Long-cavity nanosecond thulium fiber laser: a compact source of energetic mid-IR pulses

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Abstract

We demonstrate nanosecond operation in an elongated cavity thulium fiber laser: a simple scheme for pulse energy scaling and repetition rate reduction. 7.5 nJ pulses with a repetition rate of 330 kHz are achieved.

I. Introduction

Cavity elongation has been proposed as a simple scheme for both increasing the single-pulse energy of mode-locked fiber lasers by lowering their fundamental repetition rate, and accessing a time-scale of pulses in the nanosecond regime through controllable dispersion engineering of the laser cavity by the addition of passive fiber that is otherwise hard to achieve. To date, studies adopting this design strategy have focused on lasers utilizing ytterbium and erbium active media, operating in the 1 μm or 1.5 μm band [1, 2].

Here, we extend this concept to the 2 μm range – an important spectral region for spectroscopic and metrological applications – using thulium (Tm) active fiber. Importantly, we note that this shift in operating wavelength results in a cavity dispersion map that is purely anomalously dispersive, distinct from earlier studies that typically operated with a net or all-normal dispersion cavity, supporting the generation of both dissipative soliton pulses and noise-burst-like emission [3]. Dissipative solitons possess a linear chirp and can therefore be compressed to obtain near-transform limited, high-energy pulses, while noise-like bursts are characterized by femtosecond-scale sub-pulses contained within a broad envelope, and can be in fact beneficial for driving noise-seeded nonlinear processes, such as long-pulse supercontinuum generation [4]. Thus far, the performance of long-cavity thulium fiber lasers remains an open question, as there is few experimental and theoretical investigations carried out in this mid-IR band.

In this work, we report preliminary results of a mode-locked thulium fiber laser that can sustain stable mode locking as the cavity length is elongated from 6 m to 311 m, corresponding to a 50-fold increase in cavity length. The pulse duration increases to ~27 ns at a repetition rate of 330 kHz, with the inclusion of 305 m of passive fiber in the cavity. A continuous blue-shift in the central lasing wavelength is observed with increasing passive fiber.

II. Experimental Setup and Results

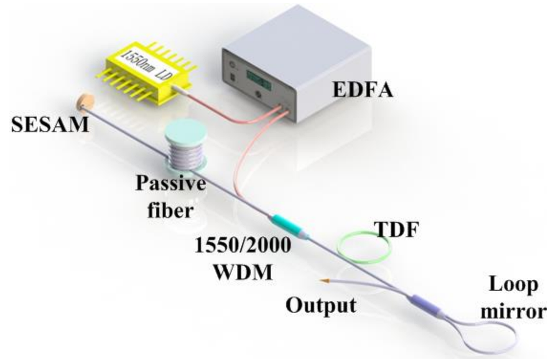

Fig.1. Experimental setup of the mode-locked Tm-doped fiber laser. (LD: laser diode, EDFA: Erbium-doped fiber amplifier)

The experimental setup of the mode-locked Tm-doped fiber laser is illustrated in Fig. 1. The pump source is provided by a laser diode (LD) operating at 1.55 μm. The LD outputs 10 mW of average power and is subsequently amplified by an erbium-doped fiber amplifier (EDFA). The amplified 1.55 μm light is injected into the cavity through a 1550/2000 wavelength-division multiplexer (WDM). The gain medium is a 2.5 m Tm-doped single mode fiber with a 9/125 core/cladding geometry. The core absorption of the Tm-fiber is ~10 dB/m at the pump wavelength of 1.55 μm. A commercial free space coupled semiconductor saturable absorber mirror (SESAM) (BATOP GmbH) is used both as the end mirror and the saturable absorber for the linear cavity. The SESAM is designed for the 2 μm band and has a modulation depth of ~30%. A fiber loop mirror utilizing a 60/40 coupler acts as the output port for the laser. Additional passive single mode fiber (SMF-28e) is inserted between the WDM and SESAM to vary the operating parameters of the laser, including: repetition rate; pulse duration; and pulse energy. The cavity length (without the additional passive fiber) is estimated to be ~6 m, which corresponds to a repetition rate of ~17.2 MHz. Stable mode-locking is observed at a pump threshold of ~120 mW and the signal to noise (SNR) of the radio frequency (RF) spectrum is more than 60 dB, indicating stable mode-locked operation. Self-starting mode-locking operation can be maintained up to ~260 mW pump when the laser output power, center wavelength, spectral bandwidth are measured to be ~16.2 mW, 1956 nm, Δλ=5.6 nm, respectively.

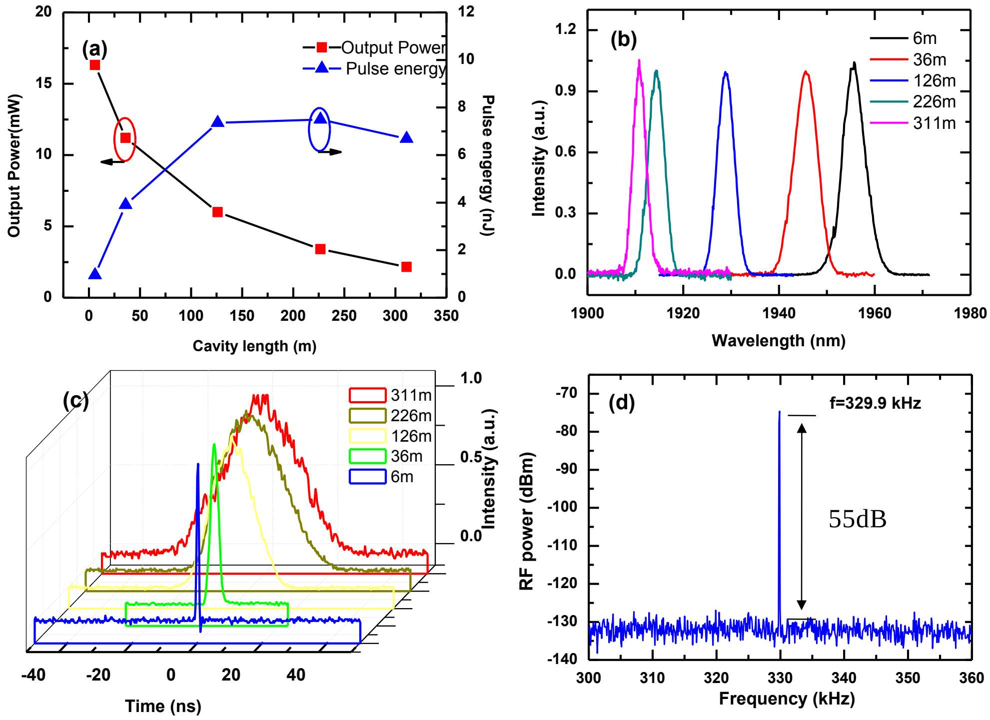

Fig.2. (a) Output power and pulse energy; (b) spectra; (c) pulse duration at different cavity lengths; (d) RF spectrum of the mode locked pulses with a cavity length of 311 m.

To investigate the effect of cavity elongation, passive fibers with different lengths are inserted into the laser without changing other cavity components. Various output characteristics are recorded for cavity lengths of 6 m, 36 m, 126 m, 226 m and 311 m. The corresponding repetition rates are ~17.2 MHz, 2.9 MHz, 815 kHz, 454 kHz and 330 kHz, respectively. Figure 2 (a) shows that the output power decreases from 16.3 mW to 2.2 mW while the pulse energy increases from 0.9 nJ and saturates at ~7.5 nJ for 226 m cavity length. At this point the fiber loss introduced by elongating the cavity length overtakes the effect of repetition reduction. A monotonic blue-shift of the center wavelength from 1957 nm to 1911 nm is observed as the cavity length increases. The gradual narrowing of the optical spectra indicates that nonlinear effects are reduced as the pulse duration increases with cavity elongation due to an increase in the overall cavity dispersion. An oscilloscope with 500 MHz electrical bandwidth is used to illustrate the pulse temporal evolution. A pulse duration of ~26.6 ns is obtained at 330 kHz repetition rate. A limited diagnostic electrical bandwidth prohibits a full characterization of the pulse duration below approximately 2 ns, but a trend of monotonic increase in duration with increasing cavity length is predicted, in agreement with earlier studies of similar laser designs. We note that the laser is able to maintain self-starting operation at all cavity lengths. Figure 2 (d) illustrates the RF spectrum for the 311 m cavity length, where a SNR of 55 dB is observed.

III. Conclusions

We have demonstrated for the first time the operation of a long-cavity Tm-doped fiber laser, operating in the 2 μm spectral range, and generating nanosecond-scale pulses. Distinct from earlier studies of long-cavity, nanosecond mode-locked sources we emphasize that the laser operates with an all-anomalous dispersion map. Detailed numerical simulations will be conducted to reveal the complex dissipative nonlinear dynamics responsible for pulse-formation and stabilization in this operating regime. We predict such a source could provide a simple compact route toward energetic pulses for applications in mid-IR spectroscopy and metrology.

Acknowledgment

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References

[1] R. I. Woodward et al., “Fiber grating compression of giant-chirped nanosecond pulses from an ultra-long nanotube mode-locked fiber laser,” *Opt. Lett.* 40, 387-390 (2015).

[2] Y. Senoo et al., “Ultralow-repetition-rate, high-energy, polarization-maintaining, Er-doped, ultrashort pulse fiber laser using single-wall-carbon nanotube saturable absorber.” *Opt. Express* 18, 20673-20680 (2010).

[3] Philippe Grelu and Nail Akhmediev, "Dissipative solitons for mode-locked lasers," *Nature Photonics* 6, 84–92 (2012)

[4] S. M. Kobtsev, S. V. Kukarin, S. V. Smirnov,"All-fiber high-energy supercontinuum pulse generator," *Laser Phys.* 20, 375-378 (2010)