S6-1

Diode-Pumped Pulsed Laser Transmitter for Coherent Wind Detection from Space

Upendra N. Singh
NASA Langley Research Center, MS 474, Hampton, VA 23681-0001
Tel: 757-864-1570 Fax: 757-864-8809
E-mail: u.n.singh@larc.nasa.gov

Abstract

This paper describes pioneering development of solid-state laser transmitter technology at NASA Langley Research Center. It also discusses the design and current development status of the coherent lidar transceiver being developed by Coherent Technologies Inc for the NASA's SPARCLE (SPAce Readiness Coherent Lidar Experiment) wind lidar mission. SPARCLE is primarily a technology demonstration mission, which is consistent with its selection as NASA's New Millennium Program (NMP) second Earth Orbiter (EO-2) mission. It is intended as a precursor mission to a fully operational satellite system, measuring global wind profiles from the Space Shuttle, with a planned launch date in March 2001.

1. Introduction

Space based coherent lidar for global wind measurement requires an all solid state laser system with high energy, high efficiency and narrow linewidth that operates in the eye safe region. 2-μm lasers have been investigated with growing interest because of their potential for use as coherent lidar transmitters; eye-safe properties and efficient diode pump operation are the key elements. Ho:Tm:YLF crystal is chosen as the laser gain medium for developing a diode-pumped 2-μm laser transmitter at NASA Langley Research Center (LaRC) as it emits radiation in the eye-safe region and can achieve efficient diode pumped operation using commercially available laser diodes. Several other laser crystals, such as Ho:Tm:YAG and Tm:YAG, can also operate in the 2-μm region, but Ho:Tm:YLF provides both high energy storage capability and efficient Q-switch operation since the upper laser level manifold, Ho $^5I_7$, has a lifetime exceeding 14 ms at room temperature [1]. It also has low up-conversion losses when compared to Ho:Tm:YAG [2,3]. The complicated population dynamics of the Ho:Tm:YLF laser has been extensively investigated and a theoretical model has been developed to aid the design and optimization of laser performance [4].

For the laser to be used as a coherent lidar transmitter, the beam quality has to be near diffraction limited and the linewidth should be no more than a few MHz, nearly transform limited. For the initial coherent wind space lidar mission, a minimum of 100 mJ per pulse is needed to obtain required measurement sensitivity and accuracy. To enable a space-shuttle mission, such as SPARCLE, one needs to develop a power oscillator to meet both the power and beam quality that a coherent lidar requires. To meet the SPARCLE requirements, a Q-switched, diode pumped Ho:Tm:YLF 2-μm laser with output energy of as much as 125 mJ at 6 Hz with an optical-to-optical efficiency of 3% [5] was developed at NASA/LaRC. When the output of this power oscillator is amplified by using four diode-pumped Ho:Tm:YLF amplifiers, an output energy of 600 mJ at 10 Hz is achieved [6,7]. This is the highest energy ever produced at 10 Hz, and is at least an order of magnitude greater than previously achieved for 2-μm diode-pumped laser at room temperature.

Coherent Technologies Inc.(CTI) is under contract to build the coherent lidar transceiver. CTI is a recipient of pulsed laser transmitter technology from NASA/LaRC and MO/LO technology from NASA/JPL. Besides laser technology, NASA Langley also provided a fully operational laser breadboard to CTI as Government Furnished Equipment (GFE).

2. System Description and Experimental Results

Schematic of injection-seeded diode-pumped Ho:Tm:YLF laser system is shown in Fig. 1. It consists of a CW seed-oscillator and a power-oscillator. The power oscillator is a 3-meter long, figure-eight ring resonator. It is injection-seeded by a CW microchip seed oscillator.

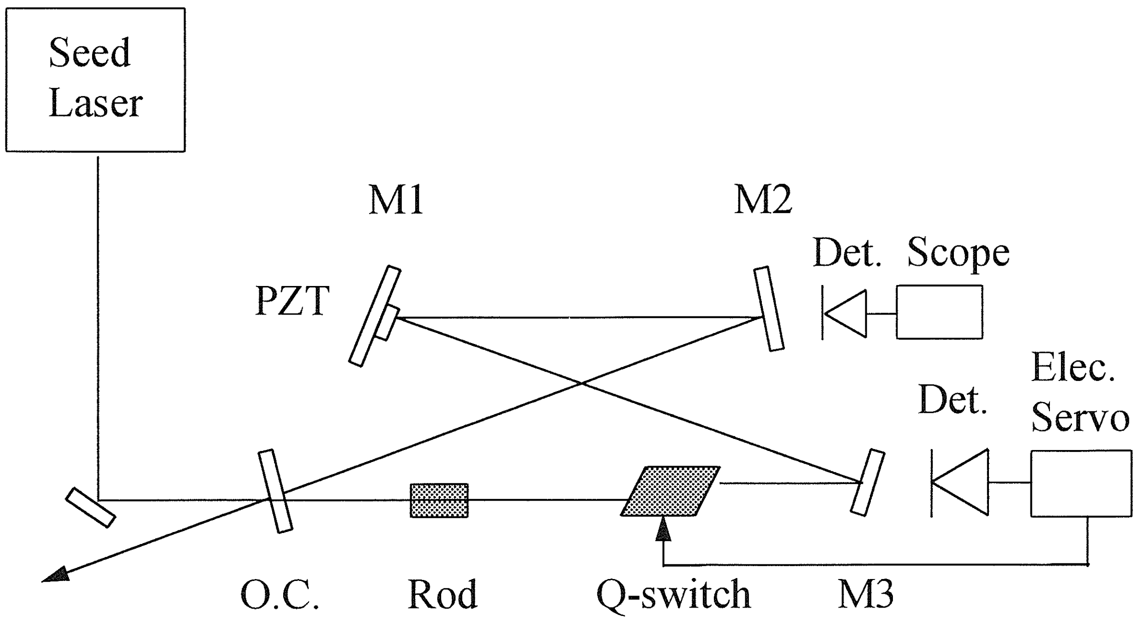

Figure 1. Schematic of injection-seeded Ho:Tm:YLF laser system

A laser schematic is depicted in Figure 1. The diode pumped, Q-switched oscillator uses a ring resonator configuration. The resonator consists of three plane mirrors and one curved mirror. M1 and M3 are high reflectivity flat mirrors; M1 is mounted on a piezoelectric (PZT) actuator. An output coupler with 82% reflectivity, as a compromise between the output energy and fluence inside the resonator, is used. M2 is a curved mirror with a three-meter radius of curvature. These mirrors are angled about 3.5° off -axis. The total resonator length for this laser is 3.3 meters. The large resonator length is a simple way to obtain the long laser pulse width that is desirable to achieve a Fourier transform limited narrow linewidth to resolve the wind velocity accurately. This geometry gives a beam waist of 0.95 mm full width at $1/e^2$ of maximum intensity at the laser crystal based on Gaussian beam simulation. Because a ring resonator provides two outputs, it is convenient for injection seeding; either path may be chosen for injecting the seed source into the resonator through the output coupler and unidirectional operation may be induced. A fused silica acousto-optic Q-switch with very low insertion loss is used to obtain Q-switched operation.

Laser output energies and pulse widths of single, Q-switched pulses at 14 ^{0}C are given as a function of pump energy in Fig. 2. For pump pulse duration of 1 millisecond (ms), the threshold for lasing is about 1.8 J and a slope efficiency of approximately 5.8 %. In view of space applications, attempts were made to operate the laser at higher laser rod temperature, allowing efficient radiative heat dissipation. The output energy was found to decrease at the rate of 3.38 mJ/^{O}C [9]. To compensate for this loss at higher rod temperatures, pump energy can be increased. Since the current of the pump diode is normally kept at its maximum, the pump duration is increased to obtain higher pump energy. The product of the pump duration and the pulse rate is kept under the maximum operating condition for the laser diode arrays. Experimental results demonstrated that a 10 % increase in pump pulse length results in 15 % increase in Q-switched laser output. Measured output energy with the rod temperature at 14 ^{0}C and a 1 ms pump pulse length were same as for a rod temperature of 19 ^{0}C with 1.1 ms pump pulse length, as indicated in Figure 2. Figure 2 also shows that the output energy increases to 125 mJ for a 1.2 ms pump pulse width. This leads to laser operation at the desired higher temperature with no apparent loss in output energy.

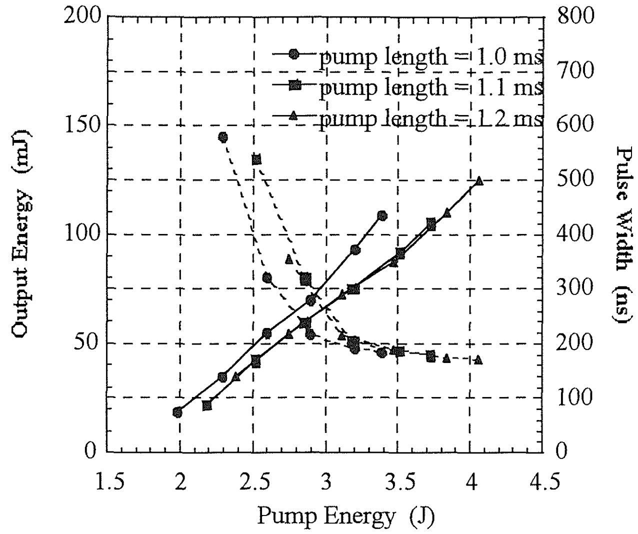

Figure 2. The output energy (solid line) and pulse width (dashed line) as a function of pump energy. The circles represents the temperature of the laser rod at 14 degree C for a pump duration of 1.0 ms. The squares and triangles represent the temperature of the laser rod at 19 degree C for the pump duration of 1.1 and 1.2 ms, respectively.

2.1. Folded Resonator

Since the instrument will be contained in two pressurized hitchhiker (HH) canisters, each about 50 cm in diameter and 72 cm long, mounted on the sill (wall) of the shuttle payload bay. In order to fit the various components in the 50 cm diameter space, it was necessary to fold the beam a number of times. The number of folds and mirror placement resulted from a detailed analysis of the folded resonator. It was optimized for energy, beam quality, polarization purity, and pulse length of the output beam.

Figure 3 shows an existing folded resonator at Coherent Technologies, Inc. It is a 3.1meter long 8-mirror ring resonator and its performance is comparable to the four-mirror ring resonator.

The performance of the folded cavity is shown in Fig. 4. When operated at 20 degree C, the normal mode energy and Q-switched energy reach 248 and 88 mJ, respectively, for a pump pulse length of 1ms. This corresponds to diode pump energy of 3.44J. When the pump energy increased to 4 J by extending the pump length to 1.2 ms, the Q-switched output increases to 106 mJ. The Q-switched pulse length is 176ns. This is comparable to performance of the four-mirror ring resonator. This configuration is a precursor to the SPARCLE pulsed laser transmitter and meets energy, pulse length and polarization requirements. Preliminary test shows that it also satisfies sensitivity specifications.

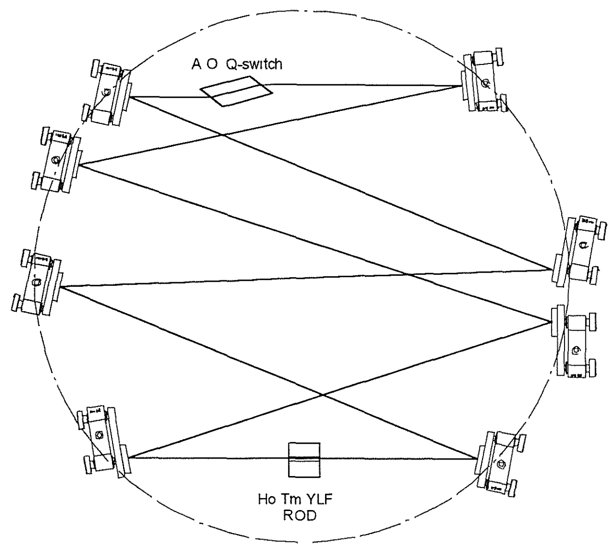

Figure 3. Power oscillator with folded cavity to fit into shuttle hitchhiker canister.

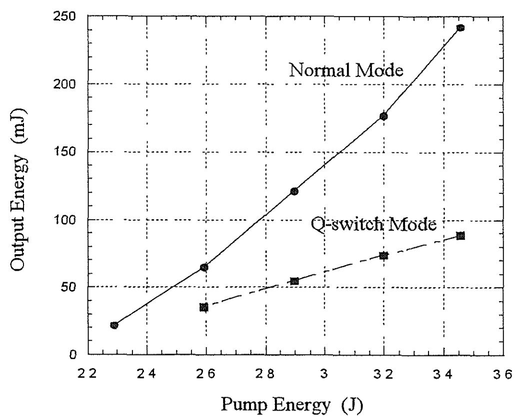

Figure 4. Output energy of the folded resonator as a function of diode pump energy for a rod temperature of 20 degrees C.

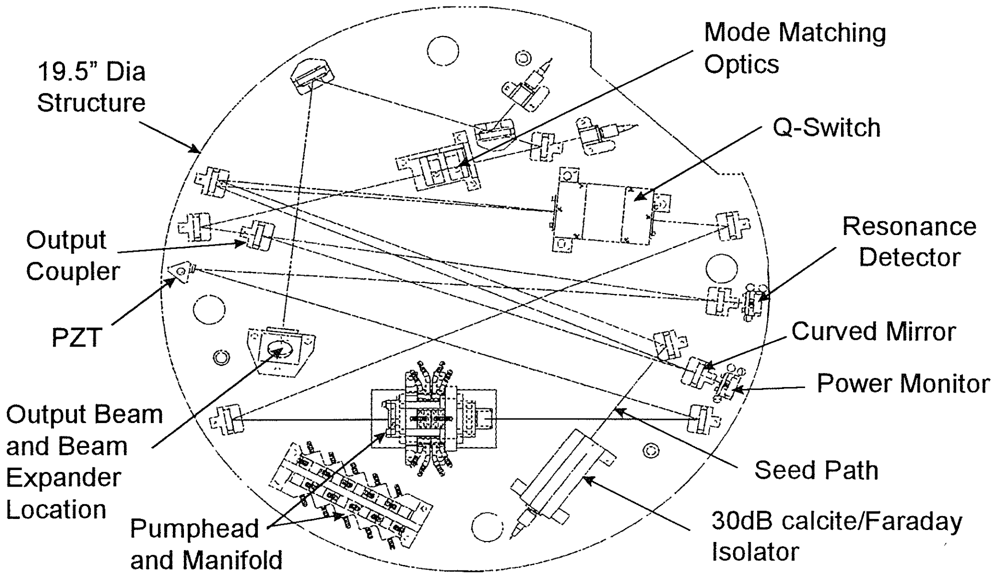

Figure 5. Optical layout of slave oscillator assembly

The optical layout of the SO Assembly designed by Coherent Technologies, Inc. is depicted in Figure 4. The support structure for the assembly is a graphite composite optical bench, designed with a low coefficient of thermal expansion (CTE), closely matching that of Invar. The bench is 19.5 inches in diameter, and about 3 inches thick, with a Cartesian internal ribbing structure. The optical bench, in combination with the optical mount designs, produces an assembly that has high optical alignment stability over the specified thermal ranges for SPARCLE, and that has a large stiffness-to-mass ratio. The latter feature helps in reducing sensitivity to vibration (most input vibration from the Shuttle, especially during launch, being at low frequencies) while reducing hardware mass. The reconfigured slave oscillator uses eight mirrors to fold the 3.3m resonator length onto the optical bench in a multi-cross pattern. The pump module and associated coolant manifold are located towards one edge of the bench. The mass of these components is to some extent compensated by location of the acousto-optic Q-switch and mode-matching optics, so as to maintain a center of mass close to the center of the optical bench. The pump module is largely unchanged in design and still requires active cooling of the laser rod and pump laser diodes. For this reason, the SPARCLE hardware includes an active coolant loop that maintains the rod and laser diodes at 18°C. The laser diodes have been modified to improve coolant sealing and double o-ring seals have been implemented in the pump module for safety purposes. The pump module supports an etalon for tuning the slave oscillator center wavelength and also a Brewster plate to improve the polarization extinction ratio of the Ho,Tm:YLF laser.

2.2. Injection-Seeded Operation

As additional risk reduction during the design phase of the SPARCLE program, CTI demonstrated injection-seeded Q-switched operation of the slave oscillator breadboard laser, reconfigured to match the flight layout depicted in Figure 5. A 15mW single frequency Ho,Tm:YLF laser with 50dB optical isolation was used to seed the slave oscillator through the first diffraction order of the existing Q-switch operating at 24MHz. Seeding was found to be extremely stable with an efficiency (percentage of pulses seeded) exceeding 99%. Figure 9 shows example data taken when the laser was injection-seeded and Q-switched. The figure shows three plots, the heterodyne detector profile of the Q-switched pulse when mixed with the seed laser output beam, an unexpanded profile of the FFT spectrum of the pulse, and an expanded version of the FFT spectrum used to measure the 3dB spectral bandwidth. The data indicates a pulse duration (intensity FHWM) of 200ns, single frequency operation of the seeded laser at a frequency offset from the seed laser frequency by 25.5MHz, and a pulse spectral bandwidth of about 1.4 MHz. The unexpanded FFT spectrum indicates that axial mode beating in the laser (expected at 90MHz spacings) is suppressed by more than 40dB from the seeded frequency component, verifying stable injection-seeded operation of the laser. The center beat frequency of 25.5MHz is slightly displaced from the Q-switch R.F. frequency of 24MHz switch build-up time. This is a feature of the ramp-and-fire injection-seeding technique and highlights the need for a reference detector in the lidar transceiver design to obtain accurate knowledge of the emitted pulse spectrum. The time-bandwidth product for the injection-seeded due to frequency pulling which occurs during the Q-pulses (pulse duration FWHM x FFT 3dB linewidth) is 0.277, verifying the ability of the ramp-and-fire technique to produce near-transform limited single frequency injection-seeded Q-switched operation.

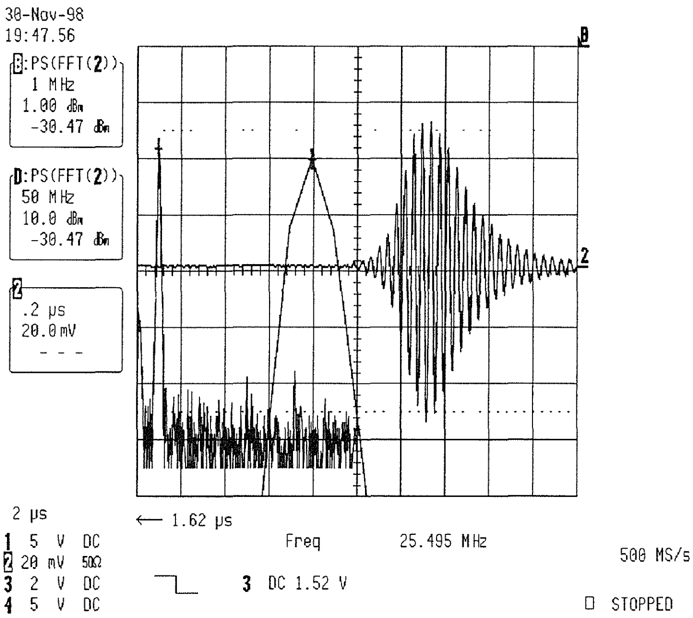

Figure 6. Injection-seeded Q-switched operation

Injection-seeded operation at the 100mJ pulse energy level was performed while tuning the seed laser over the full +/-4.5GHz tuning range required for frequency offset-locking. The injection-seeded Q-switch pulse energy varied by about 5% over the full tuning range, meeting SPARCLE requirements, and verifying the ability to use a tunable master oscillator and fixed frequency local oscillator in the lidar transceiver.

3. SPARCLE Payload Configuration

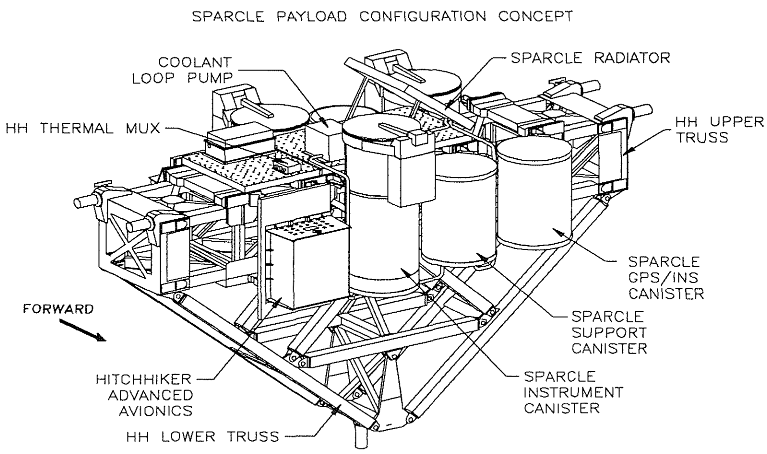

Figure 7. SPARCLE hardware configuration

The SPARCLE payload configuration is shown in Figure 7. Three separate Hitchhiker canisters are planned, the Optics (or Instrument) Canister, the Transceiver Support Canister, and the Computer Support Canister. In addition, SPARCLE will be using a single Hitchhiker Advanced Avionics Box, a space radiator located on the top of the bridge assembly, and also a coolant pump mounted external to the canisters. The cooling system for SPARCLE is self-contained, with heat being radiated out from the canister walls and the space radiator. The Optics Canister houses the lidar transceiver and so requires an optical window at one end to allow laser light to be emitted and received by the transceiver. The presence of the window compromises the structural integrity of the canister and so an automated closing lid assembly is fitted to this canister. The lid is closed over the optical window during non-operational periods, both to achieve suitable confinement of the experimental hardware within the canister (during launch and on-orbit Shuttle maneuvers), and also to prevent potential contamination of the optical window by space debris.

The hardware provided by CTI is contained in the Optics Canister and the Transceiver Support Canister. The Optics Canister contains several assemblies including the lidar transceiver, a 25x expanding telescope, and a wedge scanner. These are mounted on a common support structure to maintain accurate alignment of the optical system. The support structure is directly mounted to the canister top-plate assembly, which contains the canister optical window.

4. Conclusions

Pre-flight breadboard of a diode-pumped 2-μm injection seeded pulsed laser transmitter was developed by NASA and was delivered to CTI to build a flight quality laser transceiver. The Q-switched output energy was found to be in excess of 100 mJ at six Hz, and a near-transform limited beam with a pulse width of 170 ns. The high power and high beam quality of this laser makes it well suited as a coherent wind lidar transmitter on a space platform. Certain aspects of laser transceiver design are briefly described.

5. Conclusions

Author would like to acknowledge the contributions from the members of NASA/LaRC's 2-Micron Laser Development team. Acknowledgements are also due to Mark Philipps of CTI for his comments and contributions to the manuscript.

6. References

1. B. M. Walsh, N. P. Barnes and B. D. Bartolo, J. Luminescence, 75, 89 1997.
2. G. Hansson, A. Callenas and C. Nelsson, Proc. Advanced Solid-State Laser Conf., OSA, AWRB 12, 1993.
3. T. Y. Fan, G. Huber, R.L.Byer and P. Mitzscherlich, IEEE J. Quant. Elect. QE-24, 924 1988.
4. N. P. Barnes, E. D. Filer, C. A. Morrison and C. J. Lee, IEEE J. Quant. Elect. QE-32, 92 1996.
5. Jirong Yu, Upendra N. Singh, Norman P. Barnes and Mulugeta Petros, "125-mJ diode-pumped injection-seeded Ho:Tm:YLF laser ", Opt. Lett. 23, 780-782, 1998
6. Upendra N Singh, Jirong Yu, Mulugeta Petros, Norman P. Barnes and et. al, "Injection-seeded, room-temperature, diode-pumped Ho:Tm:YLF laser with output energy of 600 mJ at 10 Hz", OSA TOPS, 19, 194-196, 1998
7. U. N. Singh, "Development of High-Pulse Energy Ho:Tm:YLF Coherent Transmitters," Invited paper 3380-14, Proc. SPIE Vol. 3380, Conference on Laser Radar Technology and Applications III, 12th Annual International Symposium on Aerospace/Defense Sensing, Simulation, and Controls, AeroSense, Orlando, FL (15 April 1998)
8. U. N. Singh, J. A. Williams-Byrd, N. P. Barnes, J. Yu, M. Petros, G. E. Lockard and E. A. Modlin, SPIE 3104, 173, 1997