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Ultra-low repetition rate gain-switched thulium-doped fibre laser at 2 μm

Zhong Mingfei, Sun Haiyue, Liu Tongling, Huang Kun

Abstract. **Ultra-low repetition rate nanosecond pulsed seed lasers are beneficial for scaling both the pulse energy and the peak power in rare-earth doped fibre amplifiers. We report the generation of nanosecond laser pulses at 1958 nm with low repetition rates of down to 100 Hz in an all-fibre gain-switched thulium-doped fibre laser. Temporal characteristics of the generated 1958 nm laser pulses with repetition rates in the range from 100 Hz to 10 kHz are investigated in detail. It is found that the needed threshold pump energy decreases with increasing repetition rate. The experimental results are shown to be in good agreement with the results of the theoretical discussion.**

Keywords: *low-repetition rate, thulium fibre laser, laser pulse, high energy.*

1. Introduction

High-energy nanosecond laser pulses are attractive in many applications [1–3], for example, material processing, biomedicine, environmental sensing. High-energy nanosecond laser pulses generated at 1.5 μm in media doped with erbium ions have many extensive eye-safe atmospheric applications [4, 5]. However, catastrophic thermal effects, arising with increasing pump power, destroy the 1.5 μm fiber laser system due to its low optical conversion efficiency. The output of 2 μm fibre lasers [2] also fits into the eye-safe wavelength region and covers strong absorption spectral lines of many molecules, such as water, CO and CO_2, which makes these lasers promising candidates for gas tracing. These lasers have been investigated extensively in recent years. A laser source at 2 μm can be constructed on the basis of thulium-doped fibres (TDFs) [6] or holmium-doped fibres [7]. High-energy and high-peak-power 2 μm fibre lasers with a large mode area inherent in TDFs have recently become available in the market.

With the development of fibre components, nanosecond pulses at $\lambda = 2$ μm were obtained by modulating fibre pigtailed DFB lasers at 2 μm [8], as well as by *Q*-switching [9] or gain-switching [10] a fibre laser. The direct modulation of DFB lasers has the merits of flexibility of adjusting the pulse shape and pulse repetition rate, but the output pulses are characterised by a very low peak/average power, which highlights the challenges of amplification of radiation in order to meet actual applications [8]. *Q*-switching and gain-switching techniques make it possible to generate nanosecond pulses of Gaussian shape with repetition rates from tens of kHz to hundreds of kHz [11–13]. In 2007, Min Jiang et al. [11] reported the first demonstration of stable short pulses (10 ns) from a fast gain-switched thulium-doped fibre laser (TDFL) with an output pulse repetition rate from 2.5 to 50 kHz. In 2012, a fast gain-switched TDFL was theoretically studied in detail by Zhou et al. [12], who reported an all-fibre gain-switched TDFL operating in the eye-safe region at 1940 nm with repetition rates of 10 kHz, 20 kHz and 30 kHz. Limited by the power tolerating ability of fibre components, pulses which were directly generated from the gain-switched oscillator did not meet the requirement of actual applications. In order to acquire a sufficient pulse energy, the output of such lasers should be amplified using a multistage thulium-doped fibre amplifier chain [8, 14].

However, optical breakdown and thermal effects will limit the performance of the amplifier system if the seed pulse repetition rate is too high. Therefore, seed pulses with a low repetition rate (with repetition rates of hundred Hz) are very desirable for scaling the pulse energy while keeping the pump power at a low level [15, 16]. Besides, when the seed pulse repetition rates are too low (down to tens of Hz), pulse pumping methods [15, 16] could be used to suppress possible amplified spontaneous emission noise and to enhance the efficiency of the amplifier system. To this end, at a constant gain, the lower the pulse repetition rate, the higher the output pulse energy. Therefore, in many reports acoustic optical modulators are adopted to decrease the pulse repetition rate of seed pulses before they are coupled to the amplifier system. It is worthwhile and challenging to realise 2 μm laser pulses with low repetition rates directly from a fibre laser cavity without any external free-space pulse picking devices.

In this paper, we investigate an ultra-low repetition rate (down to 100 Hz) nanosecond TDFL. The laser is pumped by an electrical modulated 1550 nm pulsed laser with an output wavelength of 1958 nm at the eye-safe region and shortest pulse width of 94 ns. It is also found that the threshold pump energy decreases with increasing repetition rate of the 1550 nm pump source. We believe this laser could be used as a seed laser for pulse energy scaling systems with direct pulse pumping.

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2. Experimental setup

The experimental setup is shown in Fig. 1 and is basically made of a 1550 nm pulsed fibre laser and a gain-switched

TDFL. The 1550 nm pulsed fibre laser consists of a 1550 nm fibre pigtailed DFB laser, an erbium-doped fibre amplifier (EDFA) and an erbium-ytterbium co-doped fibre amplifier (EYDFA). The 1550 nm DFB laser is a commercial product which is driven by electrical pulses to emit nanosecond laser pulses. The pulse width of the 1550 nm seed laser can be adjusted from 15 to 1000 ns with repetition rates in the range from 100 Hz to 100 kHz. The EDFA is based on a 3.5-m length of signal mode EDF with an absorption coefficient of ~10 dB m^{-1} at 980 nm. The EDFA is core pumped by a 700 mW, 975 nm single mode laser diode through a 980/1550 nm wavelength-division multiplexer (WDM). The EYDFA is built with 5.5 m length of single mode erbium-ytterbium co-doped fibre (EYDF) and a 7 W, 975 nm laser diode. The EYDF has a core/cladding diameter of 7/130 μm and a cladding absorption of ~2 dB m^{-1} at 975 nm. The 975 nm pump laser is used to forward pump the EYDF via a $(2+1)\times 1$ fibre combiner. Two isolators (ISOs) in the 1550 nm fibre laser are used to suppress the backward amplified spontaneous emission (ASE) and protect the 1550 nm DFB laser. After amplification, the 1550 nm laser pulses are used to pump the gain-switched TDFL to realise the generation of 2 μm band laser pulses.

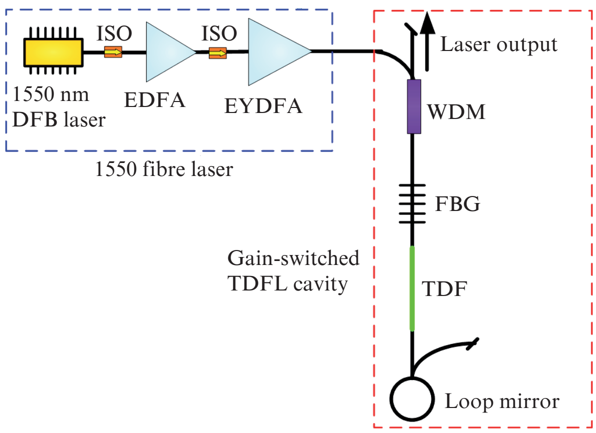

Figure 1. Experimental setup of the gain-switched TDFL.

The gain-switched TDFL consists of a 21 cm of single-mode single-clad TDF, a loop mirror and a fibre Bragg grating (FBG). The TDF has a core/cladding diameter of 5/125 μm with core numerical aperture of 0.25 and an absorption coefficient of ~300 dB m^{-1} at 1560 nm. The FBG has a reflectivity of 50% at 1958 nm and is spliced to one end of the TDF. The other end of the TDF is spliced to a fibre loop mirror fabricated with a 50/50 fibre coupler (at λ = 2 μm) as a high-reflectivity mirror. The total length of the laser cavity is about 80 cm. The FBG together with a 1550/2000 nm WDM is used to both couple the 1550 nm pump source into the laser cavity and export the generated 1958 nm gain-switched laser output. In our experiment, two optical spectral analysers (Yokogawa AQ6370 and AQ6375) are used to measure the related laser spectra. The measured system also consists a 3 W thermal power meter, a fast digital oscilloscope (1.5 GHz bandwidth), together with a 1550 nm detector and an InGaAs photon detector to measure 1958 nm pulses.

3. Experiment results and discussion

3.1. Experiments on amplification of a 1550 nm pulsed seed laser

In the first experiment, the pulse width of the 1550 nm seed laser is set at 1 μs to achieve a pulse energy as high as possible. While the repetition rate of the 1550 nm seed laser is adjusted from 100 Hz to 10 kHz, the average output power of the seed laser measured after the ISO varies from 0.28 mW at f = 100 Hz to 5.61 mW at f = 10 kHz. The seed pulse has a rectangle envelope with a pulse width of about 1 μs, but due to the gain-depletion it becomes steeper after amplification in the EYDFA.

Figure 2 shows the dependence of the output power of the YEDFA on the pump power and the spectral dependence of intensity at different seed repetition rates. Figure 2a illustrates the input power of the amplified 1550 nm radiation versus the pump power of the 975 nm laser diode at 100, 200 and 500 Hz. At f = 100 Hz, the calculated linear fitting slope efficiency η is only about 0.6%. This is reasonable because that the duty cycle of the 1550 nm seed pulse train is 0.01% and the seed power is too low and is only 0.05 mW. With increasing repetition rate of the 1550 nm seed laser, the seed power and the duty cycle of the seed pulse increase, resulting in the growth of the slope efficiency of the EYDFA (Fig. 2a). Figure 2b shows the performance of the EYDFA at f = 1, 2 and 10 kHz. When the repetition rate of the 1550 nm seed laser is increased to 10 kHz, the slope efficiency η can be raised up to 7.6% which is almost 12.7 times greater than η = 0.6% at f = 100 Hz.

Figure 2c presents the measured EYDFA output spectra at different repetition rates with a same pump power of 810 mW. One can see that the output spectra mainly consist of amplified 1550 nm pulses, together with two ASE spectral bands near λ = 1 and 1.5 μm. These two ASE spectral bands are inferred to originate from ytterbium and erbium ions in the EYDF.

3.2. Generation of 1958 nm gain-switched laser pulses

In the next experiment, we spliced the output fibre of the EYDFA with the 1550 nm port of the WDM, so that the amplified 1550 nm pulsed laser could be coupled to gain switch the TDFL. The tulium ion has a broad absorption band near 1.5 μm; in addition, we assumed that the ASE noise can be absorbed by the TDF and did not use any spectral filters after the EDYFA in the experiment. A foreseeable fast gain-switching is expected, because the TDFL cavity was made in accordance to the in-band pumping scheme previously described in [11]. The population of the $^3F_4$ energy level of thulium ions can be built up almost instantaneously following the 1550 nm pump pulse, which is a great advantage ensuring the elimination of relaxation spikes and generation of stable laser pulses at 2 μm.

3.2.1 10 kHz repetition rate. The gain-switched TDFL performance is first investigated at a pump repetition rate of 10 Hz. The threshold pump power of the gain-switched thulium-doped laser is 70 mW, corresponding to threshold pump energy of about 7.6 μJ. Figure 3 shows the output spectrum of the gain-switched TDFL at a pump power of 92 mW measured with a spectral resolution of 0.2 nm. Figure 3a illustrates a narrowband spectrum of the 1958 nm signal with an output power of 10.7 mW, showing an optical signal-to-noise

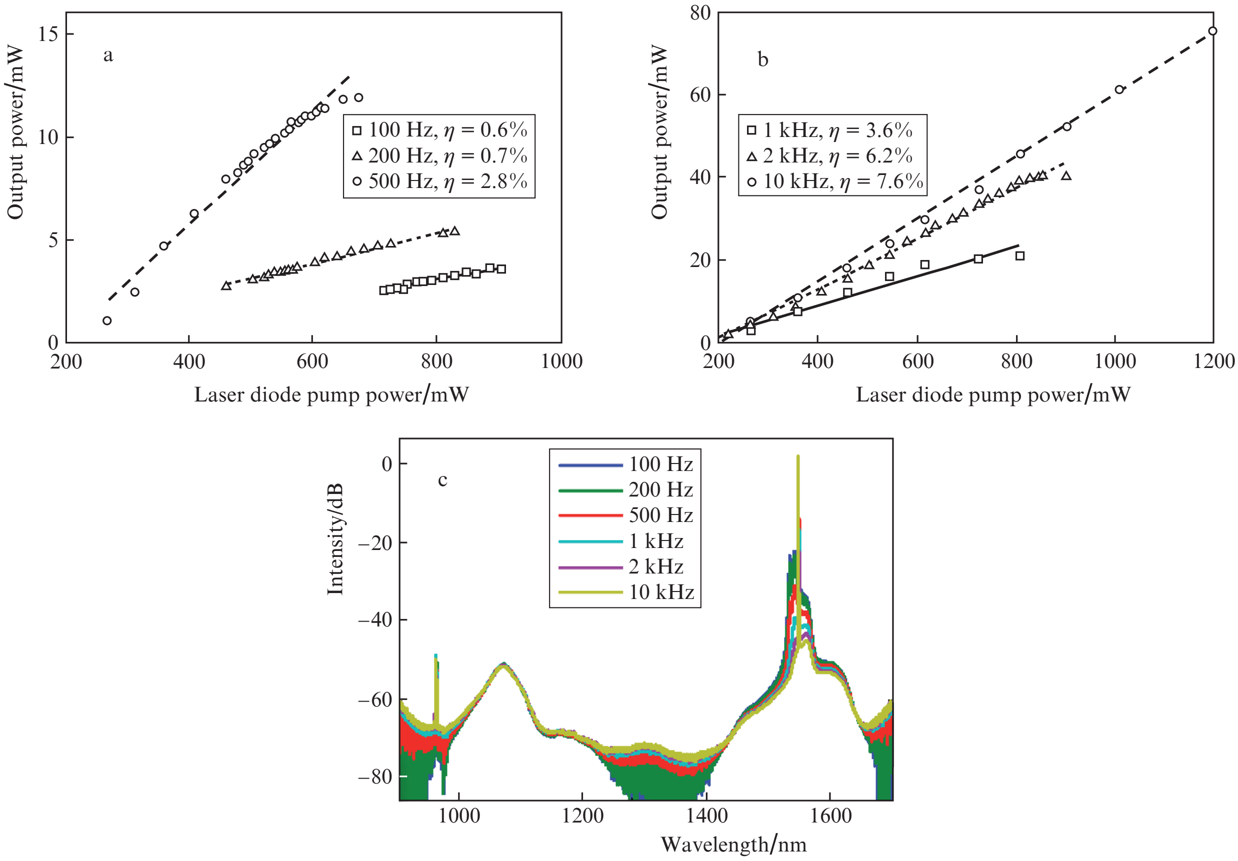

Figure 2. (Colour online) (a, b) Power characteristics of the EYDFA at different seed laser repetition rates and slope efficiencies, as well as (c) output spectra at different repetition rates.

suppression ratio better than 50 dB. The evolution of the output signal power versus the incident 1550 nm pump power is presented in Fig. 3b, indicating that the output power of the 1958 nm signal increases linearly with a fitting efficiency of 48.5%.

Figure 3c shows the output energy and pulse width of the generated signal pulses at 1958 nm versus the 1550 nm pump power. The signal pulse energy is found to increase linearly with increasing pump power while the pulse width decreases exponentially, resulting in an increase in the peak power of the output pulse. The measured pulse energy increases from 0 to 3 μJ while the pulse width decreases from 198 to 94 ns, resulting in an increase in the pulse peak power up to 30 W. However, further peak power scaling is limited because when the pump power/pump pulse energy becomes much higher, one signal laser pulse cannot deplete all the inversion population, and then a subpulse is generated. In the experiment, when the incident 1550 nm pump power is higher than 115 mW, the generation of a second pulse resulted in temporal instabilities of the output pulses. Figure 3d shows the measured stable operation of the output pulse train at $f = 10$ kHz.

3.2.2 Ultra-low repetition rate. Then, we investigated the performance of the gain-switched laser at ultra-low repetition rates below 10 kHz. We measured similar characteristics of the evolutions presenting the dependence of the output pulse energy and pulse width on the incident 1550 nm pump power. Figure 4 shows the experimental dependences of the output pulse energy and pulse width on the pump power in the gain-switched laser at 100 Hz and 1 kHz. One can see from Fig. 4a that the generated pulse energy is in the range from 0 to 2 μJ with a pulse width varying from 200 to 100 ns. These results may be greatly affected by the laser cavity parameters such as the output reflectivity and the total cavity length but independent of the pump pulse repetition rate. However, the measured threshold pump pulse energy is significantly different at different repetition rates of the pump pulse train, for instance, the measured threshold pump pulse energy for 100 Hz, 200 Hz, 10 kHz is 25.8, 15.2 and 7.6 μJ, respectively.

Figure 5 presents the threshold pump power and pump pulse energy for this gain-switched TDFL at different repetition rates. One can see that the threshold pump power and pump pulse energy for the same gain-switched TDFL cavity are different when the pump repetition rates are different. When the pump repetition rate is increased, the threshold pump power decreases. It is believed that this phenomenon is associated with the principle of gain switching. The population density in the upper laser levels could be increased due to the absorption of the pump pulse, but it will decay during the pumping intervals. The lower the pump repetition rate, the longer the decay time. Thus, the net gain of populations at low repetition rates is lower than that at high repetition rates. Therefore, the threshold pump pulse energy of the TDFL is found to be 25.8 μJ at a pump repetition rate of 100 Hz, but it decreases with increasing pump pulse repetition rate. As discussed above, the threshold pump pulse energy is 7.6 μJ when the repetition rate is 10 kHz.

The output pulse trains of the signal pulses at 1958 nm are also plotted in Fig. 6. As can be seen, the output pulse trains are very stable even at these low repetition rates. The achieved lower limit of the output repetition rate of the gain-switched

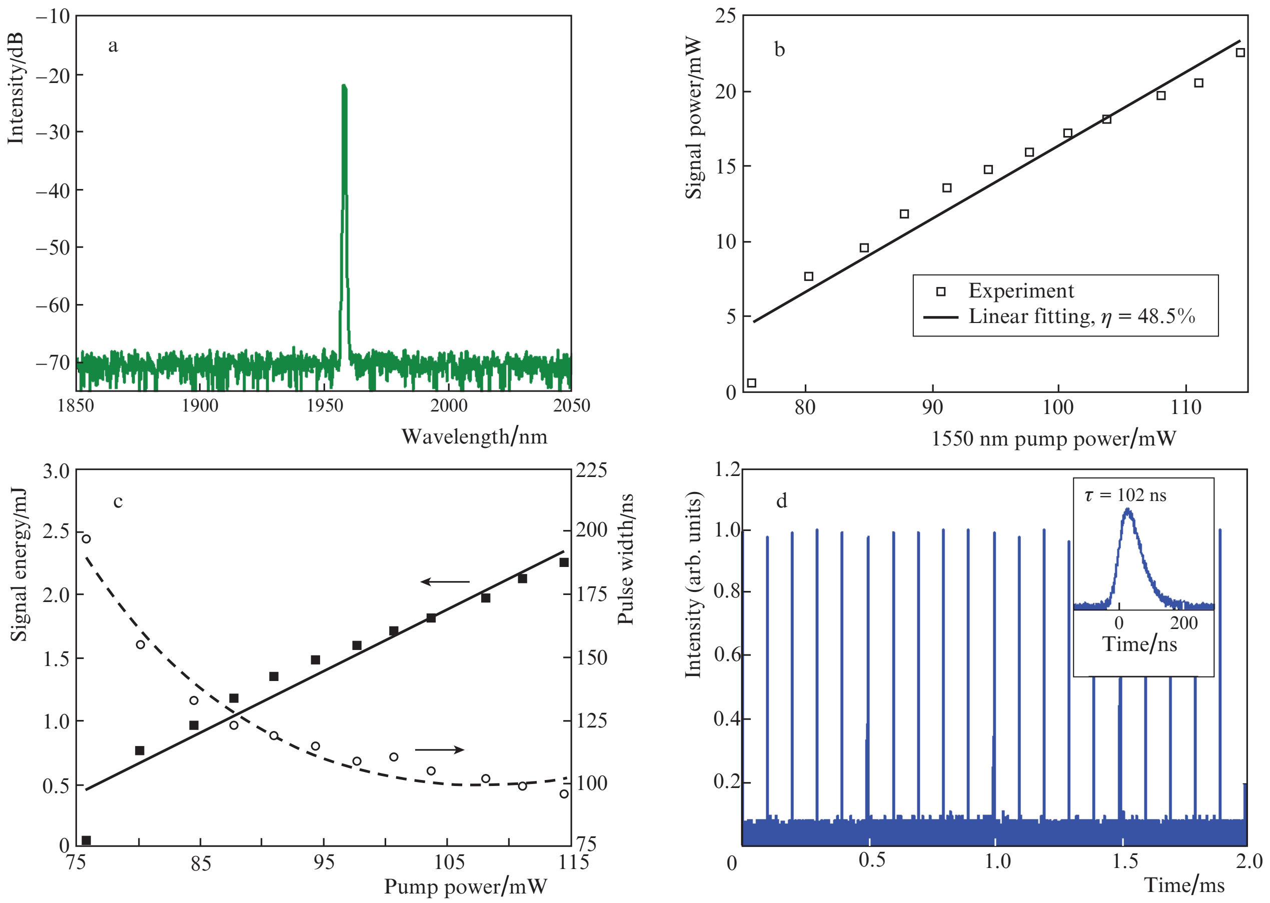

Figure 3. (a) Output spectrum of the gain-switched TDFL, (b) output power vs. pump power at λ = 1550 nm, (c) output pulse energy and pulse width vs. pump power, and (d) pulse train of the TDFL output at 10 kHz. The inset in Fig. 3d plots the shape of a 102 ns pulse.

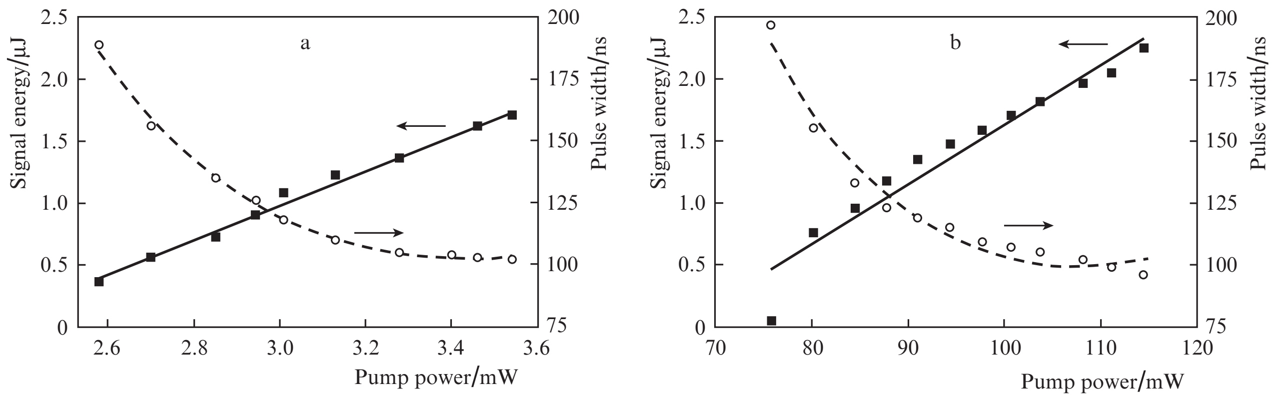

Figure 4. Output pulse energy and pulse width vs. pump power in the gain-switched laser at (a) 100 Hz and (b) 1 kHz.

TDFL is now restricted by the drive circuit of the 1550 nm pulsed seed laser. It is possible to obtain much lower repetition rates (down to several or tens of Hz) in the gain-switched pulsed laser by modulating the 1550 nm laser diode.

As the generated pulse width in the gain-switched TDFL is often several times of the photon lifetime in the cavity, T_c, which is defined by the formula $T_c = 2nLc^{-1}(-\ln R_1R_2 + 2\alpha L)$. In our experiment setup, the photon lifetime in the laser cavity is about 13.8 ns while the measured shortest pulse width of stable operation of the gain-switched TDFL is about 94 ns, which is 5.8 times higher than T_c. One possible and efficient way to further reduce the generated pulse width is to shorten the total length of the laser cavity or change the reflectivities R_1 and R_2 in order to decrease the photon lifetime in the cavity.

4. Conclusions

We have demonstrated a stable gain-switched TDFL at 1958 nm with ultra-low pump repetition rates. Temporal and power characteristics of the TDFL from 100 Hz to 10 kHz are studied in detail. It is found that when the TDFL is pumped

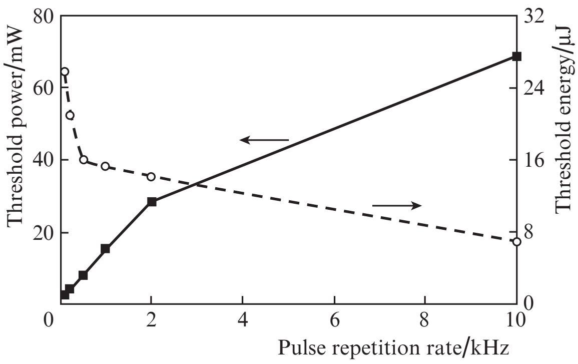

Figure 5. Threshold pump power (experiment) and pump pulse energy (calculation) for this gain-switched TDFL at different repetition rates.

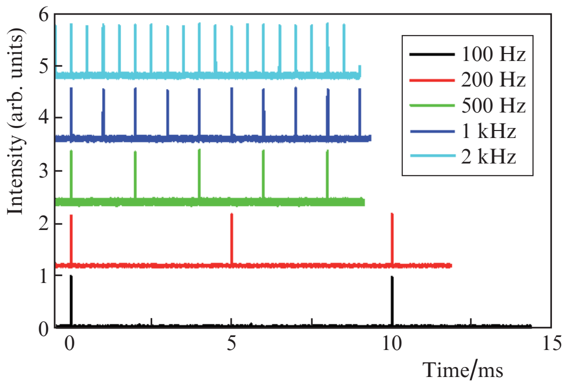

Figure 6. Output pulse trains at ultra-low repetition rates.

at low repetition rates, the threshold pump pulse energy is increased because of a huge decay of the population inversion during the pumping intervals. We believe this TDFL could be used as the seed laser for pulse energy scaling systems with direct pulse pumping.

References

1. Wei Shi, Qiang Fang, Xiushan Zhu, Norwood R.A., Peyghambarian N. *Appl. Opt.*, **53**, 6554 (2014).
2. Geng J., Wang Q., Jiang S. *Proc. SPIE*, **8164**, 816409 (2011).
3. Richardson D.J., Nilsson J., Clarkson W.A. *J. Opt. Soc. Am. B*, **27**, B63 (2010).
4. Desmoulins S., Di Teodoro F. *Opt. Express*, **16**, 2431 (2008).
5. Khitrov V., Shkunov V.V., Rockwell D.A., Zakharenkov Y.A., Strohkendl F. *Opt. Lett.*, **37**, 3963 (2012).
6. Eichhorn M. *IEEE J. Quantum Electron.*, **41**, 1574 (2005).
7. Simakov N., Hemming A., Clarkson W.A., Haub J., Carter A. *Opt. Express*, **21**, 28415 (2013).
8. Heidt A.M., Li Z., Sahu J., Shardlow P.C., Becker M., Rothhardt M., Ibsen M., Phelan R., Kelly B., Alam S.U. *Opt. Lett.*, **38**, 1615 (2013).
9. Jihong Geng, Qing Wang, Jake Smith, Tao Luo, Farzin Amzajerdian, Shibin Jiang. *Opt. Lett.*, **34**, 3713 (2009).
10. Yulong Tang, Lin Xu, Yi Yang, Jianqiu Xu. *Opt. Express*, **18**, 22964 (2010).
11. Min Jiang, Parviz Tayebati. *Opt. Lett.*, **32**, 1797 (2007).
12. Zhou Ren-Lai, Ju You-Lun, Zhao Jie, Yang Chao, Wang Yue-Zhu. *Chin. Phys. B*, **22** (6), 064208 (2013).
13. Ke Yin, Weiqiang Yang, Bin Zhang, Sheng Zeng, Jing Hou. *J. Opt. Soc. Am. B*, **30**, 2864 (2013).
14. Xu J., Xu L., Tang Y. *Proc. Lasers and Electro-Optics (CLEO) and Quantum Electronics and Laser Science Conference (QELS)* (IEEE, 2010) pp 1, 2.
15. Peng Wan, Jian Liu, Lih-Mei Yang, Farzin Amzajerdian. *Opt. Express*, **19**, 18067 (2011).
16. Chao Zheng, Mali Gong, Haitao Zhang, Ping Yan, Qirong Xiao, Ming Liu. *J. Opt.*, **15**, 052201 (2013).