Influence of Temperature on Nanosecond Pulse Amplification in Thulium Doped Fiber Lasers

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Abstract. Thulium silica doped fiber (TDF) lasers are becoming important laser sources in both research and applications in industry. A key element of all high-power lasers is thermal management and its impact on laser performance. This is particularly important in TDF lasers, which utilize an unusual cross-relation pumping scheme, and are optically less efficient than other types of fiber lasers. The present work describes an experimental investigation of thermal management in a high power, high repetition-rate, pulsed Thulium (Tm) fiber laser. A tunable nanosecond TDF laser system across the 1838 nm – 1948 nm wavelength range, has been built to propagate 2μm signal seed pulses into a TDF amplifier, comprising a polarized large mode area (PLMA) thulium fiber (TDF) with a 793nm laser diode pump source. The PLMA TDF amplifier is thermally managed by a separately controlled cooling system with a temperature varied from 12ºC to 36ºC. The maximum output energy (~400 μJ), of the system is achieved at 12ºC at 1947 nm wavelength with ~32 W of absorbed pump power at 20 kHz with a pulse duration of ~ 74 ns.

1. Introduction
The broadband wavelength emission (1.7-2.1 μm) produced by the thulium-doped fiber (TDF) laser has attracted attention in many fields, from remote-sensing [1] to free space communication [2], medical therapy [3], mid-infrared generation via optical parametric oscillators [4], and material processing [5]. The particularly unique feature of TDF is the gain peak resulting from the \( ^3\text{H}_4 \rightarrow ^3\text{F}_6 \) transition which can be optically pumped via the \( ^3\text{H}_4 \rightarrow ^3\text{H}_6 \) absorption transition by commercial 793 nm laser diode pump sources. This contribution has promised high efficiencies greater than the standard quantum defect due to the 2-for-1 cross relaxation (CR) process between thulium ions [6-7]. The efficiency of CR is related to the ground state depletion [8]. In the ground state, the population of the Stark levels is related to the applied temperature. Thus, the lasing threshold will also relate to the applied temperature [9]. Likewise, the core/cladding area ratio of TDF, doping concentration, and fiber length significantly affect the CR process through the temperature dependent Boltzmann distribution [9].
Thulium-doped fibers are silica glass-based with 2-4 % thulium doping as the active laser material. Based on the quantum defect, the fiber core/cladding diameter, and nonradiative losses, the peak thermal load in TDF is approximately 8 times larger than in Ytterbium (Yb) for an equivalent fiber geometry. As a consequence, thermal management is crucial in TDF lasers to avoid thermal failure [10]. Frith et al. [9], found the TDF slope efficiency varies significantly based on the type of thermal management employed. For an uncooled TDF, a slope efficiency of 37% was reported, while for air cooling and conduction cooling, this figure jumps to 57% and 59% respectively. Johnson et al [11], used cryogenic thermal management within the -263 °C to 100 °C range of applied temperatures on the TDF. Temperature is an effective tool to increase the short wavelength lasing near 1850 nm. Cole et al [12], employed cryogenic temperatures from -196 °C to room temperature. When pumping with 1047 nm and 1410 nm, the resulting gain measured at -196 °C was 12 dB, compared with 7 dB measured at room temperature. The higher rate of nonradiative decay out of the 3\(\text{H}_4\) level at room temperature is responsible for the lower gain observed. The current work examines the effect of temperature on the operation of a high power thulium fiber laser.

2. Experiment
The TDF laser system used in these studies consists of two stages, an oscillator and an amplifier, shown in Figure 1. The oscillator is a TDF-based tunable pulsed laser system, with 1838–1948 nm wavelength coverage. A 600 lines/mm gold-coated diffraction grating and an acousto-optic modulator (AOM) with an applied RF signal from a signal generator are used to select the desired wavelength and pulse duration, respectively. This TDF oscillator provides up to 2 W average power with a ~74 ns pulse duration at 20 kHz repetition rate.

![Figure 1](image_url). The optical layout of the experimental setup. L: Lens, M: Mirror, D.M: Dichroic Mirror, \(\lambda/2\): Half-wave plate, ISO: Isolator, W: Wedge, CCD: CCD Camera.

A free space transition stage between the oscillator and amplifier serves to seed the oscillator signal into the TDF amplifier fiber and provides protection for both stages from feedback and crosstalk between them. This stage consists of two 45° angle-of-incidence dichroic mirrors, coated for high-reflectivity (HR) operation at 2 μm and anti-reflective (AR) operation at 793 nm. A light valve, comprising a half-wave plate (\(\lambda/2\)) and isolator (ISO), is located between the mirrors to block any feedback. The seed signal suffers from an attenuation through the free space transition stage.
Because they are less efficient than Yb-doped fiber lasers, high power operation of TDF’s are more dependent on the designs for thermal management. Designs using a water cooling basin [13] or a cryogenic cooling freezer [11-12] have been investigated. Here we have designed a homemade independently temperature controlled 1.3 m longitudinal aluminum cooling system comprising a V-shaped groove to hold the fiber. This is connected to a flowing water system to diagnostics flowing water cooling in a closed cycle with water chiller. A Termotek-AG P308 water chiller is used to verify the control temperature range from 10 to 36 °C. The fiber used in this amplifier is a 1.6 m PLMA TDF (TDF-25P/400) from Nufern. A 100 W, 793 nm DILAS diode laser with a 200 µm core delivery fiber was coupled into the PLMA-TDF through an in-house designed 1:1 aspheric telescope with a dichroic mirror (D.M) for HR operation at 2 µm to separate the amplified signal from the pump. A diagnostics stage consists of a beam profile camera (Pyrocam III from Spiricon), power meter (Coherent PM 10 model, 0.25-11 µm), an optical spectrum analyzer (AQ6375 from YOKOGAWA) and a digital oscilloscope (Tektronix DPO 3052) to measure the pulse width.

3. Results & Discussion
The focus of this study was to investigate the temperature effect on pre-lasing (ASE) and the lasing states. To ensure accuracy in the temperature, a 30 minute wait time was imposed after adjusting the temperature before commencing the experiments to assure the housing was stable at the desired temperature. In addition, care was taken to ensure that the TDF-PLMA test fiber facets were unburned and undamaged after the test.

The ASE experiments were performed by pumping the TDF-PLMA amplifier with a 793nm diode laser without the use of a seed signal, for applied temperatures of 15, 20, and 28 °C. The ASE has different free lasing thresholds relative to each applied temperature, shown in Figure 2. The highest free-lasing threshold occurred at 15 °C with 120 mW output power, showing a direct correlation between free lasing threshold and applied temperature. Lower fiber temperatures lead to higher free-lasing thresholds and lower lasing. However, still lower cooling temperatures, below 11 °C, can lead to water condensation on the fiber. While the ASE spectrum has ~100 nm broadening width at 10dB, and slight differences in the optical signal to noise ratio (OSNR). The temperature dependent Boltzmann distribution of the electrons within the energy levels of thulium results in greater ground-state reabsorption of ASE at higher temperatures.

Figure 2. ASE power scale and spectrum related to the temperature

Four lasing wavelengths were selected to investigate the lasing behavior as a function of its spectrum: 1838 nm, 1877 nm, 1913 nm and 1947 nm. The 793 nm pump power launched into the TDF
amplifier was kept constant. Analogous to the ASE tests, a 30-minute wait time was employed for each of the applied temperatures were 15, 20, and 28 °C.

‘Figure (3)’ shows the results for the case of the seeded TDF amplifier. The seed energy was 35 – 70 μJ depending on the wavelength selected, while the pulse amplification gain is 7.9-15.5 dB. This amplification factor depends on the wavelength selected relative to the ASE gain spectrum and the lasing spectrum. Shorter wavelengths display an exponential growth in the pulse energy with increasing launched pump power, while the pulse energy at longer wavelengths is seen to grow linearly. At shorter wavelengths, the effect of temperature on the pulse amplification is more pronounced than at longer wavelengths, especially near the free-lasing threshold. The absorbed pump is constant, so the inversion is fixed to provide a fixed amplification factor at a given wavelength. The sensitivity to temperature decreases from ~25% variance in output energy at 1838 nm to ~10% at 1947 nm. However, since longer wavelengths are generally preferred in TDF’s, the temperature does not have a strong effect on the pulse amplification over the desired operating parameters.

Figure 3. Amplified energy related to different applied temperatures (15, 20, 24, and 28 °C), for four selective wavelengths 1838, 1877, 1913, and 1947 nm, at the same launched power scale, up to 32W.

Figure 4. Amplified pulse energy for a fixed seed energy of 47 μJ with different applied temperatures 12 – 36 °C at 1947 nm.
To investigate temperature effects further, the energy amplification at a wavelength of 1947 nm was investigated for a wider applied temperature range of 12–36 °C, with a fixed seed energy of 47 μJ. The highest pulse energy obtained was ~ 400 μJ at both 12 and 36 °C applied temperatures for 32 W absorbed power, shown in Figure 4. For temperatures lower than 12 °C atmospheric condensation occurred on the fiber mounts. Overall, under a lab operation environment there is no recorded effect of the temperature on the TDF laser operation. However, the 12 - 20 °C temperature is the likely range to avoid any damage our on the TDF facet.

![Figure 5. The relation between wavelength and pulse energy under different temperatures for TDF laser.](image)

Finally, the relation between the wavelength and laser pulse amplification for different temperatures was investigated, Figure 5. The launched pump power was kept constant at 32 W. The highest output energies achieved were at longer wavelengths with an output of 350 μJ at 1947 nm. At increasing wavelengths, the extractable energy is more effective than at shorter wavelengths. No strong dependence on the temperature was observed. These results agree well with the higher gain observed at longer wavelengths in the TDF.

4. Conclusion

This work investigated experimentally the thermal management of TDF laser systems in the high repetition-rate nanosecond pulsed regime. The system consists of TDF oscillator and amplifier, providing a nanosecond pulsed tunable seed wavelength between 1810 – 1950 nm at 20 kHz rep. rate to produce up to 2 W average power. A free space transition stage between the oscillator and amplifier delivers the seed signal into the amplifier fiber as well as prevents optical feedback. A 1.6 m PLMA-TDF with up to 100 W available pump power at 793 nm provides the amplifier stage. The amplifier PLMA-TDF has thermal management control using an aluminum V-shaped cooling house with active temperature control from a water chiller. The applied temperature range examined in this study was 12-36 °C. A negligible effect of the temperature on the PLMA-TDF laser gain was observed. Longer wavelength operation near 1947 nm is preferred to maximize the extracted energy from the amplifier, producing ~400 μJ pulse energies at 12 °C

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