

Q-switched Tm³⁺-doped multi-ring fibre laser operating at 1.96 μm

Łukasz Sójka^{1*}, Łukasz Pajewski¹, Sławomir Sujecki^{1,2}, Samir Lamrini³, Mateusz Prorok⁴, Piotr Miluski^{4**}, Marcin Kochanowicz⁴, Marek Łodziński⁵, Wojciech A. Pisarski⁶, Dominik Dorosz⁷

¹Department of Telecommunications and Teleinformatics, Wrocław University of Science and Technology, ul. Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

²Military University of Technology, ul. gen. Sylwestra Kaliskiego 2, 00-908 Warszawa, Poland

³LIMA Photonics GmbH, Weender Landstrasse 3-7, 37075 Goettingen, 37073 Goettingen, Germany

⁴Faculty of Electrical Engineering, Białystok University of Technology, ul. Wiejska 45D, 15-351 Białystok, Poland

⁵Faculty of Geology, Geophysics and Environment Protection, AGH University of Kraków, al. Adama Mickiewicza 30, 30-059 Kraków, Poland

⁶Institute of Chemistry, University of Silesia, ul. Szkolna 9, 40-007 Katowice, Poland

⁷Faculty of Materials Science and Ceramics, AGH University of Kraków, al. Adama Mickiewicza 30, 30-059 Kraków, Poland

Article info

Article history:

Received 21 Jul. 2025

Received in revised form 12 Sep. 2025

Accepted 16 Sep. 2025

Available on-line 12 Nov. 2025

Keywords:

fibre laser;

thulium-doped fibre lasers;

Q-switched fibre laser;

2 μm laser.

Abstract

A realisation of a Q-switched Tm³⁺-doped fibre laser operating at 1.96 μm wavelength is reported. The Tm³⁺-doped fibre was fabricated using a novel multi-ring modified chemical vapour deposition-chelate doping technique (MCVD-CDT) technology. The developed laser emits pulses at a repetition rate of 3 kHz with an energy of 84 μJ and a duration of 272 ns, which corresponds to a peak power of 309 W. The experimental results confirm that the fabricated Tm³⁺-doped multi-ring, large mode area fibre is a promising candidate for developing high-energy Q-switched lasers operating near 2 μm wavelength.

1. Introduction

Tm³⁺-doped fibre sources with an operating wavelength of 2 μm have recently attracted considerable attention [1–4]. The main reason for this is the growing number of applications for 2 μm lasers. Furthermore, pulsed doped fibre lasers are preferred for many of these applications. Currently, the lasers operating at a 2 μm wavelength are used in medicine, optical sensing, microprocessing of polymer materials, spectroscopy, and remote optical communications [2, 5]. Due to the overlap of the 2 μm wavelength with H₂O absorption in biological tissue, 2 μm lasers are used in various medical fields, such as urology or to fragment kidney stones [2, 6, 7]. For example, high-energy pulsed 2 μm lasers with good beam quality are especially suitable for the development of differential absorption lidar (DIAL) systems for remote detection of

water vapour [8]. For DIAL applications, Q-switched lasers are preferred because they can produce energies above 50 μJ with short pulse durations, which reduce the thermal background, while also providing good pulse-to-pulse stability. 2 μm lasers are also used for cutting, splicing, and marking polymer materials [9, 10] and can be employed for detecting greenhouse gases like CO₂, which have strong absorption in this spectral region [11, 12]. Moreover, 2 μm lasers are often used as optical pumps to generate mid-infrared (MIR) radiation [13, 14]. For example, 2 μm lasers can pump nonlinear crystals in optical parametric oscillator (OPO) systems for generating a spectrum spanning between 3 and 5 μm [13]. Additionally, a broadband MIR supercontinuum source can be achieved by pumping heavy-metal fluoride glass fibre with a pulsed Tm³⁺ fibre laser [14]. Recently, 2 μm lasers were also used to pump Tb³⁺-doped chalcogenide glass fibres that operate at wavelengths exceeding 5 μm [15].

Corresponding author at: *lukasz.sojka@pwr.edu.pl, **p.miluski@pb.edu.pl

<https://doi.org/10.24425/opelre.2025.155905>

1896-3757/ Association of Polish Electrical Engineers (SEP) and Polish Academic of Sciences (PAS). Published by PAS

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Tm³⁺ fibre lasers based on silica glass are well-developed and can provide hundreds of watts of output power in a continuous-wave (CW) operation [3, 4]. Tm³⁺ lasers can be pumped by 793 nm high-output power laser diodes. Due to the cross-relaxation mechanism under 793 nm pumping, these lasers can operate with a theoretical slope efficiency of around 70%, exceeding the Stokes limit [3, 4]. In pulsed operation, by using active Q-switching or gain-switching, these lasers can produce millijoule output energy and peak powers in the hundreds of kW [16]. Another Q-switching technique that is commonly studied in the literature is based on the use of saturable absorbers as passive Q-switch modulators. The main advantage is that a Q-switched laser cavity has a simple construction. However, passively Q-switched fibre lasers generate only a few μJ of output energy, with pulse durations in the range of a few microseconds and peak powers of only a few watts [17]. Moreover, the repetition rate generated by a passively Q-switched 2 μm fibre laser varies with pump power. It should be pointed out that for the Q-switched operation, large-core-diameter fibres are preferred because higher energy can be extracted from such a laser system. Thus, significant attention has been paid to developing Tm³⁺-doped large-core-area fibres that can operate in a transverse single mode whilst delivering high-energy, high-peak-power pulses. The commercially available large-mode-area (LMA) Tm³⁺-doped silica fibres have core diameters ranging from 16 μm to 25 μm , core numerical apertures (NA) between 0.09 and 0.16, and first cladding NA values greater than 0.46 [18]. In LMA, the core is enlarged, and the NA is reduced to maintain the single-mode operation of a Tm³⁺-doped silica fibre. Commercially available LMA fibres are mostly fabricated using the solution doping method; however, this method offers minimal possibilities for shaping the refractive index profile of rare-earth-doped preforms. Q-switched fibre lasers based on these Tm³⁺-doped fibres can deliver output energies of up to 0.3 mJ, with peak powers reaching several of kilowatts [19]. Another approach to developing Tm³⁺-doped large-core-area fibres is to utilize the photonic crystal fibre (PCF) technology. The PCF structure enables the design of large-mode-area fibres operating in a transverse single mode [20]. PCF technology provides great flexibility in shaping the refractive index profile of rare-earth-doped preforms. However, it should be mentioned that the fabrication of PCF glass preforms is a complicated and time-consuming process. Recently, much attention has been devoted to developing photonic crystal LMA Tm³⁺-doped fibres for a Q-switched laser operation. For example, in [21], a Tm³⁺-doped PCF with a mode-field area above 1000 μm^2 was used to realise an actively Q-switched fibre laser. The developed Tm³⁺-doped PCF Q-switched laser emitted 8.9 kW peak power pulses with an energy of 435 μJ and a duration of 49 ns, at a 10 kHz repetition rate and an operating wavelength of 2 μm . Also, in [20], an actively Q-switched Tm-doped PCF fibre laser emitting pulses with an energy of 2.4 mJ was demonstrated. The Q-switched oscillator employed a Tm³⁺-doped PCF featuring a core diameter of 81 μm and a cladding of 260 μm diameter for clad pumping [22]. It should be pointed out that the Tm³⁺-doped PCF had to be kept straight, which negatively affected the compatibility

of this Q-switched laser system. Recently, a Q-switched Tm³⁺ fibre laser relying on a flexible PCF with a core diameter of 50 μm was reported [23]. This laser produced pulses with pulse energies of 1.9 mJ, a pulse width of 116 ns, and a peak power of 15.4 kW [23]. An alternative approach to fabricating a Tm³⁺-doped fibre with an LMA consists of using a multi-ring structure [22]. The multi-ring structure reduces the doped core effective refractive index, thus enabling a single-mode operation with a relatively large beam diameter. This approach allows greater control over shaping the refractive index profile of rare-earth-doped preforms compared to the solution doping method, while still being far less effort-consuming than fabricating a PCF preform. Such a fibre is simpler to realise than PCF because the multi-ring preform can be made employing a well-established modified chemical vapour deposition-chelate doping technique (MCVD-CDT) technology [24]. Even though MCVD-CDT Tm³⁺-doped multi-ring fibres are well known, their performance as a lasing medium of a Q-switched fibre laser has not been studied much in the literature. Thus, in this contribution, the performance of a new construction Tm³⁺-doped MCVD-CDT multi-ring fibre is investigated in a Q-switched laser configuration.

The manuscript is organised into four sections. **Section 1** presents the introduction; **section 2** demonstrates the experimental setup. In **section 3**, the results for the Q-switched Tm³⁺-doped multi-ring fibre laser are presented and discussed. Finally, in **section 4**, the conclusions are presented.

2. Experimental methods

The Tm³⁺-doped multi-ring double-clad fibre was fabricated at Bialystok University of Technology using MCVD-CDT. This technique involves doping with rare-earth elements in the form of evaporated chelate compounds and embedding them into the structure of the doped core directly during the silica deposition process. This technology is an extension of the well-known solution doping method, where the porous structure of the core layer is impregnated with an alcohol solution of chelates and then sintered in a glass form during the subsequent MCVD process. An undeniable advantage of the solution doping method is the ability to introduce higher concentrations of active dopants, which is why it is still frequently used to produce preforms for laser fibres. Unfortunately, this method also has drawbacks, such as typically higher attenuation levels due to the need for the solution and relatively small core sizes resulting from the limited impregnability of the soot layer. Thus, this technology is typically used to fabricate step-index fibre types. The fibre refractive index profile determines the propagating beam profile. In many applications, a Gaussian beam profile in the fibre is highly desired due to the ability to precisely process it with optical systems (precision beam control, e.g., minimal focal point). To achieve this, we propose the novel construction of a fibre in which the core consists of alternating layers of active Tm³⁺-doped ions and undoped silica (presented in Fig. 1). This structure allows for the profiling of the beam shape propagated in the optical fibre. The active layers were additionally doped with Al₂O₃, which is used for better coordination of lanthanide ions (Tm³⁺) within the silica glass host structure.

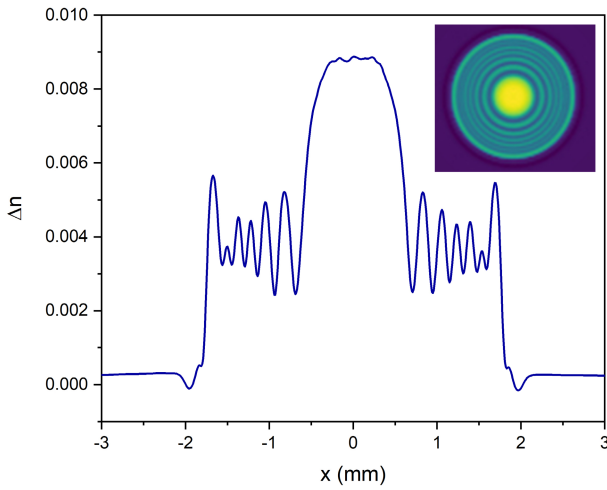


Fig. 1. The refractive index profile and map (inset) of a Tm³⁺ multi-ring preform.

The central layer had the highest concentration of Tm₂O₃ at 0.56 wt%, with Al₂O₃ concentration equal to 5.2 wt%. As a result, Δ*n* was 9 × 10⁻³. A single-mode double-clad fibre (17/240 μm core/cladding diameter) was drawn from the preform. The detailed construction, technology, and characterisation of the fibre preform [including lifetime measurements, electron probe micro-analysis using wavelength dispersive X-ray spectrometry (EPMA-WDS), and SEM images)], as well as the refractive index profile of the fibre and optical beam profile (M²_x = 1.10, M²_y = 1.23), were presented in our previous work [25] in which the construction and characterisation of a CW all-fibre laser with generation at a wavelength of 1938.8 nm (excited at 790 nm), an FWHM of 0.17 nm, and output power of 1.68 W are presented. Table 1 presents the detailed parameters of the home-made Tm³⁺-doped multi-ring double-clad fibre in comparison with commercially available Tm³⁺-doped double-clad fibres.

Figure 2 illustrates the laboratory setup of the Q-switched Tm³⁺-doped multi-ring fibre laser. In the experiment, 10 m of Tm³⁺-doped multi-ring double-clad fibre was used. To pump the Tm³⁺-doped fibre, a laser diode at 793 nm was used. The diode produced 15 W of

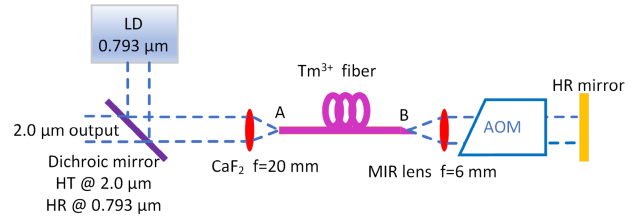


Fig. 2. The experimental layout of the Q-switched Tm³⁺-doped multi-ring fibre laser.

output power and was coupled to a multimode fibre with a 105 μm core diameter. The pump light at 793 nm was collimated using a fibre collimator and directed onto a dichroic optical mirror positioned at a 45-degree angle inside the laser cavity. The dichroic mirror was designed to reflect the pump wavelength (793 nm) while transmitting the signal wavelength around 2 μm. Efficient coupling of light into the Tm³⁺-doped fibre was achieved by employing an aspherical CaF₂ lens with f = 20 mm. To form the laser cavity, the fibre end labelled “A” in Fig. 2 was perpendicularly cleaved and served as an output mirror with a 4% reflectivity. The second mirror, used to complete the laser cavity, was a gold mirror with a high reflectivity above 95% at 2 μm. To minimise Fresnel reflections, the fibre end labelled “B” was angle cleaved. To efficiently collect and collimate the light emerging from fibre end “B,” a sapphire ball lens with f = 6 mm was used inside the laser cavity. The acousto-optic modulator (Q-switch) was made from TeO₂ (QS041-172 1.5C2P-4-MN4 Gooch&Housego), which is transparent at 2 μm wavelengths, and was placed inside the cavity. The Q-switch had a rise time of 153 ns. The pulses generated by the laser were monitored using a fast MIR detector with a time constant below 1.5 ns (PVMI-10.6, Vigo System, Poland). The detector was connected to an oscilloscope with a 500 MHz bandwidth. Laser output power was monitored by a power sensor (S415C Thorlabs). To record the spectrum emitted by the pulsed laser operating at a 2 μm wavelength, an optical monochromator combined with a ruled diffraction grating with 150 lines per mm and a sensitive MCT detector was used.

Table 1. Comparison of the parameters of active, double-clad optical fibres.

Parameter	This work, multi-ring, Tm ³⁺	LMA-TDF-25P/250-M (Nufern)	IXF-2CF-Tm-O-20-250 (iXblue)	LMA-TDF-25P/250-M (Coherent)	Tm1900-16/250DC (-PM) (LIEKKI®)
Core diameter	17 μm	24 μm ± 1.5 μm	20 μm ± 1 μm	24 μm	16.0 ± 1.5
Cladding diameter	240 μm	395.0 ± 15.0 μm	250 μm ± 5 μm	250 μm	250 ± 5
Core NA	max. 0.16	0.090 ± 0.010	0.09 ± 0.01	0.09	0.090 ± 0.010
First cladding NA	0.482	≥ 0.46	≥ 0.46	0.46	0.48
Operating wavelength	1.8–2.0 μm	2 μm	–	1.9–2.1 μm	–
Mode-field diameter	20.74 μm	22.4 μm	–	–	–
Cladding attenuation	20 dB/km @ 1310 nm	≤ 15 dB/km @ 860 nm	Clad absorption @1180 nm > 0.6 dB/m	≤ 15 dB/km at 860 nm	Cladding absorption at 789 nm 8.5 ± 2.5 dB/m
RI profile	Double clad	Double clad	Double clad	Double clad	Double clad

3. Experimental results

The performance of the Q-switched Tm^{3+} -doped fibre laser was investigated at different repetition rates and pump powers. First, the Q-switched fibre laser characteristics at a repetition rate of 7.5 kHz was tested. Figure 3(a) presents the output energy dependence in relation to pump power. The maximum output energy at the repetition rate was 46 μJ . The output energy varies linearly with respect to pump power. The available pump power limited further energy scaling. Figure 3(b) depicts the dependence of pulse duration with respect to pump power. It can be noted that an increase in pump power results in a decrease in pulse duration. This is a common observation in Q-switched fibre lasers [26, 27]. The increase in pump power results in a higher population inversion, which leads to a shorter pulse duration generated by the Q-switched fibre laser [26, 27]. The minimum pulse duration of 413 ns was measured at the maximum pump power of 14 W, available at 793 nm. Thus, the measured pulse duration corresponds to approximately four round-trip times. Figure 3(c) illustrates the peak power as a function of pump power. These results confirm that the maximum peak power achieved at a repetition rate of 7.5 kHz was 111 W. Finally, Figure 3(d) shows the measured pulse shape at the maximum available pump power and a repetition rate of 7.5 kHz. The measured pulse shape was fairly well fitted with a Gaussian function though a noticeable deviation from the Gaussian pulse shape at the trailing edge can be observed.

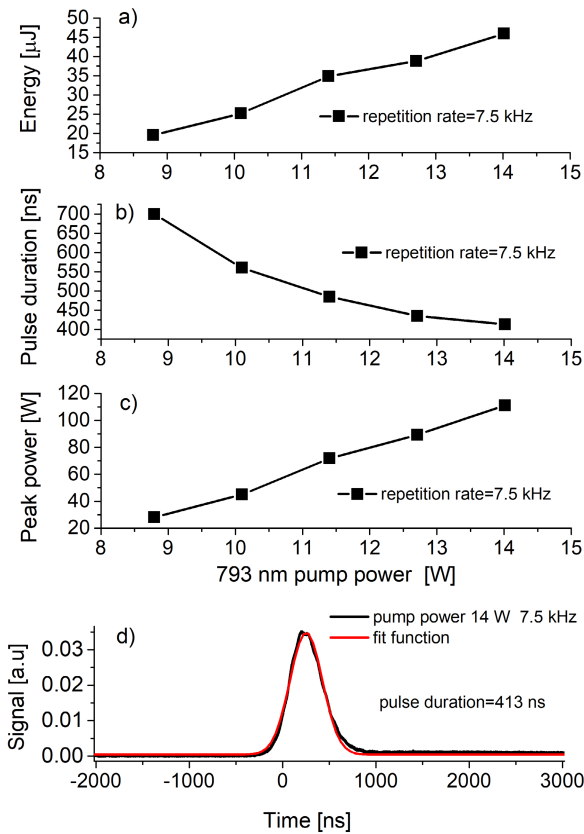


Fig. 3. (a) Pulse energy. (b) Pulse duration. (c) Peak power as a function of pump power. (d) The shortest pulse shape was measured at 7.5 kHz.

Figure 4(a) demonstrates the output energy as a function of pump power, measured at a repetition rate of 5 kHz. The maximum recorded pulse energy was 58 μJ . Figure 4(b) depicts the evolution of pulse duration vs. pump power, where the shortest pulse duration of 318 ns was measured at 5 kHz with a pump power of 14 W. Figure 4(c) presents the peak power in relation to pump power, whereby the maximum peak power of 183 W was achieved. The measured shortest pulse shape is shown in Fig. 4(d). It can be observed that at a repetition rate of 5 kHz, the maximum output energy and peak power increased when compared with the results measured at a pulse repetition frequency of 7.5 kHz (Fig. 3). This phenomenon can be understood considering that a higher population inversion builds up at a lower repetition rate, leading to an increase in output energy and a decrease in pulse duration [26, 27].

Further investigation of the Q-switched Tm^{3+} -doped multi-ring fibre laser operation was conducted at a repetition rate of 4 kHz. Figure 5(a) illustrates the output energy as a function of pump power, measured at a repetition rate of 4 kHz. The maximum output pulse energy achieved at this repetition rate is 65 μJ . Further, Figure 5(b) demonstrates the pulse duration dependence on pump power. These results show that the shortest recorded pulse duration was 277 ns. Figure 5(c) presents the evolution of peak power with respect to pump power. At a pump power of 14 W, a peak power of 235 W was achieved. Finally, the measured pulse shape with the shortest pulse duration of 277 ns at a repetition rate of 4 kHz is presented in Fig. 5(d).

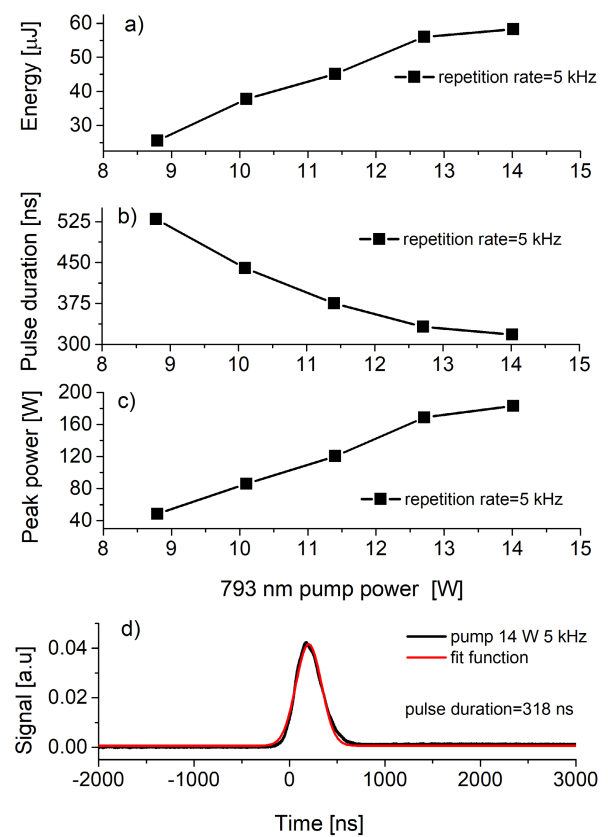


Fig. 4. (a) Pulse energy. (b) Pulse duration. (c) Peak power as a function of pump power. (d) The shortest pulse shape measured at 5 kHz.

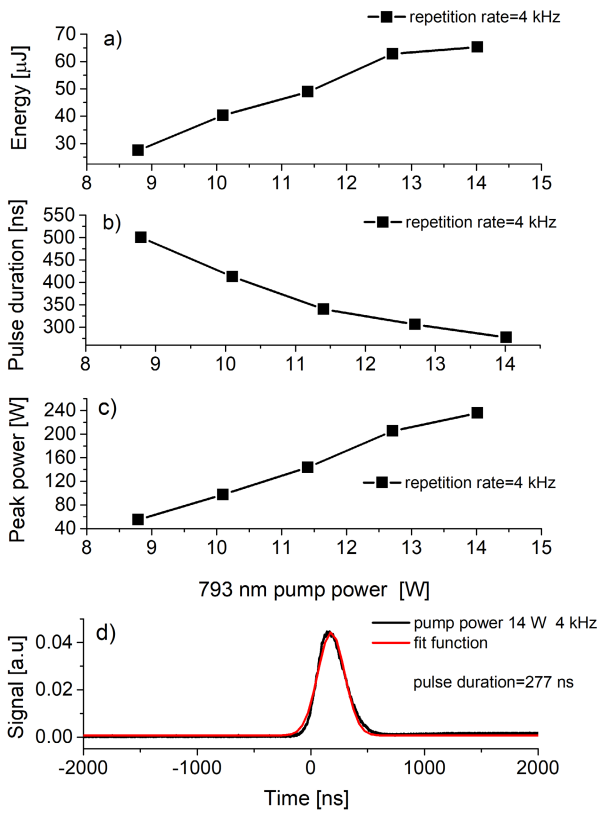


Fig. 5. (a) Pulse energy. (b) Pulse duration. (c) Peak power as a function of pump power. (d) The shortest pulse shape was measured at 4 kHz.

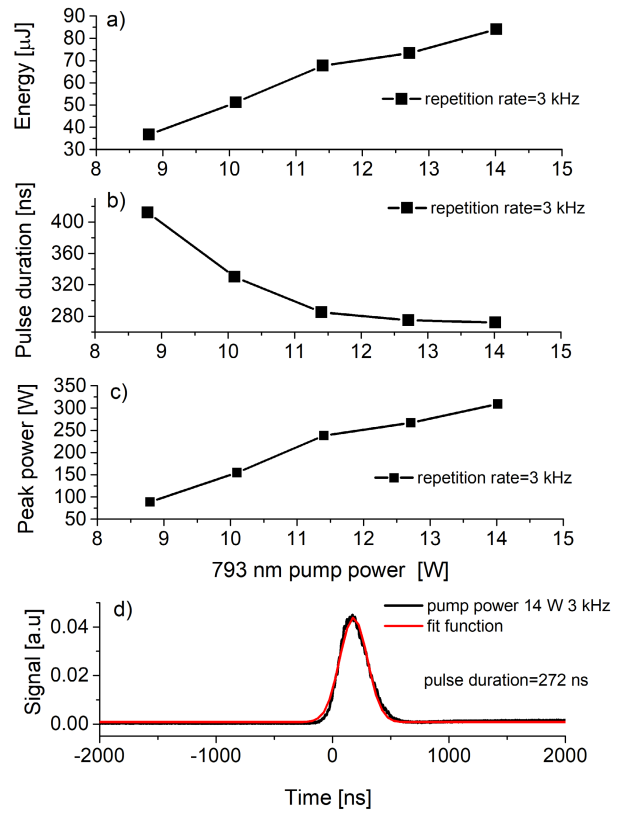


Fig. 6. (a) Pulse energy. (b) Pulse duration. (c) Peak power as a function of pump power. (d) The shortest pulse shape was measured at 3 kHz.

Figure 6(a) presents the output energy as a function of pump power, recorded at a repetition rate of 3 kHz. These results demonstrate that the laser output pulse achieved the maximum energy of 84 μJ . Figure 6(b) illustrates in turn, the dependence of pump power on pulse duration, measured at 3 kHz. From these results it can be noted that the shortest recorded pulse duration at this repetition rate of 3 kHz was 272 ns, corresponding to approximately three cavity round-trip times. Figure 6(c) illustrates the peak power evolution with respect to pump power. These results show that at a 3 kHz repetition rate, the utmost peak power of 309 W can be achieved with a 14 W pump power. Finally, Figure 6(d) shows the measured shortest pulse shape of 272 ns. As expected, the highest output energy and shortest pulse duration were recorded at a repetition rate of 3 kHz.

Table 2 summarises the highest results achieved at various repetition rates. Figure 7 shows the measured experimental pulse train at a repetition rate of 5 kHz for an incident pump power of 10.82 W. As shown in Fig. 7, the Q-switched laser operates stably.

Figure 8 shows the measured laser spectrum produced by the Tm^{3+} -doped Q-switched multi-ring fibre laser. The spectrum was measured at a pulse repetition frequency of 5 kHz and an incident pump power of 10.82 W. The laser emitted light at a wavelength of approximately 1.966 μm with a 3 dB spectral bandwidth of 12 nm. The Q-switched laser operates in a free-running regime without any spectral selective elements, such as a fibre Bragg grating (FBG) or a bulk diffraction grating.

Table 2.

Parameters of Q-switched Tm^{3+} -doped multi-ring fibre laser.

Experiment	Repetition rate [kHz]	Maximum pulse energy [μJ]	Shortest pulse duration [ns]	Maximum peak power [W]
1	7.5	46	413	111
2	5	58	318	183
3	4	65	277	235
4	3	84	272	309

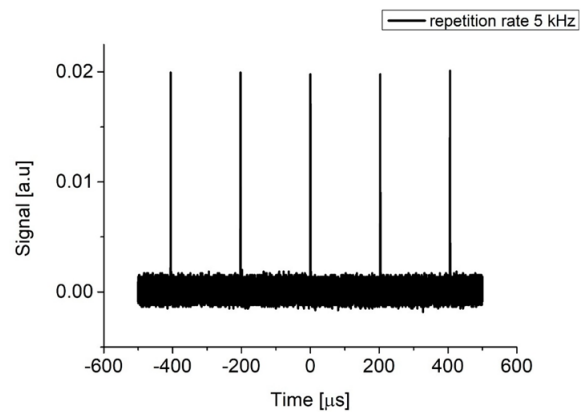


Fig. 7. Recorded typical pulse train at a pulse repetition frequency of 5 kHz, measured for an incident pump power of 10.82 W.

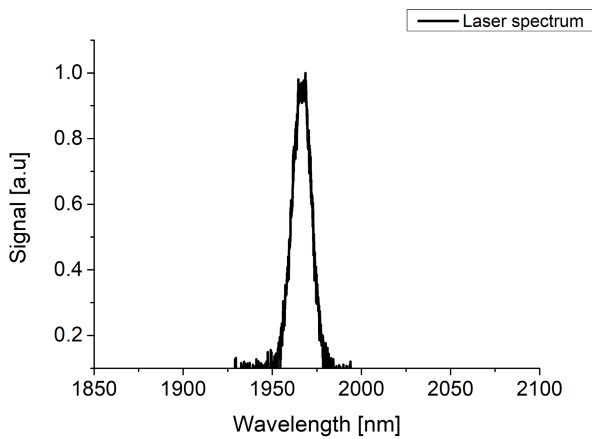


Fig. 8. Measured laser spectrum generated by the Q-switched Tm^{3+} -doped multi-ring fibre laser. The spectrum was recorded at a pulse repetition frequency of 5 kHz and an incident pump power of 10.82 W.

4. Conclusions

This paper presents a practical realisation of an actively Q-switched fibre laser with an operating wavelength of 1.96 μm . The laser has been realised using a novel Tm^{3+} -doped multi-ring fibre fabricated using the MCVD-CDT technology. The Q-switched laser dynamics was investigated at selected repetition rates and pump powers. The results show that the developed laser emitted pulses with an output energy of 84 μJ and a duration of 272 ns (corresponding to a peak power of 309 W) at a repetition rate of 3 kHz. The presented results show that the designed and fabricated Tm^{3+} -doped multi-ring fibre is a promising solution for generating high-output pulse energy and high-peak-power pulses near a 2 μm wavelength. Further work will focus on increasing the doping level of the Tm^{3+} -doped multi-ring fibre, which should result in a shorter cavity length, generating shorter pulse durations and higher peak powers.

Authors' statement

Research concept and design, Ł.S., S.S., P.M., M.K., D.D.; collection and/or assembly of data, Ł.S., Ł.P., M.P., P.M., M.K., M.Ł., W.P., D.D.; data analysis and interpretation, Ł.S., Ł.P., M.P., P.M., M.K., M.Ł., S.L., W.P., D.D.; writing the article, Ł.S., S.S., P.M.; critical revision of the article, M.K., S.L., D.D.; final approval, M.K., S.L., S.S., D.D.

Acknowledgements

The research project was funded by the National Science Centre (Poland) granted based on the decision no. UMO-2020/37/B/ST/7/03094.

References

[1] Shi, W., Fang, Q., Zhu, X., Norwood, R. A. & Peyghambarian, N. Fiber lasers and their applications [Invited]. *Appl. Opt.* **53**, 6554–6568 (2014). <https://doi.org/10.1364/AO.53.006554>

[2] Scholle, K., Lamrini, S., Koopmann, P. & Fuhrberg, P. 2 μm Laser Sources and Their Possible Applications. in *Frontiers in Guided Wave Optics and Optoelectronics* (ed. Pal, B.) (IntechOpen, 2010). <https://doi.org/10.5772/39538>

[3] Sincore, A., Bradford, J. D., Cook, J., Shah, L. & Richardson, M. C. High average power thulium-doped silica fiber lasers: Review of systems and concepts. *IEEE J. Sel. Top. Quantum Electron.* **24**, 1–8 (2018). <https://doi.org/10.1109/JSTQE.2017.2775964>

[4] Jackson, S. D. Cross relaxation and energy transfer upconversion processes relevant to the functioning of 2 μm Tm^{3+} -doped silica fibre lasers. *Opt. Commun.* **230**, 197–203 (2004). <https://doi.org/10.1016/j.optcom.2003.11.045>

[5] Scholle, K., Heumann, E. & Huber, G. Single mode Tm and Tm,Ho:LuAG lasers for LIDAR applications. *Laser Phys. Lett.* **1**, 285 (2004). <https://doi.org/10.1002/lapl.200410067>

[6] Scott, N. J., Cilip, C. M. & Fried, N. M. Thulium fiber laser ablation of urinary stones through small-core optical fibers. *IEEE J. Sel. Top. Quantum Electron.* **15**, 435–440 (2009). <https://doi.org/10.1109/JSTQE.2008.2012133>

[7] Enikeev, D. & Taratkin, M. Thulium fibre laser: Bringing lasers to a whole new level. *Eur. Urol. Open Sci.* **48**, 31–33 (2023). <https://doi.org/10.1016/j.euro.2022.07.007>

[8] Barnes, N. P., Walsh, B. M., Reichle, D. J., DeYoung, R. J. & Jiang, S. Tm:germanate fiber laser: Tuning and Q-switching. *Appl. Phys. B* **89**, 299–304 (2007). <https://doi.org/10.1007/s00340-007-2794-4>

[9] Mingareev, I. et al. Welding of polymers using a 2 μm thulium fiber laser. *Opt. Laser Technol.* **44**, 2095–2099 (2012). <https://doi.org/10.1016/j.optlastec.2012.03.020>

[10] Fuhrberg, P., Ahrens, A., Schkutow, A. & Frick, T. 2.0 μm laser transmission welding. *PhotonicsViews* **17**, 64–68 (2020). <https://doi.org/10.1002/phvs.202000013>

[11] Ghosh, A., Roy, A. S., Chowdhury, S. D., Sen, R. & Pal, A. All-fiber tunable ring laser source near 2 μm designed for CO_2 sensing. *Sens. Actuators B: Chem.* **235**, 547–553 (2016). <https://doi.org/10.1016/j.snb.2016.05.128>

[12] Hamperl, J. et al. High energy parametric laser source and frequency-comb-based wavelength reference for CO_2 and water vapor DIAL in the 2 μm region: Design and pre-development experimentations. *Atmosphere* **12**, 402 (2021). <https://doi.org/10.3390/atmos12030402>

[13] Eichhorn, M. Development of a high-pulse-energy Q-switched Tm-doped double-clad fluoride fiber laser and its application to the pumping of mid-IR lasers. *Opt. Lett.* **32**, 1056–1058 (2007). <https://doi.org/10.1364/OL.32.001056>

[14] Swiderski, J. & Michalska, M. High-power supercontinuum generation in a ZBLAN fiber with very efficient power distribution toward the mid-infrared. *Opt. Lett.* **39**, 910–913 (2014). <https://doi.org/10.1364/OL.39.000910>

[15] Koltashev, V. V. et al. 150 mW Tb^{3+} doped chalcogenide glass fiber laser emitting at $\lambda > 5 \mu\text{m}$. *Opt. Laser Technol.* **161**, 109233 (2023). <https://doi.org/10.1016/j.optlastec.2023.109233>

[16] Lenski, M. et al. In-band pumped, Q-switched thulium-doped fibre laser system delivering 140 W and 7 mJ pulse energy. *Opt. Lett.* **49**, 4042–4045 (2024). <https://doi.org/10.1364/OL.528330>

[17] Chernysheva, M. et al. High power Q-switched thulium doped fiber laser using carbon nanotube polymer composite saturable absorber. *Sci. Rep.* **6**, 24220 (2016). <https://doi.org/10.1038/srep24220>

[18] Frith, G. P. & Lancaster, D. G. Power scalable and efficient 790-nm pumped Tm^{3+} -doped fiber lasers. *Proc. SPIE* **6102**, 610208 (2006). <https://doi.org/10.1117/12.660932>

[19] Eichhorn, M. & Jackson, S. D. High-pulse-energy actively Q-switched Tm^{3+} -doped silica 2 μm fibre laser pumped at 792 nm. *Opt. Lett.* **32**, 2780–2782 (2007). <https://doi.org/10.1364/OL.32.002780>

[20] Wadsworth, W. J., Percival, R. M., Bouwmans, G., Knight, J. C. & Russell, P. St. J. High power air-clad photonic crystal fibre laser. *Opt. Express* **11**, 48–53 (2003). <https://doi.org/10.1364/OE.11.000048>

[21] Kadwani, P. et al. Q-switched thulium-doped photonic crystal fibre laser. *Opt. Lett.* **37**, 1664–1666 (2012). <https://doi.org/10.1364/OL.37.001664>

[22] Stutzki, F., Jansen, F., Jauregui, C., Limpert, J. & Tünnermann, A. 2.4 mJ, 33 W Q-switched Tm-doped fiber laser with near diffraction-limited beam quality. *Opt. Lett.* **38**, 97–99 (2013). <https://doi.org/10.1364/OL.38.000907>

[23] Schneider, J. et al. High-energy nanosecond pulse extraction from a Tm^{3+} -doped photonic crystal fiber laser emitting at 2050 nm with

- narrow linewidth. *Opt. Express* **32**, 32309–32321 (2024). <https://doi.org/10.1364/OE.531146>
- [24] Miluski, P. et al. Tm³⁺/Ho³⁺ profiled co-doped core area optical fibre for emission in the range of 1.6–2.1 μm. *Sci. Rep.* **13**, 13963 (2023). <https://doi.org/10.1038/s41598-023-41097-2>
- [25] Miluski, P. et al. Tm³⁺ doped multi-ring profile single-mode fiber laser for application in the eye-safe spectral range. *J. Light. Technol.* **42**, 3844–3851 (2024). <https://doi.org/10.1109/JLT.2024.3364154>
- [26] Sujecki, S. Numerical analysis of Q-switched erbium ion doped fluoride glass fibre laser operation including spontaneous emission. *Appl. Sci.* **8**, 803 (2018). <https://doi.org/10.3390/app8050803>
- [27] Schneider, J., Forster, P., Romano, C., Eichhorn, M. & Kieleck, C. Investigation of the pulse energy limits of actively Q-switched polarization-maintaining Tm³⁺-doped fiber lasers. *OSA Contin.* **4**, 1577–1586 (2021). <https://doi.org/10.1364/OSAC.423812>