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156 micro-J ultrafast Thulium-doped fiber laser

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ABSTRACT

A high energy, high power ultrafast laser system based on Tm doped fiber at low repetition rates was successfully developed. Pulse energy of up to 156 μJ and average power of up to 15.6 W were achieved. The laser system consisted of a mode-locked 2 μm seed oscillator and multiple-stage power amplifiers. The seed included 30 m-long dispersion compensating fiber and emitted slightly chirped pulses with spectrum bandwidth of 8 nm. The mode-locking was stable and self-started. Repetition rate of seed oscillator was 2.5 MHz. The seed pulses were stretched with normal dispersion fiber to the duration of 320 ps. A two-stage pre-amplifier was used to boost the pulse energy to 3 μJ. The pulse can be compressed to sub-picosecond. An AOM was used as a pulse picker to lower the repetition rate. The pulse was further stretched and amplified in the final stage of power amplifier. Pulse energies of up to 156 μJ were obtained at a repetition rate of 100 kHz. Pulse durations of 780 fs were obtained after pulse compression. High OSNR and low background noise were also achieved at this low repetition rate.

Keywords: Mode-locked fiber lasers; Fiber lasers; Infrared and far-infrared lasers; Pulses; Fiber optics, infrared; Fiber amplifier and oscillators; Tm doped fiber lasers; Ultrafast fiber lasers; High energy fiber lasers.

1. INTRODUCTION

High energy short pulses are very promising tools for investigation of ultrafast processes in physics and chemistry [1-4]. Thulium (Tm) doped short pulse fiber lasers at a wavelength around 2 micron joined the old family of Nd, Yb and Er-doped fiber lasers not long ago, and are gaining growing interest in many applications, such as laser sensing, free space optical communications, mid-IR spectroscopy, material processing, mid-infrared supercontinuum generation, infrared countermeasures, and efficient high harmonic X-ray generation [5-9].

Tm doped femtosecond fiber lasers had been demonstrated in several mode-locking schemes such as nonlinear polarization rotation, carbon nanotube, graphene oxide and semiconductor saturable absorbing mirrors [10-14]. However, the output pulse repetition rates from these oscillators were usually from a few tens of MHz to over 100 MHz. Laser pulse train at such high repetition rates were not convenient to achieve high pulse energy in amplification stage. And the central wavelengths were usually less than 2000nm, which was not ideal for some applications, such as sensing of CO_2 that has a strong absorption band for greater than 2000 nm [9]. Tm-doped fiber amplifiers to boost pulse energy of ultrafast pulses were also reported [14-17]. In reference [14], thulium doped fiber amplifier was used to boost Raman shifted pulses from Er/Yb source to the energy of 31 nJ. In reference [15], regular fiber with anomalous dispersion and normal-dispersion grating stretcher was used, and maximum energy of 151 nJ was obtained. In our previous work [16,17], we demonstrated a high energy MOPA based on mode-locked Tm doped fiber laser oscillator and a two-stage fiber amplifier at wavelength of 2 μm with chirped pulse amplification. The seed laser generated pulse train at a repetition rate of 2.5 MHz and the two–stage fiber amplifier boosted the pulse energy to 54 μJ with a compressed pulse width of 910 fs.

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In this paper, we present the most recent progress to further increase the pulse energy to 156 μJ, which is the highest energy femtosecond fiber to the best of our knowledge. A sequence of mode locking pulse train was directly generated in Tm doped fiber seed oscillator at central wavelength of 2020 nm. An acousto-optic modulator (AOM) was used to lower the repetition rate to 100 kHz. A spool of fiber with anomalous dispersion in 2 μm region was used to stretch pulses before amplification. Two stages of Tm doped fiber pre-amplifiers and a high energy Tm doped large mode area (LMA) fiber amplifier were used in the laser system to boost output power to 156 μJ. After pulse compression, pulse width of 780 fs was obtained.

2. EXPERIMENT SETUP

Figure 1 is the block diagram of the experimental setup for the 2 μm seed oscillator and multiple-stage power amplifiers. It is composed of a 2020 nm Tm doped fiber laser seed oscillator, a fiber stretcher, a two-stage fiber power amplifier, an AOM and a final stage high energy amplifier.

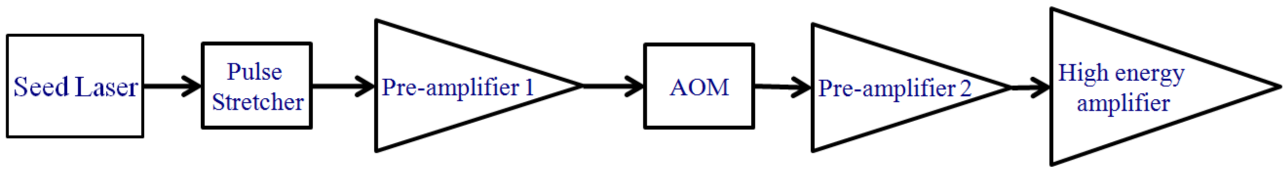

Fig. 1. Systematic diagram of 2 μm seed and power amplifier system

The structure of seed laser oscillator was described elsewhere [16,17]. Stable mode-locking was achieved at a repetition rate of around 2.5 MHz, producing pulses with about10 nJ energy and 8nm spectral bandwidth centered at 2020 nm. The seed oscillator emitted pulses with anomalous chirp. The pulse duration was about 2.2 ps. Fig. 2 shows the spectrum from seed oscillator.

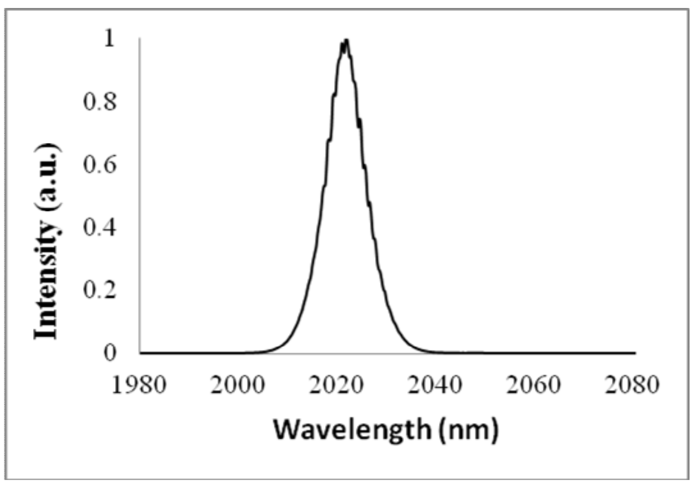

Figure 2: seed spectrum

3. TWO STAGE PRE-AMPLIFIERS

Pulses from seed oscillator were stretched by a fiber stretcher, a spool of 1000 m long regular single mode fiber (SMF-28) with anomalous dispersion. The regular fiber has an anomalous dispersion of +40 ps/nm/km in 2 μm regime. The stretcher elongated the pulses to the duration of around 320 picoseconds. Although the signal was only weakly polarized, a pigtailed PM isolator with one polarization blocked was spliced to the output end of the stretcher because the pulse picker (AOM) at the next stage was polarization sensitive. A total loss of 9.2 dB, including all splicing loss and isolator loss, was measured. 25 mW output power from seed after stretching was reduced to 3 mW, but it was sufficient to suppress amplified spontaneous emission (ASE) level in pre-amplifiers.

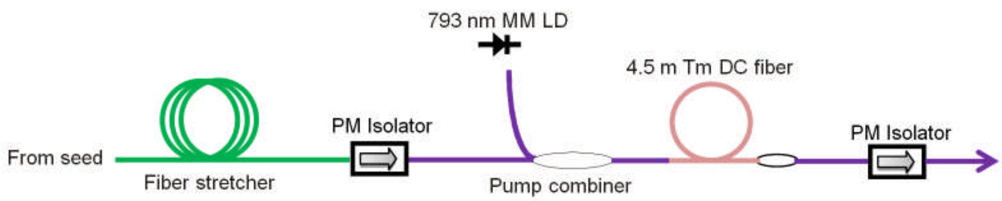

Fig. 3. First stage of amplification (pre-amplifier 1) with fiber stretcher

As a next step, pulses from the fiber stretcher were amplified in a double cladding fiber Tm doped amplifier (pre-amplifier 1). The setup of fiber stretcher and pre-amplifier 1 is shown in Fig. 3. The gain medium was a 4.5 m-long Tm doped double clad fiber with a core diameter of 6 µm. Stretched seed pulses were delivered into the amplifier. Up to 2.4 W 793 nm pump beam from one multimode laser diodes were coupled into the gain fiber. Maximum average power of 320 mW was measured after the first stage pre-amplifier. In order to further boost the pulse energy, a 2 µm fiber pigtailed AOM (Brimrose) was used as a pulse picker to lower the repetition rate from 2.5 MHz to 100 kHz. The spectra before and after AOM are shown in Fig. 4. The spectrum was slightly broadened in the first stage pre-amplifier to 10 nm. This broadening effect was mainly due to self-phase modulation (SPM) in the gain fiber. After AOM, the spectrum width was getting narrower and the central wavelength was shifted by 1 nm to the shorter wavelength side. This was caused by the wavelength difference between transmission peak of AOM and the central wavelength of seed laser. The AOM was designed to have a maximum transmission peak at 2000 nm, which favored the shorter wavelength side in the output from our laser system.

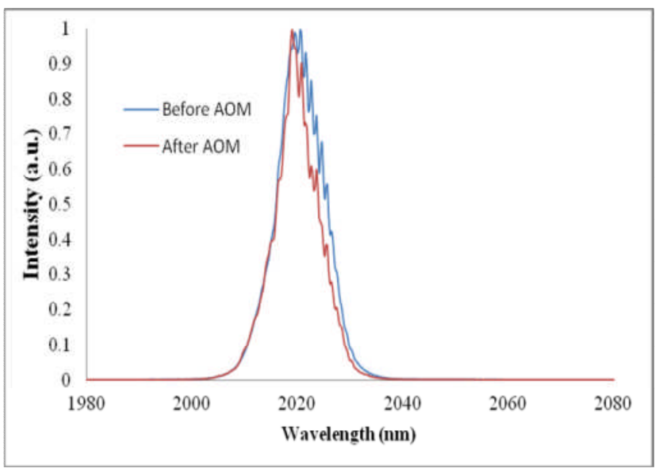

Fig.4. Spectra of pulses after first stage pre-amplifier.

The low repetition rate pulses were injected into the second stage pre-amplifier (pre-amplifier 2). The second stage of amplification was assembled in the similar way with pre-amplifier 1 by using a 5 m-long Tm doped double clad fiber with a core diameter of 10 µm. Two multimode laser diodes provided 5 W of pump power at 793 nm in total. The second stage amplified the pulse train up to an average power of 700 mW or pulse energy of 7 µJ (Fig. 5). Output spectrum at various output energy levels are shown in Fig. 6. At high pumping levels, noticeable broadenings of pulse spectrum were observed. The seed pulse had a spectrum width of 8 nm. At low output pulse energy less than or equal to 3 µJ, the spectrum width increased to around 9.5 nm, which is mainly due to the self-phase modulation in the first stage pre-amplifier. When further increase the pump level, the output spectrum widths were increased to around 15 nm at an output level of 7 µJ. The fact that spectrum broadening was more favorable to the longer wavelength side implied a Raman shift due to intense pulses in the gain fiber. In order to minimize the effect of nonlinear spectrum deterioration, we limited the output pulse energy of the second stage pre-amplifier to 3 µJ or the average power to 300 mW.

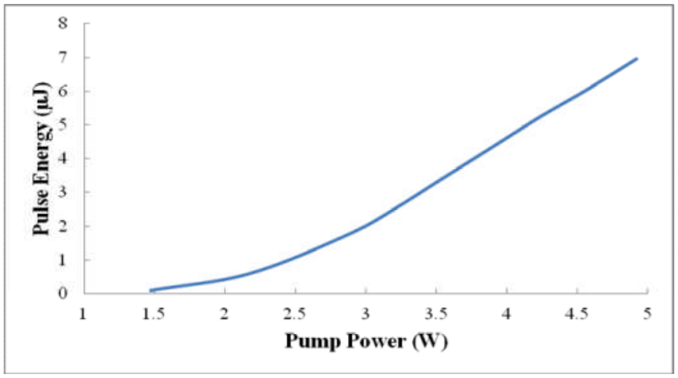

Fig. 5. Output pulse energy versus pump power of the second stage

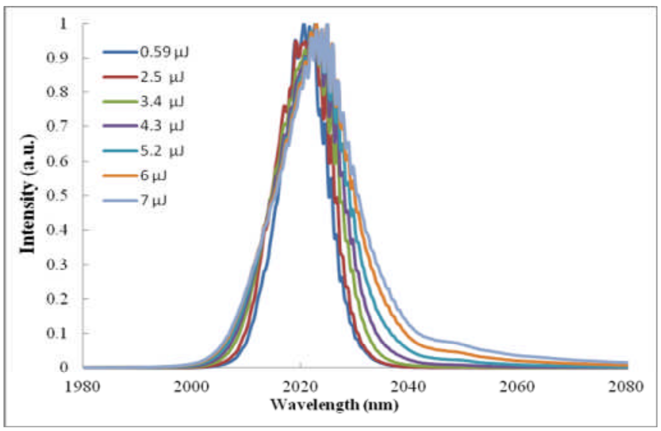

Fig. 6. Spectrum of output pulses at various pulse energy levels after pre-amplifier 2.

4. HIGH ENERGY AMPLIFIER

Figure 7 shows the setup of the final stage of high energy amplifier. The gain medium was a 1.8 m-long non-PM Tm doped double clad fiber with a core diameter of 25 µm (Nufern). Up to 73 W 793 nm pump beam from six multimode laser diodes were coupled into the gain fiber. The output pulse energy as a function of pump power is shown in Fig. 8. Pulse energy of up to 156 µJ was obtained with the maximum pump power of 73 W.

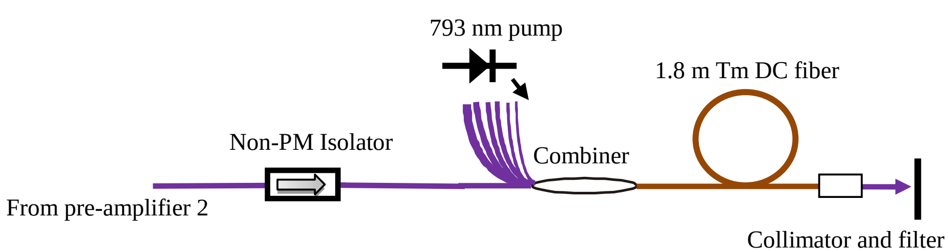

Fig. 7. Setup of high energy amplifier

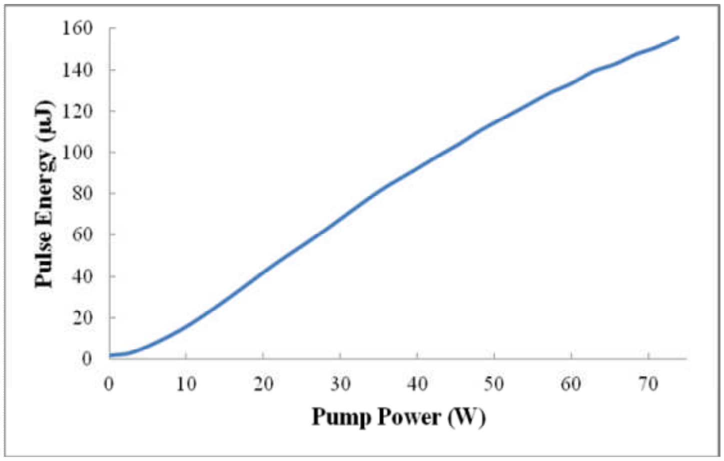

Fig. 8. Output pulse energy as a function of pump power in the final energy amplifier.

To test compression ability of amplified pulses, a small portion (4%) of laser output was injected into a conventional two-pass positive compressor [Fig. 9]. The pulse compressor was built using two gold coated gratings and two lenses. The grating had spatial frequency of 830 lines/mm and lenses had focal length of 50 cm. Assuming a $sech^2$ pulse intensity profile, the compressed pulses had a duration of 780 fs with pulse energy of 156 µJ. The autocorrelation measurement results at different energy levels are shown in Fig. 10.

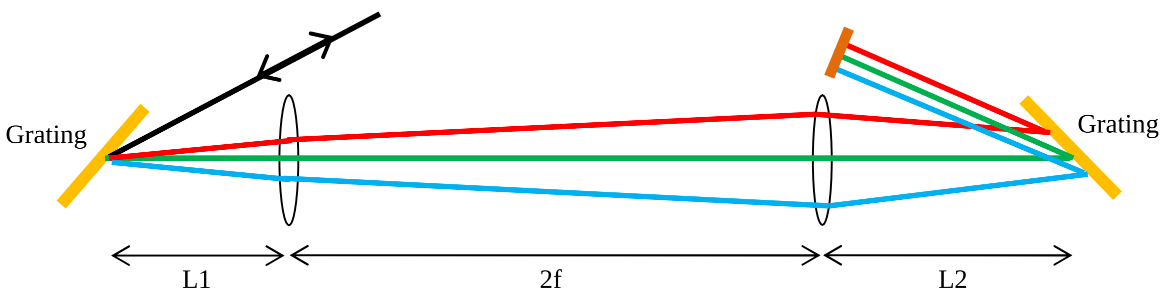

Figure 9: Schematic diagram of pulse compressor

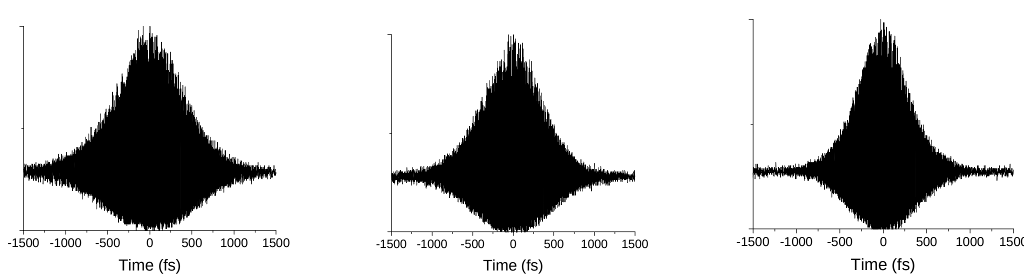

Fig. 10: Pulse width at different energy levels: 60µJ, 900 fs (Left); 104 µJ, 840 fs (Middle); 156 µJ, 780 fs (Right)

The spectra of output pulses at various energy levels are shown in Fig. 11. It does show that the spectra at higher energy get broadened due to SPM. This will help compensate the third order dispersion mismatch with the grating pair. The spectrum width was broadened from 12 nm with 14 µJ pulse energy to 30 nm with 156 µJ pulse energy. It is important to extract the peak power of the high energy amplifier by including the SPM induced spectrum broadening effects. Broadening of spectrum will give an increase in the chirped pulse width to further enhance its peak power handling to scale the energy up and also provide a balance against gain narrowing during high energy amplification. Fig.12 plots the peak power as a function of energy in the high energy amplifier by taking into account of the spectral bandwidth broadening. A peak power of up to 110 kW was achieved for this high energy amplifier. Signal to noise ratio of output pulses was always greater than 20 dB (which was limited by the oscilloscope and detectors) in this experiment. The background signal in the output pulse train was intentionally checked, no obvious CW component was observed.

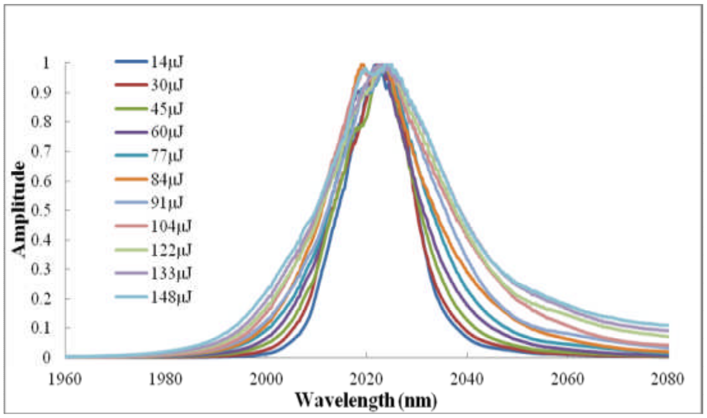

Fig. 11. Output spectrum at various pulse energy levels.

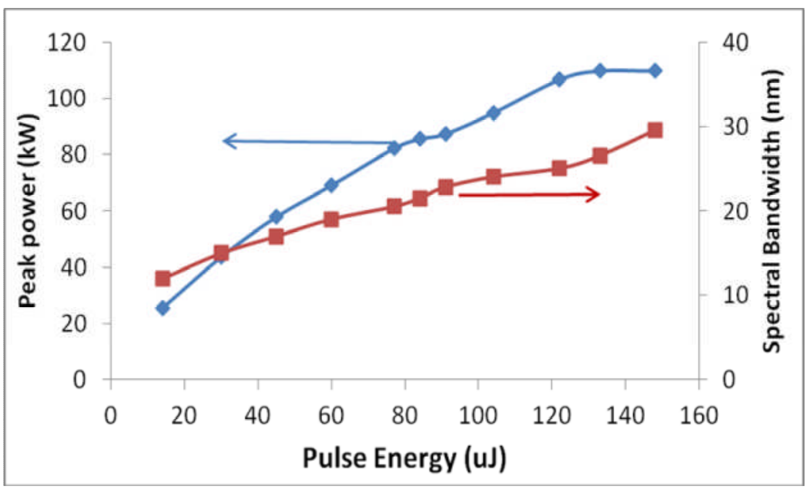

Fig.12. Autocorrelation trace of compressed pulse.

5. SUMMARY

In conclusion, we demonstrated the highest energy (156 μJ) mode locked fiber laser at a wavelength of 2020 nm. The laser consisted of fs seed oscillator, a two-stage pre-amplifiers and a high energy amplifier. The seed laser generated pulse train at a repetition rate of 2.5 MHz and an AOM was used to further lower the repetition rate to 100 kHz. Pulses were stretched by a fiber stretcher to 320 ps. The amplifiers boosted the pulse energy to 156 μJ with a compressed pulse width of 780 fs. This provides a breakthrough in developing a simple and low cost high energy mid-IR fs fiber laser system. Further scaling of the pulse energy is ongoing in PolarOnyx.

ACKNOWLEDGEMENT

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REFERENCES

[1] A. Royon, Y. Petit, G. Papon, M. Richardson, and L. Canioni, “Femtosecond laser induced photochemistry in materials tailored with photosensitive agents,” Opt. Mater. Express **1**, 866-882 (2011).
[2] G. V. Hartland, “Ultrafast studies of single semiconductor and metal nanostructures through transient absorption microscopy,”Chem. Sci.**1**, 303-309 (2010).
[3] E. A. Gibson, Z. Shen, and R. Jimenez, “Three-Pulse Photon Echo Peak Shift Spectroscopy as a Probe of Flexibility and Conformational Heterogeneity in Protein Folding," Chem. Phys Lett. **473**, 330-335 (2009).
[4] B. Xu, Y. Coello, V. V. Lozovoy, and M. Dantus,“Two-photon fluorescence excitation spectroscopy by pulse shaping ultrabroad-bandwidth femtosecond laser pulses,” Appl. Opt. **49**, 6348-6353 (2010).
[5] B. M. Walsh, “Review of Tm and Ho materials; spectroscopy and lasers,” Laser Phys. **19** (4), 855–866 (2009).
[6] M. Ebrahim-Zadeh and I. T. Sorokina, *Mid-infrared Coherent Sources And Applications* (Springer, 2008).
[7] S. Amini-Nik, D. Kraemer, M. L. Cowan, K. Gunaratne, P. Nadesan, B. A. Alman, and R. J. D. Miller, “Ultrafast Mid-IR laser scalpel: protein signals of the fundamental limits to minimally invasive surgery,” PLoS ONE **5**, e13053 (2010).
[8] T. Popmintchev, M.-C. Chen, P. Arpin, M. M. Murnane, and H. C. Kapteyn, “The attosecond nonlinear optics of bright coherent X-ray generation,” Nat. Photonics **4** (12), 822–832 (2010).
[9] W. Zeller, L. Naehle, P. Fuchs, F. Gerschuetz, L. Hildebrandt, and J. Koeth, “DFB lasers between 760 nm and 16 μm for sensing applications,” Sensors **10**, 2492–2510 (2010).
[10] L. E. Nelson, E. P. Ippen, and H. A. Haus, “Broadly tunable sub-500 fs pulses from an additive-pulse mode-locked thulium-doped fiber ring laser,” Appl. Phys. Lett. **67**, 19-21 (1995).
[11] M. A. Solodyankin, E. D. Obraztsova, A. S. Lobach, A. I. Chernov, A. V. Tausenev, V. I. Konov, and E. M. Dianov, “Mode-locked 1.93 μm thulium fiber laser with a carbon nanotube absorber,” Opt. Lett. **33**, 1336-1338 (2008).
[12] J. Liu, Q. Wang, and P. Wang, “Mode-locked 2 μm thulium-doped fiber laser with graphene oxide saturable absorber,” in *CLEO: 2012-Laser Applications to Photonic Applications*, OSA Technical Digest (CD) (Optical society of America, 2012), paper JW2A. 76.
[13] Q. Wang, J. Geng, T. Luo, and S. Jiang, “Mode-locked 2 mum laser with highly thulium-doped silicate fiber,” Opt. Lett. **34** (23), 3616–3618 (2009).
[14] G. Imeshev and M. E. Fermann, “230-kW peak power femtosecond pulses from a high power tunable source based on amplification in Tm-doped fiber,” Opt. Express **13**, 7424-7431 (2005).
[15] F. Haxsen, D. Wandt, U. Morgner, J. Neumann, and D. Kracht, “Pulse energy of 151 nJ from ultrafast thulium-doped chirped-pulse fiber amplifier,” Opt. Lett. **35**, 2991-2993, (2010).
[16] L. M. Yang, P. Wan, V. Protopopov, and J. Liu, “2 μm femtosecond fiber laser at low repetition rate and high pulse energy,” Opt. Express **20**(5), 5683–5688 (2012).
[17] P. Wan, L. M. Yang, and J. Liu, “High pulse energy 2 μm femtosecond fiber laser,” Opt. Express 21, 1798-1803 (2013).