UV Lifetime Laser Demonstrator for Space-Based Applications

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ABSTRACT

A long-lived UV laser is an enabling technology for a number of high-priority, space-based lidar instruments. These include next generation cloud and aerosol lidars that incorporates a UV channel, direct detection 3-D wind lidars, and ozone DIAL (differential absorption lidar) system. In previous SBIR funded work we developed techniques for increasing the survivability of components in high power UV lasers and demonstrated improved operational lifetimes. In this Phase III ESTO funded effort we are designing and building a TRL (Technology Readiness Level) 6 demonstrator that will have increased output power and a space-qualifiable package that is mechanically robust and thermally-stable. For full space compatibility, thermal control will be through pure conductive cooling. Contamination control processes and optical coatings will be chosen that are compatible with lifetimes in excess of 1 billion shots. The 1064nm output will be frequency tripled to provide greater than 100mJ pulses of 355nm light at 150 Hz. After completing the laser module build in the third quarter of 2015 we will initiate lifetime testing, followed by thermal/vacuum (TVAC) and vibration testing to demonstrate that the design is at TRL 6.

Keywords: UV lasers, single-frequency lasers, space-based lasers, TRL 6 lasers, diode-pumped lasers

INTRODUCTION

A 15 W, 50-200 Hz UV laser with a lifetime in excess of 1 billion shots is an enabling technology for a number of potential space-based lidar missions that have been identified as priorities in the NRC Earth Science Decadal Survey. These missions, with examples of NASA funded airborne lidar systems that are being developed as technology demonstrators for them, are listed below.

1. Aerosol/Cloud/Ecosystems (ACE) – This mission will be an expanded scope follow-on to the highly successful CALIPSO cloud and aerosol lidar mission. Researchers at NASA Langley[1] and at NASA GSFC[2] have been developing three wavelength (1064 nm, 532 nm, and 355 nm) High Spectral Resolution Lidar (HSRL) systems as candidate technologies for the ACE mission. The 355 nm channel of a space-based version of this lidar would require from a few to several hundred mJ/pulse at 355 nm with a repetition rate in the 50-150 Hz range.
2. 3-D Winds – Space-based measurement of tropospheric winds with global coverage has been identified as a key mission for both weather and climate modeling. At least two lidar technologies that are capable of clear air measurements are being developed with NASA funding as potential candidates for the winds mission. One is a direct detection wind lidar operating at 355 nm such as the Tropospheric Wind Lidar Technology Experiment (TWiLiTE)[3] that was built at GSFC. A scaled up version of the TWiLiTE system could be used to meet the 3-D Winds Mission requirements. A second NASA funded technology being developed at Ball Aerospace is the Optical Auto-Covariance Wind Lidar (OAWL)[4] system which also operates at 355 nm. Both of these lidar technologies use a laser in the 100-500 mJ/pulse with a repetition rate in the 50-200 Hz range.
3. Global Atmospheric Composition Mission (GACM) – An Ozone DIAL system could be a key instrument for this mission. A scaled up version of the NASA funded Global Ozone Lidar Demonstrator (GOLD) being developed at NASA Langley[1,5] is a strong contender for the GACM mission requirements for global ozone measurements. A key technology needed for a space-based version of GOLD is a high energy 355 nm pump laser that is up-converted to wavelengths in the 300-320 nm range for use in the ozone measurements.

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It is clear that a 100-500 mJ UV lifetime demonstrator would be a valuable tool for advancing the TRL of the lasers needed for those missions. The other key TRL-6 elements are thermal/vacuum testing and vibration testing in relevant environments. We are developing a laser module that can used for lifetime testing can also meet the vibrational and vacuum operational requirements of a space-flight mission. We accomplished this by using key opto-mechanical design features that have been developed in previous Phase 2 SBIRs as well as the ICESat-2 laser transmitters[6] as the basis for the proposed UV Lifetime Demonstrator (UVLD).

LASER MODULE DESIGN

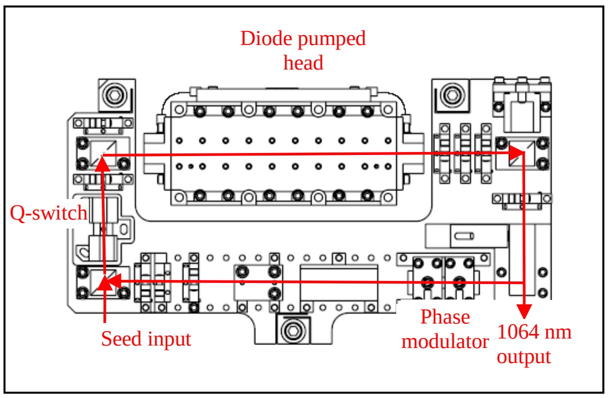
Performance goals

Our original approach to the laser design was for a 15 W UV laser operating at 50 Hz. As part of the program development we held periodic reviews of the design goals with our ESTO sponsors as well as interested lidar system developers. Based on their inputs we changed the final set up for the 1064 nm pump laser to be 150 Hz operation while still maintaining close to 40 W average power output. The final goal for the UV average power at 355 nm was still 15 W. Table 1 summarizes the performance goals for the UVLD system.

Table 1. Final performance goals for the UV Lifetime demonstrator.

Parameter	Units	Performance Goal
Repetition rate	Hz	150
Pulsewidth	ns	~15
1064 nm pump power	W	37.5
1064 nm pump energy	mJ/pulse	250
355 power	W	15
355 pulse energy	mJ/pulse	100
1064 nm linewidth	MHz	<100 (single axial mode)
1064 nm pump beam quality	M^2	< 2
355 nm beam quality	M^2	< 3

Figure 1. Heritage injection seeded ring oscillator design



Design heritage

The 1064 nm pump laser will be an injection-seeded, single-frequency Master Oscillator/Power Amplifier (MOPA) design. By eliminating mode beating, the probability of optical damage is significantly decreased and the long term

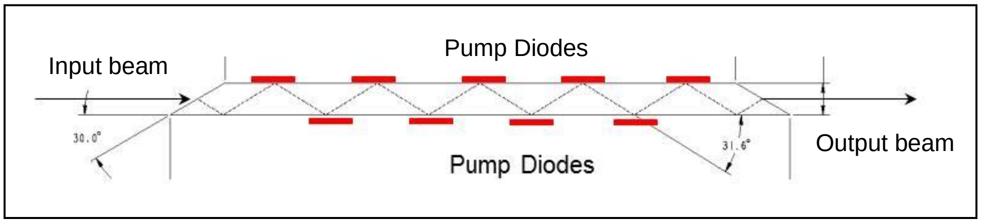
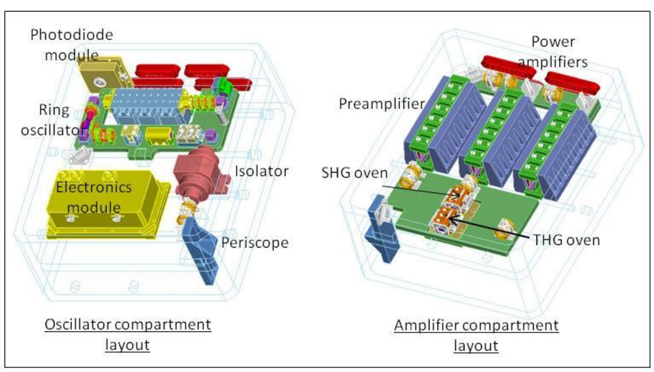


Figure 2. Representative pump on bounce amplifier design

reliability increased. Fibertek has used NASA ATIP, ESTO, and SBIR funding to develop this technology into a space-qualifiable package. The GOLD and HSRL lasers built for NASA Langley are our 3rd generation of this type of laser. Figure 1 shows a typical layout of the injection seeded ring laser that was be used as the oscillator for the MOPA design. The preamplifier and first power amplifier designs would be same pump on bounce designs developed for the HSRL and GOLD lasers. The basic approach, illustrated in Figure 2, positions a pump array at each of the bounce points in a total internal reflection (TIR) zigzag slab. The resulting increased overlap between the pump and extracting beams improves efficiency and beam quality. The tips of the slab are at Brewster angle to provide low loss without coatings for p-polarized input.

The opto-mechanical designs of the GOLD/HSRL lasers and the ICESat-2 flight laser will be the basis for the required 1064 nm pump laser. An overview of the HSRL/GOLD laser layout that illustrates the partitioning of the optics between the two laser module compartments is shown in Figure 3. One compartment contains the injection seeded ring laser and its supporting electronics and the other compartment contains the amplifiers and nonlinear optics. Both compartments are sealed to the external environment and back filled with clean, dry air. Openings in the center plane ensure the two compartments are at the same internal pressure. This dual compartment design has been successfully tested in vacuum and is the packaging design basis for the ICESat-2 units that have been fully space-qualified and delivered to NASA GSFC. There was a significant investment by the ICESat-2 mission in this accomplishment. The test regimen required to meet the ICESat-2 mission definition of TRL-6 included successfully completing random vibration testing at a level of 14 grms in all three axes as well as mission level operational and survival thermal vacuum testing. An early key task in the HEUVD program was to develop a derivative of the ICESat-2 laser canister design that incorporates the design features discussed above and illustrated in Figures 1-3. An integral electronics module was beyond the cost scope of the

Figure 3. Typical airborne laser design



HEUVD program. Our approach was to use rack mounted electronics that are a blend of custom and commercial components.

Power amplifier design and modeling

For the previously used pump on bounce design that had diode stacks mounted with the bars parallel to the primary slab axis, an input beam of 3 mm resulted in a beam footprint on the TIR face of 1 cm, the standard length of the diode bars from which the pump arrays are built. If the extracting beam size exceeds the pump footprint on the TIR surface, the beam quality will begin to degrade due to non-spherical and difficult to correct surface deformations at inflection points in the thermal (and thus index) profiles at the edges of the pumped regions. Scaling to the higher pulse energies needed for this system requires a final power amplifier design that accepts a 5-6 mm input beam but does not exhibit the beam distortion that would be exhibited by a pump on bounce using single 1 cm long pump arrays at the bounce points.

Our approach to improving the final power amplifier design was to take advantage of the newer conductively cooled diode array packages that have become available in the last few years. The designs have higher power bars stacked at a larger pitch such that the mounted diode arrays can have the bars aligned orthogonally to the primary slab axis as shown in Figure 4. A two sided-pumped and cooled power amplifier based on this approach has been modeled, built and tested at the pump module level. It used 17 bar arrays based on 200 W peak power QCW bars mounted on a 1.2 mm pitch. The resulting 19.2 mm footprint on the TIR surface of the slab matches well to foot of a 5-6 mm diameter input beam.

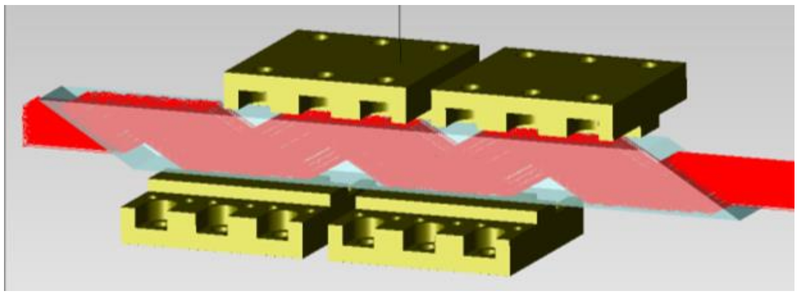


Figure 4. Schematic of the pump diode configuration for the power amplifier pump design. Four diode stacks are centered on the central four bounce points of a six-bounce zig-zag slab.

1064 nm pump laser and UV conversion module

Although the oscillator and amplifier modules in the heritage airborne laser designs were conductively cooled to the mid-plane of the dual compartment optics module, the mid-plane still contained internal liquid cooled channels. A key update to the UVLD design was to transition to full conductive cooling. A variety of geometries were considered and modeled for both thermal and pressure distortion effects. A properly designed rectangular geometry with all the amplifiers mounted to one wall was shown to provide good insensitivity to thermal and pressure distortion effects and was the simplest to interface to the rest of the lidar system. Figure 5 provides and overview of the final optical layout for the laser optics module. The ring oscillator and first two amplifiers are in one compartment and the final power amplifier and nonlinear converters in the other compartment. The overall dimensions, weight, and external interfaces (thermal, optical, mechanical, and electrical) of the laser optics module are illustrated schematically in Figure 6. The cold plate interface shown in Figure 6 could be easily replaced by a heat pipe interface for a flight system. The flexure mounting design was derived from the flight-qualified ICESat-2 design and analyzed to show that it would survive the same vibration testing regimen to which the ICESat-2 lasers were tested.

Another key performance goal of this program is to improve the lifetime of the UV generation section. In general, the lifetime of our previous airborne designs was good but did tend to exhibit long term (i.e. at the hundreds to thousands of hours of operation) degradation of the optics in the UV generation section, especially the output face of the LBO crystal used for 355 nm generation. The cause of the degradation was not definitively determined, but two possible causes are the long term effects of trace contamination in the sealed box or a not well understood direct interaction of the UV photons with the coatings or the coating/bulk substrate interface. Our approach in this program was to quantify the lifetime effect of minimizing trace gas phase contamination effects on the UV generation section. This was accomplished by the following features in the design and processing of the UV section.

1. The LBO for third harmonic generation was contained in a nearly polymer free module that was isolated from contaminants in the rest of the laser. The only polymer in that module is the Viton o-rings used to seal the lid and windows.
2. All of the components in the laser module were precision cleaned and vacuum-baked to the standards of the lasers for ICESat-2 mission. Vacuum baking was continued until the outgassing rates, as determined by temperature-controlled quartz crystal microbalance measurements, met the very low ICESat-2 standards.
3. A telescope in the THG module expands the beam by 4X before leaving the module.

Figure 5. Overview of the two optical compartments in the UV Lifetime Demonstrator

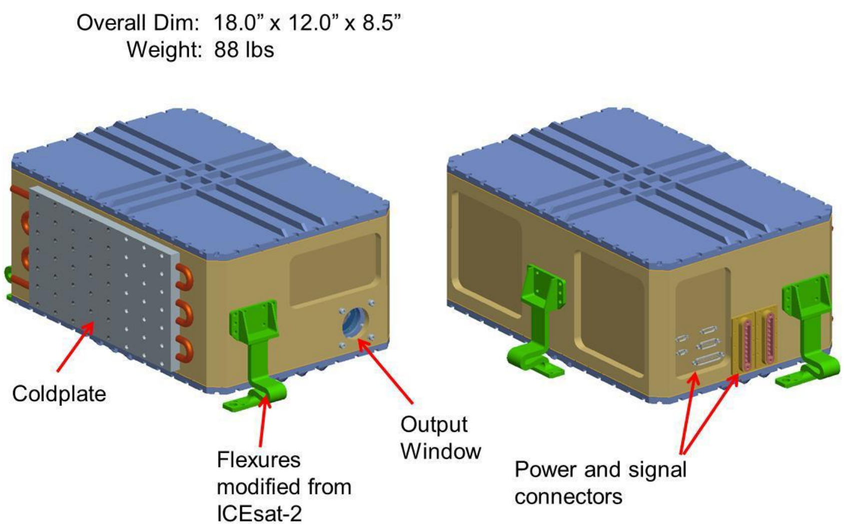


Figure 6. Dimensions, weights and interfaces of the UVLD laser optics module

HARDWARE ASSEMBLY AND TEST STATUS

As of early summer 2015 the electronics required to run the laser were complete and the optics module was assembled through the final power amplifier and fully tested and characterized through the second amplifier. As shown in Tables 2 and 3, the performance of the oscillator and first two amplifiers is meeting our design goals with margin. The assembly status of the two compartments of the laser module is shown is shown in Figures 7 and 8.

Table 2. Injection seeded resonator performance.

Parameter	Units	Goal	Demonstrated
Wavelength	nm (air)	1064 (nominal)	1064.3936
Repetition rate	Hz	150	150
1064 nm pulse energy	mJ	≥ 25 mJ	34
Pulse width	ns	10 – 20	14
Beam quality	M^2	≥ 1.5	1.3
Linewidth	MHz	≤ 100	≤ 70

Table 3. Performance after amplifier 2.

Parameter	Units	Goal	Demonstrated
Repetition rate	Hz	150	150
1064 nm pulse energy	mJ	≥ 150 mJ	> 200 mJ
Pulse width	ns	10 – 20	14
Beam quality	M^2	≤ 1.8	1.5

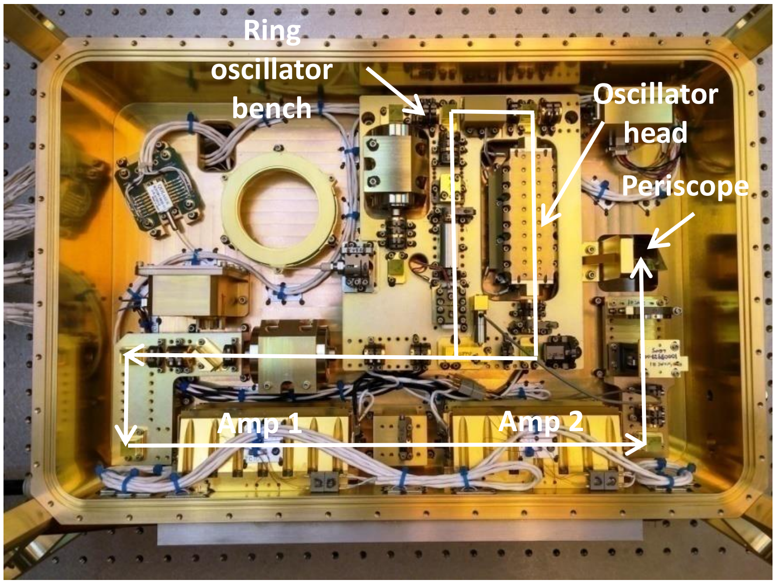


Figure 7. View of compartment containing the ring oscillator, amplifier 1, and amplifier 2

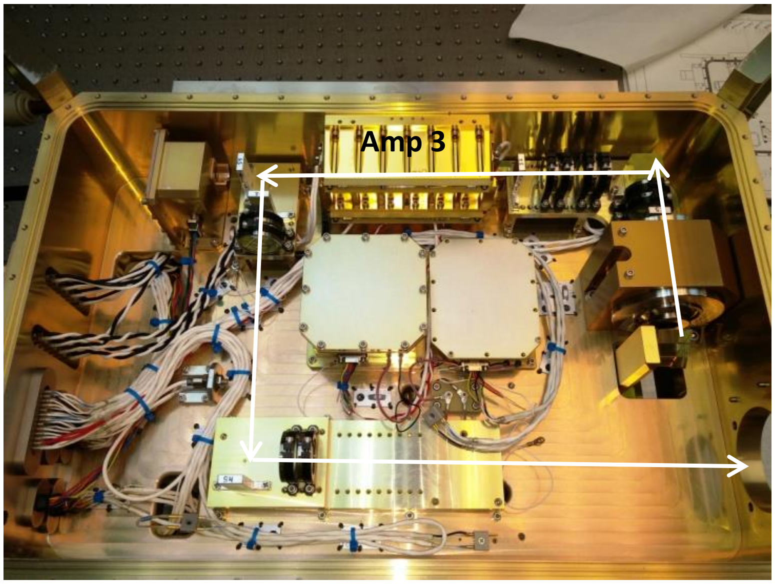


Figure 8. View of compartment containing amplifier 3. The nonlinear converters are not yet installed.

LIFETIME TESTING AND ENVIRONMENTAL TESTING

The lifetime testing sequence for the laser will consist of the four steps that are listed and briefly described below.

1. A high repetition rate, lower pulse energy (20 kHz, ~ 6W of UV) test of a smaller size (6mm x 6 mm x 25 mm vs. a final UVLD size of 12mm x 12mm x 25 mm) LBO tripler mounted in a clean box that has been built and processed identically to the one that will be in the UVDL. The LBO is from the same vendor as the larger crystals and was coated in the same lot. The pump source for the test is a brassboard version of the ICESat-2 laser that was used in lifetime testing for the ICESat-2 mission. The peak intensities of the output UV will be similar to the UVLD but the spot sizes will be much smaller. The purpose of this test is to serve as an initial screening for the LBO tripler coatings and as an initial validation of our cleaning processes for the UV module. We anticipate running this test for about 1 month. This corresponds to over 50 billion shots.
2. A 4 month, 532 nm only life test of the UVLD laser to assess the 532 nm lifetime. The LBO tripler will not be installed. The purpose of this test is to verify the LBO doubler coating and the cleanliness of the 1064 nm laser transmitter. There is also interest in these results for missions that would only use the 1064 nm and 532 nm output of the laser.
3. A 4 month, half power 355 nm life test of the laser transmitter for initial UV lifetime assessment. This test provides an initial lower power validation of the LBO tripler coatings and cleaning processes of the UV module. It will also provide some insight to the intensity dependence of any long term decay that may be surfaced in this sequence of tests.
4. A 4 month, full power 355 nm life test of the full UVLD laser transmitter for final UV lifetime assessment. This test will not provide validation of our approach for a full 3 year mission but will provide trend data on any UV degradation that may occur.

After the life testing is completed we will execute TVAC testing followed by random vibration testing. The TVAC profiles will be chosen to meet the requirements of the GSFC General Environmental Verification Standard (document # GSFC-STD-7000). The profiles for the initial random vibration testing will be chosen to envelope the actual flight requirements for the CALIPSO, ICESat-1 and ICESat-2 missions.

SUMMARY

The UV lifetime demonstrator is an ESTO funded project to develop a baseline UV laser design that could meet the requirements of a number of potential space-based Earth Science measurements. The design of the laser is complete and it is the process of final assembly. It is on track to meet the performance goal for the system. Once the laser build is completed, a series of lifetime and environmental tests will be executed to advance the laser design to TRL 6.

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