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2015 Laser Phys. Lett. 12 015102

(http://iopscience.iop.org/1612-202X/12/1/015102)

IOP Publishing | Astro Ltd Laser Physics Letters
Laser Phys. Lett. **12** (2015) 015102 (5pp) doi:10.1088/1612-2011/12/1/015102

# All-fiberized polarized mode-locked thulium-doped fibre laser

**Baofu Zhang**[1], **Dingxiang Cao**[2], **Zhongxing Jiao**[1] and **Biao Wang**[1]

[1] State Key Laboratory of Optoelectronic Materials and Technologies, School of Physics and Engineering, Sun Yat-sen University, Guangzhou 510275, People's Republic of China
[2] Advacned Fiber Resources (Zhuhai) Ltd, Zhuhai 519080, People's Republic of China

E-mail: jiaozhx@mail.sysu.edu.cn and wangbiao@mail.sysu.edu.cn

Received 11 October 2014, revised 5 November 2014
Accepted for publication 5 November 2014
Published 27 November 2014

**Abstract**
We present an all-fiberized polarized mode-locked thulium-doped fibre laser system operating at the 2 $\mu$m region. Passively mode-locking by a semiconductor saturable absorber mirror, the laser generated 20.2 ps pulses at a repetition rate of 10.22 MHz. The maximum average output power of 56 mW with pulse energy of 5.48 nJ was achieved, and the output beam was more than 99.6% linearly polarized. To the best of our knowledge, it is the first mode-locked polarized thulium-doped fibre laser with all-fiberized configuration.

Keywords: mode-locked, thulium-doped fibre laser, all-fiberized

(Some figures may appear in colour only in the online journal)

## 1. Introduction

In recent years, there is a considerable research interest in ultra-fast laser sources at the 2 $\mu$m region due to their potential applications in ophthalmology [1], surgery [2, 3], precision metrology [4, 5], and wavelength conversion to ultra-fast mid-infrared lasers [6, 7]. These 2 $\mu$m ultra-fast sources can be achieved by passively mode-locked laser systems using thulium-doped material as their gain mediums. Among them, thulium-doped fibre lasers (TDFLs) offer major practical advantages compared to solid-state lasers, including compact design, good spatial mode quality and reduced thermal effects. Moreover, TDFL systems can achieve repetition rates lower than 10 MHz, avoiding the plasma shielding effects and meeting the requirement for a variety of micromachining applications [8].

To date, mode-locked TDFLs have been reported by several research groups [9–13]. The first passively mode-locked TDFL was demonstrated by Nelson *et al* in 1995, and it was mode locked by utilizing nonlinear polarization evolution (NPE) in unidirectional ring configuration [9]. In addition, semiconductor saturable absorber mirrors (SESAMs), single-walled carbon nanotube saturable absorbers (SWCNT-SAs) and graphene saturable absorbers (GSAs) have also been used in the mode-locked operation of TDFLs [10–13]. Among them, passively mode-locking mechanisms including NPE, SWCNT-SAs and GSAs provide efficient all-fibre methods for realizing ultra-fast TDFL systems. However, the operating modes of those systems may suffer from environmental sensitivity since isolators and polarization controllers are required for their ring cavity configuration; moreover, additive polarizers with power loss are needed in those systems in order to produce polarized output, which is required in wavelength conversion to the mid-infrared region.

To overcome these limitations, the introduction of polarization-maintaining (PM) fibre would be preferred, for true environmental stability and polarized output. Furthermore, an all-PM-fibre oscillator is necessary. With the intention to achieve 2 $\mu$m environmentally-stable and polarized ultra-short pulses, our approach is to insert compact PM modules into our all-fiberized mode-locked TDFL system. 'All-fiberized' mentioned above is slightly different from 'all-fibre'. The latter means all components in the laser are constructed in the fibre, such as fibre Bragg gratings. The former refers to the fact that free-space components, such as mirrors, are used in the laser but are embedded into modules with fibre pigtails to be spliced into the system. Similar to an 'all-fibre' configuration, an 'all-fiberized' laser system takes advantage of its compact size and simple construction.

In this letter, we present a monolithic all-fiberized and polarized mode-locked TDFL system. To the best of our knowledge, it is the first mode-locked TDFL with an

 

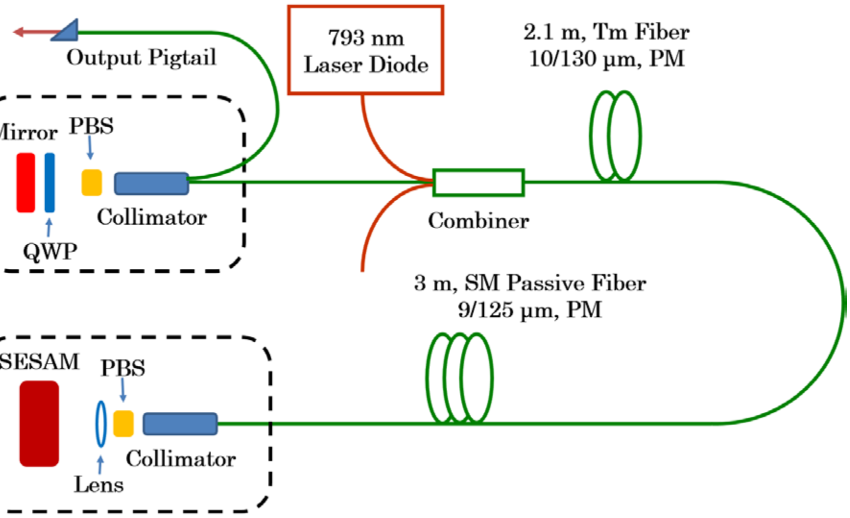


**Figure 1.** The scheme of the all-fiberized mode-locked thulium-doped fibre laser. QWP, quarter wave plate; PBS, polarizing beam splitter; PM, polarization maintaining; SM, single mode; SESAM, semiconductor saturable absorber mirror.

all-fiberized configuration. Passively mode-locking by a SESAM, the self-starting TDFL produced 20.2 ps pulses with maximum average power of 56 mW and central wavelength around 2054.67 nm.

## 2. Experiments

The schematic of our mode-locked TDFL system with a linear cavity configuration is depicted in figure 1. The pump source is a commercial continuous-wave (CW) laser diode operating at 793 nm. The pump power was coupled into the laser cavity through a combiner (ITF) whose signal port and output port are constructed on double-clad PM fibre with a 10 $\mu$m core and 130 $\mu$m cladding (10/130). Measurement showed that 87.4% of the pump power was inserted into the laser system, and the insertion loss of the combiner in the cavity was about 0.05 dB. A 2.1 m long thulium-doped fibre (Nufern), with the same structure as the output port of the combiner, was utilized as the gain medium. Its length was chosen for the optimized output power since a strong reabsorption effect at the laser wavelength caused by a longer thulium-doped fibre would introduce undesirable resonator loss. A 3 m long single-mode (SM) PM passive fibre was spliced to the thulium-doped fibre. The SM PM passive fibre has a 9/125 (core/cladding) structure; this single-clad fibre acted to strip out residue cladding light from double-clad thulium-doped fibre in order to protect the SESAM. Moreover, the passive fibre increased the cavity length for the purpose of achieving stable mode-locked pulses [14].

As shown in figure 1, two fiberized modules were used as the mode-locking element and the output coupler (OC) in our linear cavity, respectively. The fiberized mode-locking module including a fibre collimator (AFR), a polarizing beam splitter (PBS), a focusing lens and a 4 × 4 $mm^2$ SESAM (BATOP) was spliced to the PM passive fibre. The SESAM was chosen to be the mode-locked element in the laser system because of its stable performance and commercial availability. The high reflection band of our SESAM is from 1900 to 2080 nm, corresponding to the potential emission bandwidth of the thulium-doped fibre, with its relaxation time constant about 10 ps and the modulation depth of 18%. The spot on the SESAM, controlled by the fibre collimator and the focusing lens, was designed to be 200 $\mu$m in diameter in order to ensure the sufficient saturation fluence and to avoid the optical damage. In addition, anomalous dispersions of the thulium-doped fibre and the passive fibre used in our TDFL are measured to be $-76\,ps^2\,km^{-1}$ and $-67\,ps^2\,km^{-1}$ at the laser wavelength, respectively. The net dispersion of the cavity is calculated to be $-0.6735\,ps^2$; the small amount of dispersion introduced by the free space components is neglected.

The key to achieving a low CW mode-locking threshold in our system was to minimize the cavity losses [14]. In the mode-locking module, the coupling efficiency of reflected light was optimized with precise alignment of the SESAM and the collimator. Moreover, we noted that the insertion loss of the SESAM was slightly different according to the polarization of input light. Therefore, the SESAM was rotated to an orientation with minimum insertion loss to the slow-axis light propagating in PM fibre. The whole mode-locking module with 1.0 dB insertion loss was packaged into a copper heat sink. The fiberized OC module consisted of a fibre collimator, a PBS, a quarter wave plate and a monochrome mirror. The monochrome mirror has a high reflectivity ($R > 98\%$) at the laser wavelength (1900 ~ 2080 nm). The fibre collimator in this module was constructed with a special double-fibre-pigtail configuration. The reflection port of the OC module was spliced to the signal port of the combiner and the transmission port was spliced to a coated 8°-cleaved output pigtail with high transmittance ($T > 99.9\%$) at the laser wavelength. With adjustment to the principle axis of the quarter wave plate, the reflectivity of the OC module could be changed; in our TDFL system, the optimal reflectivity of the OC module was 90%. Similarly, the mirror and the collimator were precisely aligned in order to minimize the insertion loss of this module. The whole OC module with 1.2 dB insertion loss was packaged

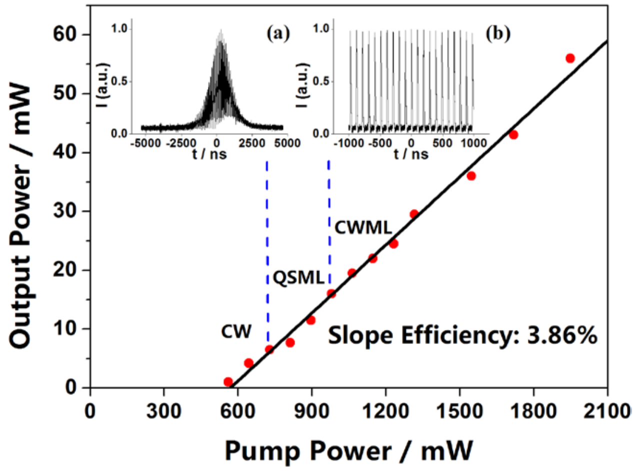


**Figure 2.** The average output power versus absorbed pump power in mode-locked thulium-doped fibre. CW, continues-wave; QSML, Q-switched mode-locking; CWML, continues-wave mode-locking. Inset: (*a*) pulse trace of QSML, (*b*) pulse trace of CWML.

into a glass casing. PBSs used in both modules ensured low loss for the light propagating in slow-axis direction and high loss in fast-axis direction. Fibres used in the mode-locked module, the OC module and the output pigtail had the same structure with the SM PM passive fibre mentioned above. The total laser cavity length was 9.77 m. Two fiberized modules were mounted on the aluminium heat sink and cooled by forced air at room temperature.

## 3. Results

Figure 2 illustrates the average output power versus the absorbed pump power of the TDFL. There were three distinct stages in our system when increasing the pump power: CW operation regime, Q-switched mode-locking (QSML) regime and CW mode-locking regime. As shown in figure 2, the laser threshold was 560.2 mW; it was higher compared to the ring cavity mentioned above [11–13] mainly attributed to the cavity loss introduced by the fiberized modules and the reabsorption loss associated with the long thulium-doped fibre. At first, the TDFL operated in the CW regime after the laser threshold was reached. Then, when the absorbed pump power increased to 728 mW, the TDFL began to operate in the QSML regime; the measured QSML pulses were shown in inset (*a*) of figure 2. CW mode-locking of the TDFL was self-started as the absorbed pump power increased up to 979.8 mW. The laser remained stable CW mode-locking up to the maximum absorbed pump power of 1949 mW. The maximum average output power was measured to be 56 mW, with a slope efficiency of 3.86%. In the CW mode-locking regime, stable pulses at a repetition rate of 10.22 MHz (corresponding to the cavity length of 9.77 m) were obtained, with pulse-to-pulse amplitude fluctuation less than 5% in the 200 ns per division timescale; the measured CW mode-locking pulse trains were shown in inset (*b*) of figure 2.

The output polarization extinction ratio (PER) of the TDFL system was measured by propagating the output power into a polarization analyser. When the TDFL operated in the CW mode-locking regime with maximum pump power, a PER of 24.17 dB was recorded, indicating that the laser was more than 99.6% linearly polarized in this condition. Misalignments of two fiberized modules and thermal effects caused by high intracavity power might result in such mild depolarization.

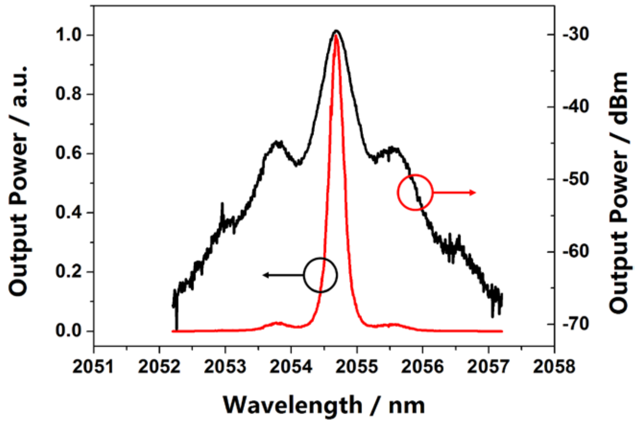


**Figure 3.** The spectrum of the mode-locked thulium-doped fibre laser on linear and logarithm scales.

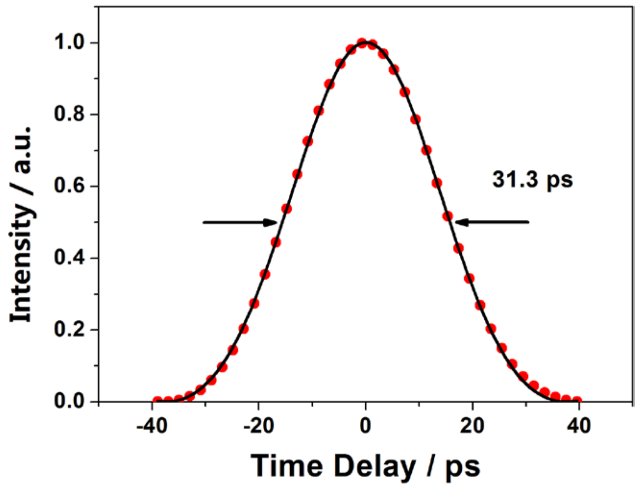


**Figure 4.** The intensity autocorrelation trace of thulium-doped fibre laser.

Figures 3 and 4 show the spectrum and intensity autocorrelation trace of the CW mode-locked pulses, respectively. The spectrum was measured by an optical spectrum analyser (YOKOGAWA) with a resolution of 0.0467 nm. As can be seen in figure 3, the 3 dB spectrum bandwidth (FWHM) of the pulses was measured to be 0.2729 nm, centred in 2054.6727 nm. The narrow spectrum was considered to be caused by larger losses at a shorter wavelength due to strong reabsorption effects in the long thulium-doped fibre in combination with a large amount of feedback (the OC reflectivity of 90% in our TDFL [15]). This was also confirmed by the centre wavelength of 2054 nm, which was closed to the long end of the normal operating region in the thulium-doped fibre. Moreover, as shown in figure 3, with the large reabsorption loss and the anomalous dispersion in the cavity, some of the sidebands fell within the spectrum of the soliton [16]. A home-made intensity autocorrelator was employed in the CW mode-locked pulse width measurement. As shown in figure 4, the measured autocorrelation width of 31.3 ps corresponds to a pulse duration of 20.2 ps by assuming a hyperbolic-secant pulse shape. The long pulse duration was limited by the finite narrow bandwidth, and hence the SESAM with a relaxation time constant of about 10 ps acted as a fast saturable absorber in our experiment. Therefore, with the fast saturable regime and large modulation depth of the SESAM, our laser remained stable against multiple-pulse breakup [17, 18] when the output pulse energy of 5.48 nJ was obtained. A corresponding time-bandwidth product of 0.391, achieved by the CW mode-locked pulses in our TDFL system, indicated that the output pulses were slightly chirped compared to the transform-limit value of 0.315 for the hyperbolic-secant pulse.

## 4. Discussion and conclusion

In this study, we provide an alternative version of the mode-locked TDFL with an all-fiberized and environmentally-stable configuration, compared to prior works with all-fibre ring cavities [11–13]. Stable polarized mode-locked pulse generation has been achieved in our TDFL system. The key to progress in our work is the employment of the fiberized modules and PM fibres. Although free-space components such as SESAM and PBS are included in the fiberized modules, they can be firmly embedded with a compact structure, avoiding environmental disturbances. Similar to other fibre components, these modules, with fibre pigtails serving as output ports, can be spliced to fibre laser systems conveniently.

In addition, fiberized modules offer new approaches to construct mode-locked TDFL systems. First, SESAM used in our laser can be replaced by other passively mode-locking components with their favourable properties, e.g. SWCNT-SAs and GSAs. Therefore, polarized environmentally-stable mode-locked pulses can be obtained in those TDFL systems. Moreover, mirrors and/or other optical elements can be integrated in fiberized modules. These fiberized modules ensure the construction of all-fiberized mode-locked fibre lasers with linear cavities instead of unidirectional ring cavities. Conventionally, isolators are needed in unidirectional ring cavities, but commercially available high-power isolators at the 2 $\mu$m region have 2–3 dB insertion loss. Therefore, such fiberized modules make it possible to construct all-fiberized high-power mode-locked TDFL seed sources with low thresholds.

In summary, to the best of our knowledge, we are the first to demonstrate an all-fiberized polarized mode-locked TDFL system. Pumped by a 793 nm laser diode and mode-locked by a SESAM, the laser generated stable 20.2 ps mode-locked pulses at a repetition rate of 10.22 MHz, with a central wavelength of 2054.67 nm. The maximum average output power of 56 mW with a pulse energy of 5.48 nJ more than 99.6% linearly-polarized has been achieved. With further power scaling by a thulium-doped fibre amplifier, the mode-locked TDFL system will be sufficient to meet the requirements for seeding a mode-locked mid-infrared optical parametric oscillator.

## Acknowledgments

The authors would like to acknowledge Advanced Fiber Resources (Zhuhai) Ltd for the technical support of this work. Special thanks go to Jiannan Lu, Yi Xu, Wenfu Liang and Haiming Li for their guidance and teaching in fibre device fabrication. This work was partially supported by the National Natural Science Foundation of China under grants 61308056, 61008025, 11232015, 11072271 and 11204044, the Research Fund for the Doctoral Program of Higher Education of China under grants 20120171110005 and 20130171130003, the Project Supported by Guangdong Natural Science Foundation under grant S2012010010172, and the Opening Project of Science and Technology on Reliability Physics and Application Technology of Electronic Component Laboratory under grant ZHD201203.

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