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SPIE.

Event: SPIE Defense + Security, 2018, Orlando, Florida, United States

Progress on high-power Yb, Tm, and Raman fiber lasers

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ABSTRACT

To advance the science of high power fiber lasers, in-house drawn specialty optical fibers are investigated. Ongoing research involves the fabrication and testing of Yb- and Tm-doped fibers at 1μm and 2μm. Using specialized fiber and pump mixing geometries, dopant profiles and system configurations, the performance of our in-house drawn active fibers has been examined. Results on a highly multi-mode, high average power pulsed Raman fiber amplifier pumped by a thin disc laser are presented. The Raman fiber is a large mode-area graded index fiber, also drawn in house. Finally, the development of capabilities for kilometer range propagation experiments of kW-level CW and TW-level pulsed lasers at the TISTEF laser range is reported.

Keywords:
Thulium, Ytterbium, fiber laser, Raman laser, laser propagation, graded-index fiber, fiber development

1. INTRODUCTION

Over the past two decades, the average power output of fiber lasers has increased tremendously. State of the art systems utilizing Yb-doped fibers now provide diffraction limited output at the multi-kW level. However, further power scaling is currently hindered by a nonlinearity known as transverse modal instability (TMI). As this phenomenon is dependent on the average power and thermal load, high power fiber lasers and amplifiers quickly run into this issue in the 1-5 kW regime. Recent works have explored potential mitigation strategies for modal instability including bend induced loss and differential modal loss inside the fiber gain medium. However, to engineer diffraction-limited systems up to and beyond 10 kW, new strategies are necessary. Recent theoretical work has shown that the modal instability threshold increases as λ^2 which suggests that moving to longer wavelengths with Tm-doped fibers may be advantageous. Raman fiber amplifiers also present a novel technique for generating kW-class systems, although the effects of TMI in these systems has yet to be identified. Currently, we have ongoing work regarding each of these three fiber laser platforms. This manuscript summarizes our recent experimental work on 1 μm, 2 μm, and Raman fiber lasers.

Besides the development of new laser sources, the recent acquisition of space at the Townes Institute Science and Technology Experimentation Facility (TISTEF) allows for the study of laser propagation at long range. TISTEF includes a 1 km laser range, outfitted with a full suite of diagnostics, along with a fully equipped laser laboratory and infrastructure.

2. YTTERBIUM FIBER DEVELOPMENT

In this study, we explore the optical performance of an in-house drawn, low-numerical aperture (NA) Yb:fiber. This fiber consists of a specialty all-glass pump cladding to confine the pump light and provide efficient mode-mixing and pump absorption. This all glass pump cladding is extremely robust and alleviates issues associated with low-index polymer pump claddings. Overall, an output of 578 W is obtained with 81.6 % slope efficiency at 1061 nm. This system was limited only by the fiber length and available pump power, indicating excellent potential for future power scaling.

Laser Technology for Defense and Security XIV, edited by Mark Dubinskiy,
Timothy C. Newell, Proc. of SPIE Vol. 10637, 1063702 · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2305241

Low-NA Yb:fiber Design and Performance

The Yb:fiber used in this experiment was an in-house drawn, low-NA Yb-doped fiber. This fiber had a 22 µm core diameter and a 430 µm specialty, all-glass pump cladding with NA of ~0.22 and 660 µm total outer diameter. The core is doped with 0.1 mol% Yb_2O_3 and 1.5 mol% Al_2O_3, providing a core numerical aperture (NA) of 0.048. The measured refractive index profile of the fiber is shown in Fig. 1 displaying excellent index uniformity across the core.

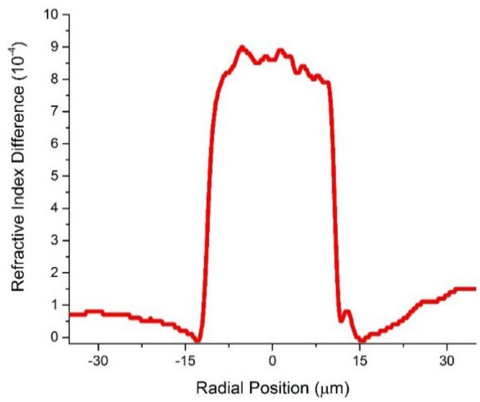

Figure 1: Measured refractive index profile across the core region of the low-NA fiber.

The amplifier setup, shown in Fig. 2, consisted of a 12 m piece of the low-NA fiber. The fiber was mounted on a custom fabricated 40 cm outer diameter mandrel to prevent thermal failure of the polymer. The amplifier was pumped at 976 nm up to 900 W by a 220 µm, NA=0.22 fiber delivered pump diode and seeded at 1061 nm with up to 20 W using a commercial single-mode fiber laser. Dichroic mirrors were used to discriminate between the pump and signal light. A total pump absorption of 7.5 dB was obtained, corresponding to 0.6 dB/m absorption in the 12 m fiber. The amplified signal output from the amplifier was analyzed with a 1 kW, water-cooled power meter and beam profiles were obtained using a wedge pickoff.

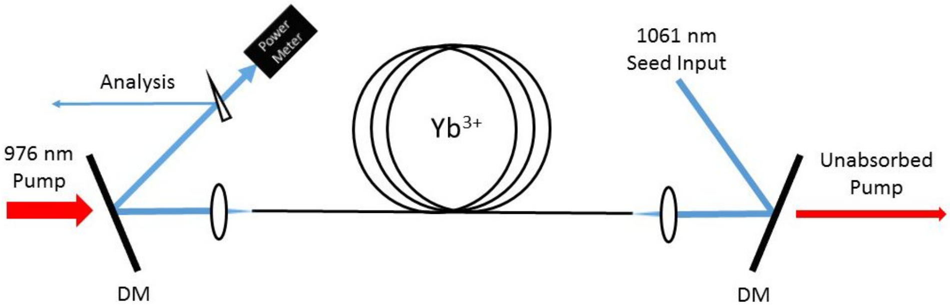

Figure 2: Experimental layout of the in-house drawn Yb:fiber amplifier. DM - dichroic mirror.

The amplifier output power and slope efficiency are shown in Fig. 3. We experimentally obtained 580 W of signal with 81.6% slope efficiency. The inset in Fig. 3 shows the output beam profile, demonstrating excellent beam quality.

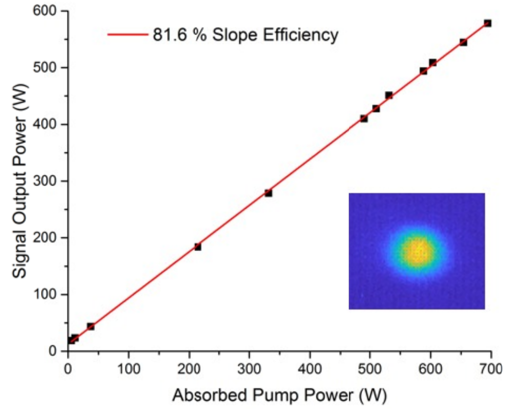

Figure 3: Amplified signal output power and slope efficiency of the low-NA fiber.

3. THULIUM FIBER DEVELOPMENT

Following from the development of Ytterbium-doped fibers for advanced 1-kW laser systems, we have also begun fabricating Thulium-doped fibers (Tm:fiber) for lasers operating at 2 µm. These lasers are utilized for critical applications such as: pump source for mid-infrared generation, exploiting the high atmospheric transmission window at 2.1 µm, and defensive countermeasures that require eye-safe wavelengths.

The purchased thulium-doped preform was doped with 2.5 wt.% Tm^{3+} ions and suffered large refractive index modulations. The preform was therefore homogenized by stacking-and-drawing 37 cores three times to smooth the transverse refractive index profile. The homogenized thulium-doped preform was used to fabricate two test fibers, one octagonal clad and one polarization maintaining (PM).

Octagonal Tm:fiber Design and Performance

The in-house drawn octagonal fiber has a 16 µm core diameter and a measured numerical aperture (NA) of 0.13. Therefore, the V-number is 3.27 at 2 µm supporting 2 spatial modes (LP_{01} and LP_{11}). The 105 µm diameter octagonal cladding enhances the pump absorption relative to a circular cladding. Figure 4 shows the fiber cross-section and refractive index profile for the octagonal Tm:fiber. The measured small signal, cladding absorption at 793 nm is 10.5 dB/m. A 2 meter Tm:fiber was initially tested as an amplifier seeded at 2053 nm. Figure 4 shows the output power and beam quality from the amplifier. With optimized free-space coupling, the amplified beam demonstrates a single-mode profile. The measured 37% slope efficiency agrees with simulations. Higher doping concentrations (>4 wt.%) are desired for efficiently utilizing the cross-relaxation process to reach >50% efficiencies [1].

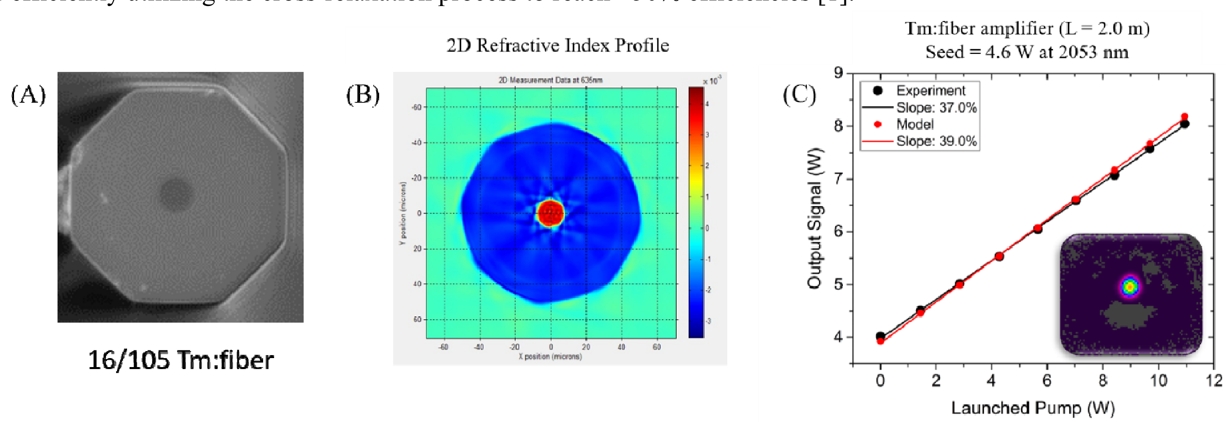

Figure 4. (A) Back-lit image of the in-house drawn Tm:fiber facet. The core/cladding diameter is 16/105 µm. **(B)** Refractive index profile of the fiber, the core NA is measured to be 0.13. **(C)** The Tm:fiber amplifier seeded at 2053 nm, the measured slope efficiency agrees with simulations. **Inset:** The amplifier delivers a single-mode output beam.

Polarization Maintaining Tm:fiber Design and Performance

The in-house drawn PM Tm:fiber has a 10 µm core diameter with 0.13 NA providing a V-number of 2.04, therefore this fiber is strictly single-mode at 2 µm. The circular pump cladding has a 130 µm diameter to match existing, commercially-available pump combiners and components. Figure 5 shows the fiber cross-section and refractive index profile for the PM 10/130 Tm:fiber drawn in-house. Unlike the previous octagonal fiber, this fiber was used for developing a Watt-level, wavelength tunable oscillator. A 5 meter length Tm:fiber was cladding pumped at 793 nm through a fiber pump combiner. The cavity was formed by a free-space diffraction grating for wavelength flexibility, and a flat cleave as the output coupler. The oscillator produced 8 W average power with single-mode beam quality, as shown in Figure 5. The PM Tm:fiber oscillator could operate over a wide >140 nm wavelength tuning range, extending from 1890 nm to 2030 nm, depicted in Figure 5. The measured FWHM spectral linewidths were less than 100 pm with OSNR > 55 dB. The measured polarization extinction ratio was 12 dB. Additional 793 nm pump diodes could be incorporated to boost the output power to 20 W, and a 1560 nm source could be included for core-pumping to enable shorter wavelength operation.

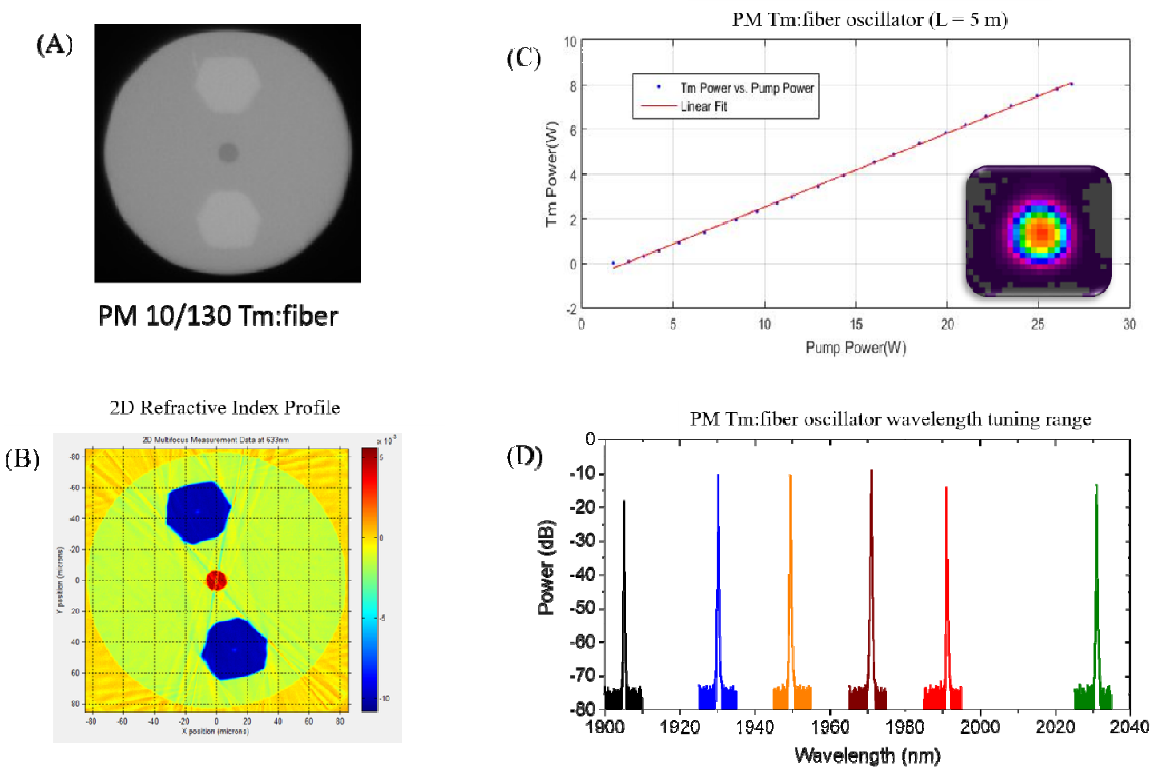

Figure 5. (A) Back-lit image of the in-house drawn PM Tm:fiber facet. The core/cladding diameter is 10/130 µm. **(B)** Refractive index profile of the fiber, the core NA is measured to be 0.13. **(C)** The PM Tm:fiber as an oscillator to deliver 8 W. **Inset:** The oscillator delivers a single-mode output beam. **(D)** Oscillator wavelength flexibility was enabled by rotating a free-space gold-coated diffraction grating to cover from 1890 – 2030 nm (1890 nm missing from plot).

4. RAMAN FIBER AMPLIFIER

The development of Raman lasers has increased significantly in the last 5 years, owing to significant improvement in diode and fiber laser pumping options and interest in achieving high power at otherwise difficult wavelengths [2-4]. The Raman gain bandwidth in silica fiber is on the order of 40 nm, and it is possible to use cascaded Stokes signals to achieve conversion in a range as broad as 400 nm [4,5]. Additionally, any source of sufficient brightness can be used to pump a Raman laser, limited only to the transparency window of the gain medium. Finally, Raman lasers are resistant to transverse modal instability, thanks to a reduced heat load per unit length, a resistance to photodarkening, and low small signal gain in the higher order modes compared to rare-earth doped fiber [2,3,6].

In this study, a custom drawn graded-index fiber was pumped with a commercial Trumpf Tru-Micro 7050, co-propagated with a low power seed at the wavelength of the first Stokes shift. The first Stokes signal line at 1080nm was 70 W average power at 50 kHz and 1.4 mJ in 30 ns pulses, limited by the brightness mismatch of the fiber and the pump at higher average power. This output was accomplished with a launched pump energy of 4.3 mJ, corresponding to a maximum conversion efficiency of 36%.

Graded-index Fiber Design

The graded-index fiber used in this experiment was drawn in house, with a core size of 200 µm and a refractive index contrast of 0.03 with a parabolic geometry, shown in Figure 6. The cladding extends to a diameter of 275 µm, and the fiber is protected by a high index polymer jacket. Graded index fibers are common media for Raman fiber lasers as they allow for brightness enhancement without separate pump and signal claddings [7]. In this experiment, the fiber was 12 m long.

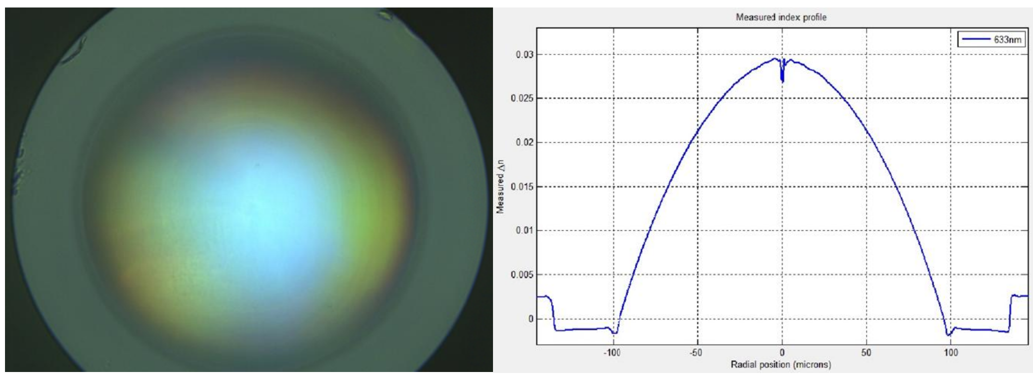

Figure 6: Microscope image and refractive index profile of the in-house drawn graded-index fiber.

Raman Amplifier Experiment and Performance

The amplifier setup, shown in Figure 7, consists of the TruMicro 7050, the amplified seed diode, the multi-mode graded-index fiber (MM-GRIN fiber), coupling optics and diagnostics. The TruMicro 7050 pump laser generates 1030 nm, 30 ns pulses up to 100 kHz and 80 mJ. In this experiment, 4.3 mJ pulses were used at 50 kHz because the beam quality degrades at higher average powers. The seed is a single mode diode at 1080 nm amplified to 230 mW. The pump and seed light are co-propagated using a dichroic mirror and a shared coupling lens, with approximately 90% coupling efficiency for both into the fiber. A power meter and OSA were used to monitor the output beam, and a second beam splitter was used to separate residual pump and signal for beam quality comparisons.

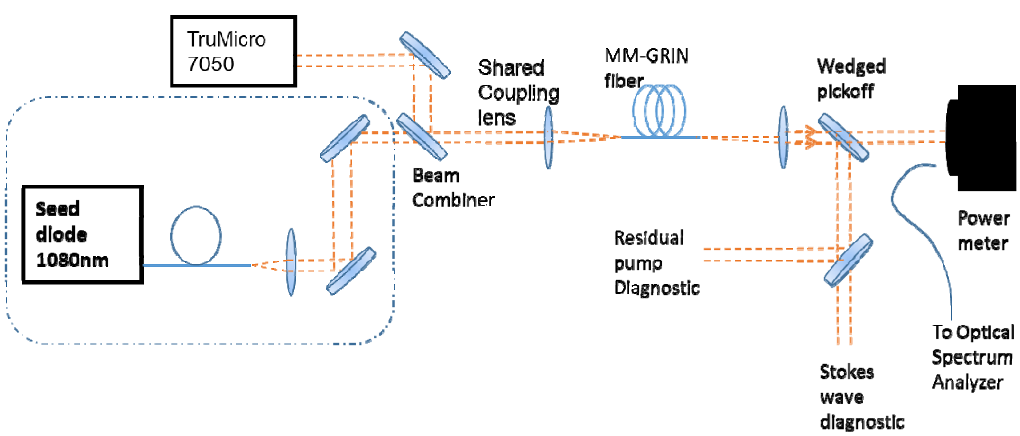

Figure 7: Experimental setup of the Raman amplifier. The TruMicro pulsed 1030 nm pump laser is coupled into a large area MM-GRIN fiber, co-propagating with a low power CW seed at 1080 nm.

The output spectrum at 4.3 mJ and 50 kHz is shown in Figure 8. In order to demonstrate the effect of even a very low power seed on output spectrum, the spectrum was recorded with and without the seed. It is important to note that in order to achieve this high efficiency, the seed was spatially detuned from ideal coupling, accelerating the conversion of higher order modes to first Stokes. This allows for an improvement in efficiency and total power converted to a single Stokes line, but at the expense of beam quality. The maximum achieved power in the first Stokes was 1.4 mJ, corresponding to 70 W average power. The primary limitation to higher average power was catastrophic fiber failure due to light in the cladding. In order to continue towards the full achievable pump power, a MM-GRIN with a 300 µm core diameter is being manufactured.

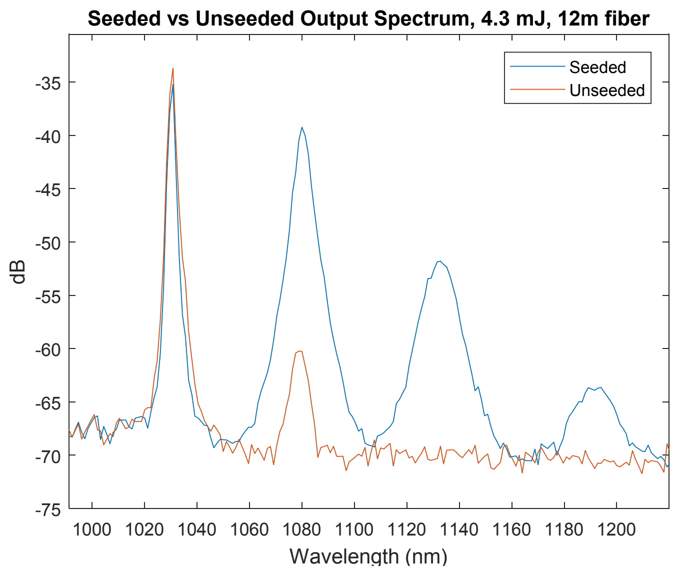

Figure 8: Output spectrum of Raman laser at 4.3 mJ input.

5. TISTEF LASER PROPAGATION FACILITY

In conjunction with the Wavefront Propagation Research Group at the University of Central Florida, several new laboratory installations are in development at the TISTEF laser range at the Kennedy Space Center. The facility includes a laboratory for high power lasers, including kW class fiber lasers and 10 kW class solid state lasers; several long propagation ranges for tests up to 1 km, with plans for 6 km; and a full suite of meteorological measurement devices and laser tracking systems. The new fiber lasers developed at CREOL will be installed and tested at extreme long range using the facilities at TISTEF.

In addition, a mobile ultra-fast high energy laser facility (MU-HELF) has been installed there for studying the long range propagation of pulses undergoing filamentation. The MU-HELF is a self-contained laboratory with a 500 mJ, 100 fs laser system in a class 1000 cleanroom. It has the capability of arbitrary beam steering by way of a two axis beam projection and tracking system called the LOTIS, and will take advantage of the suite of diagnostics available at TISTEF to perform analyses on filaments at the multi-kilometer range.

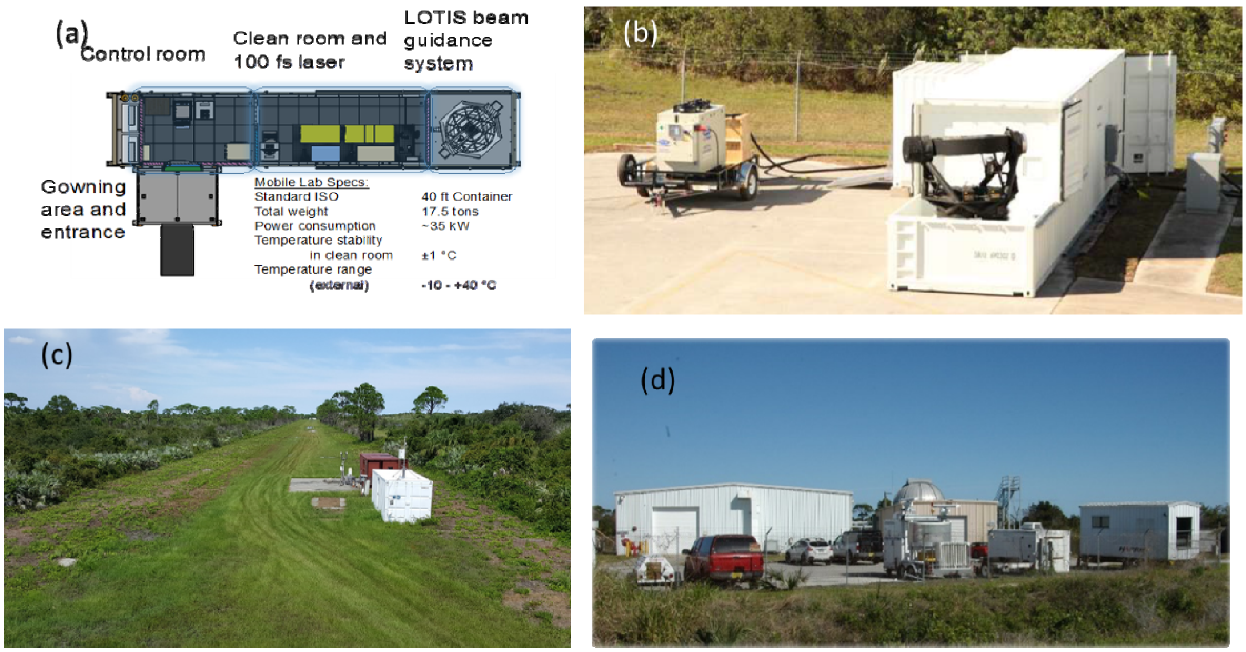

Figure 9: The MU-HELF system (a, b) produces multi-terawatt pulse energies, to be propagated down a 1 km enclosed, secure propagation range (c) located at TISTEF (d).

6. CONLCUSION

We present the work being done at the University of Central Florida toward high power CW lasers in ytterbium and thulium, and the work toward high average power Raman lasers in graded-index fiber. A ytterbium-doped fiber amplifier, constructed from fiber drawn in-house, was demonstrated with a maximum output power of 578 W. Future work entails fabricating longer fiber lengths and acquiring higher pump diodes for power scaling. For lasers operating at 2 µm, fabrication of various in-house drawn thulium-doped fibers has been presented. These fibers demonstrate single-mode beam quality with multi-Watt output for operation from 1890 – 2030 nm. Lastly, graded-index fibers were drawn in-house enabling a Raman fiber laser pumped by a 30 ns pulsed thin-disk laser. This system generated an output energy of 1.4 mJ at 1080 nm. With continued development in fiber design and construction, laser development at the University of Central Florida is approaching kW-class Raman and Yb:fiber systems, as well as 100W-class Tm:fiber systems. Finally, the acquisition of a laboratory and propagation range located at Kennedy Space Center is discussed, with plans for implementing our in-house drawn fiber lasers for experiments at long range.

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