A 2 µm, gain-switched Tm-doped fiber laser and an amplifier system with an output average power of 9 W at 50 kHz

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Abstract—We demonstrate a gain-switched thulium-doped fiber laser and amplifier system (TDFL&A) operating at a wavelength of 1994.7nm. A pulsed fiber Master Oscillator Power Amplifier (MOPA) at 1.55µm was used to gain-switch the Tm fiber laser via in-band pumping. In the next step, the gain-switched pulses were amplified in a cladding-pumped Tm-doped fiber amplifier pumped by up to 30 W at 793nm. For the pulse repetition frequency (PRF) of 100kHz, the laser system delivered the maximum average output power as high as 9.03W with a slope efficiency of 36.4%. For the PRF of 50 kHz, stable 25-ns pulses with energy of 0.18mJ corresponding to a peak-power of 6.8kW were achieved. The performance of the laser system is described.

Lasers operating at ~2-µm have already proved to be good sources of coherent radiation used in medicine, spectroscopy, gas sensing, direct energy systems or nonlinear frequency conversion systems [e.g., 1-7]. Particularly, Tm^{3+}-doped fiber lasers (TDFLs) have attracted great attention of many research groups recently. They seem to be especially suitable for producing 2-µm laser radiation due to: (1) strong absorption spectrum that has good overlap with the emission spectrum of commercially available 793-nm laser diodes, (2) the energy-level structure of Tm^{3+} ions providing the quantum efficiency of a laser close to 200% through the cross relaxation process and (3) wide tunability over the emission band spanning from ~1.7 to 2.1µm. TDFLs can effectively generate continuous wave (CW) output power (exceeding even 1 kW level [8]) as well as pulses of a nanosecond [9-10] or picosecond [11-12] width.

Many applications require 2-µm pulses of short, usually on the nanosecond scale, duration with appropriate kW peak power and generated at high (>10 kHz) PRF. Such values can be directly achieved by simple Q-switching of laser losses [e.g., 13-15]. However, in the case of all Q-switched lasers the pulse width is dependent on repetition rate, which may be a problem for some applications, especially for those where a high degree of control on pulse parameters is needed. Therefore, an alternative method of pulse operation seems to be gain-switching where pulse operation is realized by laser gain on/off switching via pump power modulation [12, 16]. In particular, fast gain-switching, together with in-band pumping, can provide stable 2-µm pulses of short duration at PRF of a few tens of kHz [17]. Furthermore, a gain-switching technique offers simple laser geometry (there is no need to use additional in-cavity components, which is convenient for ensuring an all-fiber configuration) and a narrow bandwidth of laser output (by using fiber Bragg gratings).

To realize fast gain switching of TDFLs effectively, they can be pumped by short (<200ns) pulses at a wavelength of ~1.5µm [17-18] or ~1.9µm [19]. This allowed obtaining 2-µm pulses as short as 10ns [17] and pulses with energy of up to 1.3mJ [16].

This paper presents results on a 2-µm, fast gain switched, narrow-band Tm^{3+}-doped fiber laser and amplifier system with average output power as high as 9W and with a diffraction-limited output beam.

The block diagram of the TDFL&A system is shown in Fig. 1. It consists of three main parts: (1) a fiber MOPA operating at 1.55 µm, (2) core-pumped TDFL and (3) cladding-pumped Tm-doped fiber amplifier (TDFA).

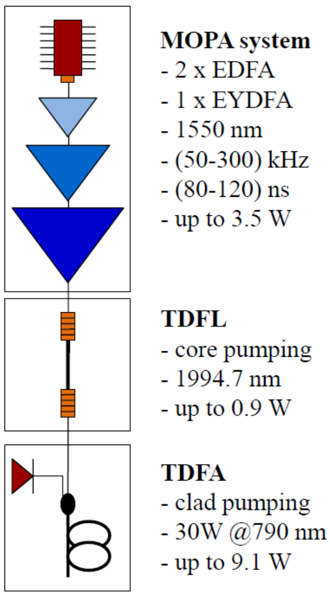

Fig. 1. Block diagram of the experimental setup.

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A 20-cm long Tm-doped, single mode, polarization maintaining (PM), double-clad silica fiber was used as an active medium of the TDFL. It had a 10µm core diameter with a NA of 0.15 and an inner cladding of the 130µm diameter and an NA of 0.46. The active fiber was core-pumped by a pulsed 1.55µm MOPA system delivering pulses of (80-120)ns at an independently changeable repetition rate in the range from 50 to 300kHz. The MOPA system consisting of a semiconductor DFB laser seed followed by a cascade of Er and Er/Yb amplifiers was capable to deliver energy of several tens of µJ and average power of up to 3.5W. About 90% of pump power was absorbed by the Tm-doped fiber core. A pair of fiber Bragg gratings (FBGs) provided the feedback, in which a high reflector (HR) FBG had a >99% reflectivity at the wavelengths of 1994.5nm and a bandwidth of 1.5nm, whereas the output coupler (OC) FBG had the reflectivity of 90% at 1994.6nm. The pulse train from the gain-switched TDFL, after optical isolation, was directly launched into a ~2.5-m long large-mode-area (LMA) Tm-doped fiber characterized by the core/clad diameter of 25/250µm. It was cladding pumped in co-propagating configuration by a 793-nm, 30-W laser diode with 100/125µm (0.22 NA) fiber pigtail. The output end of the Tm-doped LMA fiber was angle cleaved by ~8° to eliminate back reflections. Due to the quasi-three-level nature of thulium dopant, the active fiber cooling is critical for achieving a high conversion efficiency. Therefore, both pieces of Tm-doped fibers were coiled on a 10-cm diameter cylinders placed on a water-cooled copper plate that was kept at ~16°C. Furthermore, all the system components were fusion spliced, thus making it all-fiber. The laser output beam was collimated and then passed through a dichroic optical filter to separate the 2µm signal from the unabsorbed pump.

The laser system was tested at PRF ranging from 50 to 300kHz, resulted from the RC circuit applied in the control unit of the DFB laser diode, seeding the MOPA. The main aim of the experiment was to achieve as short as possible kW-class pulses generated at possibly high PRF. Applying the frequency ranging from 50 to 100kHz guaranteed achieving ~25ns pulses. For higher PRFs the output pulses were longer - the available pump pulse energy was too low to reach a suitably high gain / cavity losses ratio and thus support generation of short pulses. It is obvious that for higher repetition rates and constant (maximum available) pump power, pulse energies are smaller and pulse durations are longer, which results from gain switching dynamics. The duration of 1.55-µm pump pulse was set to be ~100ns. The maximum pump power at 793nm wavelength, launched into the amplifier, was 30.2W, of which over 95% was absorbed by the LMA fiber used in the TDFA. Time-energetic characteristics of the laser system are presented in Figs. 2-4.

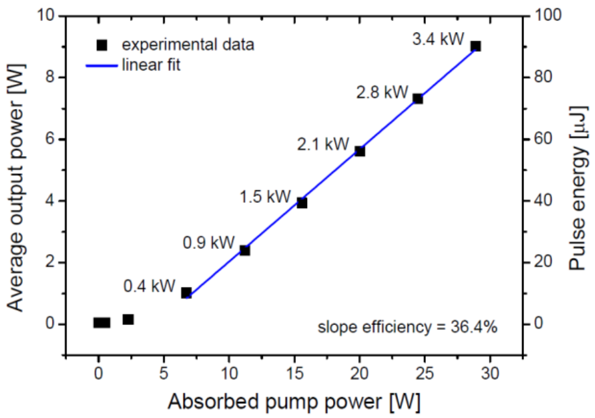

Fig. 2. Average output power and pulse energy of the TDFL&A for the PRF of 100kHz versus absorbed pump power at 793nm.

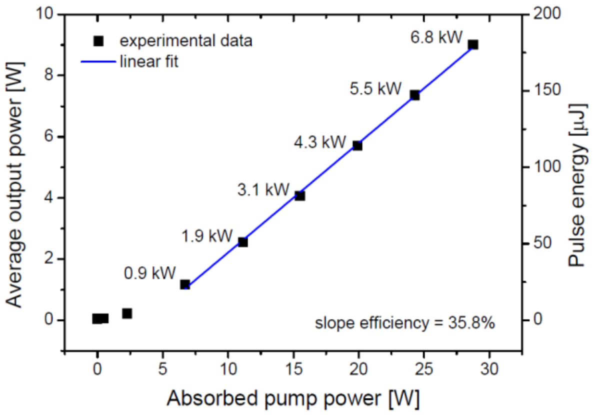

Fig. 3. Average output power and pulse energy of the TDFL&A for the PRF of 50kHz versus absorbed pump power at 793nm.

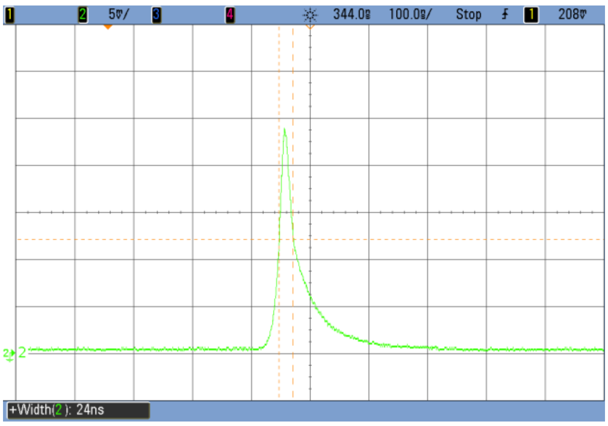

Fig. 4. Temporal profile of a typical, stable 2-µm laser pulse.

The maximum output power for the applied PRFs and pulses with ~25ns duration was only limited by the available pump power. Figures 2-3 show the average output power and pulse energy of the amplified pulses as a function of absorbed pump power. The output power increases linearly with an increase in 793nm pump power of the TDFA and the higher the PRF, the more 2-µm power can be achieved. For the PRF of 100kHz and maximum available pump power (30.2W), the output power was measured to be 9.03W (90µJ of energy in a 25-ns pulse) with the slope efficiency of 36.4%. Lowering the frequency to 50kHz resulted in a very small decrease in output power, only to 9W with a slope efficiency of 35.8%. The corresponding pulse energy and peak power for this case were 0.18mJ and 6.8kW, respectively. The pulse energy (E_{pulse}) was calculated by dividing the average output power ($P_{average}$) by PRF, whereas the output pulse peak power, assuming a Gaussian shape, was found as $P_{peak}=0.94\ E_{pulse} \times t_{pulse}^{-1}$, where t_{pulse} is the output pulse duration (FWHM). Figure 4 shows the measured oscilloscope trace of 2-µm, stable laser pulse measured at PRF of 50kHz and for the maximum performance of the laser system. Time characteristics were recorded using a fast photodetector with a rising time of less than 35ps (EOT, ET-5000F) and an oscilloscope with a 1GHz bandwidth, (Agilent Technologies, MSO7104B). The duration of the shortest, stable pulse was ~25ns and the pulse envelope had a slightly asymmetric shape with a steeper rising edge and a slower trailing edge - like in the case of a classical Q-switched pulse shape. As can be seen, the output pulse is smooth and clean without any relaxation spikes present.

Figure 5 shows the spectrum of the amplified pulse train at PRF of 50kHz and for output power of 9W. The laser system emitted the wavelength centred at 1994.7nm with a bandwidth of 1.59nm measured at 10dB below the maximum peak. The spectrum was slightly broadened compared with that emitted by the TDFL, which can be attributed to a self-phase modulation (SPM) effect occurring when high-peak-power pulses are amplified in a small area core of a gain fiber. The output laser beam was of very good quality (Fig. 6) with M^2 =1.1.

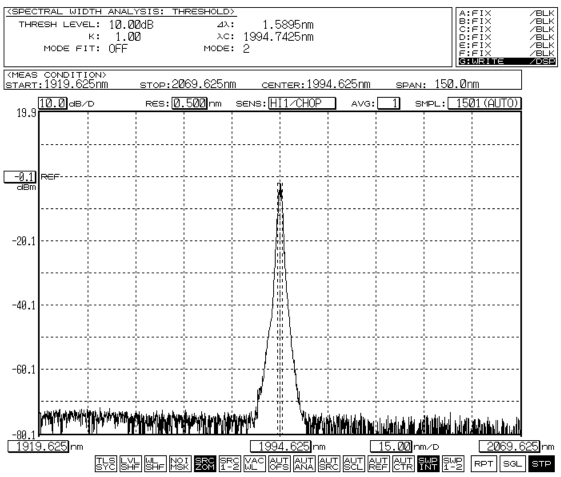

Fig. 5. Emission spectrum of the gain-switched TDFL&A system.

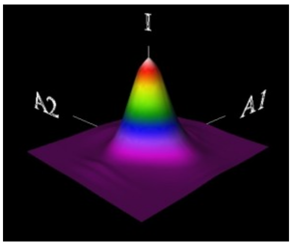

Fig. 6. Far-field beam profile (50kHz, 25ns, 9W of output power).

The output parameters of the developed gain-switched TDFL&A system are more than sufficient to be used as an "eye-safe" laser transmitter or as a pump source for mid-infrared optical parametric oscillators.

In conclusion, we have reported over 9W of average output power from a gain-switched Tm-doped silica fibre laser and amplifier system operated at 1994.7nm. The maximum demonstrated slope efficiency was 36.4% with respect to the absorbed pump power at 793nm. The laser system delivered 25ns pulses at the PRF of 50-100kHz and with a maximum peak power of 6.8kW. Improvements in the laser cavity and amplification stage design, along with the implementation of more powerful pump source will further increase the fibre laser output energy/peak power.

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