Solid-state Laser Development for the *in Situ* Spectroscopic Europa Explorer Instrument

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Abstract— **The *in Situ* Spectroscopic Europa Explorer (iSEE) instrument is an ultra-compact laser-enabled Raman spectrometer instrument that meets the top-level science requirements for multiple future planetary *in situ* missions to explore the surface and atmospheric chemistry of planetary bodies across the Solar System. Enceladus, Europa, the Moon, Mars, and Venus are some of the primary targets for future NASA missions to search for extraterrestrial life and potentially habitable environments beyond Earth, further our understanding of the timing and formation of the Solar System and identify potentially viable economic resources such as water and/or valuable metal assets. We report on the advancement and space flight qualification of a compact, robust, solid-state laser operating at 515 nm that serves as the excitation source for the iSEE investigation.**

Table of Contents

1. Introduction

The iSEE instrument is a compact, versatile Raman spectrometer instrument currently under development at Impossible Sensing and NASA Goddard Space Flight Center (GSFC). The iSEE instrument has been designed to meet the science objectives of future missions to several targets across the Solar System, and with different spacecraft configurations including orbiters, flythroughs, landers, and rovers. The objective of the iSEE instrument technology development program is to mature the instrument to a technology readiness level (TRL) 6 [1], a key milestone for all space flight hardware that demonstrates the instrument can meet performance requirements in relevant space environments. Once TRL 6 is demonstrated the iSEE instrument will be well positioned for future planetary mission proposal opportunities.

At NASA GSFC we are designing, building, testing, and qualifying the laser subsystem for the iSEE instrument. The laser is a diode pumped solid state Yb:YAG microchip laser oscillator, frequency doubled to 515 nm and coupled to a multi-mode fiber for delivery to the Raman spectrometer probe. Optical models were developed to optimize the second harmonic generation conversion efficiency and determine the optimal non-linear crystal material and specifications. A breadboard laser was built and tested to demonstrate the performance requirements and validate the optical models. The breadboard laser was delivered to Impossible Sensing for breadboard instrument testing. The engineering test unit (ETU) has been designed and fabricated and is in the assembly process. The iSEE ETU laser has been designed to meet the performance, form factor, and environmental requirements of the iSEE instrument. The ETU laser will go through performance characterization and environmental testing including vibration/shock and thermal vacuum testing (TVAC) at GSFC. The laser will be delivered to Impossible Sensing for integration and testing with the Raman spectrometer instrument after completion of the qualification testing campaign in early 2023.

2. Science Objectives

iSEE is designed to enable search for life in the Solar System and resource exploration on the Moon. Specifically, iSEE delivers fast molecular and structural analysis without the need for sample processing. These are unprecedented and lean screening capabilities that inform downstream, more complex operations. For example, on Europa, ice samples would be delivered to a lander. iSEE would detect trace amounts of organic material. This would trigger the next batch of analysis, which could include mass spectrometry, to determine biotic v abiotic origin of those organics. Where iSEE does not detect the presence of organics, that ice sample can be discarded, thus saving precious time and power in complex isotopic analysis. On the Moon, iSEE would rapidly determine surface mineralogy and ice distribution at a distance, which would indicate mission planners—or robots—where to drill. Table 1 summarizes these, and other science objectives enabled by iSEE, along with key performance metrics of the instrument.

Table 1. Mission focus areas, science objectives, and key iSEE science capabilities.

Mission focus area	Mission Objectives and *Priority Science Goals*	*i*SEE Science Objectives	*i*SEE capabilities
Europa Lander	Understand the composition and chemistry of non-ice material ***Search for evidence of life***	1. Detect & quantify **organic compounds** 2. Search for **biomolecules** 3. Search for sources of **chemical energy** 4. Determine fine-scale **mineralogy** 5. Ice **crystallinity & ice phase** distribution	• Organic content ≤ 1 ppb in solid matrices • Mineralogy and volatile content ≤ 0.1 wt. % • Spatial resolution ~25 µm • 250 ms acquisition times for full spectrum at max resolution • On-spectrometer chemometrics • Small footprint: 2.5 Kg, 4,000 cc • Dual external (arm) and internal laboratory analysis with fiber-Raman heads
Comet Surface Sample Return	Characterize the surface region sampled		
Lunar South Pole-Aitken Basin Sample Return	Document the geologic context of the landing site		
Ocean Worlds (Enceladus)	***Search for evidence of life*** Assess habitability		
Mars (Discovery)	***Search for evidence of life*** Assess habitability		

3. LASER REQUIREMENTS

Laser Performance Requirements

The iSEE instrument requires a pulsed 515 nm wavelength and narrow spectral bandwidth laser as the excitation source for the Raman spectrometer. The green wavelength was chosen based on the tradeoff in excitation and detection efficiency as it stimulates the strongest Raman signals from geological samples (both ExoMars RLS and Mars 2020 SuperCam instruments utilize a green excitation laser for Raman analyses) [2,3]. A pulsed laser source in combination with gated detection of the Raman emission removes spectral interference from background ambient light and mitigates long-lived sample fluorescence in Raman spectroscopy [4,5,6]. A narrow spectral bandwidth laser is needed to achieve the spectral resolution of the Raman spectrometer [7]. The iSEE laser performance requirements are described in Table 2.

Environmental Requirements

As part of the technology development program, the iSEE laser will go through space flight qualification steps including vibration/shock and thermal vacuum (TVAC) testing at GSFC to advance the design to TRL6. The environmental requirements for the iSEE laser were derived based the General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects as well as Mars environments [8,9]. The iSEE laser will operate at a nominal temperature of 20°C ± 1°C. The operate without damage range is 10°C to 30°C, and the non-operation survival temperature range is -25°C to 40°C. The iSEE laser temperature requirements are shown in Table 3. Structural and thermal models have been created for the iSEE laser and analysis is in progress. Both structural and thermal analysis will be completed prior to the environmental test campaign.

Table 2. Laser performance requirements for the iSEE instrument.

Parameter	iSEE Requirements
Wavelength	515 ± 0.1 nm
Pulse Energy	20 µJ
Pulse Repetition Frequency	10 kHz
Pulse Width	1 ns
Spectral Bandwidth	<20 pm
Wavelength Stability	±0.1 nm
Fiber Optic Core Diameter	105 - 200 µm
Fiber Optic NA	0.22
Laser Enclosure	>1 atm Clean Dry Air

Table 3. iSEE laser temperature requirements.

Temperature Requirement	iSEE Laser
Operational Temperature	T_o (20°C) ± 1°C
Operate without damage	10°C to 30°C
Non-operational survival temperature	-25°C to 40°C

4. LASER DESIGN

Laser Design

The iSEE laser is a diode-pumped 1030 nm Yb:YAG microchip laser with a second harmonic generator (SHG) to achieve an output wavelength of 515 nm and coupled to a multi-mode fiber for delivery to the Raman spectrometer probe. The fundamental 1030 nm laser operates at a pulse repetition frequency (PRF) of 10 kHz with pulse energy of ~95 µJ and ~800 ps pulse width.

A 940 nm, 10W laser diode from IPG is used as the pump laser for the Yb:YAG microchip laser oscillator. The 940 nm pump laser diode is fiber coupled and operates in CW mode. It is mounted to a thermoelectric cooler (TEC) to provide thermal pump wavelength stability. The output pump laser beam is collimated and focused with a pair of lenses for end-pumping the Yb:YAG crystal. The oscillator is passively q-switched using a Cr^{4+}:YAG saturable absorber diffusion bonded to the Yb:YAG crystal. A narrow bandwidth volume Bragg grating (VBG) is used as the output coupler for the oscillator to achieve a narrow spectral bandwidth of 17 pm. The VBG is bonded to a TEC for temperature control and spectral tuning. The Yb:YAG microchip laser oscillator was developed previously at GSFC under a NASA Instrument Incubator Program. This laser performance has been demonstrated on an airborne campaign as part of the Airborne Lidar Surface Topography Simulator (A-LISTS) instrument [10].

A 30 mm focal length lens is placed at the output of the 1030 nm oscillator to achieve a collimated beam diameter of ~0.350 mm at $1/e^2$ or ~0.2 mm at full width at half maximum (FWHM) for efficient SHG to 515 nm. A 15 mm long Type II KTP (potassium titanyl phosphate) crystal is used for SHG. The 1030 nm output is linearly polarized so a half-wave plate is used to achieve the orthogonal polarization needed for Type II critical phase matching for SHG. A pair of Risley wedges are used for beam steering and alignment in the KTP crystal. After the KTP crystal, the residual fundamental 1030 nm is separated from the 515 nm beam using a pair of dichroic filters. Another pair of Risley wedges, a tilt plate, and a focusing lens are used to coupling of the 515 nm beam into the multimode optical fiber to produce an output laser pulse energy of 20 µJ. A silicon photodiode captures a small amount of the 1030 nm beam and serves as a start pulse detector for time synchronization with the Raman spectrometer instrument.

A custom vacuum fiber feedthrough assembly was designed with two 105 µm core and 0.22 NA fibers, and two 200 µm core and 0.22 NA fibers. One fiber is needed for coupling the laser to the iSEE instrument, and the additionally fibers provide redundancy and design flexibility for integration with the iSEE instrument. The fiber feedthrough assembly was fabricated by Coastal Connections and is mounted to the laser enclosure using an O-ring to maintain a hermetic seal. The fibers are routed inside the laser enclosure and terminated with a ferrule with a custom 4° angle polish to prevent reflections back to the oscillator. The output fibers are designed to operate in vacuum with low outgassing PEEK jacketing and terminated with FC/APC connectors with a standard 8° angle polish. A picture of the vacuum fiber feedthrough assembly is shown in Figure 1.

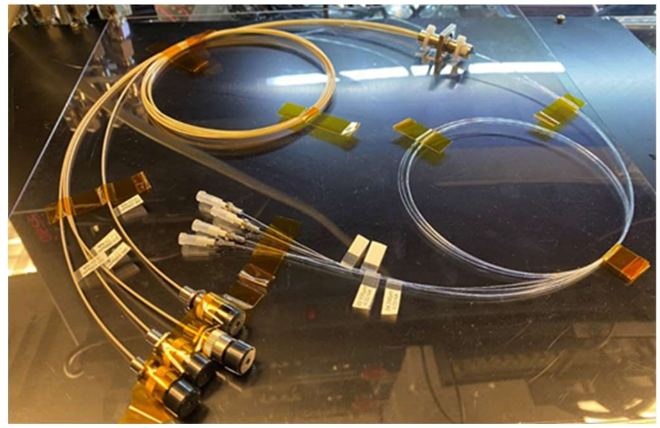

Figure 1. iSEE laser vacuum fiber feedthrough assembly.

Opto-Mechanical Design

The laser enclosure is pressurized with >1 atm of clean dry air to reduce the risk of contamination induced laser damage [11,12,13,14,15,16,17,18,19]. Contamination induced laser damage is one of the major concerns for spaceborne lasers. By pressurizing the laser enclosure with clean dry air, it will significantly lower the outgassing rate and the presence of oxygen will reduce the adsorption of contaminants (particularly organic species) on the laser optics. Additionally, we select only low outgassing materials, and precision clean all hardware and opto-mechanical components prior to assembly.

The laser has been designed to minimize the size, weight, and power (SWaP) for a planetary lander instrument with minimal resources. The laser enclosure is made of aluminum with over all dimensions: 5.75 in x 7.75 in x 1.8 in and mass 1.77 kg. The iSEE laser enclosure is mounted on pedestals with flexures for alignment and to provide thermal stability during TVAC testing. Additionally, there is a water-cooled plate attached to the bottom of the laser enclosure to provide a constant thermal interface of 20°C to the laser enclosure for laboratory testing. The opto-mechanical component mounts are based on previous flight heritage designs. The CAD model of the iSEE laser is shown in Figure 2.

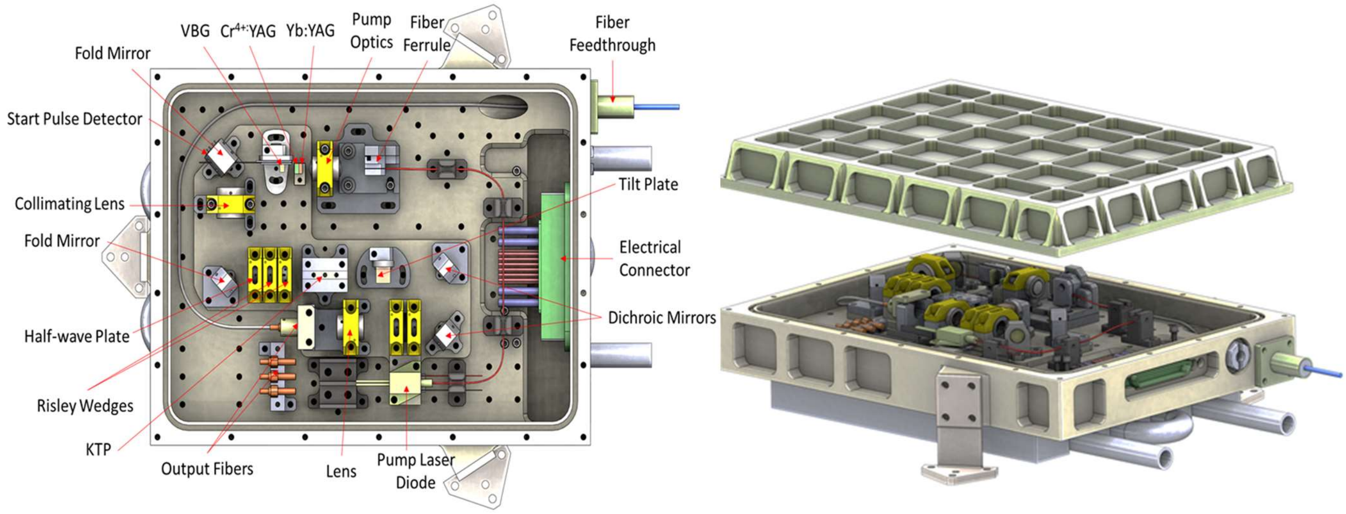

Figure 2. CAD model of the iSEE laser.

5. Laser Modeling and Breadboard Laser Performance

Non-linear Optical Modeling

We developed non-linear optical models to optimize the SHG conversion efficiency from 1030 nm to 515 nm in the iSEE laser design. We have identified two non-linear crystal materials for SHG, KTP and LBO (lithium triborate). Based on the optical modeling we were able to determine the optimal material, non-linear optical crystal length, and beam size for maximum conversion efficiency to 515 nm.

The optical model was developed using SNLO software and the input parameters were based on the iSEE laser breadboard performance (1030 nm pulse energy = 92.3 µJ and pulse width = 0.85 ns) [20]. The KTP crystal length was varied between 2.5 mm and 40 mm. The beam diameter, defined as full width at half maximum (FWHM) was varied between 0.2 – 0.55 mm. Figure 3 show the results of the SNLO optical model for SHG to 515 nm using Type II KTP as a function of both beam diameter and crystal length. Approximately 73 µJ or ~79% SHG conversion efficiency can be achieved for all beam sizes between 0.2 – 0.55 mm (FWHM) by increasing the crystal length between 12.5 – 40 mm. The shortest KTP crystal that can be used to reach the maximum conversion efficiency is 12.5 mm with a 0.2 mm (FWHM) beam size.

Two optical models were developed for SHG using LBO with different phase matching conditions: Type I (1030.0(o) + 1030.0(o) = 515.0(e)), and Type II (1030.0(o) + 1030.0(e) = 515.0(o)). For this model the same breadboard laser parameters were used (1030 nm pulse energy = 92.3 µJ and pulse width = 0.85 ns). The beam diameter was varied between 0.2 – 0.4 mm (FWHM), and the crystal length was varied between 5 - 50 mm. Figure 4 shows the results of the SNLO model for SHG to 515 nm using Type I LBO and Type II LBO as a function of both beam diameter and crystal length.

Figure 5 shows the performance of all 3 non-linear crystal options evaluated with SNLO: Type II KTP, Type I LBO, and Type II LBO. The maximum 515 nm energy can be achieved with a 10-20 mm long Type II KTP crystal and a beam diameter of 0.2 mm (FWHM). A similar 515 nm output energy can be achieved using a longer (>30 mm) Type I LBO crystal with a beam size of 0.2 mm (FWHM). The Type II LBO crystal does not generate enough 515 nm energy at any length or beam size. Based on the optical model results a 15 mm long KTP crystal was selected for SHG in the iSEE ETU laser design.

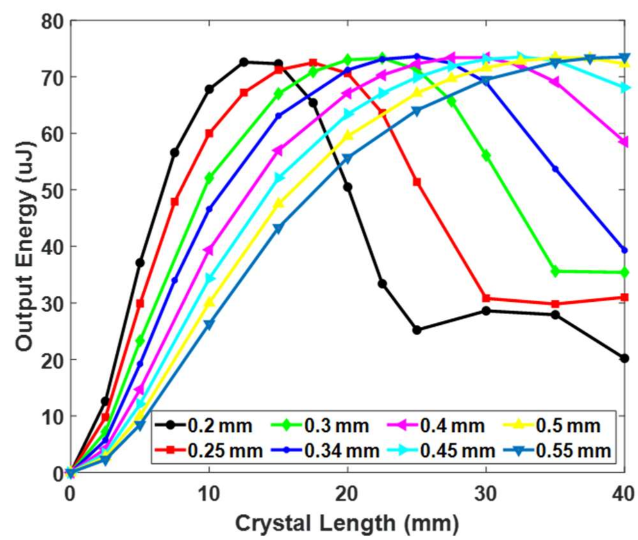

Figure 3. SNLO modelling results for 515 nm SHG output pulse energy using Type II KTP crystal as a function of beam diameter and KTP crystal length.

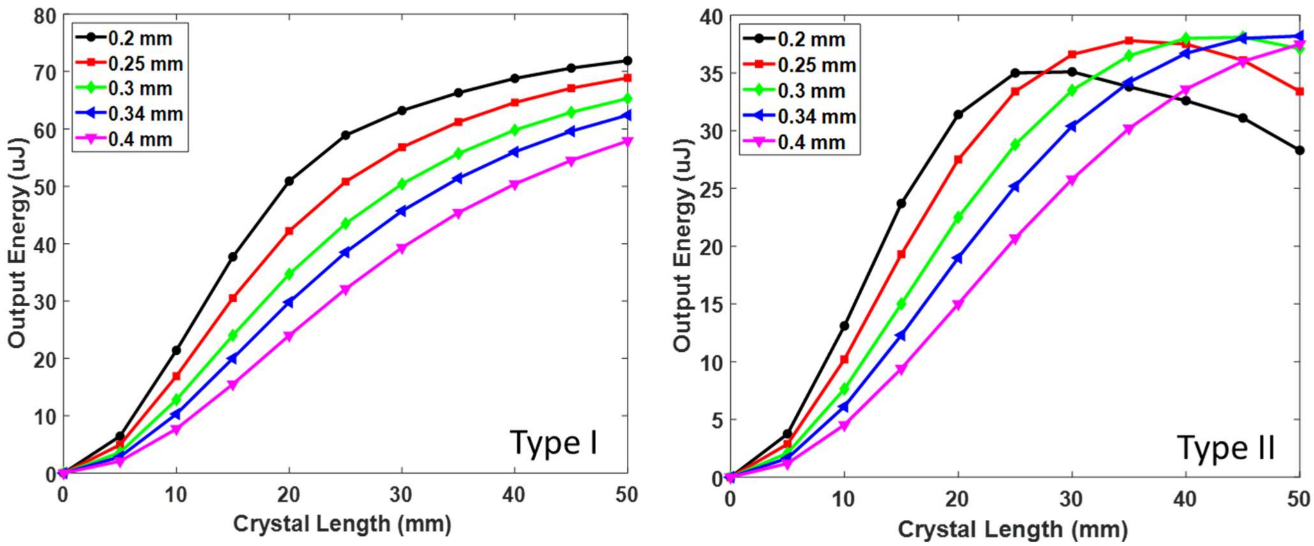

Figure 4. SNLO modelling results for 515 nm SHG output pulse energy using Type I LBO (left) and Type II LBO (right) crystal as a function of beam diameter and KTP crystal length.

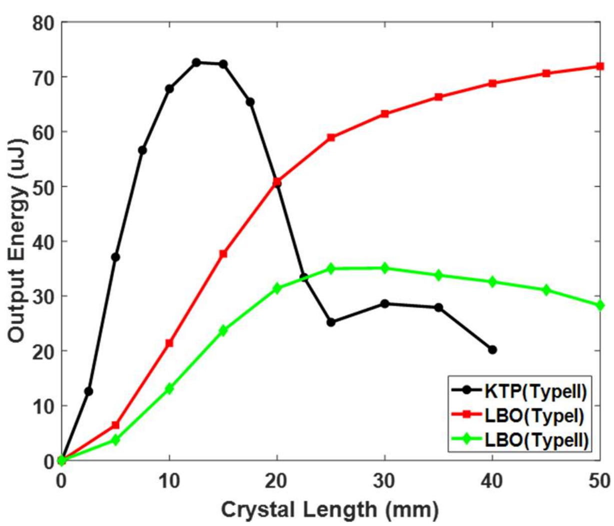

Figure 5. SNLO modelling results for SHG using KTP, Type I LBO, and Type II LBO as a function of crystal length for a 0.2 mm diameter (FWHM) beam.

Breadboard Laser Performance

A breadboard iSEE laser was built using a TRL4 Yb:YAG microchip oscillator built for A-LISTS to generate the fundamental 1030 nm [21]. The 1030 nm laser operated at a PRF of 10 kHz, and pulse energy of 97 µJ. The VBG was maintained at a temperature of 19.5°C. A 12 mm long Type II KTP crystal was used for SHG. The 1030 nm beam was collimated to a beam waist size of ~0.2 mm FWHM to maximize SHG conversion efficiency. The KTP crystal was maintained at 28.65 °C using a TEC. The 515 nm free space output energy was measured to be 61 µJ corresponding to a 63% SHG conversion efficiency. A 50 mm focusing lens was used to couple the 515 nm beam to a 105 µm core, 0.1 NA fiber patch cable. A half-wave plate was used to attenuate the 515 nm beam by changing the phase matching condition and reducing the SHG conversion efficiency to 515 nm to minimize the risk of damaging the fiber end face. The focusing lens was positioned so the spot size was defocused at the fiber end face to further reduce the risk of damage at the air-glass interface of the fiber. The pulse energy was measured at the fiber optic output to be >20 µJ to meet project requirements, and no further coupling optimization was done to avoid damaging the fiber optic. The breadboard laser is shown in Figure 6. The breadboard laser was delivered to Impossible Sensing for integration and testing with the breadboard iSEE instrument.

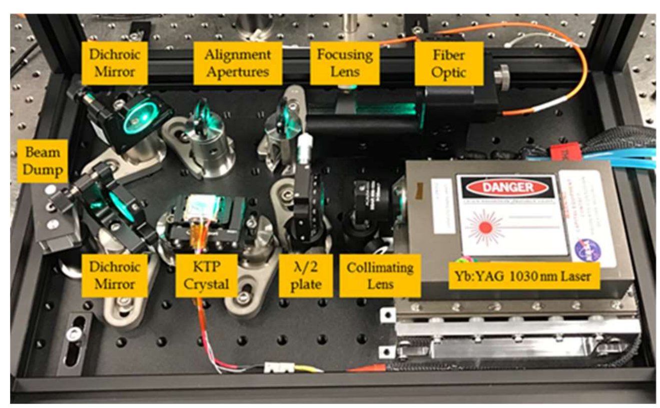

Figure 6. iSEE breadboard laser.

6. Engineering Test Unit Laser

Pump Laser Diode Testing

Ten IPG PLD-10 pump laser diodes were tested and characterized in continuous wave (CW) mode at 25°C. The following measurements were taken on all 10 pump laser diodes: optical power as a function of current, threshold, slope, efficiency, voltage, center wavelength, and linewidth. The characterization data was compared to the vendor supplied data and all the pump laser diodes met the vendor specifications. Figure 7 shows the measured pump laser optical power and efficiency as a function of current, and the spectral measurement of the pump laser diode at 25°C. One out of the ten pump diodes will be used for the ETU laser assembly.

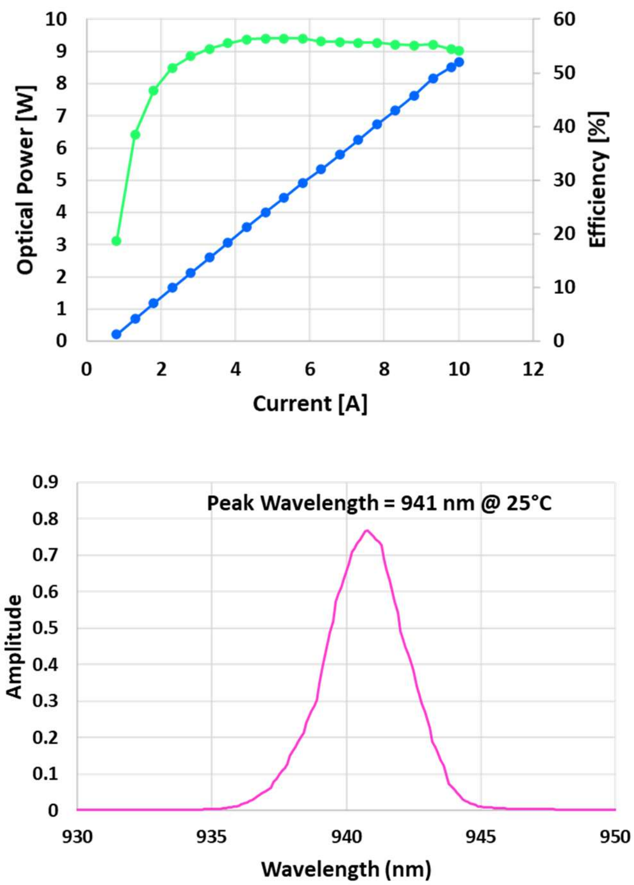

Figure 7. Pump laser diode optical power and efficiency as a function of current (top) and spectrum measured at 25°C.

ETU Laser Assembly

The engineering test unit (ETU) laser design is complete, and the enclosure and all opto-mechanical components have been fabricated. All laser, optics, and opto-mechanical components have been received at GSFC. The ETU laser assembly is currently in progress. All optics have been bonded to mechanical cells for integration and alignment into the laser enclosure. The electrical wire harness and routing is currently in progress. Figure 8 shows a picture of the ETU laser during assembly.

Structural and thermal analysis of the iSEE laser is on-going and will be completed prior to the environmental test campaign in the fall/winter of 2022. Once the assembly is complete the laser will go through performance characterization, shock/vibration and TVAC testing at GSFC prior to delivery to Impossible Sensing for integration with the iSEE instrument in early 2023.

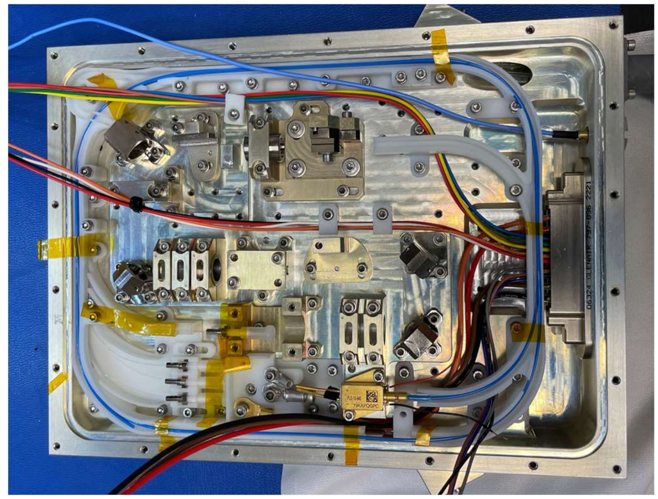

Figure 8. iSEE engineering test unit laser during assembly and electrical harness routing and integration.

7. SUMMARY

GSFC is developing and space flight qualifying a compact and robust fiber-coupled 515 nm laser for the iSEE instrument with the goal of reaching TRL 6 by the end of the technology development program. The laser has been designed for a planetary mission with limited resources. The iSEE instrument is a next generation Raman spectrometer instrument that meets the science goals and objectives of numerous targets for future planetary missions across the Solar System.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support from NASA Maturation of Instruments for Solar System Exploration (MatISSE) Program.

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BIOGRAPHY

Molly Fahey *is a laser scientist in the Laser and Electro-Optics Branch at Goddard Space Flight Center where she supports the development of laser hardware and electro-optic components for current and future Earth science, Planetary science, Heliophysics, and Astrophysics space flight programs. She received a BA in Physics from the College of St. Benedict/St. John's University, St. Joseph, MN in 2005, and a MS in Mechanical Engineering from Florida Institute of Technology, Melbourne, FL in 2007.*

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Matthew Mullin *is a laser engineer at NASA Goddard Space Flight Center and is currently on the team developing a space qualified UV laser for the mass spectrometer on board the Dragonfly Mission. He also works on several laser-based technology development efforts at NASA Goddard including the in-situ Spectroscopic Europa Explorer (iSEE) laser system; and other lunar research instruments such as the Potassium Argon Laser Experiment - KArLE. He graduated from The American University in 2018 with a BA in*

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Michael Bolleter *is an engineering technician at NASA Goddard Space Flight Center with a focus on electrical packaging through the entire instrument development cycle including design, assembly, and I&T. He has prior experience in advanced instrumentation systems for testing experimental jet engines and helicopters. He graduated with A.S. degrees in Electrical Power Technology and Electronics from Palm Beach State College.*

Pablo Sobron *received a PhD in Physics and Technology Materials from the University of Valladolid in 2008. Since then, he's developed new technologies to explore Mars and other planetary bodies, catalogue biodiversity and critical mineral deposits in the seafloor, measure and eliminate greenhouse gas emissions, and monitor carbon capture and sequestration in soil and in the ocean. Sobron founded Impossible Sensing in 2016 to commercialize solutions for these applications.*

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William Mamakos *founded Design Interface Inc. in 2001. Design Interface is an established company that is focused on providing professional Design Engineering Services serving Government and Commercial markets, as well as the research and science communities. Mr. Mamakos has designed and developed complex mechanical, optical-mechanical, electro-mechanical instruments and mechanisms for ground based, airborne and spaceborne instruments and payloads for over 37 years. Specializing in precision spaceborne optical instruments, lasers, and mechanisms as well as electronic packaging of high voltage electronics, power converters and detectors.*