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Spaceflight 100 W, 1940 nm Polarization Maintaining Tm Doped Fiber Laser for Pumping Q-Switched 2 µm Ho:YLF

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ABSTRACT

Fibertek has designed and is building a spaceflight (TRL 6) high-efficiency, high-reliability (97.2% for 5-year mission) 100 W average, 1940 nm thulium-doped fiber laser (TDFL) meeting all requirements for a NASA Earth Science spaceflight 2 µm Ho:YLF pump laser. These include polarization extinction ratio (PER) >16 dB, diffraction limited beam quality, narrow linewidth (0.35 nm), and >50% optical-to-optical efficiency. The high-reliability laser package is optimized for space environment and is 10.6″ x 13.8″ x 4.4″ in size and 30 lbs in weight. A summary of the laser package design is presented, including structural and thermal analysis. Preliminary environmental testing results of the space laser are also presented. A spaceflight 100 W PM Tm laser provides a path to space for a pulsed, Q-switched 2 µm Ho:YLF laser with ~80 mJ/pulse at 100-200 Hz.

Keywords: Thulium, fiber laser, wind sensing, space, Ho:YLF, space-based, spaceflight, 2 um

1. INTRODUCTION

This paper reports progress toward developing a Technology Readiness Level 6 (TRL-6) spaceflight 100 W polarization maintaining (PM) thulium (Tm) laser needed for 2 µm wind lidar. The design is a compact, high-reliability package capable of greater than 5-year mission lifetime while operating in space satellite missions 24 hours per day, 365 days per year (24/7). The overall program goal is to demonstrate a TRL-6 package and conduct environmental testing of the space laser. Preliminary results are presented below. This design leverages heritage Fibertek erbium (Er) space fiber transmitters shown in Figure 1. The design presented is for a 2 um Tm laser but the package can be adopted for 1.5 um Er and 1 um ytterbium (Yb) high-power fiber lasers and amplifiers.

The space-based Tm laser supports a path to space for a pulsed, Q-switched 2 µm Ho:YLF laser with up to 80 mJ/pulse at 100-200 Hz. NASA has conducted aircraft-based coherent wind lidar and carbon dioxide (CO_2) and water vapor concentration lidar measurements that show considerable promise.[1,2] Lidar performance design studies from a low earth orbit (LEO) satellite indicate that 80 mJ of pulsed 2 µm energy enables the simultaneous measurements of CO_2 and water vapor[3] using Integrated Path Differential Absorption (IPDA) and global wind light detection and ranging (lidar). NASA laser experiments have shown that 100 W of 1940 nm peak pump power is needed to generate 80 mJ/pulse.[4] NASA and the 2007 National Research Council (NRC) Earth Science Decadal Study[5] have identified CO_2 lidar as a key technology needed to address global climate change research. The study identifies 2 µm laser technology as critical to CO_2 studies and for measuring three dimensional (3D) tropospheric winds.

Thulium-doped fiber amplifier (TDFA) technology is well suited for supporting high-gain, high-average-power lasers at 1940 nm.[6-11] TDFAs are built with highly reliable fiber pigtailed optical components, which in many respects benefit from the reliability heritage of commercial telecommunications and high-power industrial lasers. A cladding-pumped TDFA with 793 nm multimode diode pumps is the optimum laser configuration for the high-power level and space applications, where high reliability and a minimum number of components are sought. We expect high power and efficiency can be achieved across a broad wavelength range from 1900 nm to >2200 nm.[5]

This effort heavily leverages Fibertek heritage in space erbium and ytterbium fiber lasers. Fibertek has previously developed a similar narrow linewidth erbium-based space TRL-6 transmitter[12,13] for CO_2 lidar[14,15] at 1571 nm. We have also developed a transmitter for deep space optical communications that provides 6 W average power using pulse position modulation (PPM) with up to 1 kW peak power.[16-19] The 20 W TRL-6 transmitter has been vibration tested to NASA General Environmental Verification Standard (GEVS) and has been thermal cycled at survival and operational temperatures as shown in Figure 1. Fibertek has also demonstrated pulsed versions at 1.5 µm with ~ 1 mJ/pulse, 1 µsec pulsewidth, and 800 W peak power for range resolved and high signal-to-noise ratio (SNR) lidars.[20]

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Figure 1. A 20 W fiber amplifier laser optical module (LOM) for lidar and optical communications (left), on a vibration table (center), and in a thermal vacuum chamber (right).

This paper is organized onto five parts:

- Part 1: Introduction
- Part 2: Thulium laser requirements
- Part 3: Space tracible design and performance – Description of the laser design and performance including reliability analysis and finite element model (FEM) structural and thermal modeling.
- Part 4: Results for the vibration, stress, and structural analysis.
- Part 5: Thermal analysis results for the laser package are summarized.
- Part 6: Preliminary Vibration testing of the partially populated laser package is presented.
- Part 7: Conclusions

2. THULIUM PUMP LASER REQUIREMENTS

Table 1 lists the Ho:YLF laser requirements. The performance specifications are driven by the 2 µm energy requirements for wind lidar measurements. Pump power requirements are based on Q-switched 2 µm Ho:YLF laser experiments reported by NASA. Center wavelength requirement is 1940 nm. A high degree of center wavelength stability +/-0.25 nm is required over the temperature operation range. The laser also needs to achieve a narrow linewidth operation with bandwidth <0.5 nm. Laser outputs must be highly stable, 100 W polarized output power. Output beam quality needs to be near diffraction limited M^2 <2 and achieve a high level of power efficiency >10%. The laser package goal is to withstand a vibration level compatible with NASA's GEVS.[22] The laser is conductively cooled with athermal operation between 10-30°C. Small size and weight for the laser package are highly desirable. Fibertek has developed a highly efficient 1940 nm laser system that meets all the requirements. Fibertek is advancing the TRL from 3 to 6 with TRL-6 environmental testing.

Table 1. Requirements for NASA 1.94 µm laser transmitter. (Check boxes indicate performance has been met or exceeded.)

#	Parameters	Requirement/Goal	Achieved[21]	Comments and Fibertek Approach
1	Center Wavelengths	1940 nm	9	
2	Output Optical Average Power	$P_{avg}\geq$60 W (requirement) $\geq$100 W (target)	9100 W	40% power margin for 60 W operation
3	Bandwidth	<0.5 nm	9<0.35 nm	Instrument limited measurement
4	Polarization Extinction Ratio (PER)	PM	9>16 dB	All-PM fiber system
5	Total Electrical Power Efficiency	>10%	9>22%	
6	Mode Quality	<2	9<1.1	Single mode fiber output
7	Packaging - Size	Low SWaP	910.6″x13.8″x4.4″	Compact design. Expect <13.7 kg
8	Packaging - Vibration	GEVS[22] standard	9	Structural Analysis and Test

#	Parameters	Requirement/Goal	chieved[21]	Comments and Fibertek Approach
9	Packaging - Environ ent	Vacuum	9	Structural An lysis and Test
10	Reliability	>5-year lifetime	9>95%	Reliability Analysis

3. SPACE TRACIBLE DESIGN AND PERFORMANCE

This section provides a brief description of the optical design and a summary of the optical performance of the laser. More details about the optical performance can be found in reference [21]. Figure 2 shows the space qualifiable laser package. The laser optical module (LOM) contains pump diodes, all fibers and fiber optic components, and monitor electronics. The LOM housing is fixed at the base/bottom surface and is conductively cooled from the same bottom surface. The laser electronics module (LEM) is located at the top of the laser. LEM volume is designed such that it can accommodate diode drivers, power conditioning circuitry, and control electronics.

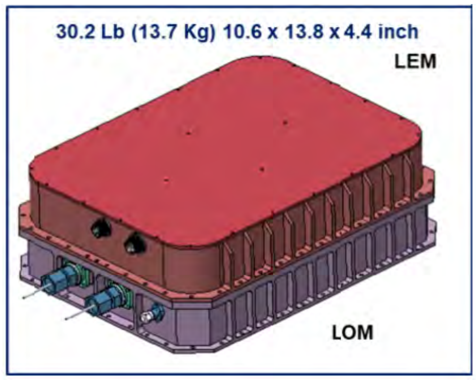

Figure 2. (left) Space qualifiable laser electrical (LEM) and optical module (LOM) mechanical design characteristics, and (right) top level LOM system schematics.

The laser consists of a Tm fiber laser and amplifier. Figure 3 shows output optical characteristics of the power amplifier. Figure 3 (left) shows input 793 nm pump power vs. output 1940 nm signal power. Figure 3 (right) shows measured power stability over several hours. Excellent power stability with standard deviation of <1% is measured. The power amplifier is operated in the saturated regime where minimal output power variation is measured. Figure 3 (right inset) shows the measured output optical spectrum. An excellent amplified spontaneous emission (ASE) suppression >40 dB is achieved. No spectral broadening is observed in the power amplifier. Bandwidth is <0.35 nm. A Tm PM fiber laser oscillator achieves narrow bandwidth (<0.2 nm) with the 20 dB PER, and diffraction limited beam quality. An average power of 100 W is achieved with optical-to-optical (o-o) efficiency of 55%. The amplifier is pumped with up to 181 W of pump power. The laser sustains the high PER, diffraction limited beam quality, and narrow linewidth.

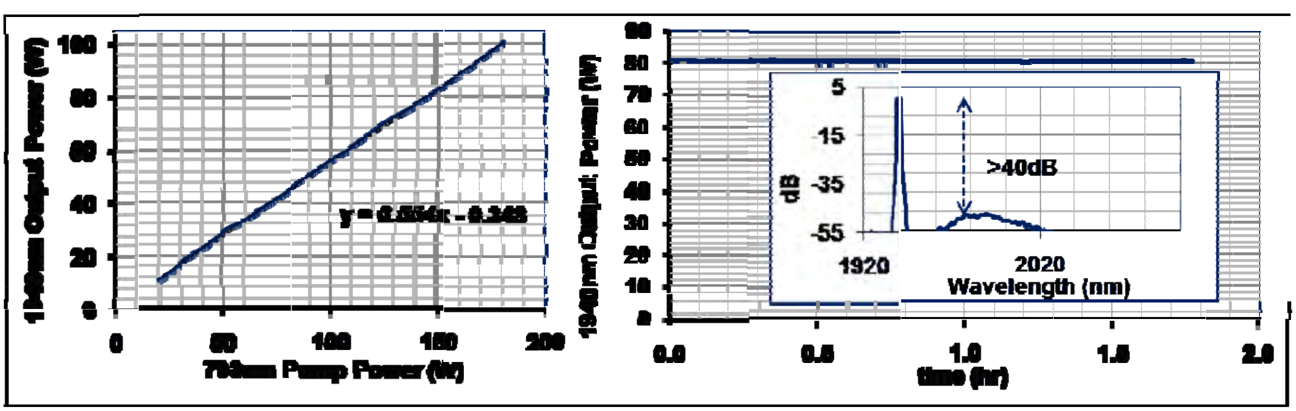

Figure 3. (left) Measured input diode pump power vs. output 1940 nm power, (right) measured optical power stability, and (inset) output optical spectrum.

The laser transmitter is designed for >5-year reliable operation at 100 W power level when operated 24/7 in space. A detailed reliability model is developed to support the optical design of the high-power laser. The analysis includes the reliability failure in time (FIT) numbers for all the optical components, splices, pump diodes, pump diode electronics, and controller electronics. Pump diode drivers are based on comparable space-qualified drivers that Fibertek has developed for previous programs. In the optical design, redundancies of optical and electrical components are chosen such that the 5-year reliability requirement is met. The analysis also accounts for derated operation of the optical components. The 1940 nm PM Tm-doped fiber laser uses double-clad, single-mode gain fibers and is compatible with small form factor packaging. All the component vendors also are suppliers of the telecom and industrial laser industries and are able to provide significant component reliability data for the purchased components. Based on the reliability model, sufficient pump diode and diode driver redundancies are built into the oscillator and the power amplifier.

Figure 4 shows the calculated reliability of >97% (FIT = 652) assuming 24/7 operation over 5 years. The high reliability is achieved by using significant redundancy and derating for the laser pump diodes and significant redundancy for the electronics.

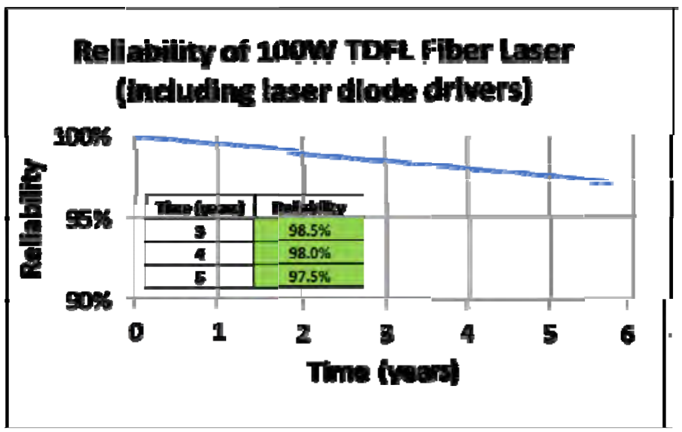

Figure 4. Overall Tm transmitter reliability is calculated to be 97% for 5-year spaceflight operations assuming 24/7 operation and includes estimates for all components and subsystems and accommodation for redundancy.

Table 2 shows estimated LOM efficiency using measured performances of the pump diodes and the amplifier stages. Highly efficient >48% high-power, multimode 793 nm pump diodes are used for pumping the power amplifiers. The system requires a total electrical power of 411 W into the pump diodes to support 100 W output optical power. LOM efficiency is 24.3%, which is defined as the total output optical power divided by the laser diode pump electrical power.

Table 2. Demonstrated power budget for LOM at 100 W optical output power.

100 W Optical Power	Optical to-Optical Efficiency	Pump Diode Efficiency	Total Electrical Power into Pump diodes
Oscillator	0%	52%	32 W
Power Amplifier	55%	48%	379 W
Total Electrical Power into Pump Diodes (W)			**411 W**
LOM Efficiency			**24.3%**

4. VIBRATION, STRESS, AND PRESSURE VACUUM STRUCTURAL ANALYSIS

A structrual analysis model of the laser is developed for supporting the mechanical design of the space-qualifiable laser. Three laser packaging concepts with different levels of complexity in terms of number of layers and with differeing size, weight, and power (SWaP) properties were considred. Structural analysis is used in all three concepts to downselect design to the package presented in this paper. Vibration and pressure analyses were performed to evaluate launch loads and on-orbit performance in vacuum. A 3D structural finite element model, shown in Figure 5 (left), was built in

ANSYS v18.1 software to examine stresses in the aluminum housing and fasteners in addition to acceleration levels at the electro-optic components. Figure 5 (right) shows the calculated vibration mode shapes for the housing.

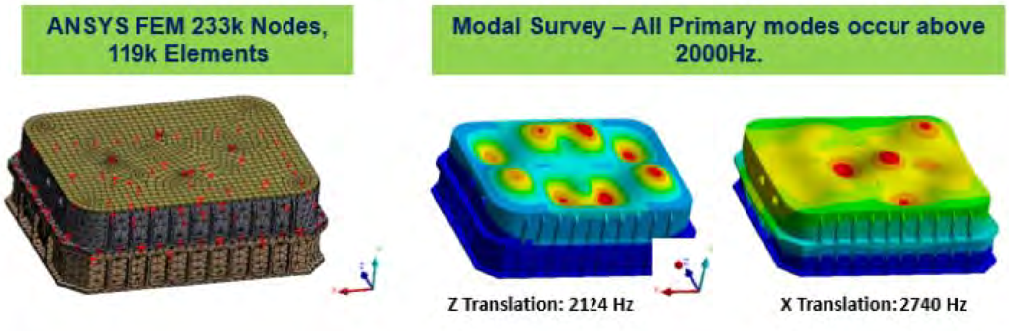

Figure 5. (left) Finite element model description–solid model in ANSYS 233k nodes, 119k elements for vibration analysis, and (right) vibration modes.

Extensive vibration analysis was performed in order to guarantee acceptable levels of vibration loads on the optical and electronics components during launch conditions. For purposes of this analysis, 14.1 GRMS random vibration input levels are chosen from the NASA GEVS document.[22] These loads are generally considered as conservatively high loads that envelope most launch vehicle vibration environments.

The worst-case vibration load that the electronics housed in the LEM compartment will experience was evaluated. The model predicts 20 GRMS acceleration in the normal direction as the worst-case vibration level, which is tolerable for electronics. There is some minor coupling to the top LEM cover, which resonates between 1100-1200 Hz, that contributes to the overall power spectral density (PSD) energy level in the LEM. The LOM housing design for the multi-level lower benches where the optical components are mounted achieves negligible amplification in vibration levels. Thus, optical components are expected to experience no more than the ~15 GRMS.

Figure 6 shows calculated total deformation and stresses for the LOM housing and MDM connector when an internal pressure of 18 psi is applied (1 atm + 3 psi over pressure + air expansion over mission temperature profile). A very small maximum total deformation of 0.002″ is predicted due to the ribbing. A maximum stress of 7.2 ksi and 15.4 ksi are predicted for LEM and LOM housings, respectively. These stress levels present a sufficient 2.6x margin for housing material. For the welded connector the maximum calculated stress is 1958 psi which presents a 4x margin for the welded connector due to the T0 temper that occurs from the welding process.

LEM/LOM fastener stresses are quantified under 18 psi pressure differential as well. All fasteners have positive margin in a vacuum environment. The LEM is very stiff, which helps distribute the pressure load among the fasteners. There is very little shear load. Assumed Factors of Safety (FS) are 1.25 and 1.4 for yield and ultimate strengths, respectively.

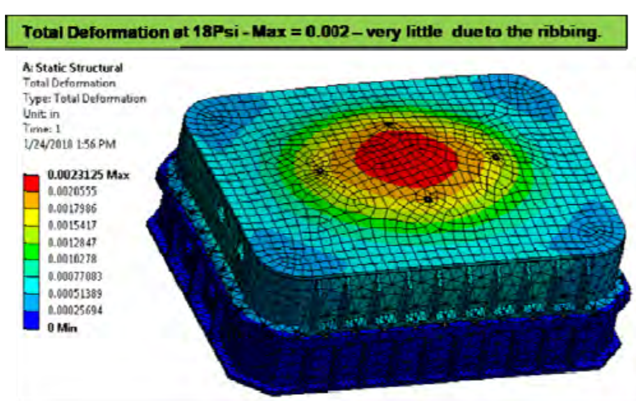

Figure 6. Simulated (top) spatial distribution of total deformation.

5. THERMAL ANALYSIS

A comprehensive thermal model is developed for the high-power laser using ANSYS v18.1 to solve for optical component and electronics steady-state temperatures. The finite element model contains 129k thermal solid elements with 281k nodes. Figure 7 shows finite element model description and the boundary conditions. The 100 W laser is designed to remove heat through the structure to its base mounting surface, which is a conductive thermal interface. For the analysis, the base temperature is kept at the worst case 40°C. During the mechanical housing design significant effort was spent to minimize temperature differentials between the base plate and various critical optical components housed in the bottom LOM and the electronic boards housed in the higher LEM section. Conservative heat consumption numbers are used in the analysis. The analysis includes heat loads due to the diode drivers, power conditioning electronics, and control electronics. The power amplifier stage dissipates the bulk of the heat (more than 90%). The thermal analysis quantifies margins on all of the internal electro-optical components. All components are found to have positive margin compared to their specified limits assuming a 40°C laser base mounting temperature.

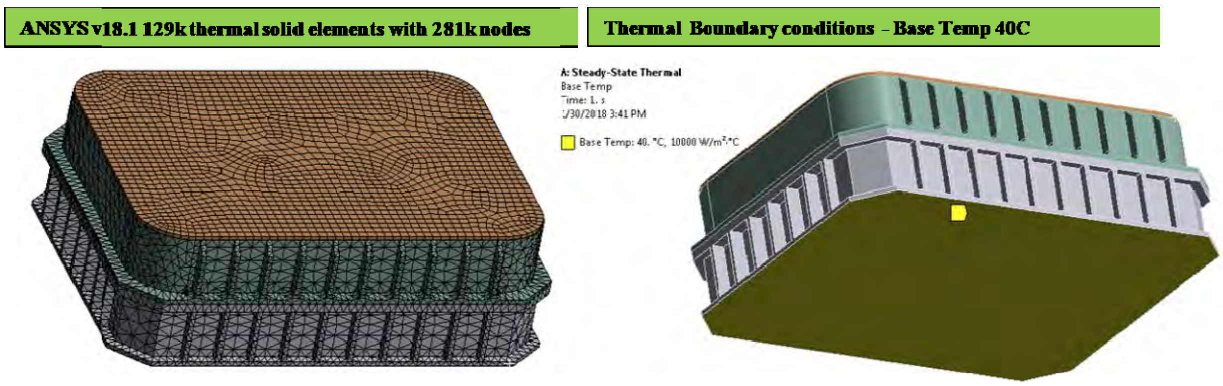

Figure 7. (left) Finite element model description–thermal model in ANSYS v18.1, 129k thermal solid elements with 281 nodes, and (right) thermal boundary conditions where the base temperature is kept at 40°C.

6. PRELIMIANRY VIBRATION TEST – PARTIALLY POPULATED LASER

Fibertek has carried out vibration testing of the partially populated laser package to 14.1 GRMS random vibration input levels based on the NASA GEVS document.[21] The objective of the test was to characterize three-axis vibration response levels at multiple points of the multi-layer laser structure and verify the predictions of the ANSYS FEM structural model. Good correlation between the model and experimental data was achieved. Furthermore, the key high-power optical components including pump diodes, isolators, and filters were installed in the laser package and subjected to the vibration testing. Many of the 2 µm fiber components used in this laser are also widely used in the telecommunications and industrial laser industry and had already been individually tested to Telcordia GR-63-CORE 5.4.2 and MIL-STD-883. Some of the high-power components in the laser system were not qualified by vendors to this high degree of the vibrational integrity—as part of the test prequalification, these high-power components were targeted as a risk reduction task.

Figure 8 shows the partially populated laser package mounted on the vibration shaker. The laser was tested in three axes to 14.1 GRMS levels. Two sets of vibration measurements were carried out due to higher than expected vibration levels during the first test. The ANSYS FEM was used to correlate the first set of results and determine assumption inconsistencies between the multi-layer structure and the shaker interface plate. In the first experiment, the installed high-power fiber-optic components experienced ~30 GRMS vibration levels and survived without any measurable degradation. For the second test, which also included the high-power optical components, corrective actions were implemented to improve the vibration performance of the laser canister.

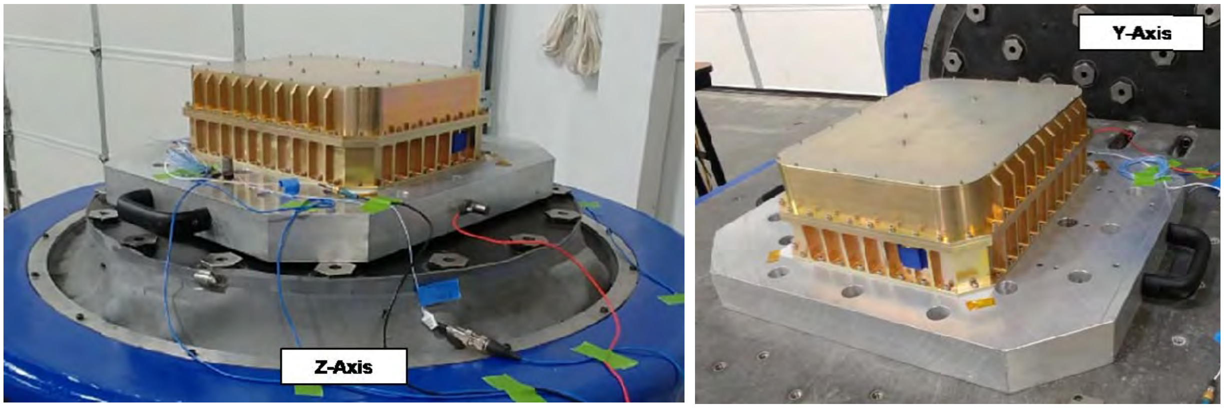

Figure 8. Pictures of the partially populated laser packaged mounted on the vibration shaker.

Excellent agreement between the model and measured spectral responses was achieved for various locations in the laser structure. Measured vibration levels at the high-power optical components are 16.3 and 15.6 GRMS in X and Y directions, respectively. The LOM is not expected to resonate in Z when properly attached to the spacecraft. For the LEM, the worst case predicted levels are 21 GRMS in Z. The installed high-power components successfully survived both vibration tests even though the components experienced significantly more than the planned levels of vibration. With the demonstrated performance of the partially populated laser, we expect with high confidence that the final delivered laser will be capable of withstanding the necessary vibration levels for demonstrating TRL-6 level maturity.

7. CONCLUSIONS

Fibertek has designed and is building a space-qualifiable, space-tracible 100 W average power fiber laser well on its way to being TRL-6. The 1940 nm thulium doped fiber laser (TDFL) meets all the requirements for a NASA Earth Science spaceflight 2 μm Ho:YLF pump laser including a >5-year mission lifetime. High-power laser design was achieved in a compact 10.6″ x 13.8″ x 4.4″ size. During the design of the laser package extensive thermal and structural FEM modeling was performed to guarantee compliance with the space environment. Preliminary environmental testing results show the potential for the laser package to achieve TRL-6 with future environmental testing. The laser is planned to go through thermal vacuum (TVAC) testing before the delivery in 2019.

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