Proceedings of The National Conference
On Undergraduate Research (NCUR) 2017
University of Memphis, TN
Memphis, Tennessee
April 7-9 2017

All-PM Thulium Doped Fiber Laser System

Alejandro M. Alderete
Department of Electrical Engineering and Computer Science
United States Military Academy
West Point, New York 10997

Faculty Advisors: Dr. Kirk Ingold

Abstract

Fiber-based laser systems are convenient and have become a primary tool in applications ranging from optical communications to directed energy systems for defense applications. The technology of these lasers based on ytterbium (Yb^{3+})-doped silica fiber lasers has matured significantly in recent years and has become the primary commercial product in the domain for high-energy applications. A down side is the wavelength range (1000 – 1100 nm) emitted by these lasers pose a serious eye hazard. An alternative and efficient alternative to this technology is a fiber laser based on thulium (Tm^{3+})-doped silica fiber. Thulium-doped fiber lasers are advantageous because they operated in a wavelength range (1850 – 2100 nm) that is considered 'eye-safe'. This range has broad applications in free-space optical communications, directed energy systems, and remote sensing. In this research we focused on building an all-fiber continuous-wave laser using single-mode, polarization maintaining Tm-doped silica fiber and components. The output of this laser has a potentially tunable wavelength range of 1850 – 2100 nm and operates in a single polarization mode. Along with higher power capabilities, Tm-doped fibers have the possibility of high efficiencies peaking at 80%. The author used commercial-grade fusion fiber splicer to integrate all components and build a laser resonator.

Keywords: Fiber laser, Thulium, pump laser, characterization

1. Background and Motivation

Fiber lasers doped with thulium offer 'eye safe' laser light within the range of 1850-2100nm [1-3]. Operation within this region allows for many advantages over fiber laser systems in shorter wavelengths. Thulium-doped optical fiber allows for a tunable laser along with a stronger fiber [3-5] when combined with silica. It has been previously shown that fiber lasers have high efficiency [6], spatial mode stability [1], ease of use, and a tunable wavelength [5]. The large bandwidth available from Tm-doped silica fibers offers a flexible solution for tunable laser at the border of the mid-infrared spectrum. When the thulium is excited using laser light at 790 nm it produces two excited thulium ions [1-3] through the cross relaxation process [7]. The theoretical efficiency can reach a maximum of 81% [1-6]. The figure below shows the process of the excitation of thulium using the 790nm light.

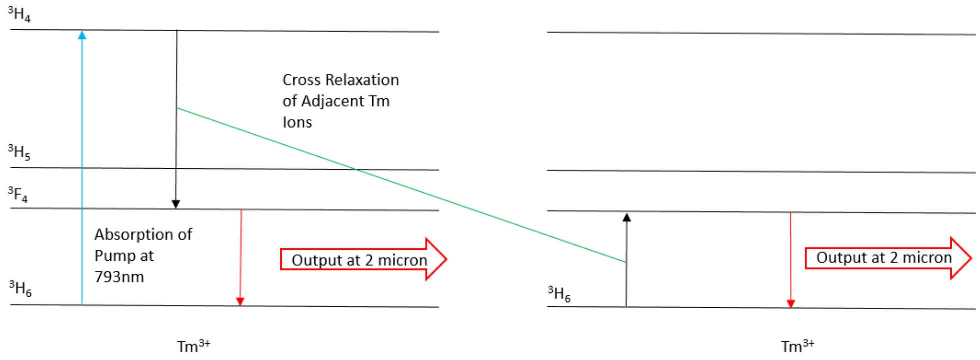

Figure 1: Thulium Excitation with Cross Relaxation [7]

This high efficiency along with the broad applications make thulium doped fiber an optimal candidate for fiber laser construction. Laser light emitted from a thulium doped fiber system can be used for eye-safe LIDAR, spectroscopy, remote sensing, and generation of mid-infrared light sources [1, 5-6]. This is West Point's first thulium fiber laser. This fiber laser is the foundation for ground work that others will use for many more projects. Future cadets at West Point can use it as a base for understanding how to build these systems and how to make them better. The goal of the project is not only to build a working thulium doped fiber laser that emits around 2000nm but also validate other systems such as fiber splicing and component characterization.

2. Fusion Splicing and Splice Loss Characterization

Before building the fiber laser we needed to learn how to properly splice optical fibers and characterize approximate losses associated with the fiber splices. Characterization of the optical fiber and the associated splice loss was important in estimating the total loss in the fiber laser resonator. Splicing was an integral part of this experiment because building an all fiber laser system required splicing many different types of fiber together to create the resonant cavity, to include coupling the pump laser into the cavity. Fibers with varying salient characteristics, such as core diameters, require different splicing parameters and we had to practice to reduce the overall splice loss. We set up a preliminary experiment to characterize this splice loss. We used a 9 meter length of SMF-28e fiber, marked at 1-meter intervals to estimate the average splice loss. Using a stable 1570-nm fiber laser connected to the fiber and measured transmitted power as a baseline for the remainder of the experiment. Starting at the first marked interval, we cut the fiber and then spliced the two fiber ends together using a Vytran GPX-3800 Glass Processing System. For a typical splice, we stripped, cleaned and cleaved both ends of the fibers being spliced. Figure 2 shows two different fibers following the splicing process with approximately -0.11dB and -0.02dB of measured loss, respectively.

Figure 2: Images of two different fiber splices with (a) -0.11dB and (b) -0.02dB of measured loss, respectively.

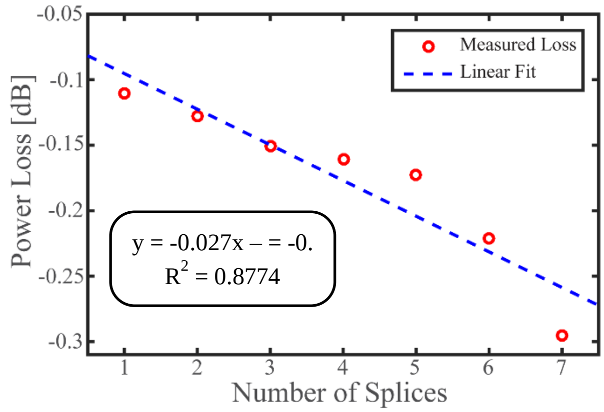

Figure 3: Splice Loss Characterization with an Increasing Number of Splices at 1570nm, SMF-28e fiber

As shown in Figure 3, we estimated the average power loss to be 0.027 dB per splice. Something important to note is that the PM-2000 and thulium doped fibers used in the laser resonator have different characteristics than the SMF-28e. As an example, both fibers are constructed with stress rods along the longitudinal direction designed to maintain the polarization of the guided light. These stress rods must be aligned during splicing to ensure proper operation. The addition of these stress rods make the splicing procedure more difficult and can lead to different losses. Figure 4 shows an image of the end of a PM-2000 fiber after the cleaving process. The core can be identified by the small black dot in the center and the two lighter circles to the sides are the stress rods.

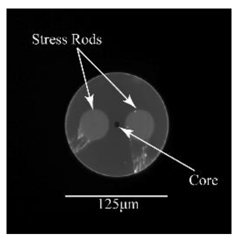

Figure 4: PM-2000 Fiber after cleaving showing the fiber core and stress rods

Due to a limited amount of these fibers available and the lack of 2000nm source, we were unable to fully characterize the splices performed in the construction of the laser. Thus, the average splice losses measured here are only an estimate of the minimum splice losses in the experiment. For future experiments and work with the laser, we can repeat this experiment using the 2000nm output from laser built in this work, instead of the 1570nm laser, to better estimate of the associated splice loss.

3. Experimental Setup

The experimental setup for the all-PM thulium-doped fiber laser is shown in Figure 5. The pump laser is a DILAS Laser designed to operate near 793 nm. The laser is capable of producing 35W of optical power. The laser is operated with a driver supplying 60 amps at 2 volts. The pump laser also has an internal photodiode used for output power measurements. A programmed Arduino Uno is incorporated with this photodiode and an LCD display to display the approximate pump laser output power. We used the manufacture data to calibrate this system. The pump laser is mounted onto a thermoelectric controller (TEC) for thermal management. The TEC was set to maintain 25º C for the extent of this experiment. The pump is spliced to a 2x1+1 pump combiner. This pump combiner couples the pump laser to the resonant cavity. We used 1-m of the thulium doped silica fiber as the gain medium spliced to the output of the pump combiner. According to the manufacturer's specifications, the gain fiber is designed to absorb the 793nm pump light around 8dB/meter. The thulium doped fiber is then spliced onto the isolator. The isolator is oriented in the counter-propagating direction from the pump. This orientation not only isolates the 2000nm light to a clockwise direction, but blocks the residual 793nm light from the resonant cavity. The final component of the cavity is the output coupler. The output coupler is a 90:10, designed for 1550nm. It outputs 90% of the laser output and puts the remaining 10% back into the system. As the coupler was designed for 1550nm, these nominal values are only estimates.

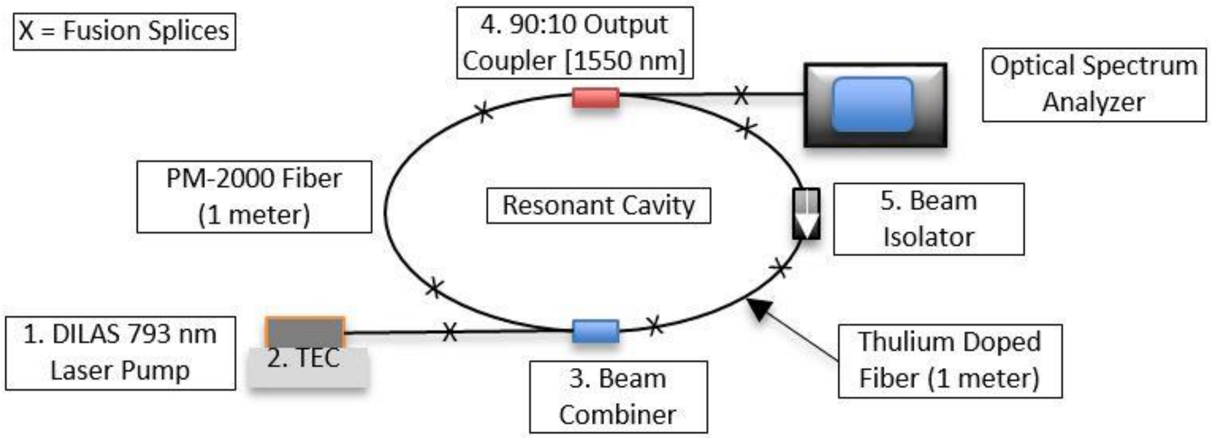

Figure 5: Experimental Setup of Fiber Laser System

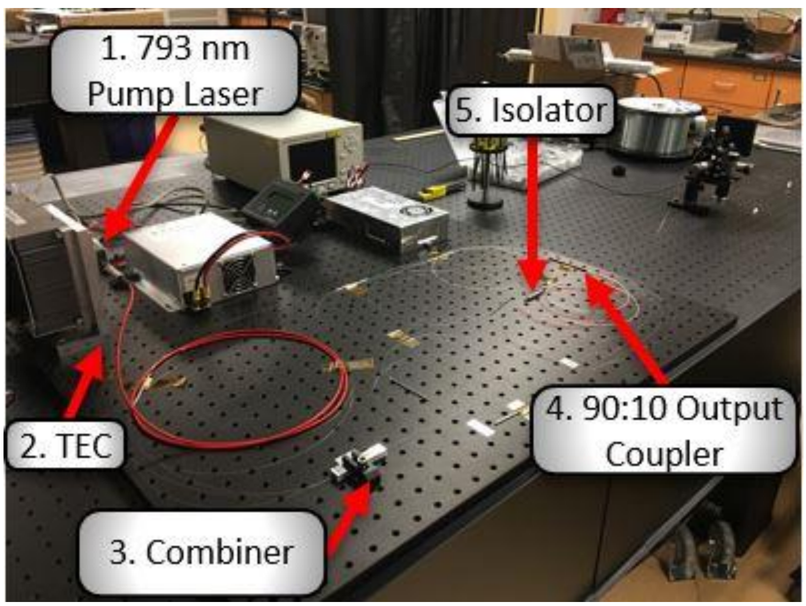

Figure 6: Actual Experimental Setup of Fiber Laser System

Prior to splicing the laser cavity together, we characterized the output of the 793nm pump laser with varying supply currents. We measured the output power before and after splicing on the pump combiner. The results of this preliminary experiment are shown in Figure 7. These results confirm the provided manufacturer's specifications. The pump threshold is at 7.4A. Additionally, the pump is operated at 25°C, controlled by the TEC. Finally, we used an optical spectrum analyzer (OSA) to measure the spectral properties of the pump laser. These results are shown in Figure 8.

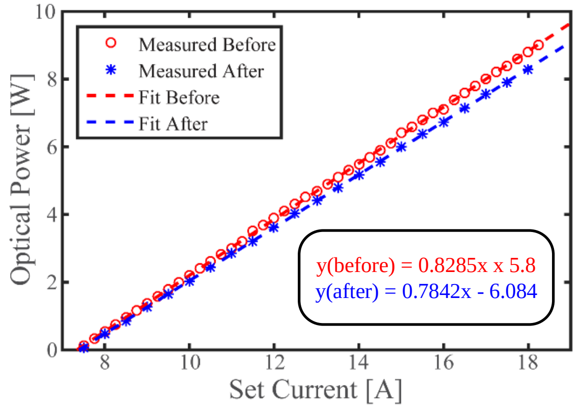

Figure 7: Pump Laser output power before and after the pump combiner

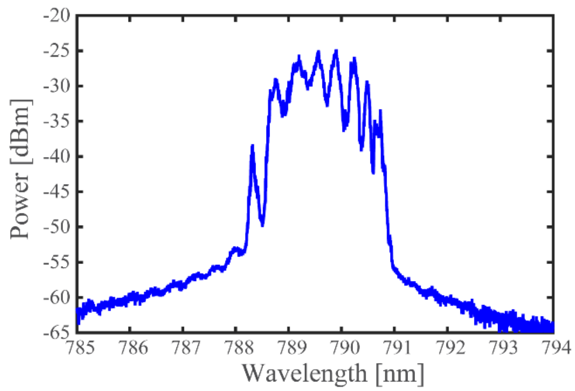

Figure 8: Pump laser spectrum at 25°C

Once the pump laser was characterized and the isolator and output coupler were spliced into the system, we characterized the output of the laser. Using the average splice loss measured previously and the manufacturer's specifications for insertion loss and other losses, we estimated the total cavity loss to be roughly 12dB. We operated the laser by adjusting the input current in the pump laser. We initially measured the output spectrum using the OSA. Once the laser reached threshold and oscillation occurred, we first characterized the output spectrum for varying input currents and then estimated the efficiency of the laser using the measured output powers.

4. Results

The threshold of the fiber laser was when pumping at 14.5A, corresponding to approximately 6.4W. Prior to oscillation, we identified amplified spontaneous emission (ASE) across the entire thulium spectrum, as expected. At 6.4W of optical input power from the pump laser the laser reached threshold. As we increased the input pump power, multiple modes would turn on and off centered close to 1950nm. The measured spectra at different pump powers is shown in Figure 9. The absorption lines below 1950nm are consistent with the well-known water absorption peaks at these wavelengths. Additionally, we measured approximately 50dB of ASE suppression ratio.

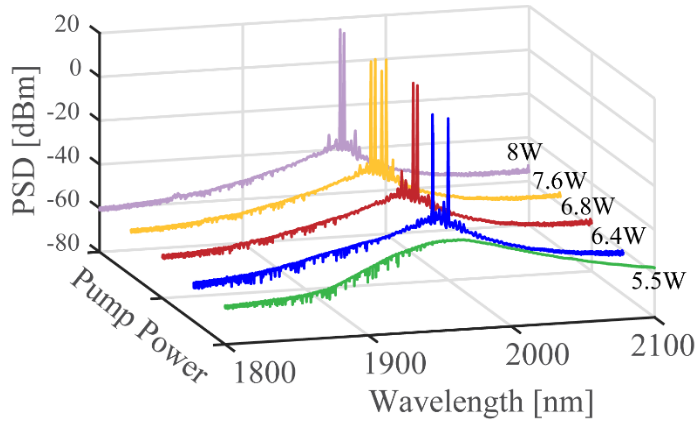

Figure 9: Spectral characterization of fiber laser at varying pump powers.

Additionally, the 200nm of available bandwidth that could potentially be accessed using a tunable filter in the system. The filter could not only allow a tuned output spectrum, but also suppress the multiple operating modes given a narrow enough bandwidth in the filter.

Finally, we characterized the slope efficiency of the laser shown in Figure 10. The highest achieved output of the fiber laser system was at approximately 350mW of optical power. We did not increase the pump power beyond this 11W to prevent damage to the internal cavity components. For the same reason, we used a 90:10 coupler to limit to overall feedback in the cavity to 10% of the internal cavity power. The overall laser efficiency was 8.4% estimated by a linear fit to the data. We attribute the low efficiency additional losses in the cavity than initially estimated. As an example, we expect the splice losses to be slightly higher and the output coupler likely had more losses than given by the specifications, due to the fact that the coupler was designed for 1550nm.

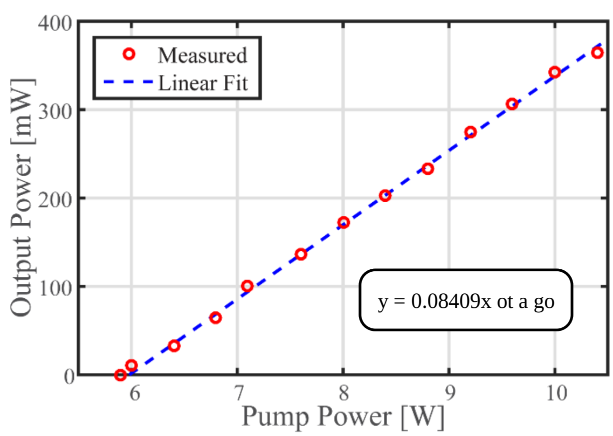

Figure 10: Laser Efficiency of the Fiber Laser System when compared to Input Pump Power

5. Future Work

One of the goals for the future improvements of this project would be to improve the slope efficiency. First, we could integrate an output coupler specifically designed for the 2000nm wavelengths. Additionally we could work to reduce the splice loss. Now that we have a working 2000nm laser, we could repeat the initial experiment to measure the splice losses using the same fibers we used in the laser. Finally, we could adjust the temperature of the pump laser, in turn changing the pump wavelength, using the TEC to determine the optimal temperature that maximizes absorption in the gain fiber.

6. Acknowledgements

The authors acknowledge the Army Research Office and the Department of Electrical Engineering & Computer Science for funding this project. We also thank the Mr. Mike Soffos for his hard work machining necessary parts.

7. References

[1] P. F. Moulton, G. A. Rines, E. V. Slobodtchikov, K. F. Wall, G. Frith, B. Samson, and A. L. G. Carter, "Tm-Doped Fiber Lasers: Fundamentals and Power Scaling." In IEEE Journal of Selected Topics in Quantum Electronics, Vol. 15, No. 1. January 2009.

[2] Q. Wang, G. Jihong, and S. Jiang, "2-μm Fiber Laser Sources for Sensing." In Optical Engineering. Vol. 53, No. 6. June 2014.

[3] Z. S. Sacks, Z. Schiffer, and D. David. "Long wavelength operation of double-clad Tm:silica fiber lasers." Fiber Lasers IV: Technology, Systems, and Applications, 2007.

[4] K. Yin, Z. Rongzhen, B. Zhang, G. Liu, P. Zhou, and J. Hou. "300 W-level, wavelength-widely-tunable, all-fiber integrated thulium-doped fiber laser." Optics Express 24, no. 10 (2016): 11085.

[5] T. S. Mccomb, R. A. Sims, C. C. C. Willis, P. Kadwani, V. Sudesh, L. Shah, and M. Richardson, "High-power widely tunable thulium fiber lasers." Applied Optics 49, no. 32 (2010): 6236.

[6] K. Yin, B. Zhang, G. Xue, L. Li, and J. Hou. "High-power all-fiber wavelength-tunable thulium doped fiber laser at 2 μm." Optics Express 22, no. 17 (2014): 19947.

[7] S. D. Jackson, "Cross relaxation and energy transfer upconversion processes relevant to the functioning of 2μm, Tm^{3+}-doped silica fiber lasers," Opt. Commun., vol. 230, pp. 197–203, 2004.