Efficient Ho:LuLiF MOPA Laser Transmitter for Space Pathfinder Coherent Wind Lidar

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Abstract: Supported by NASA's Earth Science Technology Office (ESTO), a new lidar transmitter system is developed under the Wind-Space Pathfinder coherent wind lidar project. It is an efficient Ho:LuLiF master oscillator power amplifier system (MOPA) that is capable of generating 15 watts power and 180 ns pulse width at 200 Hz PRF with excellent beam quality. The laser is injection seeded to provide stable single longitudinal frequency output. The laser beam polarization can be switched between "S" and "P" alternatively. Thus, the "S" and "P" beams can be directed to two separate telescopes at different directions to provide true horizontal wind measurement without a moving part in the lidar system. The laser power, pulse width and beam quality fulfill the space lidar system's figure-of-merit (FOM) and measurement accuracy requirements.

Keyword: Coherent Laser Radar, 2-micron Laser

1 Introduction

High energy, Q-switched 2-µm laser sources have been developed for many applications including environmental and climate monitoring. The DAWN airborne coherent lidar system developed at NASA Langley is for measuring 3D wind profiles [1]. The DAWN laser transmitter produces 2-µm pulses with an output energy of 250 mJ and 180 ns pulse width at 10 Hz pulse repetition frequency (PRF) and it has successfully demonstrated its capability through multiple airborne campaigns. To make effective wind profile measurements, laser parameters such as output energy, pulse width, and pulse repetition frequency need to be carefully valued to meet the sensitivity and accuracy of the wind lidar system requirements. The DAWN laser was designed to meet the space borne coherent lidar requirements at low pulse repetition rate. A moderate high repetition lidar system clearly offers better science prospective and system reliability advantages. The Wind-Space Pathfinder coherent wind lidar (Wind-SP) at moderate high repetition rate is developed to advance the space lidar technologies. The Wind-SP laser specification is derived to match or exceed the DAWN instrument performance.

A significant advantage of using the moderate high pulse rate laser is the improved science product from space. Many simulations of space performance by wind lidar proponents have not considered earth's ubiquitous regions of significant cloud cover. Almost all candidate space wind lidars plan to average laser shots over approximately an 80-km long ground track for each vertical profile of wind. For many wind lidar concepts, laser shots blocked by clouds will greatly increase wind measurement error. In some concepts, the corruption by clouds will invalidate the calibration of the entire measurement. Coherent detection is unique in that the wind measurement accuracy is not degraded as increasing laser shots are blocked by clouds. Rather the wind accuracy continues to be excellent while the required aerosol concentration increases. Cloudy regions have many holes for laser beams to pass through and measure lower altitude winds. The 200 Hz pulse rate laser will increase the probability of passing through these cloud holes by a factor of 20 vs. the DAWN pulse rate of 10 Hz. Similarly, there will be more cloud top winds measured, which are crucial to NWP and cal/val of cloud tracked winds.

2 SP Laser Requirements

The coherent lidar SNR is proportional to the laser pulse energy and pulse width described by equation (1)

$$\text{Figure Of Merit (FOM)} \propto \mathrm{E}\sqrt{f}\,\tau^{0.285}\,\frac{2}{1+(\mathrm{M}^2)^2} \tag{1}$$

where E is output energy in J, f is pulse repetition rate, τ is pulse width in ns, and M^2 is the beam quality factor. If the DAWN is operated at 10Hz, the FOM is 3.14 which is defined as baseline or goal value for Wind-SP laser design. The FOM is 2.22 when the DAWN is at 5 Hz which is defined as threshold value.

Table 1. Key Parameters for DAWN and Wind-SP Lidar System

	DAWN	Wind-SP
Laser Material	LuLiF	LuLiF
Laser Wave Length (nm)	2053.495	2052.92
Pumping Method	Side Pumping	End Pumping
Energy (mJ)	250	56/42
PRF (Hz)	10/5	200
Pulse Width (ns)	180	180/150
Beam Quality M^2	1.1	1.1
Figure Of Merit	3.14/2.22 for PRF 10/5 Hz	3.14/2.22 for Energy 56/42 mJ

The four key parameters in the equation (1) need be carefully selected to build a practical and effective lidar system for space missions. The figure-of-merit (FOM) of the DAWN system applied to the Wind-SP system. For scaling the airborne wind lidar system into a space borne system, it was suggested by the airborne campaign results and simulation studies that the lidar transmitter with higher repetition frequency would enhance wind profile measurements. Since the measurement error of wind velocity increases with shorter pulse width, the pulse width of the laser shall be maintained at 180ns or wider. Table 1 listed the key parameters for DAWN and Wind-SP system. The third column in Table 1 are the Wind-SP laser energy (baseline/threshold), pulse repetition rate, pulse width, and beam quality to achieve the space coherent wind lidar FOM baseline and threshold values.

3 Laser Transmitter Development

There are, in general, two laser architectures for the Wind-SP laser. One is a power oscillator (PO) and another is master oscillator power amplifier (MOPA) architecture. The power oscillator architecture offers simplicity in system structure and laser power stability. A major technical challenge to meet the wind lidar requirement listed in Table 1 is to achieve high power output energy while maintaining long pulse width to ensure both sensitivity and accuracy of the measurements. These two parameters usually work against each other. The output energy and the pulse width relation of a Q-switched laser is well described in the literature. A trade study and experimental validation was performed in early stage of the development. It was shown that it was difficult to meet the laser energy and pulse width requirement simultaneously in the power oscillator design. It could reach the desired energy, but the pulse width is too narrow, or vice versa. In addition, the efficiency of the laser was very low when the required energy was reached. It was decided early on that the MOPA architecture is the only appropriate approach to make the Wind-SP laser meets all the laser requirements with high laser efficiency.

The schematic of the laser setup is shown in Figure 1. The laser oscillator is comprised of cavity mirrors CM1 to CM7, an output coupler (OC), a laser crystal and a Q-switch (QS). The pump laser is a commercially available Tm:fiber laser manufactured by IPG photonics. Its maximum output power is 100 W in continuous wave mode and random polarization at the wavelength of 1.938 µm. The size of the pump beam was reshaped with two-mirror telescope optics before being coupled into the oscillator crystal through the CM1 cavity mirror. The CM1 is a dichroic mirror coated for high reflection at 2.053 µm and high transmission at 1.938 µm. The oscillator was built in a ring cavity configuration and a retro-reflector PrM6 was placed after the output coupler to make the laser output unidirectional. A Ho:LuLiF crystal was used as laser gain medium. An acousto-optic modulator (AOM) manufactured by Gooch & Housego was installed for Q-switching. The main objective in determining the oscillator design was to maintain the pulse width longer than 180 ns, while producing enough output energy and leftover pump energy so that the final laser parameters after amplification would satisfy the lidar transmitter FOM requirements at 200 Hz PRF. It was determined that ~5 kW/cm^2 of pump density with 3.6 m cavity length sufficed the condition. The design approach using the pump density above 5 kW/ cm^2 either hindered it from meeting the pulse width requirement or decreased the overall system power consumption efficiency.

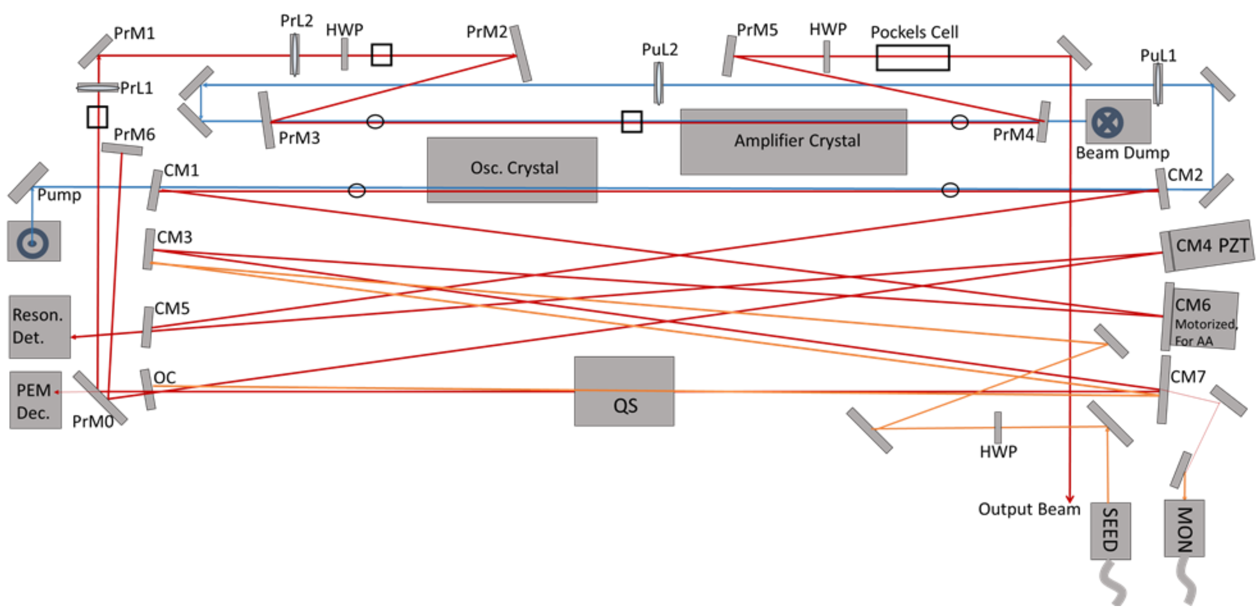

Figure 1 Wind-SP laser diagram

The amplifier was set up using a single pass geometry. The amplifier crystal is also made of Ho:LuLiF crystal. The unabsorbed pump beam in the oscillator crystal was redirected to pump the amplifier crystal. The c-axis of the amplifier crystal is orthogonal to that of the oscillator and the polarization of the 2-µm oscillator output was rotated 90° with a half wave plate before it enters the amplifier crystal. Both pump beam and the 2-µm beam sizes were reshaped for better overlapping within the crystal to obtain optimum amplifier gain.

Figure 2 shows the laser oscillator performance. The laser power achieved larger than 6 W (30 mJ) and pulse width larger than 180 ns at the total pump power 60 W. The oscillator crystal absorbed ~35 W of the total pump power and leaves ~25 W for pumping the amplifier. Figure 3 plots the amplifier power output and pulse width as function of pump power. It shows that at pump power 65 W, it meets the laser energy and pulse width requirements listed in Table 1. The output energy of ~ 75 mJ and 180 ns pulse width at 200 Hz was achieved at the pump power of 76.2 W. The corresponding amplifier gain was ~ 2 and the optical-to-optical efficiency of the system was ~ 20 %. The lidar transmitter FOM is ~ 4.34, exceeding the FOM of 3.14 of the baseline requirement. To our best knowledge, the efficiency of the system is the highest among other reported equivalent systems, considering the power, pulse width, and repetition frequency.

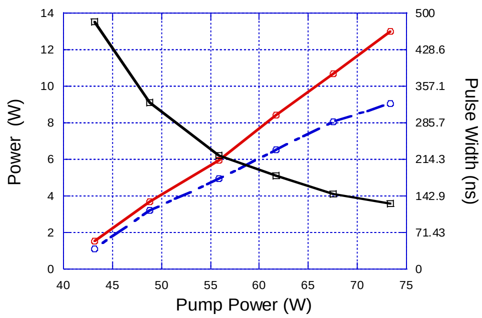

Figure 2 Oscillator Performance

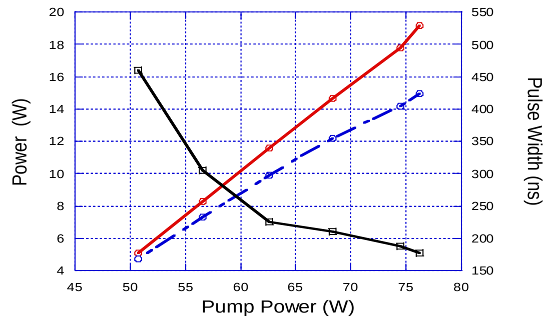

Figure 3 Amplifier Performance

The laser is injection seeded to provide single longitudinal frequency. The seed beam is introduced into cavity through the first order of the AO Q-switch. The seeding is remarkably stable in both time and frequency domain. The jitter is estimated less than ~50 ns in time and less than 1 MHz in frequency. The beam quality is measured at M^2 value of 1.07.

The output laser beam from the amplifier is directed into a Pockels cell by mirrors PrM4 and PrM5. The PrM4 and PrM5 mirrors are dichromic mirrors which are highly transmitting the pump beam and highly reflecting the 2-micron beam. Thus, the laser beam after the PrM4 and PrM5 is purely at 2-micron wavelength. The left-over pump beam after PrM4 is directed into a beam dump. The laser beam passes through a Pockels cell which is used to change the laser beam polarization. When the Pockels cell voltage is off, the laser beam is at P polarization state. The laser beam polarization is turned to S polarization state when the Pockels cell is charged. The P and S polarized beam are separated by a thin film polarizer (TFP). The P and S beam exit the Wind-SP transceiver enclosure through an AR coated window side by side with 18 mm between them. The P and S beams are directed to respective identical beam expanders. The beam expanders transmit the pulsed laser beam into atmosphere and collect the atmospheric return signals. The P and S beam expanders can be set to an azimuth angle difference of 90° so that horizontal wind profile can be deduced. Thus there is no heavy mechanical moving part, which for DAWN is a wedge scanner. It offers great system integrity advantage for a space system.

4 Conclusion

An advanced coherent-detection Doppler aerosol Wind–Space Pathfinder lidar system (Wind-SP) at moderate high repetition rate is developed to demonstrate the technologies needed for a potential first Pathfinder, coherent-only space mission to measure global 3-D winds. The Wind-SP lidar transmitter parameters meet or exceed the requirements for such a space mission listed in Table 1. It is built from the successful Doppler Aerosol WiNd (DAWN) airborne coherent wind lidar heritage to advance the new moderate high pulse rate 2-micron laser technology, the new transmitter thermal management architecture, the new dual beam output arrangement, the new receiver, and the new data retrieval algorithm. The lidar system worked very stably and reliably during the final ground atmospheric lidar demonstrations. It is being infused into an air-borne lidar system to further test and mature the coherent lidar system.

5 References

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