

PACS numbers: 42.60.Da; 42.55.Wd; 42.55.Xi; 42.60.Fc
DOI: 10.1070/QE2014v044n04ABEH015210

Generation of 25-ns pulses with a peak power of over 10 kW from a gain-switched, 2-μm Tm-doped fibre laser and amplifier system

J. Swiderski, M. Michalska, W. Pichola, M. Mamajek

Abstract. **We report on an all-fibre, gain-switched, Tm^{3+}-doped silica fibre laser and amplifier system generating a train of pulses at a wavelength of 1994.4 nm. When operating at a pulse repetition frequency $f = 100$ kHz, it delivered the maximum average power as high as 9.03 W with a slope efficiency of 36.4%. At $f = 26$ kHz, stable 25-ns pulses with an energy of 0.28 mJ corresponding to a peak power of 10.5 kW were obtained. The performance of the laser system is described.**

Keywords: *thulium-doped fibre lasers, gain-switching, laser resonators, pulse amplification.*

1. Introduction

Laser sources operating in the mid-IR spectral band have been receiving a particular attention in recent years due to their wide range of applications in medicine, spectroscopy, trace gas sensing, direct energy systems and nonlinear frequency conversion [1–7]. Considering this spectral band, thulium-doped fibre lasers (TDFLs), cladding pumped at 793 nm and emitting in the ~1.6–2.1 μm range, have already proved to be high-power class laser sources with a continuous wave (cw) output exceeding 1 kW [8, 9]. Furthermore, the process of cross-relaxation in the Tm^{3+} ions, enabling the 'two-for-one' excitation of the upper laser level, significantly improves (theoretically by 2 times) the quantum efficiency of TDFLs [10], which additionally makes them attractive compared to their counterparts – 1.55 μm erbium-doped fibre lasers. Some applications require 2-μm pulses of short, usually on the nanosecond scale, duration with a kW peak power and at high (>10 kHz) pulse repetition frequencies. Such values can be directly achieved by simple *Q*-switching of laser losses [see, e.g., 11–15]. However, in case of all *Q*-switched lasers the pulse width is dependent on the repetition frequency, which may be a problem for some applications, especially for the ones where a high degree of control of pulse parameters is needed. Therefore, an alternative method of pulse operation seems to be gain-switching where pulse operation is realised by laser gain on/off switching via a pump power modulation [16–18]. In particular, fast gain-switching, together with resonant pumping, can provide stable 2-μm pulses of short (<100 ns) duration at a pulse repetition frequency *f* of a few tens of kHz [19]. To realise fast gain switching of TDFLs effectively, they can be pumped by short (<200 ns) pulses at the wavelength of ~1.5 μm [e.g., 17, 19, 20] or ~1.9 μm [16, 21]. This allowed obtaining 25-ns pulses with the energy of up to 35 μJ in an all-fibre laser system [17] and 61-ns pulses with the energy of 1.3 mJ and corresponding peak power of 21.3 kW in a not-all-fibre TDFL [16]. A very interesting concept of a narrow-pulse-width gain-switched TDFL has been recently proposed by Tang et al. [22] who reported stable gain-switched pulses with over 100 kW of peak power. In this approach the 2-μm output pulses generated by the TDFL were launched into a 10-m long single-mode fibre and then, utilising the Rayleigh induced Stimulated Brillouin Scattering (SBS) effect, they were narrowed down to ~20 ns. The only drawback of this approach is the wide (over 250 nm) output spectrum, which is typical for supercontinuum (SC) generation.

This paper presents the results relating to a 2-μm, fast gain switched, narrow-band thulium-doped fibre laser and amplifier system with an average output power as high as 9.03 W and with an almost diffraction-limited output beam.

J. Swiderski, M. Michalska, W. Pichola, M. Mamajek Institute of Optoelectronics, Military University of Technology, 2 Kaliskiego Street, 00-908 Warsaw, Poland; e-mail: jswiderski.ioe.mut@gmail.com

Received 16 April 2013
Kvantovaya Elektronika **44** (4) 294–297 (2014)
Submitted in English

2. Laser system setup

The setup of laser system is shown in Fig. 1. It consisted of three main parts: a fibre-based 1.55-μm pump laser system built in master oscillator power amplifier (MOPA) configuration, a core-pumped TDFL and a thulium-doped fibre amplifier (TDFA). The MOPA delivered a train of ~120 ns pulses

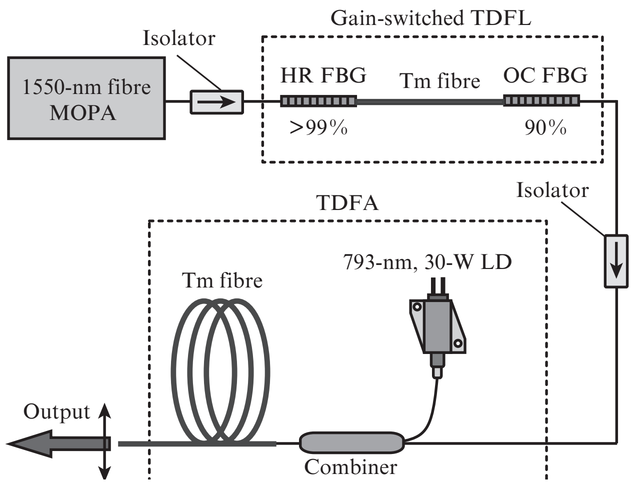

Figure 1. Schematic of the experimental setup.

at a changeable (26 – 100 kHz) pulse repetition frequency with the average power of up to 3.5 W, thus providing pump pulse parameters suitable for fast gain switching. The laser was built with the use of a 20-cm long Tm-doped (~2 wt. %), single mode, polarisation maintaining (PM), double-clad silica fibre. The active fibre had a core/clad diameter of 10/130 μm with corresponding numerical apertures (NAs) of 0.15/0.46. The optical cavity was formed by a highly reflective (HR) fibre Bragg grating (FBG) of more than 99% reflectivity (bandwidth of 1.5 nm at 1994.5 nm) and an output coupler (OC) FBG of 90% reflectivity with a 3 dB reflection bandwidth of 0.5 nm. The detailed description of the construction of the MOPA and core-pumped TDFL can be found in [20].

The output from the gain-switched TDFL, equipped with a fibre optical isolator, was directly fusion spliced to the input fibre pigtail of the (2 + 1)×1 pump power combiner of the thulium-doped fibre amplifier (TDFA). The TDFA was built with the use of ~2.5-m long Tm^{3+}-doped fibre (TDF), characterised by the same parameters as mentioned above. It was cladding-pumped in co-propagating configuration by a 793-nm, 30-W laser diode (LD) with a 100/125 μm (0.22 NA) fibre pigtail. The output end of the TDF was angle cleaved by ~8° to eliminate any back reflections. Due to the quasi-three-level nature of thulium dopant, the active fibre cooling is critical for achieving a high conversion efficiency. Therefore, both pieces of active fibres 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-fibre. The laser output beam was collimated and then passed through a dichroic optical filter to separate the 2 μm signal from the unabsorbed pump light at λ = 1.55 μm.

3. Results

The laser system was tested at f ranging from 26 to 100 kHz. The lower frequency limit resulted from the RC circuit applied in the control unit of the DFB laser, seeding the MOPA. The system could work at higher repetition frequencies; however, at f > 100 kHz the pump pulse energy was too low to reach a suitably high gain/cavity loss ratio and thus support generation of short (<50 ns) pulses. It is obvious that for higher repetition frequencies 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 120 ns. For each f applied, the energy of pump pulses was selected to obtain the 2-μm output pulses with duration as short as possible while keeping the output pulse stable. During the experiment it was noticed that selecting a too high pump pulse energy made the output pulse show significant overmodulations and pulsation in its amplitude. Also the pulse jitter increased. Therefore, in the laser system, presented in Fig. 1, a train of stable pulses with duration of ~25 ns generated at the maximum frequency of 100 kHz was amplified. The maximum pump power at 790 nm wavelength, launched into the amplifier, was 30.2 W, of which over 95% was absorbed by Tm^{3+} ions.

Figure 2 shows the spectrum of the amplified 25-ns pulses at f = 26 kHz, which was measured by an optical spectrum analyser (Yokogawa, AQ6370). When the laser operated at its maximum performance, it emitted the wavelength centred at 1994.4 nm with a FWHM spectral width of 1.2 nm. The spectrum was slightly broadened comparing with that emitted by the TDFL. It can be attributed to self-phase modulation

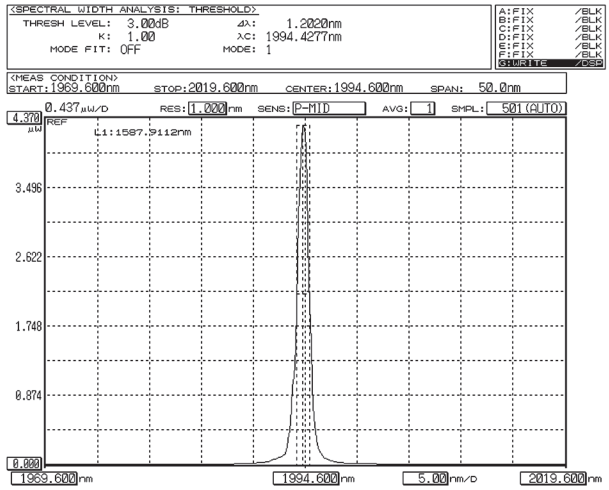

Figure 2. Emission spectrum of 2-μm pulses.

(SPM) effect occurring when high-peak-power pulses are amplified in a small area core of the gain fibre. The spectrum of the output signal recorded for higher frequencies was also centred at 1994.4 and its width was comparable.

The maximum output power for the specified f and pulses with 25 ns in duration was only limited by the available pump power. Figure 3 shows the average output power and pulse energy of the amplified pulses at four different f as a function of absorbed pump power. The power was measured by a power meter (Ophir, Laserstar) with a thermal sensor response range of 0.19 to 20 μm.

As can be seen in Fig. 3, the output power increases linearly with increasing 790-nm pump power of the TDFA and the larger the f the higher power at 2 μm can be achieved. At f = 100 kHz and maximum available pump power (30.2 W), the output power was 9.03 W (90 μJ of energy in a 25-ns pulse) with the slope efficiency of 36.4%. Lowering f to 26 kHz resulted in the output power of 7.28 W with the slope efficiency of 31.1%. The corresponding pulse energy and peak power for this case was 0.28 mJ and 10.53 kW, respectively. The pulse energy E_{pulse} was calculated by dividing the average output power P_{av} by f, whereas the output pulse peak power, assuming a Gaussian shape, was found as $P_{peak} = 0.94E_{pulse}t_{pulse}^{-1}$, where t_{pulse} is the output pulse duration (FWHM). The observed changes in slope efficiency (from 36.4% to 31.1%) resulted from the fact that the amplifier did not work in conditions close to saturation. The output power instability (measured over 10 min runtime) was estimated to be <1%.

Figure 4 shows the measured oscilloscope trace of 2-μm, stable laser pulse measured at f = 26 kHz and for maximum performance of the laser system. Time characteristics were recorded using a fast photodetector with rising time of less than 35 ps (EOT, ET-5000F) and an oscilloscope with 1 GHz bandwidth (Agilent Technologies, MSO7104B).

The duration of the shortest, stable pulse was 25 ns and the pulse envelope had a slightly asymmetric shape with a steeper rising edge and a slower trailing edge – like in 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 presents the measured beam radius at different positions after the lens. The measurements were carried out

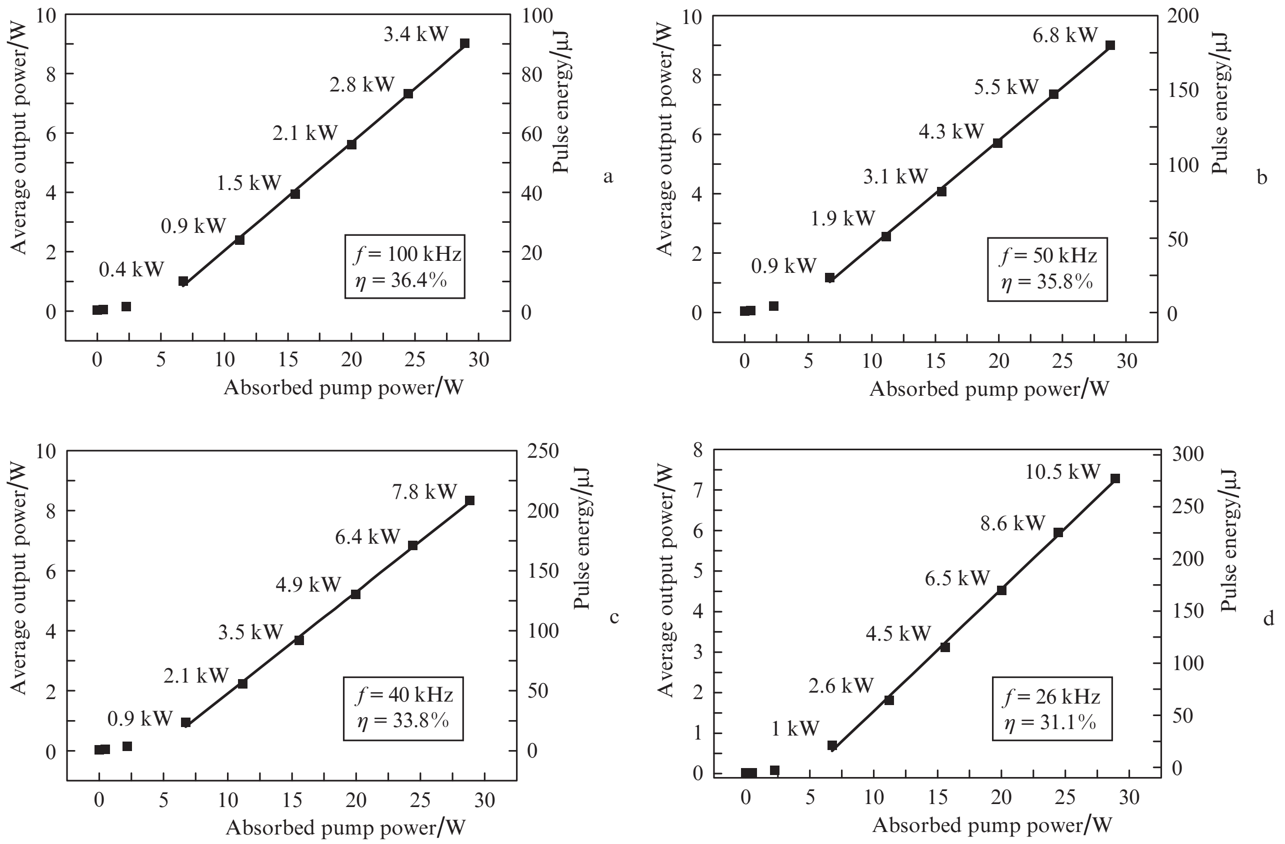

Figure 3. Average output power and pulse energy of the TDFA vs. absorbed pump power at 790 nm for $f =$ (a) 100 kHz, (b) 50 kHz, (c) 40 kHz and (d) 26 kHz.

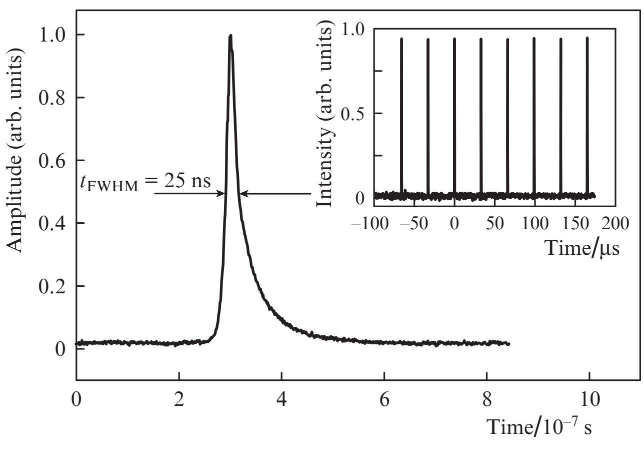

Figure 4. Temporal profile of the ultrashort, stable output laser pulse. Inset, laser pulse train at $f = 26$ kHz.

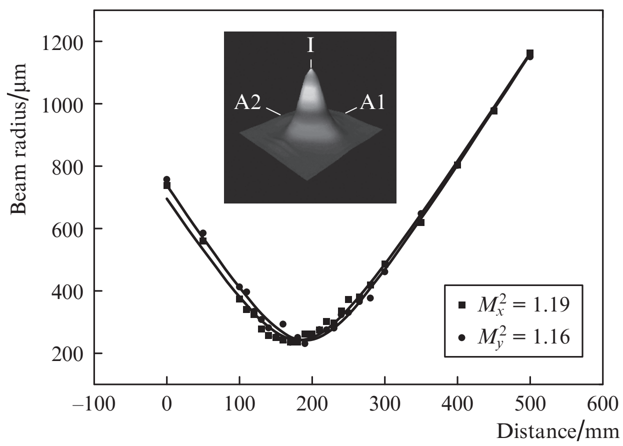

Figure 5. Beam radius for the amplified laser output as a function of distance from the focusing lens, measured for maximum laser system performance ($f = 26$ kHz). Inset, far-field beam profile.

with the use of a fully automated M^2 system using the beam propagation analyser with a pyroelectric profiler (NanoModeScan, Ophir). By fitting the Guausian beam standard expression to the measured data, the beam quality factor was estimated to be $M_x^2 = 1.19$ and $M_y^2 = 1.16$.

The output parameters of the developed gain-switched Tm-doped fibre laser and amplifier are more than sufficient to use it as an 'eye-safe' laser transmitter or as a pump source for mid-IR optical parametric oscillators. Further output power scaling up as well as improving the laser system efficiency is possible by applying more pump power as well as optimizing the laser cavity of the TDFL (fibre length, output coupling) and adopting more efficient cooling methods for the active fibres. The beam quality parameter could also be improved by much accurate angle cleaving of the laser fibre output.

4. Conclusions

In conclusion, an all-fibre, 2-μm gain-switched thulium-doped fibre laser and amplifier system was presented, delivering stable 25-ns pulses with 0.28-mJ energy and corresponding 10.53-kW peak power. The maximum output average power, measured at f = 100 kHz, was 9.03 W with a slope efficiency of 36.4%.

Acknowledgements. The authors are grateful to Jan Karczewski for his support of this work. This research was partially supported by the Polish National Science Centre (Project No. 724/N-MIFL/2010/0).

References

1. Scott N.J., Cilip C.M., Fried N.M. *IEEE J. Sel. Top. Quantum Electron.*, **15**, 435 (2009).
2. Baudelet M., Willis C.C.C., Shah L., Richardson M. *Opt. Express*, **18**, 7905 (2010).
3. Koch G.J., Beyon J.Y., Barnes B.W., Petros M., Yu J., Amzajerdian F., Kavaya M.J., Singh U.N. *Opt. Eng.*, **46**, 116201 (2007).
4. Sprangle P., Ting A., Penano J., Fischer R., Hafizi B. *IEEE J. Quantum Electron.*, **45**, 138 (2009).
5. Creeden D., Ketteridge P.A., Budni P.A., Setzler S.D., Young Y.E., McCarthy J.C., Zawilski K., Schunemann P.G., Pollak T.M., Chicklis E.P., Jiang M. *Opt. Lett.*, **33**, 315 (2008).
6. Swiderski J., Michalska M. *Laser Phys. Lett.*, **10**, 035105 (2013).
7. Kurkov A.S., Kamynin V.A., Tsvetkov V.B., Sadovnikowa Y.E., Marakulin A.V., Minashina L.A. *Kvantovaya Elektron.*, **42**, 778 (2012) [*Quantum Electron.*, **42**, 778 (2012)].
8. http://www.qpeak.com/Aboutus/news.shtml.
9. Ehrenreich T., Leveille R., Majid I., Tankala K., in *Proc. SPIE 'Fiber Laser VII: Technol. Syst. Applicat.'*, 1-15 (2010).
10. Jackson S.D. *Nature Photon.*, **6**, 423 (2012).
11. Eichhorn M. *Opt. Lett.*, **32**, 1056 (2007).
12. Eichhorn M., Jackson S.D. *Opt. Lett.*, **33**, 1044 (2008).
13. El-Sherif A.F., King T. *Opt. Lett.*, **28**, 22 (2003).
14. Geng J., Wang Q., Luo T., Amzajerdian F., Jiang S. *Opt. Lett.*, **34**, 3713 (2009).
15. Swiderski J., Zajac A., Konieczny P., Skorczakowski M. *Opt. Express*, **12**, 3554 (2004).
16. Tang Y., Li F., Xu J. *IEEE Photon Technol. Lett.*, **23**, 893 (2011).
17. Simakov N., Hemming A., Bennetts S., Haub J. *Opt. Express*, **19**, 14949 (2011).
18. Zhou R.L., Zhao J., Yuang C., Chen Z.Y., Ju Y.L., Wang Y.Z. *Chin. Phys. Lett.*, **29**, 064201-1 (2012).
19. Jiang M., Tayebati P. *Opt. Lett.*, **32**, 1797 (2007).
20. Swiderski J., Maciejewska M., Kwiatkowski J., Mamajek M. *Laser Phys. Lett.*, **10**, 015107 (2013).
21. Tang Y., Xu L., Yang Y., Xu J. *Opt. Express*, **18**, 22964 (2010).
22. Tang Y., Li F., Xu J. *Laser Phys. Lett.*, **10**, 035101 (2013).