An all-fiber, polarized, core-pumped heat-resistant thulium-doped master oscillator power amplifier

2013 Laser Phys. 23 085101

(http://iopscience.iop.org/1555-6611/23/8/085101)

Laser Phys. 23 (2013) 085101 (5pp) doi:10.1088/1054-660X/23/8/085101

An all-fiber, polarized, core-pumped heat-resistant thulium-doped master oscillator power amplifier

Zhongxing Jiao, Baofu Zhang and Biao Wang

School of Physics and Engineering, Sun Yat-sen University, Guangzhou 510275, People's Republic of China

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

Received 8 April 2013, in final form 25 April 2013
Accepted for publication 25 April 2013
Published 13 June 2013
Online at stacks.iop.org/LP/23/085101

Abstract

We present an all-fiber, polarized, core-pumped heat-resistant thulium-doped master oscillator power amplifier (MOPA) system. The laser operated at a wavelength of 1926.7 nm with a spectral linewidth of less than 70 pm. For a repetition rate of 100 kHz, a maximum average power of 750 mW with a slope efficiency of 48.8% and pulse duration of 41 ns was achieved. Even without active cooling, no observable thermal effects occurred when the laser was operated at room temperature. To the best of our knowledge, this core-pumped heat-resistant MOPA configuration is the first reported in the 2 μm region.

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

1. Introduction

The number of applications calling for 2 μm pulsed lasers with robust and compact size, high average power and good beam quality is rapidly increasing. Compared to other laser designs, thulium-doped fiber lasers (TDFLs), which have a greater than 300 nm potential emission bandwidth (1.8–2.1 μm), can meet those requirements due to their distinct advantages in thermal management. They are attracting widespread interest in fields such as optical countermeasures, medical applications, environmental detection and wavelength conversion to the mid-infrared [1–7].

Actively Q-switched TDFLs have been reported as achieving 2 μm laser output with a high pulse energy and high peak power [8–10]. A diode-pumped Q-switched TDFL was presented by Eichhorn and Jackson, providing average powers of 30 W at pulse widths of 41 ns and repetition rates from 10 to 125 kHz [8]. Wills *et al* improved the Q-switched TDFL system into a polarization-maintaining (PM) structure with a maximum pulse energy of 225 μJ at 2052 nm and a 200 ns duration at 20 kHz using a volume Bragg grating [10]. However, the inherently long cavity length, and hence long round trip time of the actively Q-switched TDFL system leads to an inevitably long pulse duration, which is not suitable for many applications requiring sub-100 ns 2 μm or even sub-50 ns 2 μm pulses. In addition, the free-space components used in the actively Q-switched TDFLs, such as acousto-optic modulators, cavity mirrors and lenses may make the system more complicated and difficult to align.

To obtain short 2 μm laser pulses, a gain-switched TDFL pumped by pulsed a 1.55 μm erbium-doped fiber laser is found to be an attractive candidate. Its achievable all-fiber structure based on fiber Bragg gratings (FBGs) provides an efficient method for generating sub-100 ns 2 μm pulses with high efficiency. Gain-switched TDFL systems have been demonstrated by several groups [11–14]. Stable 10 ns 2 μm pulses with a peak power over 1 kW and a slope efficiency of 50% were achieved by Jiang and Tayebati [11]. Simakov *et al* presented a gain-switched TDFL system that produced polarized 2 μm output pulses with a duration of 25 ns and a pulse energy of 35 μJ by utilizing PM thulium-doped fiber and PM FBGs [12]. However, although the fiber laser has advantages in thermal management, attributed to its larger surface area to volume ratio, signs of thermal degradation and drops in the slope efficiency, ascribed to the heat load produced from high absorption of the pump power, were

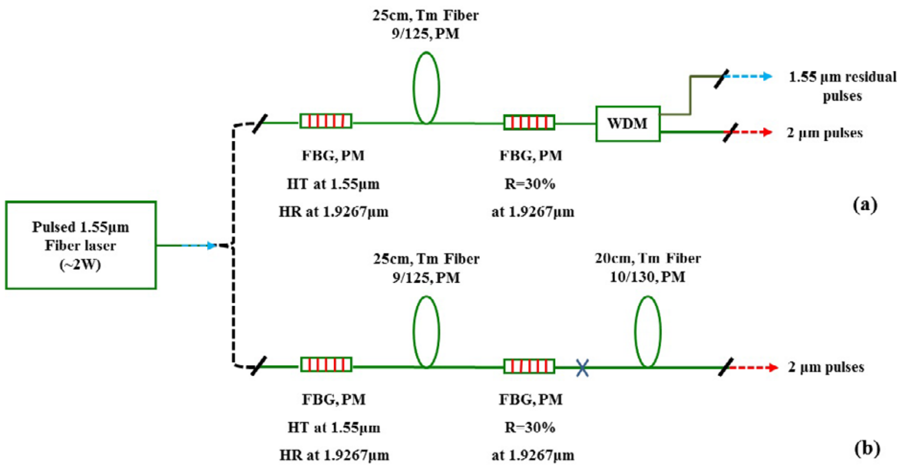

Figure 1. The experimental setup of (a) the gain-switched master oscillator, (b) the gain-switched MOPA system.

recorded in several gain-switched TDFL systems [12, 14]. In order to prevent these thermal issues, Hollitt *et al* constructed a pulsed TDFL system with 3 m of active thulium-doped fiber with a low dopant concentration [13]; however, a sub-100 ns pulse duration would be difficult to achieve in this case because of the extremely long cavity length of the laser.

Our approach is to realize a heat-resistant TDFL system by increasing the absorption length of the pump power, preventing the heat load from depositing in the short laser cavity. In this paper, to our best knowledge, we demonstrate the first sub-50 ns pulses generation from an all-fiber polarized gain-switched TDFL with a core-pumped master oscillator power amplifier (MOPA) configuration, where thulium-doped fiber with a low dopant concentration is utilized as the gain medium of the seed oscillator and thulium-doped fiber with a high dopant concentration serves as the amplifier. The TDFL generated a linearly polarized laser output of 41 ns pulses with an average power of 750 mW and a slope efficiency of 48.8% at a repetition rate of 100 kHz. The center wavelength of the TDFL is 1926.7 nm, with a narrow linewidth less than 70 pm. Moreover, without any active cooling, the system operated at a room temperature of 20 °C; no thermal issues have been observed.

2. Experiment

2.1. The gain-switched master oscillator

The schematic of the gain-switched master oscillator in our TDFL system is depicted in figure 1(a). The pump source of the master oscillator consisted of a pulsed 1.55 μm erbium-doped fiber laser (Amonics) and a function signal generator (Agilent) which can control the pump characteristics by changing the parameters of the voltage pulses. In order to achieve sub-100 ns pulse generation from the TDFL, the pump source was devised to provide stable 1.55 μm pulses with average powers up to 2 W and a duration of 100 ns at a repetition rate of 100 kHz. The resonator configuration of the master oscillator was formed by a single-mode polarization-maintaining (PM) thulium-doped fiber (Nufern) and a pair of FBGs (AFR), which were used as the cavity mirrors. The thulium-doped fiber had a low-dopant-concentration (0.3 wt%) structure with a core diameter of 9 μm, a cladding diameter of 125 μm and a core numerical aperture (NA) of 0.15. Its length was designed to be 25 cm for the purpose of ensuring a short cavity length to produce sub-100 ns pulses. The input FBG had high reflectivity ($R > 99\%$) at a wavelength of 1926.7 nm (fast axis), and the other FBG, serving as an output coupler, had a 30% reflectivity at 1926.7 nm (slow axis). Both FBGs were written into PM passive fiber with a 10/130 (core/cladding) structure, and they had a narrow bandwidth of 0.1 nm in order to produce narrow-linewidth output. Although the core and cladding diameters of the FBGs were different from those of the thulium-doped fiber, their NA were also 0.15; therefore, the splices between the FBGs and the thulium-doped fiber were considered to be low-loss (<0.1 dB). Moreover, for the sake of achieving single polarization operation, the splice of the output coupler and the thulium-doped fiber was based on a similar method described by Simakov *et al* [12]; but more precise alignments of the stress rods were needed due to the narrow bandwidth of the FBGs. The whole cavity length of the gain-switched master oscillator was 55 cm. Because the output characteristic of the MOPA architecture is mainly determined by the master oscillator, a wavelength division multiplexer (WDM) (AFR) was spliced to the pigtail of the output FBG to separate the residual pump laser and 2 μm output and detect them.

2.2. The gain-switched MOPA system

In the gain-switched master oscillator, low-dopant-concentration thulium-doped fiber was chosen to be the gain medium to avoid thermal issues because the heat load yielded from the absorption of the pump power would be low. However, the low dopant concentration and short length of the thulium-doped fiber led to insufficient pump absorption, and hence the pump power would be wasted. Therefore, a power amplifier stage was needed in this TDFL system.

The experimental setup of the gain-switched MOPA configuration is depicted in figure 1(b). The master oscillator part remained the same as shown in figure 1(a), except that the WDM was removed. As the power amplifier, a double-clad PM thulium-doped fiber (Nufern) with a high dopant concentration (2 wt%) was spliced to the end of the output FBG. Therefore, the residual 1.55 μm pump power was injected into the core of thulium-doped fiber to amplify the 2 μm seed laser which was produced from the master oscillator. This thulium-doped fiber had a 10/130 (core/cladding) structure and its length was designed to be 20 cm to take advantage of the residual 1.55 μm pump power. With accurate splicing, more than 90% of the launched 1.55 μm pump power was believed to be absorbed in this MOPA system. Furthermore, the absorption length of pump power in the TDFL system increased, and hence the heat load generated from the pumping process was allowed to dissipate over the total length of the system to avoid thermal degeneration.

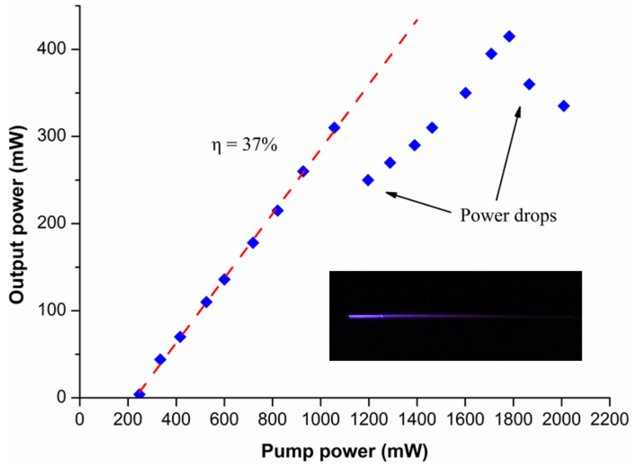

Figure 2. The average output power of the gain-switched TDFL with a single oscillator versus the 1.55 μm pump power at a repetition rate of 100 kHz. Two sudden drops of the output power were found. Inset: purple fluorescence observed in the thulium-doped fiber at a high pump power.

2.3. The gain-switched TDFL with single oscillator

A comparative experiment based on a gain-switched single oscillator configuration was carried out. Its experimental setup was similar to the gain-switched master oscillator presented in figure 1(a). The only difference was that a double-clad PM thulium-doped fiber served as the gain medium, with the same structure mentioned in section 2.2 and its length of 25 cm. The pump source was the same as the one described in section 2.1; input and output FBGs with the same parameters were utilized as cavity mirrors in this resonator. Moreover, the splice of the thulium-doped fiber and the output coupler still followed the method stated in [12]. The total cavity length of this single oscillator system was also 55 cm. All experiments mentioned in section 2 were conducted at a room temperature of 20 °C, without any active thermal management.

3. Results

3.1. The gain-switched TDFL with single oscillator

The 2 μm average power produced from the gain-switched single oscillator (described in section 2.3) at a repetition rate of 100 kHz is presented in figure 2. Two drops in the output power could be found at pump powers of 1.2 W and 1.83 W, respectively. The threshold of the single oscillator was 247.4 mW and the slope efficiency before the first drop was 37%. The maximum output power was measured to be 415 mW at a pump power of 1.78 W when the TDFL operated in an unstable mode. The optical-to-optical conversion efficiency of 1.55 μm pump power to 2 μm was barely 21.3%. In fact, the output power data was recorded after the TDFL operated at that pump power for more than one minute. The first power drop did not occur immediately as the pump power increased to 1.2 W, but it occurred when a purple fluorescence was observed in the part of thulium-doped fiber which was attached to the splice point with the input FBG (figure 2). The first drop of output power and the appearance of purple fluorescence could be qualitatively described by an energy transfer mechanism corresponding to the $^1G_4$ level in the thulium ions. The heat load produced from the pump absorption process increased the temperature of the thulium-doped fiber, and its population shifted to a higher energy level ($^1G_4$) by consuming the pump power; the laser output power, and hence the laser efficiency, was reduced. However, the mechanism of the second power drop remains unknown and needs further consideration.

3.2. The gain-switched master oscillator

The 2 μm output power and the residual 1.55 μm pump power of the gain-switched master oscillator operating at a repetition rate of 100 kHz are presented in figure 3. Compared to the single oscillator configuration in section 3.1, this master oscillator had a higher threshold of 405 mW because the thulium-doped fiber as its gain medium had a lower dopant concentration. As shown in figure 3, both the output power and the residual pump power increased as the 1.55 μm injected pump power increased; a maximum output power of 326 mW was achieved at the maximum injected pump power of 1.95 W, simultaneously with an appreciably high residual pump power of 1.07 W .

3.3. The gain-switched MOPA system

The 2 μm output power of the gain-switched MOPA system operating at a repetition rate of 100 kHz is presented in figure 4. Compared with the master oscillator part mentioned above, the MOPA system had a slightly higher threshold of 444 mW; this was caused by weak reabsorption at the laser

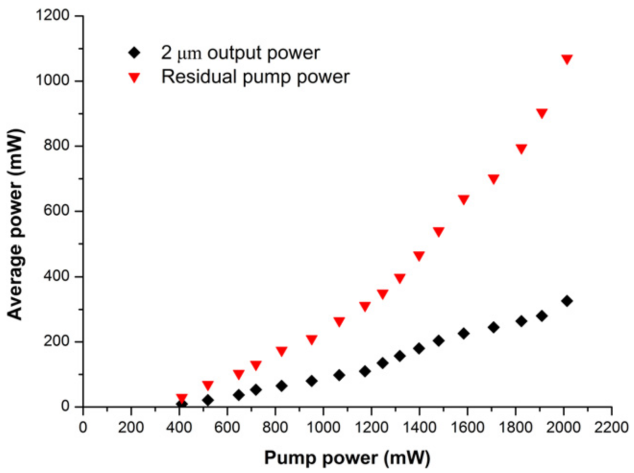

Figure 3. The 2 μm output power and the residual pump power of the gain-switched master oscillator versus the 1.55 μm pump power at a repetition rate of 100 kHz.

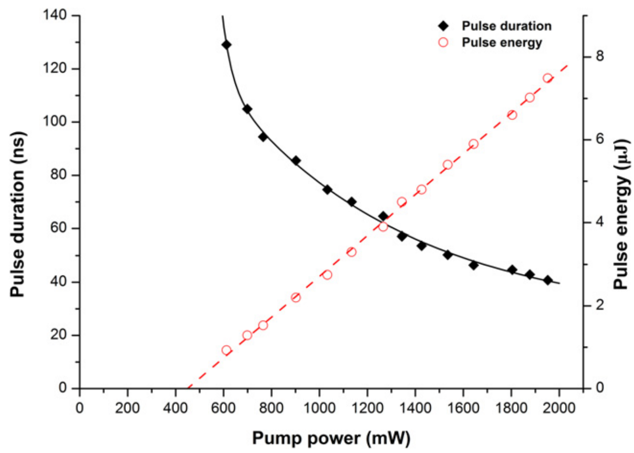

Figure 5. The output pulse duration and pulse energy of the gain-switched MOPA system at a repetition rate of 100 kHz versus the 1.55 μm pump power.

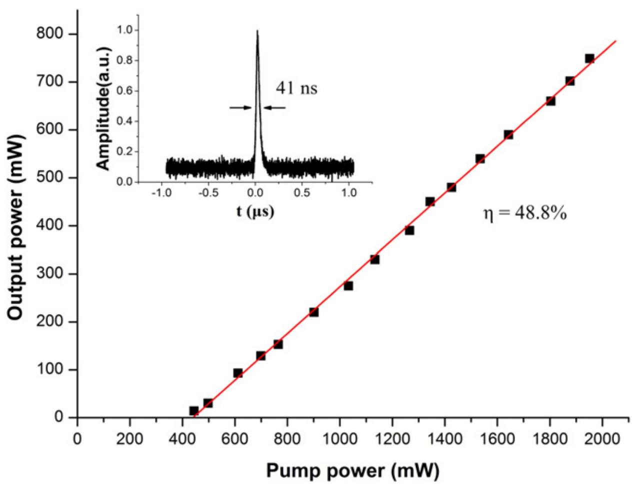

Figure 4. The 2 μm output power of the gain-switched MOPA system versus the 1.55 μm pump power at a repetition rate of 100 kHz. Inset: temporal trace of the 2 μm output pulse with a duration of 41 ns.

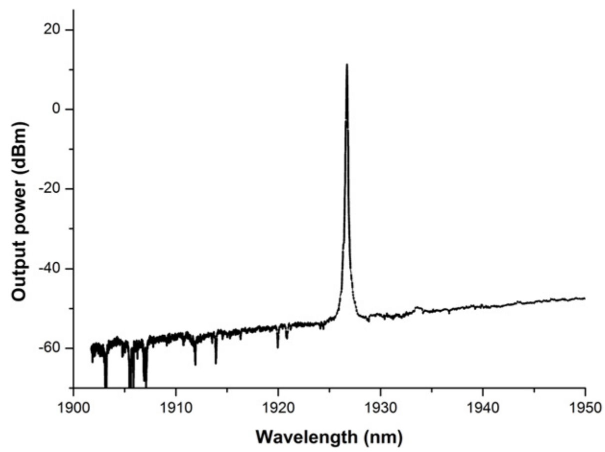

Figure 6. The spectrum of the gain-switch MOPA system operating at a repetition rate of 100 kHz with a center wavelength of 1926.7 nm and a 3 dB bandwidth of 0.067 nm.

wavelength in the thulium-doped fiber of the amplifier stage. As shown in figure 4, the gain-switched TDFL with MOPA architecture operated at a slope efficiency of 48.8% with respect to 1.55 μm pump power. A maximum output power of 750 mW was obtained when the pump power was 1.95 W, which was restricted by the upper limit of the pump power. Moreover, no thermal effects were noticed, and the output power remained stable with only slight fluctuations when the MOPA system operated at the maximum pump power over an hour.

The pulse characteristics of the 2 μm output operating at a repetition of 100 kHz were measured by an InGaAs biased detector and a color digital oscilloscope (Tektronix, TDS3032). A temporal trace of the 2 μm pulse with 41 ns duration at the maximum pump power is displayed in the inset of figure 4; the 2 μm pulse energy and the 2 μm pulse duration versus pump power are presented in figure 5. It can be observed from figure 5 that a higher pump power, and hence more energetic pump pulses, resulted in a higher output pulse energy and a shorter output pulse duration, which was in good agreement with the theory of gain switching [15, 16].

The output polarization extinction ratio of the gain-switched MOPA system was measured by propagating the 2 μm laser output into a cylindrical polarization analyzer. An extinction ratio of 17.1 dB was recorded when the MOPA system operated at a repetition rate of 100 kHz, indicating that the 2 μm output was more than 98% linearly polarized. The depolarization might be caused by inaccurate alignment between those PM fibers.

An optical spectrum analyzer (OSA) (YOKOGAWA, AQ6375) was utilized in the spectral measurement of the 2 μm laser output. As presented in figure 6, the wavelength of the laser output was 1926.7 nm, consistent with the center wavelength in both PM FBGs. The measured 3 dB linewidth was 0.067 nm, which was close to the minimum resolution of the OSA, attributed to the narrow bandwidth of the FBGs.

Moreover, no noticeable nonlinear optical phenomena or amplified spontaneous emission could be observed in the optical spectrum.

4. Conclusion

In summary, we have realized an all-fiber polarized gain-switched TDFL system with a core-pumped MOPA architecture which could produce sub-50 ns 2 μm laser pulses. A low-dopant-concentration thulium-doped fiber and a high-dopant-concentration thulium-doped fiber were utilized in the oscillator stage and the amplifier stage, respectively. The gain-switched TDFL system generated 41 ns pulses with a maximum average power of 750 mW and a slope efficiency of 48.8%, without any noticeable thermal effects. Single polarization operation at a wavelength of 1926.7 nm with a narrow spectral width less than 70 pm was achieved in this all-fiber configuration. With further power scaling and structure improvements, this TDFL system can be applied to a wide range of applications requiring pulsed 2 μm lasers with narrow duration and narrow linewidth.

Acknowledgments

The authors would like to acknowledge Advanced Fiber Resources (Zhuhai) Ltd for providing us with the opportunity to learn about fiber lasers and fiber components. Special thanks to Deping Zhao for helpful discussions and to Qian Fu for assistance with splicing. This work was partially supported by the National Natural Science Foundation of China under grants 61008025, 11232015 and 11072271, the Specialized Research Foundation for the Doctoral Program of Chinese Higher Education under grant 20100171120024, the Project Supported by Guangdong Natural Science Foundation under grant S2012010010172, the Project Supported by the Opening Fund of Laboratory Sun Yat-sen University, the Fundamental Research Funds for the Central Universities of China under grant 11lgpy55, and the Opening Project of Science and Technology on Reliability Physics and Application Technology of Electronic Component Laboratory under grant ZHD201203.

References

[1] Fan T Y 2005 Laser beam combining for high-power, high-radiance sources *IEEE J. Sel. Top. Quantum Electron.* **11** 567–77

[2] Frith G, McComb T, Samson B, Torruellas W, Carter A, Farroni J, Farley K and Tankala K 2008 Latest developments in 790nm-pumped Tm-doped fibre laser systems for DIRCM applications *Proc. SPIE* **7115** 711507

[3] Fried N M and Murray K E 2005 High-power thulium fiber laser ablation of urinary tissues at 1.94 μm *J. Endourol.* **19** 25–31

[4] Scott N J 2005 Thulium fiber laser ablation of urinary stones through small-core optical fibers *IEEE J. Sel. Top. Quantum Electron.* **15** 435–40

[5] Lemberg V, Rozhetskin D D and Jadczak C 2008 Medium-power tissue ablation using 1940 nm thulium fiber laser *Biomedical Optics, OSA Technical Digest (CD)* p BTuF4

[6] Koch G J, Beyon J Y, Barnes B W, Petros M, Yu J, Amzajerdian F, Kavaya M J and Singh U N 2007 High-energy 2 μm Doppler Lidar for wind measurements *Opt. Eng.* **46** 116201–14

[7] Creeden D *et al* 2008 Mid-infrared $ZnGeP_2$ parametric oscillator directly pumped by a pulsed 2 μm Tm-doped fiber laser *Opt. Lett.* **33** 315–7

[8] Eichhorn M and Jackson S D 2007 High-pulse-energy actively *Q*-switched Tm^{3+}-doped silica 2 μm fiber laser pumped at 792 nm *Opt. Lett.* **32** 2780–2

[9] Eichhorn M 2010 Pulsed 2 μm fiber lases direct and pumping applications in defence and security *Proc. SPIE* **7836** 78360B

[10] Willis C C C, Shah L, Baudelet M, Kadwan P, McComb T S, Andrew R, Sudesh V and Richardson M 2010 High-energy *Q*-switched Tm^{3+}-doped polarization maintaining silica fiber laser *Proc. SPIE* **7580** 758003

[11] Jiang M and Tayebati P 2007 Stable 10 ns, kilowatt peak-power pulse generation from a gain-switched Tm-doped fiber laser *Opt. Lett.* **32** 1797–9

[12] Simakov N, Hemming A, Bennetts S and Haub J 2011 Efficient, polarised, gain-switched operation of a Tm-doped fiber laser *Opt. Express* **19** 14949–54

[13] Hollitt S, Simakov N, Hemming A, Haub J and Carter A 2012 A linearly polarized, pulsed Ho-doped fiber laser *Opt. Express* **20** 16285–90

[14] Swiderski J, Maciejewska M, Kwiatkowski J and Mamajek M 2013 An all-fiber, resonantly pumped, gain-switched, 2 μm Tm-doped silica fiber laser *Laser Phys. Lett.* **19** 015107

[15] Siegman A E 1986 *Lasers* (New York: University Science Books)

[16] Koechner W 1999 *Solid-State Laser Engineering* (Berlin: Springer)