High energy, single-mode, all-solid-state Nd:YAG laser

Narasimha S. Prasad[1], Upendra N. Singh[1] and Floyd Hovis[2]
[1]NASA Langley Research Center, 5 N. Dryden St., MS 468, Hampton, VA 23692
[2]Fibertek, Inc., 510 Herndon Parkway, Herndon, VA 20170

Abstract-In this paper, recent progress made in the design and development of an all-solid-state, single longitudinal mode, conductively cooled Nd:YAG laser operating at 1064 nm wavelength for UV lidar for ozone sensing applications is presented. Currently, this pump laser provides an output pulse energy of >1.1 J/pulse at 50 Hz PRF and a pulsewidth of 22 ns. The spatial profile of the output beam is a rectangular super Gaussian. Electrical-to-optical system efficiency of greater than 7% and a minimum M^2 value of <2 have been achieved.

I. Introduction

NASA is actively engaged in the development of space-based active remote sensing missions using lidar techniques. To develop reliable and robust laser based lidar systems, NASA began the Laser Risk Reduction Program (LRRP) in 2002 [1]. Jointly run by Langley Research center and Goddard Space Flight Center, the LRRP is designed to advance laser performances as well as to mitigate associated risks in critical components such as pump diodes for remote sensing applications from space based platforms. The technical objective of LRRP is to develop high-energy, solid-state, conductively cooled and single longitudinal mode 1 micron and 2 micron lasers and appropriate wavelength conversion technologies suitable for four lidar techniques namely altimetry, Doppler, Differential Absorption Lidar (DIAL), and basic backscatter signal strength profiling. These four techniques would enable six priority earth science measurements of surface and ice mapping, horizontal vector wind profiling, river currents monitoring, carbon dioxide (CO_2) profiling, ozone (O_3) profiling, and aerosols/clouds monitoring. The overall goal of LRRP is to advance laser technologies to the point that science mission proposals could be confident of acceptable risk upon selection.

For ozone profiling, efficient 1-micron to UV wavelength conversion technology to generate tunable, pulsed UV wavelengths of 308 nm and 320 nm is being pursued. Accordingly, the Nd:YAG laser is being developed to pump a nonlinear optics based UV converter arrangement to generate 320 nm and 308 nm wavelengths by means of 532 nm wavelength. The 532 nm wavelength is obtained from the 1064 nm wavelength using a LBO crystal via second harmonic generation process. The nonlinear optics arrangement consists of a novel optical parametric oscillator (OPO), known as Rotated Image Singly Resonant Twisted Rectangle (RISTRA) module and a sum frequency generation unit. This high energy low repetition rate UV transmitter is being developed for atmospheric ozone profiling using differential absorption lidar (DIAL) technique suitable for space-based platforms.

Modeling and simulation studies have indicated the requirement of high pulse energy of >200 mJ with low pulse repetition rates at UV wavelengths to achieve enhanced performance during strong daylight conditions. The viability of a relatively efficient scheme involving a Nd:YAG pump laser operating at 1064 nm and the nonlinear optics based arrangement comprising of an optical parametric oscillator (OPO) and a sum frequency generator (SFG) to obtain >200 mJ/pulse at UV wavelengths has been established under laboratory conditions. The RISTRA configuration has demonstrated to provide enhanced output beam quality. So far, the RISTRA OPO has demonstrated greater than 85% depletion and 20% optical conversion efficiencies with stable mode quality [2-4]. For these experiments, a flash lamp pumped Nd:YAG laser was used. However, our goal is to pump the UV converter arrangement with an all solid-state pump laser. Hence, the diode pumped Nd:YAG laser development is being pursued in parallel to the development of UV converter technology [5].

For flight worthy and space-qualifiable systems, compact, conductively cooled, and solid-state design configuration is vital [6,7]. A single frequency pump source to generate UV wavelengths is required for efficient differential absorption lidar (DIAL) measurement of ozone. The high energy pump laser is achieved by upgrading a 300 mJ/pulse Nd:YAG laser that was developed under NASA's Advanced Technology Initiative Program (ATIP). This ATIP laser consisted of a ring oscillator and dual amplifiers, Amplifier 1 and Amplifier 2 [8,9] and operated at 50 Hz. Amplifiers 3 and 4 have been added to obtain output energy greater than 1.0 J/pulse. The diode pumping increases efficiency and reduces size and weight. Conduction cooling eliminates circulating liquids and increases MTBF values. The goal is to obtain high beam quality, that facilitates a reduction in the size of the transmit optics, and to enhance the nonlinear conversion processes used to produce the desired UV wavelengths. Flat top pump profile is preferred for optimal RISTRA OPO operation required to enhance the UV conversion efficiency In the following sections, recent progress made in building the solid-state Nd:YAG pump laser is discussed.

II. Technical Approach

The technical approach for the development of a reliable, robust and efficient diode-pumped Nd:YAG pump laser is based on an oscillator/amplifier design configuration. The important features of the all solid-state pump laser are as follows: (a) injection seeded ring laser that improves emission brightness (M^2)), (b) diode-pumped zigzag slab amplifiers that allow robust and efficient design for use in space environment, (c) advanced E-O phase modulator material that allows high frequency cavity modulation for improved stability injection seeding, (d) alignment insensitive/boresight stable 1.0 mm cavity and optical bench for achieving stable and reliable operation, (e) conduction cooled operation that eliminates circulating liquids within cavity, and (e) space-qualifiable component designs that establishes a path to a space-based mission. The optical layout of the Nd:YAG pump laser is illustrated in Fig. 1. The layout illustrates ATIP laser, amplifier 3 and amplifier 4. The ATIP laser consists of an oscillator head, amplifier 1 and amplifier 2. Considerable progress has been made in the design, fabrication and testing of this diode pumped Nd:YAG pump laser.

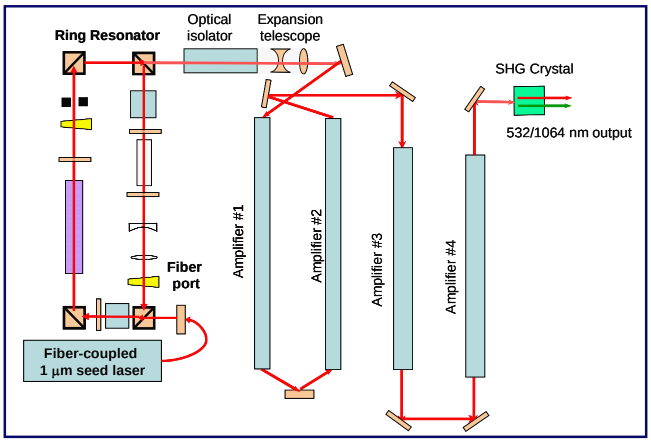

Fig. 1. The Nd:YAG pump laser optical layout.

III. Oscillator Configuration

Our approach to the oscillator head design was to incorporate a design that demonstrated the key features needed for a flight system and that could be easily modified for an actual flight build. To this end, we developed a design that used a bridge structure to mount and conductively cool the zigzag slab to a pedestal on which the pump diodes were mounted. For the laboratory studies described here the pedestal was conductively coupled to a liquid-cooled plate for heat removal, but the transition to a radiatively cooled interface plate would be straightforward. The single frequency ring laser design is illustrated in the left section of Fig. 1.

The design incorporates diode-pumped, conductively cooled Nd:YAG slabs as the gain media. The oscillator is a telescopic ring resonator design that can be easily reconfigured for a variety of operational scenarios. In order to achieve the desired single-frequency operation of the ring oscillator, we have developed a variation of the so-called "ramp and fire" approach to injection seeding that uses a rubidium titanyl phosphate (RTP) electro-optic modulator to vary the effective cavity length rather than a mirror mounted on a piezo-electric transducer (PZT). Near-stable operation allows trading beam quality against output energy by appropriate choice of mode limiting aperture. In our case for 50 HZ PRF operation,

- 30 mJ TEM_{00}, M^2 =1.2 at 50 Hz
- 30 mJ TEM_{00}, M^2 =1.3 at 100 Hz
- 50 mJ square supergaussian, M^2 = 1.4

Injection seeding using an RTP phase modulator provides reduced sensitivity to high frequency vibration. PZT stabilization of cavity length reduces sensitivities to thermal fluctuations. Since stability over a range of environmental conditions will be needed for field operation of the laser, we have developed a design for the ring resonator optical bench that incorporates Zerodur, a low expansion ceramic, as the bench material and is illustrated in Fig. 2. Zerodur optical bench results in high alignment and boresight stability.

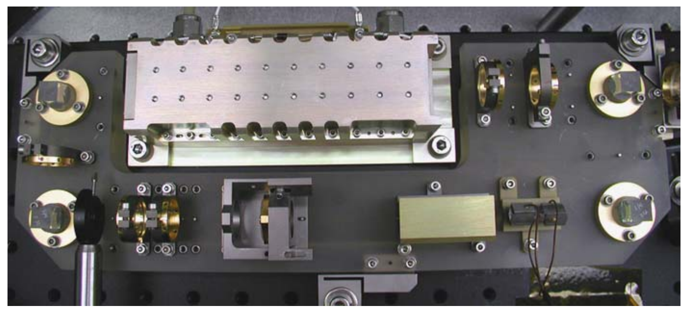

Fig. 2. Oscillator head mounted on a zerodur optical bench (12 cm x 32 cm).

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The amplifier design for the system is based on a higher efficiency version of the well developed zigzag slab technology. The testing and development status of each of these key technology components are described in the following sections.

IV. Configuration Of Amplifier 1 And Amplifier 2

The amplifier configuration is based on single-sided pumped and cooled design. Fig. 3 shows the dual amplifier configuration. Near-normal incidence simplifies AR coatings and, pump on bounce geometry allows high gain fill factor and hence, high slope efficiency. To begin with, the amplifier performance was modeled using simple Franz-Nodvic approach. For purposes of modeling, the oscillator configuration consisting of 100 µs pump pulse, 55 W/bar and 100 bars were utilized. The oscillator output of 50 mJ/pulse, 0.41 cm x 0.41 cm square beam, and M^2 = 1.2 were considered. The amplifier configuration involving variable pump pulse width, 55 W/bar and 112 bars/amplifier was utilized. The modeled and measured results of the amplifier output versus 808 nm pump pulse width are illustrated in Fig. 4. The measurements have validated our modeling approach. The output from the second amplifier is coupled to amplifier 3. Application of model to the use of higher power pump arrays (40 mJ TEM_{00} input,75 W/bar, 200 µs pump pulses) predicts over 500 mJ/pulse of output.

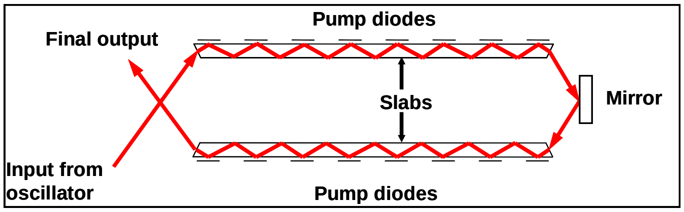

Fig. 3. The amplifier 1 and amplifier 2 configurations.

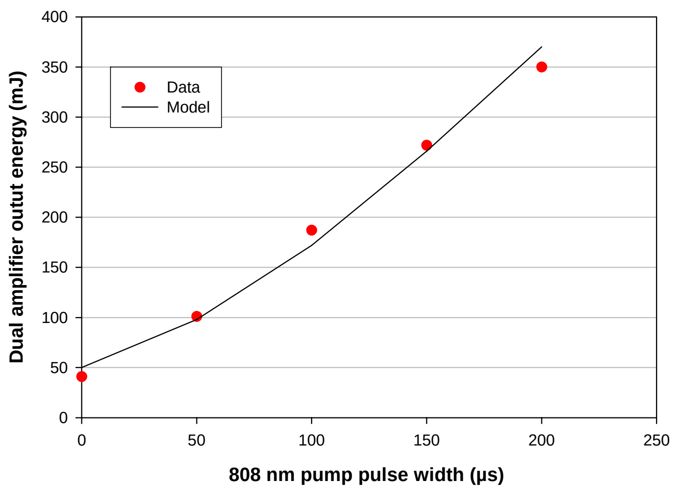

Fig. 4. Modeled and measured data for Amplifiers 1 and 2.

V. Configuration Of Amplifier 3 and Amplifier 4

The amplifiers 3 and 4 are configured as 2-sided pumped Brewster angle slab design. Fig. 5 shows the design configuration of amplifier 3 and amplifier 4 units. In the case of amplifier 3, the Brewster angle cut is used to simplify the optical alignment for single pass operation. The Brewster angle slab design is a mature technology because it reduces risk based on synthesis of previously developed pump on bounce and Brewster angle designs. Furthermore, it exhibits reduced tendency for parasitic oscillation since parasitic control in Brewster slabs is well established, and pump on bounce geometry allows good beam overlap with high gain regions and minimal diffraction effects due to edges.

Fig. 6 shows the modeling, extraction results, and the near field output beam profile of power amplifier 3. The pump conditions are 75 W peak per bar @ 808 nm and pump pulsewidth of 150 µs. Up to 700 mJ of output pulse energy was obtained. The electrical efficiency was over 11% and the electrical to optical efficiency was over 7%. The near field beam profile is also shown in Fig. 6. The preliminary M^2 measurements found a value of ~2 for the output from amplifier 3. The near-field spatial profile corresponds to a

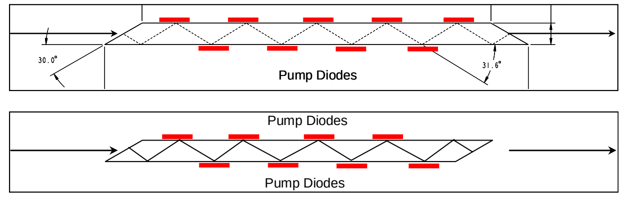

Fig. 5. The 2-sided pumped Brewster angle slab designs. Design is a synthesis of Brewster angle and pump on bounce approaches. Top Figure: Amplifier 3 design. Bottom Figure: Amplifier 4 design

rectangular supergaussian. The beam symmetry was further reduced by fine tuning the cylindrical compensating lens. The amplifier design achieved the desired goals of high effective fill factor and extraction efficiency with minimal beam quality degradation due to diffraction from slab edges.

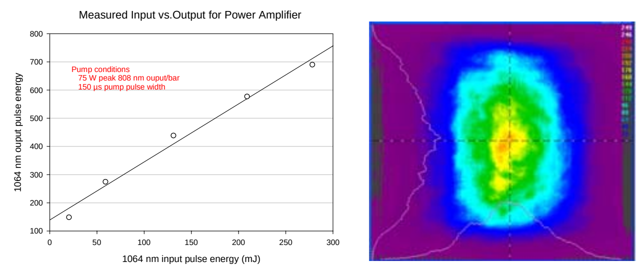

Fig. 6. Performance of amplifier 3. Left Figure: Modeling and measured output pulse energy results. Right Figure: Near-field beam profile measurement.

The amplifier 4 design configuration is shown in Fig. 5 and is similar to that of amplifier 3. The goal of amplifier 4 operation is to extract equal to or greater than 1.2 J/pulse. The even bounce Brewster angle design reduces beam pointing change due to slab movement and equal number of arrays per string (4) simplifies diode driver electrical design. Increased cross section of 10 mm x10 mm allows >1 J output pulse energy with beam fluence of <2.5 J/cm^2. From the prototype amplifier measurements we project that over 500 mJ/pulse can be extracted from the final amplifier design configuration. The performance modeling results shown in Fig. 7 predicts that extracting the amplifier 4 with the 700 mJ input can achieve >1 J/pulse. Modeling is based on Franz-Nodvic approach for amplifying a square (in time) pulse. Modeling includes all key parameters explicitly. In this case, number of pump diodes (192), peak diode power (75 W), diode pulse width, input oscillator pulse energy (= 60 mJ), input beam diameter, gain path length in amplifier and slab volume. The model accounts for reduced gain for second pass. For 210 µs diode pump pulses, >1 J per pulse output is predicted. Hence, the dual 2-sided pumped amplifier design configuration is anticipated to meet the requirements of most space-based direct detection wind lidars designs

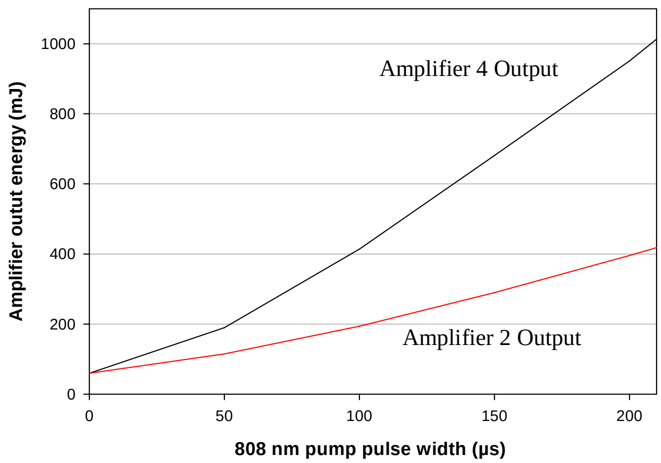

Fig. 7. Typical modeled output of 2-sided pumped and cooled Amplifier 2 and Amplifier 4 for 60 mJ input to Amplifier 1.

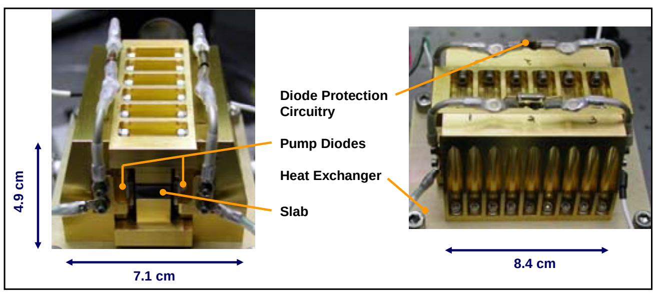

Fig. 8. Prototype two-sided pumped and cooled head design.

VI. Final Laser Assembly and Test Results

Prototype amplifier 3 and amplifier 4 units are shown in Fig. 8. Fig. 9 shows the final laser assembly with all four amplifiers. The laser oscillator was operated at 50 Hz PRF. Due to limitations of the current drive electronics, only 58 W peak power per diode bar pumped the amplifiers. At these pumping levels, the output of amplifier 4 was measured. Greater than 1100 mJ/pulse was obtained leading to an electrical-to-optical efficiency of >7%. As shown in Fig. 10, the measured average power at 50 Hz of 51.0 W (1020 mJ/pulse) for an input electrical power to all pump diodes of 724 W. The pulsewidth of the amplifier 3 is 16 ns. The pulsewidth stretches to 22 ns at 1.1 J/pulse due to amplifier 4. Fig. 11 illustrates the final laser output beam quality measurements at output energy of 1.05 J/pulse. At 50 Hz, full power beam quality measurements yielded M_x^2=2.5 and M_y^2 = 2.5. However at 1.1 J/pulse, M^2 was found to be ~3. Hence, the current optical arrangement allows to trade between beam quality and output energy to certain extent. Further output beam characterization is under way. The oscillator has the capability to operate at a PRF of 100 Hz.

Fig. 12 shows the optical layout shown in Fig. 9 assembled inside a compact unit. The laser box allows the selection of amplifiers for operation at random. This selection provides an opportunity to achieve several levels of output power approximately 5 W increments. Fig. 12 shows the customized electronics driver assembly packaged inside a compact box.

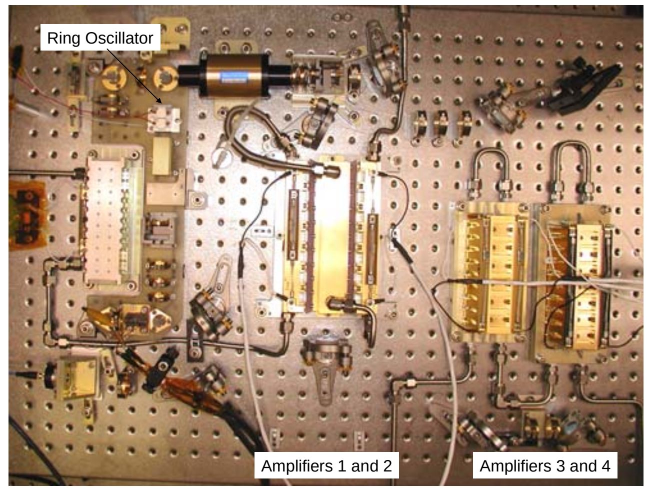

Fig. 9. The final Nd:YAG pump laser assembly with ring laser oscillator and four amplifiers.

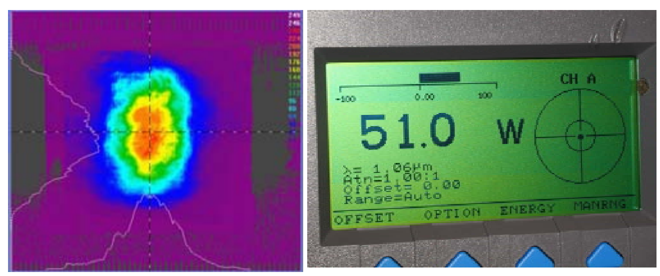

Fig. 10. Near-field beam profile and a typical average output power reading due to amplifier 4 at 50 Hz PRF. Maximum average power measured is ~53 W.

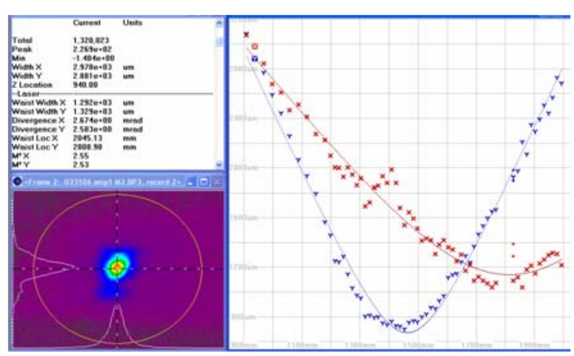

Fig. 11. Typical laser beam quality measurement.

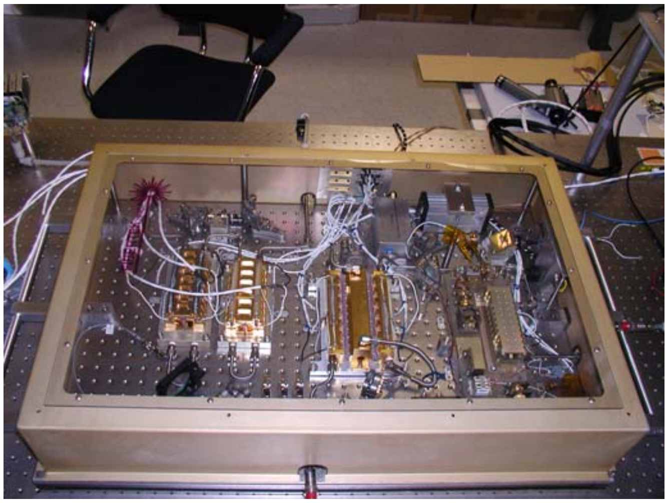

Fig. 12. Laser assembled inside a box.

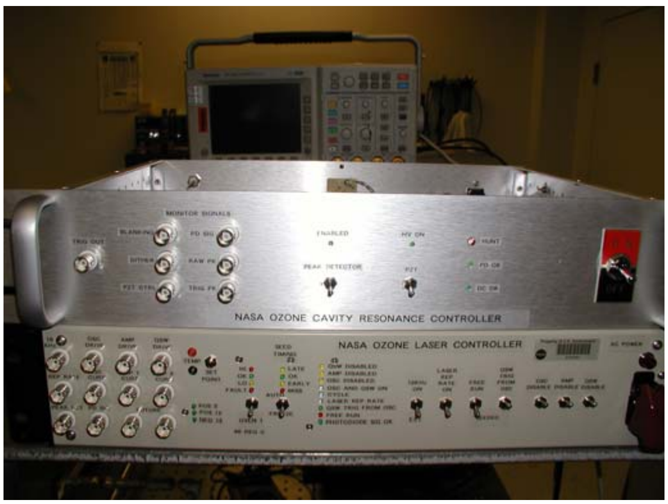

Fig. 13. Turnkey control electronics box.

Following packaging, the laser performance testing is nearing completion. Since 532 nm is required to pump an UV converter, plans are underway to install a second harmonic generation unit. Based on conversion efficiency and potential thermal problems, either a KTP or LBO crystal will be utilized to generate 532 nm.

VII. Summary And Conclusions

In this paper, the development of a diode pumped, single longitudinal mode, and conductively cooled Nd:YAG laser for pumping a UV converter arrangement is discussed. Greater than 1.1 J/pulse at 50 Hz and 22 ns has been achieved. The pump laser will be utilized for generation of 305 nm and 320 nm suitable for ozone sensing through DIAL technique. The optical assembly and control electronics have been suitably packaged for operational convenience.

Acknowledgements

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