A Monolithic Thulium Doped Single Mode Fiber Laser with 1.5ns Pulsewidth and 8kW Peak Power

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ABSTRACT

Here we report a compact monolithic 2000nm pulsed laser with a single spatial mode output, ~1.5ns pulse duration, 8kW peak power and >200mW average power at 20 kHz repetition rate. The gain-switched laser, consisting of a pair of fiber Bragg gratings and 0.5m of thulium-doped single cladding fiber, was core pumped by a high peak power pulsed 1.5μm laser. When the input pulse energy of the 20 kHz pump pulses was sufficient enough to saturate the Thulium doped fiber, a stable 20 kHz pulse train was observed with measured linewidth of 0.05nm which corresponds to the limit of resolution for the Optical Spectrum Analyzer. This compact, pulsed 2000 nm laser, to the authors' limited knowledge, represents the first Tm-doped fiber laser with 8kW peak power and several ns pulse duration; which is less than the previously reported tens of ns pulsewidth previously reported from gain-switched Tm-doped fiber lasers.

Keywords: thulium doped fiber laser, eye-safe laser, gain-switch, pulse laser

1. INTRODUCTION

The broad emission spectrum of Tm-doped silica fibers has spurred enormous interest in 2μm fiber laser development for applications including laser remote sensing, medical laser ablation, counter-measures and high power CW for "eye-safer" laser developments. Wavelength tuning of Tm-fiber lasers has been demonstrated from 1850nm to 2130nm, spanning various gas and water absorption features and extending into useful atmospheric transmission windows. The recent developments in high power 790nm laser diodes and Tm-doped fibers optimized for cross-section energy transfer between Thulium ions have significantly increased the achievable output power of Tm-doped fiber lasers, culminating in the recent demonstration of a 1kW CW Tm-doped fiber MOPA at 2040nm. This work on the Tm-fiber has in turn stimulated intensive development efforts from components manufacturers enabling 2μm fiber laser systems to mirror the path of Yb doped fiber lasers towards monolithic, all-fiber systems using gratings, couplers and fiber coupled diodes. In particular, 2μm pulsed lasers with ns pulses and kHz repetition rate generated from Tm-doped fiber lasers have been gaining popularity in applications such as laser surgery, multi-photon microscopy, eye-safe LIDAR, laser ranger finders and wavelength conversion to mid- or far-infrared[1,4]. Various methods of generating pulsed 2μm lasers have been reported to date: Q-switched Tm-doped silica fibers to generate relatively longer pulses[2,3], ranging from 100ns to several hundred nanoseconds; mode-locked Q-switched Tm-doped fiber laser can generate high repetition and short pulses of picoseconds to several hundred femtoseconds[6,7]; gain-switched Tm-doped fiber laser can generate 2μm pulses with kHz repetition rate and pulsewidth ranging from several tens to 100 ns[1,5,8].

Here we report, to the author's limited knowledge, the first demonstration of 2μm pulsed laser with 1.5ns pulsewidth and 8kW peak power in a compact monolithic package (6"x6"x2"). The extension of gain switched 2μm fiber sources to short pulse durations around 1nsec is particularly interesting, filling a niche caused by the lack of availability of alternatives, such as directly modulated diodes at 2μm. Furthermore, the compatibility with this source for further amplification in LMA fiber amplifiers is obviously the next step towards higher pulse energy and peak power with 1nsec pulses at 2μm.

2. EXPERIMENTAL SETUP

Due to the rather long relaxation time (>10us) from the 2um emission band, ns or faster gain-switching is difficult to achieve in a Tm-doped fiber laser pumped at 790nm. To overcome this difficulty, gain-switched 2μm pulsed lasers are typically pumped by a high peak power pulsed 1.5µm fiber laser so as to "resonantly" pump the Tm-doped fiber laser. These fiber sources, based on cladding pumped Er:Yb fibers lasing around 1560nm, have an excellent overlap with the absorption band of the Tmdoped fibers (as shown in Fig. 1). The 1.5µm pump source typically operates with around 40% slope efficiency and is in turn pumped by high efficiency 9XXnm laser diodes, making the source compact, efficient and monolithic by design. As the gain-switched 2µm pulses grow from the build-up of the Tm-inversion, the generated 2µm pulse duration decreases with an increase in the pump pulse energy and a reduction in the cavity length. In this work, a core-pumping scheme was chosen to reduce the Tm- fiber length and enable us to generate shorter 2µm pulses (~1nsec) than previously reported.

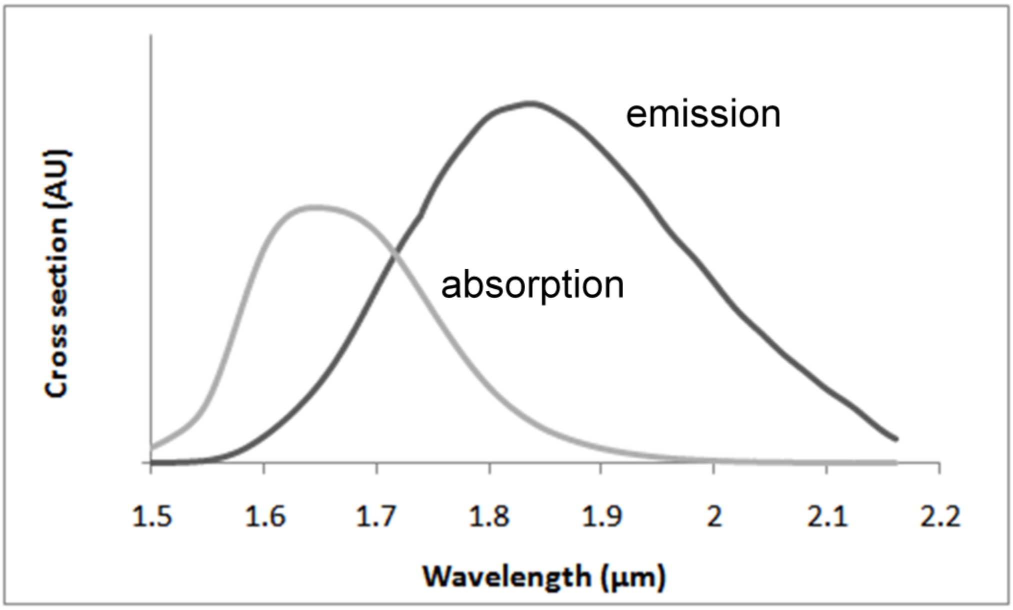

Figure 1: Absorption and emission cross-sections for Tm-doped silica fibers

The gain-switched Tm-doped fiber laser consists of a commercially available 1.5µm pulsed laser (NuTx from Nufern), a pair of 2000nm fiber Bragg gratings, and a 0.5m length of PM-TSF-9/125 fiber as shown in Figs.2 and 3. The fiber has a cutoff wavelength by design of ~1.75µm. The 1.5µm pulsed laser consists of a modulated commercial laser diode to generate the 1.5µm signal with ns pulse-duration, a two-stage pre-amplifier which is core-pumped by single mode 1480nm diodes and an Erbium and Ytterbium co-doped power-amplifier, cladding pumped at 940nm. The PM-TSF-9/125 fiber is a Tm-doped single clad fiber with a 9µm core diameter, 0.15 core NA, and an effective mode field diameter of 10.5µm at 2000nm. The effective pump absorption of the PM-TSF-9/125 fiber is ~12dB/m at the pump wavelength of 1.5µm. A 1% fiber tap was placed between the pre-amplifier and the power-amplifier of the 1.5µm pulsed laser to monitor the pre-amplifier output of the NuTx. A dichroic filter was used at the output end to separate the generated 2µm signal and the residual 1.5µm pulses, for characterizing the laser output.

The output of the 1.5µm NuTx was spliced directly onto a highly-reflective (HR) fiber grating with 99% reflectivity at 2000nm, to core-pump the Tm-doped single-cladding fibers. A fiber grating with 15%-reflectivity at 2000nm was used as the output coupler (OC). Various Tm-doped fiber lengths were evaluated over the course of the experiment. In our experience, dropped pulses and unstable pulses were observed when the fiber length is longer than 0.5m. The pulse instability is attributed to the strong re-absorption of the Thulium ions. When the fiber length was less than 0.5m, the average power of the generated 2µm pulses decreased due to the reduced pump absorption. Therefore, the optimal fiber length for this gain-switched 2µm pulsed laser was deemed to be ~0.5m. Two fast extended InGaAs detectors (from EO Tech) with 35ps rise and fall time were used to measure the residual 1.5µm pump and the generated 2.0µm signal pulses respectively.

Other than the dichoric filter, which was used in free space to analyze the laser performance, the entire system was of a monolithic, all-fiber structure. Furthermore, since there are only three more splices from the output fiber of the 1.5µm pulsed pump laser, the entire 2µm pulse laser was able to be packaged into the same mechanical housing of the 1.5µm NuTx laser. Furtherrnore the gain-switched 2µm pulsed laser utilizes the same electrical control interface as the existing 1.5µm NuTx laser.

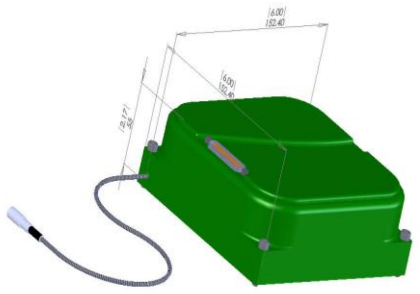

Figure 2: Illustrative CAD drawing of the monolithic 2µm pulsed laser.

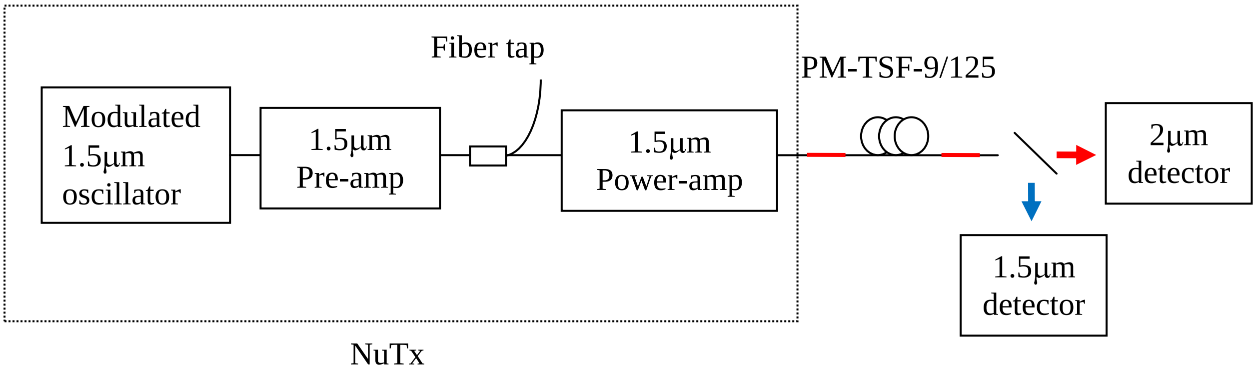

Figure 3: Optical schematics of the monolithic 2µm pulsed laser.

3. RESULTS AND DISCUSSIONS

While the repetition rate of the 1.5µm pulsed pump laser is adjustable from 20kHz to 500kHz, the average output power of the 1.5µm laser varies only slightly from 1W at 20kHz to 1.2W at 500kHz, as the current on the pump diodes is pre-set and not adjustable during the operation. In another words, as the repetition rate increases, the pulse energy and the peak power from the 1.5µm pulse laser decreases. While varying the repetition rate of the 1.5µm pump laser, it was observed that stable gain switched 2µm pulses were only achieved when the pulse repetition rate was set at 20kHz. When the pulse repetition rate is higher than 20kHz, the energy per pulse in the 1.5µm pump laser decreases and resulted in dropped 2µm pulses and/or pulse instability. Similar behavior was observed when the Tm-doped fiber length exceeded 0.5m and we speculate that the strong re-absorption of the Thulium ions is the cause. In order to have a stable gain-switched 2µm pulse, the pump pulse energy has to saturate or bleach through the Tm-doped fiber.

The gain switched Tm-doped fiber laser had a rather high lasing threshold. The onset of lasing was not achieved until the energy of the pump pulses reached 25µJ, or 500mW average power (for pulses with 20kHz repetition rate), which corresponds to 2.5kW for the seed laser pulses at 10ns pulse width, as shown in Fig. 4. It was noticed that the 2µm output became saturated when the 1.5µm pump power reached ~900mW, which corresponds to 4.5kW peak power. At such high peak power, the 1.5µm pump pulses began to generate stimulated Raman scattering which decreased the peak power of pump pulses and resulted in decreased slope efficiency for the 2µm signal.

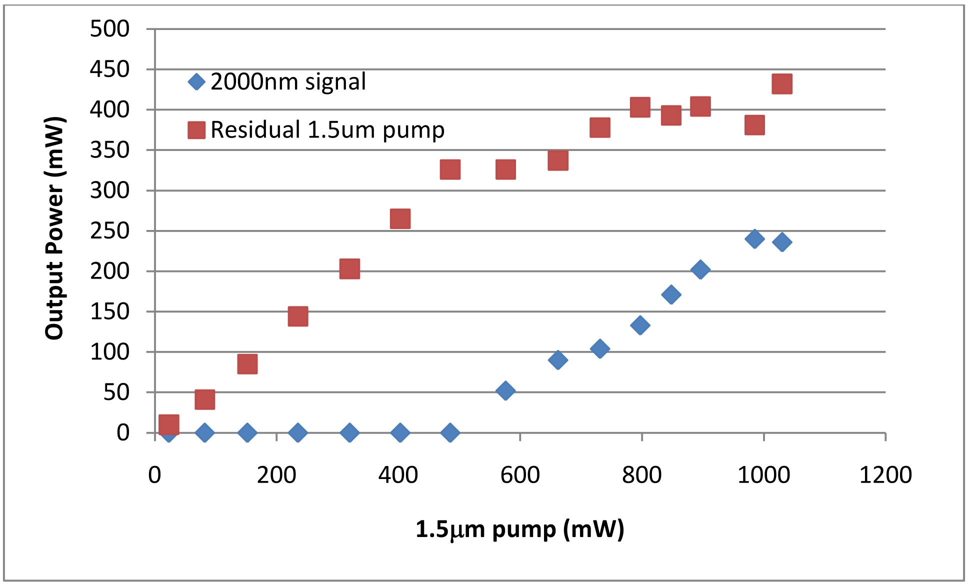

Figure 4: Average Power at 2µm along with the residual 1.5µm pump light from the laser

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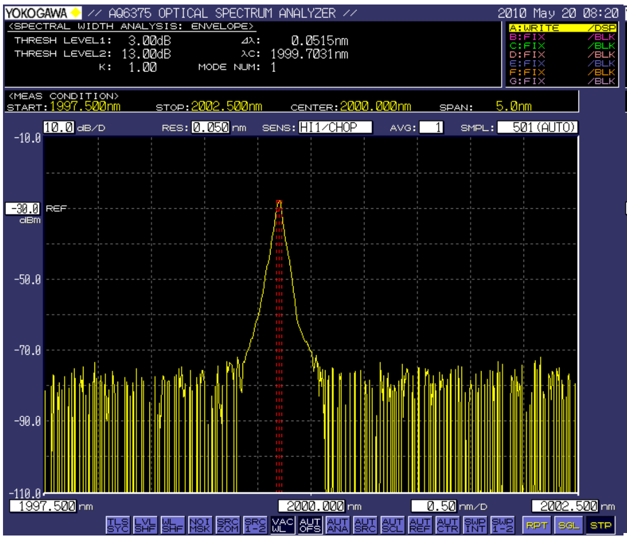

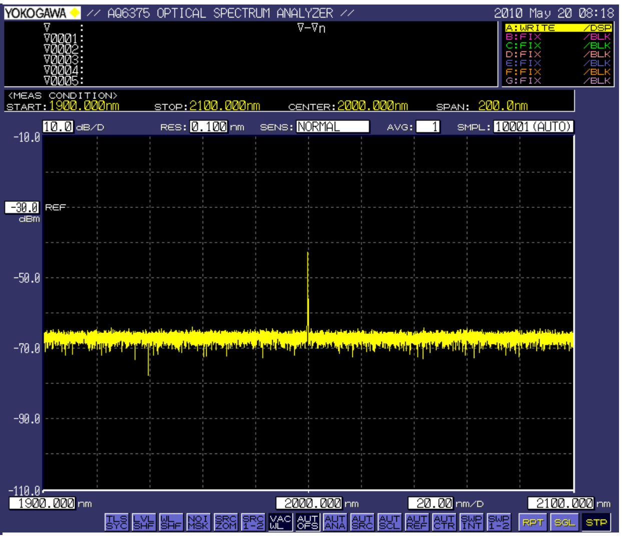

Figure 5: linewidth measurement of the 2µm signal

Figure 6: spectrum of the generated 2µm signal

As shown in Fig. 5, the measured 3dB linewidth of the generated 2µm signal was 0.05nm, corresponding to ~3.5GHz. The linewidth measurement is limited by the minimum resolution (0.05nm) of the Optical Spectrum Analyzer, but we do not expect the output laser linewidth to beless than GHz, as there was no additional wavelength stabilization mechanism implemented in this gain-switched 2µm laser. As a result of broader linewidth and short interaction length, no stimulated Brillouin scattering was observed as shown in Fig. 5. In addition, no parasitic lasing or noticeable ASE peak was observed in the wavelength region from 1900nm to 2100nm as shown in Fig. 6. Furthermore, no trace of Raman scattering was found in the optical spectrum, even as the peak power approached 8kW, thanks to the relatively short cavity length and 10.5µm mode-field-diameter..

The temporal characteristics of the gain switched fiber laser pulses are shown in Figs. 7 and 8. The pulse-width of the generated 2µm signal is ~1.5ns, which corresponds to the maximum peak power of 8kW, when the 2µm output power saturates at ~220mW output power and around 20 kHz repetition rate. To overcome the strong re-absorption from the high dopant concentration of Thulium ions, only 0.5m of PM-TSF-9/125 fibers was used to achieve stable gain-switched pulses and highest power. When the Tm fiber length is longer than 0.5m an unstable mode-locked pulse train was observed, while the repetition rate of the pulse train envelops either maintained the same repetition rate of the 1.5µm pump pulses or half of the repetition rate of the pump pulses, depending on the repetition rate of the 1.5µm pump pulses.

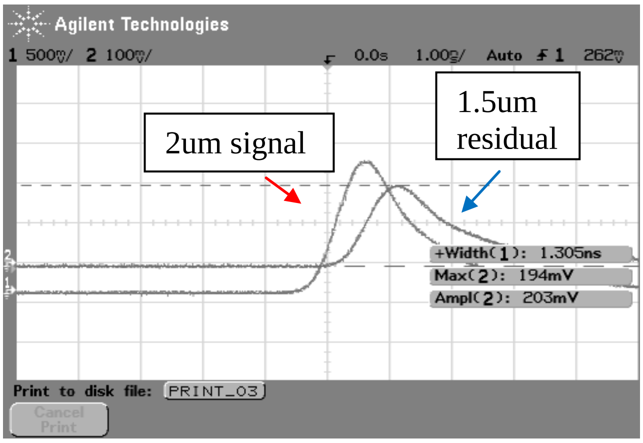

Figure 7: pulsewidth measurement of the generated 2µm pulses.

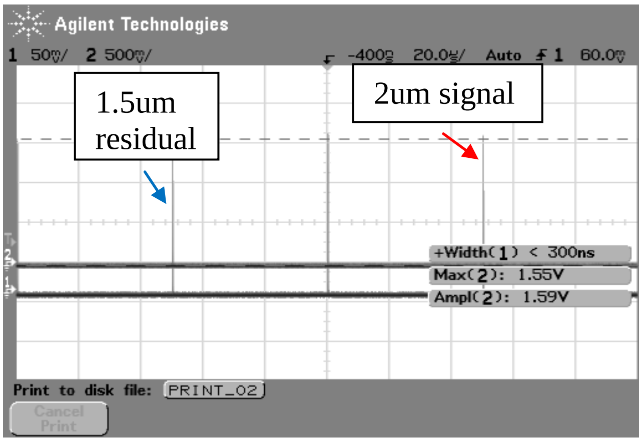

Figure 8: generated 2µm pulses at 20kHz repetition rate.

The rather short 2μm cavity length means that the pulse build up time is much shorter and overall cavity gain is lower due to the reduced pump absorption. Thus it requires a much higher peak power from the 1.5μm pump pulses, 2.5kW peak power of the 1.5μm pump pulses in this case, to trigger the 2μm pulse generation. On the fast digital oscilloscope, the residual pump pulses were monitored against the generated 2μm pulses while the 2μm pulses were used as the trigger. Thanks to the rather short cavity buildup time, the generated 2μm pulses in fact overlapped with the trailing edge of the pump pulses. As a result, the residual 1.5μm pump pulses were observed to be just a little bit behind the generated 2μm pulses as shown in Fig. 7. It was also noticed that higher 1.5μm pump laser powers, shortened the cavity buildup time, and triggered the earlier occurrence of the 2μm pulses.

4. CONCLUSION

In conclusion, we have demonstrated a compact, monolithic 2μm pulsed laser with 1.5ns pulsewidth and a maximum of 8kW peak power at a 20 kHz repetition rate. The key difference from the previously reported gain-switched Tm fiber lasers is the adoption of a high peak power (several kW) 1.5μm pulsed laser as the pump source which enabled us to generate very short pulses of ~1ns at 2μm from a 0.5m long Tm-doped fiber. Furthermore, the results presented here are directly obtained from the gain switched Tm-laser cavity and have not been amplified in an LMA fiber amplifier stage as is commonly performed to achieve such peak powers, though with longer pulses. Further improvements in slope efficiency and various repetition rates are expected with optimization of fiber length and higher Tm-doping concentration. It is also planned to integrate this compact, monolithic gain switched Tm-doped fiber laser with a high power Tm-doped fiber amplifier for further power scaling.

In addition, the unstable mode-locking-like pulse train, observed before the laser reached stable gain-switched operation, suggests that the highly-doped Thulium fibers are capable of operating as a saturable absorber to trigger passive Q-switch or passive mode-locked operation and this behavior will also be further investigated.

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