S. Dutta and U. N. Singh, Characterization of InGaSb/GaSb p-n photo detectors", in the 1.0-2.4 mm wavelength range", Optical Engineering Letters, 43(5) 1014-1015 (2004).
[9] T.F. Refaat, M.N. Abedin, O.V. Sulima, S. Ismail, and U.N. Singh, "AlGaAsSb/InGaAsSb Phototransistors for 2-µm Remote Sensing Applications," Optical Engineering Letters, 43(7) 1647-1650 (2004).
[10] Hyung Lee, Yingxin Bai, Jirong Yu, and U. Singh, "Proton and Gamma Radiation Effects in Un-doped, Single-doped and co-doped YLF4 andLuLiF4", JThE37, CLEO/IQEC 2009 in Baltimore, Maryland, May 31-June 5, 2009
[11] Grady J. Koch, Jeffrey Y. Beyon, Paul E. Petzar, Mulugeta Petros, Jirong Yu, Bo C. Trieu, Michael J Kavaya, Upendra N. Singh, Edward A. Modlin, Bruce W. Barnes, Belay B. Demoz "Field testing of high-energy 2µm Doppler lidar" Journal of Applied Remote Sensing Volume 4, Issue 1, January 2010.
[12] Michael J. Kavaya, Jeffrey Y. Beyon, Grady J. Koch, Mulugeta Petros, Paul J. Petzar, Upendra N. Singh, Bo C. Trieu, and Jirong Yu, "The Doppler Aerosol Wind (DAWN) Airborne, Wind-Profiling Coherent-Detection Lidar System: Overview and Preliminary Flight Results ", *J. Atmos. Oceanic Technol.*, **31**, 826–842, 2014: