# Amplification at 2.3-µm in 1.9-µm thulium-doped silica fiber laser

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**Abstract:** A high-power 1.9-µm $Tm^{3+}$-doped silica fiber laser generates 7.3-dB of gain at 2.3 µm when cladding-pumped with 207 W of power at 793 nm. We attribute the 2.3-µm gain to the transition $^3H_4 \rightarrow {}^3H_5$ of $Tm^{3+}$.

## 1. Introduction

Due to its intricate energy level structure, $Tm^{3+}$-doped fibers (TDFs) can produce gain and laser emission on a multitude of transitions at wavelengths from the visible to the near-infrared [1]. In recent years, emission from the $^3H_4 \rightarrow {}^3H_5$ transition at 2.3 µm has garnered attention because of applications including non-invasive glucose blood testing, optical metrology of combustion processes, and atmosphere gas sensing [2]. However, the $^3H_4$ multi-phonon relaxation rate is high in silica, as is the 2.3-µm propagation loss (typically 0.5 dB/m or more). Therefore, the current mainstream method for this spectral range in TDFs is to use other hosts, e.g., tellurite and fluoride glasses [3]. However, such fibers are difficult to splice, making all-fiber devices much more difficult than with silica fibers. Furthermore, the damage threshold is much lower than in silica fiber.

In this paper, we demonstrate amplification at 2.3-µm on the $^3H_4 \rightarrow {}^3H_5$ transition of a signal passing through a high-power Tm-doped silica fiber laser emitting on the $^3F_4 \rightarrow {}^3H_6$ transition at 1.9 µm This was cladding-pumped quasi-continuous-wave (QCW) at 793 nm ($^3H_6 \rightarrow {}^3H_4$) with 4-ms pulses at a 5.1-Hz pulse repetition frequency (PRF). At the maximum instantaneous 793-nm power of 207 W, the system produced 7.3 dB of instantaneous net gain and 19.1 dB of on-off gain at 2.3 µm.

## 2. Experimental configuration

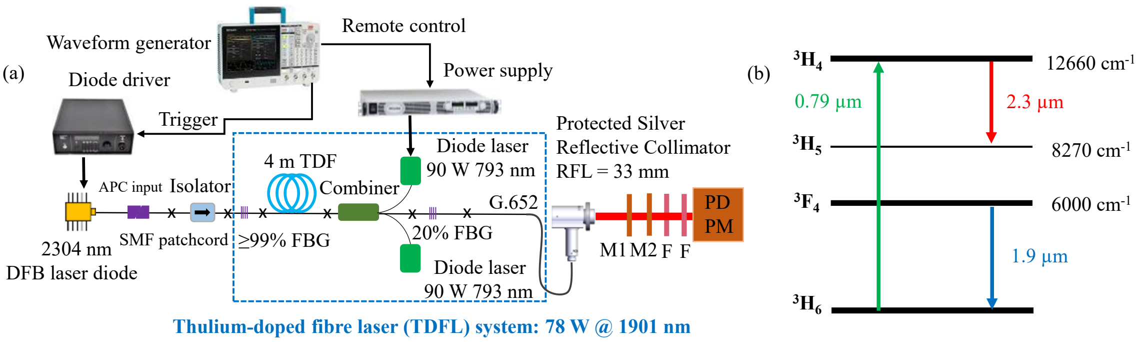


Fig. 1. (a) Schematic of Tm-doped fiber laser seeded by a polarized fiber-coupled 2304 nm DFB diode laser. FBG: fiber Bragg grating, TDF: thulium doped fiber, SMF: single mode fiber (G.652), APC: angle-polished connector, PM: power meter, PD: photodetector, M1 & M2: Pump-reflecting dichroic mirrors, F: pump-blocking filter. (b) Partial energy level diagram of $Tm^{3+}$ showing the pump absorption at 0.79 µm, the laser emission at 1.9 µm, and the 2.3-µm transition.

Figure 1 illustrates our experimental setup and a partial energy level diagram of $Tm^{3+}$. The Tm-doped silica fiber (NRL 220802 TDF) was 4 m long. It had a core-diameter of 7.4 µm and an octagonal cladding with diameter 120 µm (flat-to-flat). The peak inner-cladding absorption at 0.79 µm was 3.5 dB/m. The TDF was taped to a water-cooled plane cold-plate without any thermal interface material. It was cladding-pumped by two 793-nm diode lasers (nLight, e18) rated at 90 W. These were driven in series by a power supply (TDK Lambda Genesys 100-15), which was controlled by a waveform generator (Tektronix AFG31052) in order to on-off-modulate the $Tm^{3+}$-doped fiber laser (TDFL) with 4-ms pulses at a PRF of 5.1 Hz. The output of the TDF was spliced to a standard single-mode fiber (G.652), terminated with an angled connector. This was fixed to a reflective collimator (Thorlabs RC08APC-P01), which resulted in a beam of ~6 mm diameter at the $1/e^2$ intensity level. Two pump-reflecting dichroic mirrors (Thorlabs DMLP1800) and filters (Thorlabs FB2250-500) removed any residual pump. Diagnostics equipment included a 20.6-MHz Thorlabs DET05D2 extended InGaAs detector, a 1.5-GHz Keysight

InfiniiVision MSOX4154A oscilloscope, and a thermal power sensor (Gentec Maestro with head XLP12-3S-H2-D0). Optical spectra were measured but did not show anything of note and are not included here.

Laser operation at 1901 nm prevents build-up of $Tm^{3+}$-ions in $^3F_4$ with its much longer lifetime of, e.g., ~0.4 ms. For this, a highly-reflecting and a 20%-reflecting fiber Bragg grating defined the laser cavity. At the maximum 793-nm power of 207 W, the instantaneous output power reached 78 W at 1901 nm. There was no roll-off.

For 2.3-µm amplification, the TDFL was seeded by a fiber-coupled 2304 nm, 4 mW, DFB diode laser (Nanoplus DFB-2304-2.5), launched through the back-end of the TDFL via an optical isolator (Shinkosha). The seed laser was also operated QCW, current-modulated with 2-ms pulses from a diode driver (Spectra Diode Labs SDL-820) with switching time stated to be ~12 µs. The diode driver was triggered by the waveform generator to synchronize it with the 793-nm pulses. The 2304-nm seed light thus propagated through the TDFL. The signal loss through the unpumped TDFL was measured to 11.8 dB. The total length of fiber in the signal path was ~8.55 m. We have measured the propagation loss at 2304 nm in various high-silica fibers to typically 0.5 – 1 dB/m, so we expect that the propagation loss makes up most of the 11.8 dB. The connectors, isolator, fiber Bragg gratings, and splices also contribute to the loss.

## 3. Experimental results and discussion

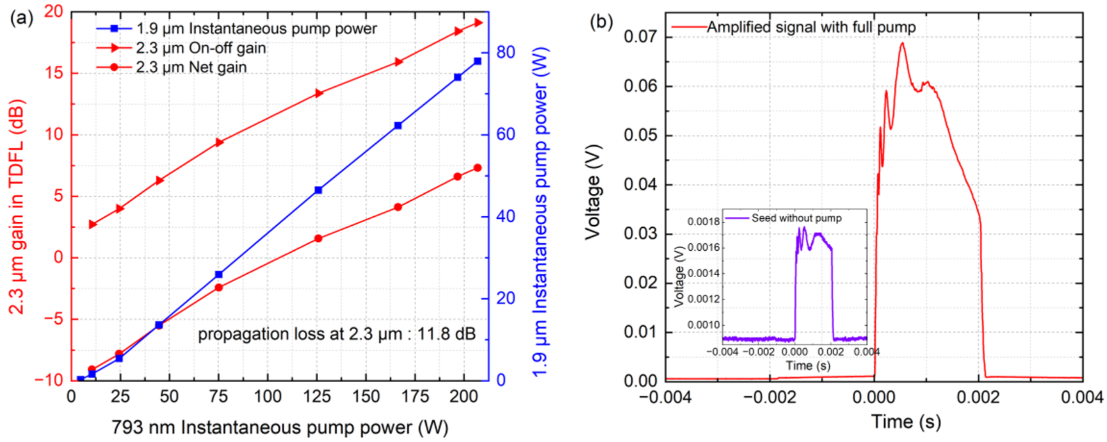


Fig. 1. (a) On-off gain and net gain of the 2304-nm signal pulses in the TDFL, as well as the 1.9 µm instantaneous output power, *vs*. 793-nm instantaneous pump power. (b) Time trace of signal exiting the TDFL without pumping and with full pumping.

Fig. 2 (a) displays the 2.3-µm on-off gain and net gain, as well as the 1.9 µm instantaneous output power as a function of instantaneous 793-nm pump power. At full 793-nm pump power, the signal power exiting the TDFL increased by 19.1 dB, i.e., the on-off gain of the signal pulses was 19.1 dB. This exceeds the 11.8-dB loss, resulting in 7.3 dB of net gain through the TDFL (including the isolator). We determined the on-off gain as the ratio of the areas under the signal pulse using functionality available on the oscilloscope. We also used the thermal power meter to determine the gain from measurements of the average power and obtained consistent results. In this case, the pump-off signal power was measured with a continuous-wave signal, since otherwise the power was too low for the thermal power meter.

We attribute the gain in the TDFL to the $^3H_4 \rightarrow {}^3H_5$ transition in $Tm^{3+}$ as Fig. 1 (b) shows. Stimulated Raman scattering could also contribute to the gain, but this contribution would be small: The energy difference between pump and signal corresponds to 920.1 $cm^{-1}$. This is approximately twice the Raman shift to the peak Raman gain, to regions where the Raman gain may be ~10% of the peak Raman gain and well below 1 dB in total.

Fig. 2 (b) shows examples of temporal traces of the 2-ms signal pulses exiting the TDFL, captured by the extended InGaAs detector. The duration remains at 2 ms (full-width at half-maximum) for all powers although there are power fluctuations of around 2 dB. The time constants of all involved transitions are small compared to the time scales in Fig. 2 (b). Therefore, the inversion dynamics alone seems unlikely to be the cause of the fluctuations, which may be related to heating of the TDF. The additional sharp peaks in the trace may be caused by multi-path interference (e.g., a residual etalon in the isolator), which varies with the shift in wavelength as the 2304-nm diode laser heats up during the 2-ms seed pulses.

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## 4. References

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