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Abstract. We describe in detail a high energy, high power ultrafast thulium-doped fiber laser system. The pulse energy of 156 μJ was realized. The laser system is comprised of a mode-locked 2020-nm seed oscillator and multiple-stage power/energy amplifiers. The seed oscillator output pulses at a repetition rate of 2.5 MHz. The seed pulses were stretched with the anomalous dispersion fiber to the duration of 320 ps. An acousto-optic modulator was used as a pulse picker to lower the repetition rate. A two-stage preamplifier was used to boost the pulse energy to 3 μJ. The pulse energies of up to 156 μJ and the average power of 15.6 W were obtained from the final stage of power amplifier at a repetition rate of 100 kHz with a slope efficiency of 26%. The pulse durations of 780 fs were obtained after pulse compression. High optical signal-to-noise ratio (OSNR) and low background noise were also achieved at this low repetition rate. [DOI: 10.1117/1.OE.53.5.051508]

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.

Paper 131139SS received Jul. 30, 2013; revised manuscript received Oct. 9, 2013; accepted for publication Nov. 18, 2013; published online Dec. 31, 2013.

1 Introduction

High-energy short pulses emission at an eye-safer wavelength of 2-μm region are desirable for many applications such as laser sensing, free space optical communications, midinfrared (IR) spectroscopy, material processing, laser-induced breakdown spectroscopy, midIR supercontinuum generation, IR countermeasures, and efficient high harmonic X-ray generation.[1–8] Thulium (Tm)-doped short-pulse fiber lasers are of particular interest for such applications because they offer the potential for compact and robust construction.

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.[9–13] However, the output pulse repetition rates from these oscillators were usually from a few tens of megahertz to over 100 MHz. Laser pulse trains at such high repetition rates were not convenient to achieve high pulse energy in amplification stage. Also, the central wavelengths were usually <2000 nm, which were not ideal for some applications, such as sensing of CO_2 that has a strong absorption band for >2000 nm.[8]

Tm-doped fiber amplifiers to boost the pulse energy of ultrafast pulses were also reported.[13–16] Imeshev et al. used a Tm-doped fiber amplifier to boost the Raman shifted pulses from Er/Yb source to the energy of 31 nJ.[13] Haxsen et al. used a regular fiber with anomalous dispersion and normal-dispersion grating stretcher to obtain maximum energy of 151 nJ.[14] In our previous work,[15,16] we demonstrated a high energy master oscillator power amplifier (MOPA) based on the mode-locked Tm-doped fiber laser oscillator and a two-stage fiber amplifier at a wavelength of 2 μm with chirped pulse amplification. The seed laser generated a 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.

In this paper, we present the most recent progress to further increase the pulse energy to 156 μJ, which is the highest pulse energy from a femtosecond Tm-doped fiber laser to the best of our knowledge. A sequence of mode locking pulse train was directly generated in a Tm-doped fiber seed oscillator at the 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 the 2-μm region was used to stretch pulses before amplification. Two stages of Tm-doped fiber preamplifiers and a high energy Tm-doped large mode area fiber amplifier were used in the laser system to boost the output power to 156 μJ. After the pulse compression, the 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.

The structure of the seed laser oscillator was described elsewhere.[15,16] Stable mode locking was achieved at a repetition rate of around 2.5 MHz, producing pulses with about 10 nJ energy. The output coupler was located at the point where the pulse had a maximum stretching. Hence, the seed oscillator emitted pulses with anomalous chirps and duration of about 2.2 ps. The output spectrum was centered at 2020 nm with a bandwidth of 8 nm (Fig. 2), corresponding to a 0.54 ps duration in transform-limited pulses.

3 Two Stage Preamplifiers

Pulses from the seed oscillator were stretched by a fiber stretcher, a spool of 1000-m long regular single mode fiber with anomalous dispersion. The regular fiber has an anomalous dispersion of +40 ps/nm/km in the 2-μm regime. The stretcher elongated the pulses to the duration of around 320 ps. Although the signal was only weakly polarized,

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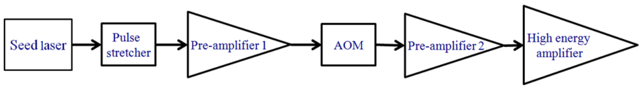

Fig. 1 Systematic diagram of 2 μm seed and power amplifier system.

a pigtailed polarization maintaining (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 losses, was measured. After pulse stretching, the 25 mW output power from the seed oscillator was reduced to 3 mW, but it was sufficient to suppress amplified spontaneous emission level in preamplifiers.

As a next step, pulses from the fiber stretcher were amplified in a double cladding Tm-doped fiber amplifier (preamplifier 1). The setup of fiber stretcher and preamplifier 1 is shown in Fig. 3. The gain medium was a 4.5-m long Tm-doped double cladding 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 diode was coupled into the gain fiber. A maximum average power of 320 mW was measured after the first stage preamplifier. In order to further boost the pulse energy, a 2-μm fiber pigtailed AOM (Brimrose, Sparks Glencoe, Maryland) 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 preamplifier to 10 nm. This broadening effect was mainly due to the 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 a transmission peak of AOM and the central wavelength of the 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.

The low repetition rate pulses were injected into the second stage preamplifier (preamplifier 2). The second stage of amplification was assembled in the similar way with preamplifier 1 by using a 5-m long Tm-doped double cladding fiber with a core diameter of 10 μm. Two multimode laser diodes provided 5 W of pump power at 793 nm in total.

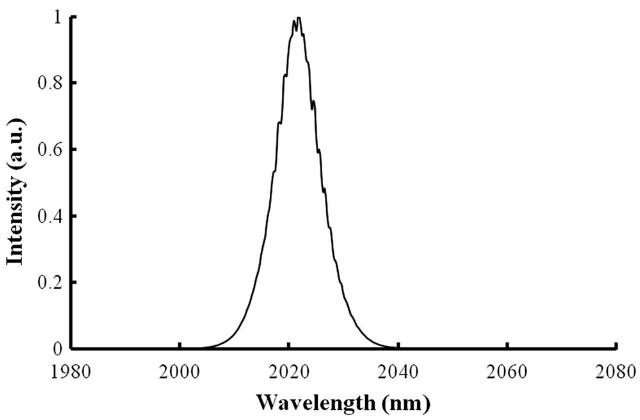

Fig. 2 Seed spectrum.

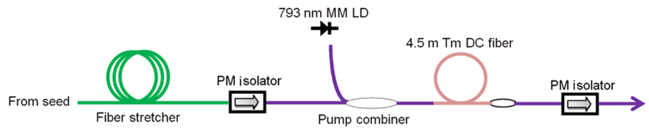

Fig. 3 First stage of amplification (preamplifier 1) with fiber stretcher.

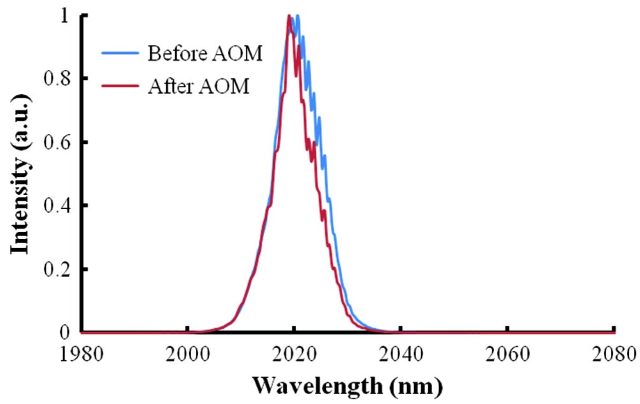

Fig. 4 Spectra of pulses after first stage preamplifier.

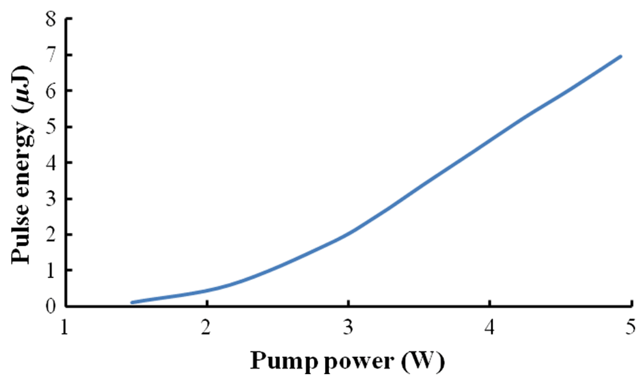

Fig. 5 Output pulse energy versus pump power of the second stage.

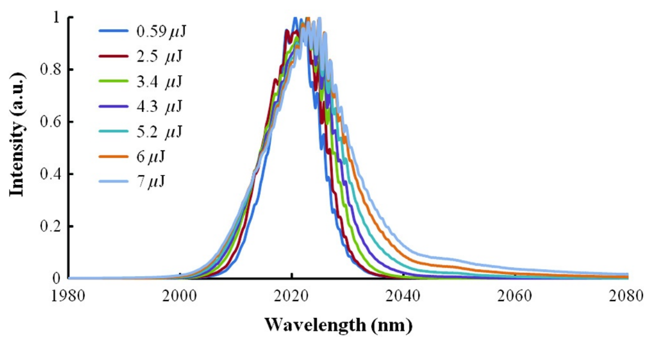

Fig. 6 Spectrum of output pulses at various pulse energy levels after preamplifier 2.

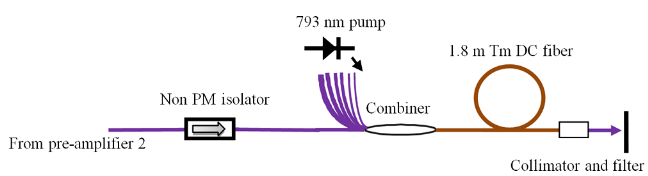

Fig. 7 Setup of high-energy amplifier.

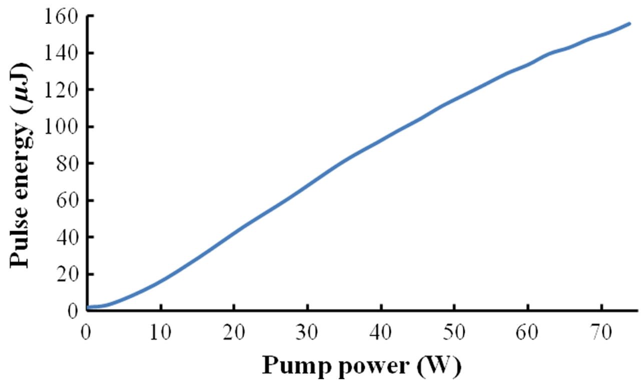

Fig. 8 Output pulse energy as a function of pump power in the final energy amplifier.

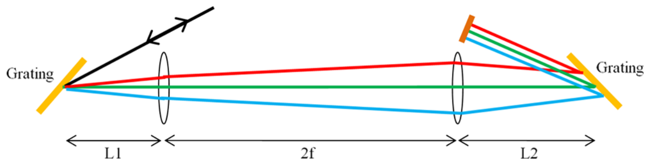

Fig. 9 Schematic diagram of the pulse compressor.

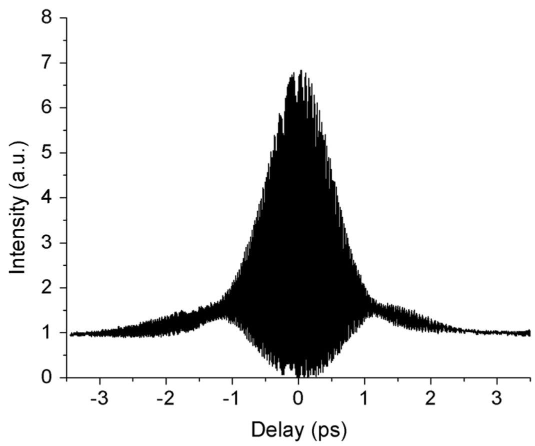

Fig. 10 Pulse width at energy level of 156 μJ, 780 fs.

The second stage amplifier amplified the pulse train up to an average power of 700 mW or a pulse energy of 7 μJ (Fig. 5). Output spectra at various output energy levels are shown in Fig. 6. At high pumping levels, noticeable broadenings of pulse spectra 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 SPM in the first stage preamplifier. When we further increased the pump level, the output spectrum widths were increased to around 15 nm at an output level of 7 μJ. The fact that the spectrum broadening was more favorable to the longer wavelength side implied a Raman shift due to the 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 preamplifier to 3 μJ or the average power to 300 mW.

4 High-Energy Amplifier

Figure 7 shows the setup of the final stage of the high-energy amplifier. The gain medium was a 1.8-m long nonPM Tm-doped double cladding fiber with a core diameter of 25 μm (Nufern, East Granby, Connecticut). 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. The pulse energy of up to 156 μJ and the average power of 15.6 W were obtained with a slope efficiency of 26%.

To test the 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 a spatial frequency of 830 lines/mm and the lenses had a focal length of 50 cm. Assuming a sech^2 pulse intensity profile, the compressed pulses had a duration of 780 fs with the pulse energy of 156 μJ. The autocorrelation measurement is shown in Fig. 10.

The spectra of output pulses at various energy levels are shown in Fig. 11. It does show that the spectra at higher energies get broadened due to the SPM. This will help to 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.

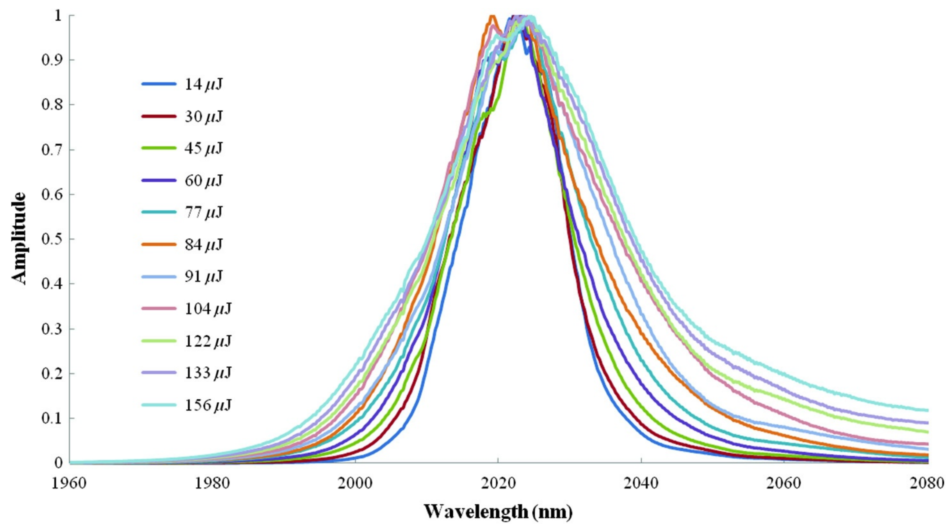

Fig. 11 Output spectrum at various pulse energy levels.

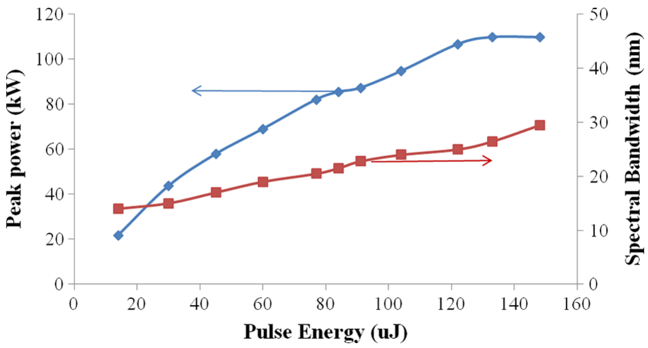

Fig. 12 Peak power and spectrum bandwidth at various pulse energy levels.

It is important to extract the peak power of the high-energy amplifier by including the SPM induced spectrum broadening effects. Broadening of the 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 the gain narrowing effect during high-energy amplification. Figure 12 plots the peak power as a function of energy in the high-energy amplifier by taking into account the spectral bandwidth broadening. A peak power of up to 110 kW was achieved for this high-energy amplifier. When further increasing the pump power, a strong Raman effect was observed and transferred much pulse energy to the longer wavelengths. Signal-to-noise ratio of output pulses was always >20 dB (which was limited by the oscilloscope and detectors) in this experiment. The background signal in the output pulse train was intentionally checked and no continuous wave (CW) component was observed.

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 an fs seed oscillator, a two-stage preamplifiers 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. The 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 midIR fs fiber laser system. Further scaling of the pulse energy is ongoing in PolarOnyx.

Acknowledgments

This project is supported in part by the Department of Energy SBIR Program.

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Peng Wan is currently a senior laser scientist in PolarOnyx, Inc. He received his PhD in physics from University of California at Riverside, California. He is skilled with laser and laser optics, nonlinear optics, deep UV microscope, Raman generation and analysis, and ultrahigh vacuum systems. His current research interests include high-power laser system, fiber optics, and nonlinear frequency conversion for the use in laser systems with the wavelength ranging from deep UV to mid-IR.

Lih-Mei Yang received the PhD from University of Michigan, Ann Arbor, in 1996 and demonstrated the first high-energy femtosecond up-conversion fiber laser using multimode gain fiber. In 2000, Lihmei joined the amplifier team of the Lucent Technologies, Microelectronics Group and led to design fiber amplifiers including Raman amplifiers. In 2005, she joined PolarOnyx to develop all fiber-based femtosecond fiber lasers and is a key member for the development of high energy/power femtosecond fiber lasers.

Jian Liu is the founder of PolarOnyx, Inc. He earned his PhD from the University of Texas at Austin. He led Lucent/Bell Labs L-band erbium-doped fiber (EDF) development. In PolarOnyx, he led the development of a series of award winning femtosecond fiber laser products. He has authored over 60 publications and over 28 patents. He is a member of SPIE and OSA.