High pulse energy 2 μm femtosecond fiber laser

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Abstract: In the paper, a 2 μm high energy fs fiber laser and amplification system is presented based on Tm doped fibers. The seed laser was designed to generate pulse train at 2024 nm at a repetition rate of 2.5 MHz. An AOM was used as a pulse picker to further lower the repetition rate down to 100 kHz. Two-stage fiber pre-amplifiers and a high energy large mode area (LMA) fiber amplifier were used to boost pulse energy up to 54 μJ before pulse compressor with chirped pulse amplification technique. After compressor, pulse energy of 36.7μJ and pulse duration of 910 fs and were obtained.

OCIS codes: (140.4050) Mode-locked lasers; (140.3510) Lasers, fiber; (140.3070) Infrared and far-infrared lasers; (320.5550) Pulses; (060.2390) Fiber optics, infrared; (060.2320) Fiber optics amplifiers and oscillators.

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1. Introduction

High energy ultrafast Thulium (Tm) doped fiber lasers at wavelength of 2 μm are gaining attentions 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 [1–5]. The advantages of fiber lasers, such as compactness, light-weight, reliable operation, and high wall-plug efficiency, are well recognized both in academia and industry.

Tm doped femtosecond fiber lasers had been demonstrated in several mode-locking schemes such as nonlinear polarization rotation, carbon nanotube, graphene oxide and

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semiconductor saturable absorbing mirrors [6–10]. 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 [5]. Tm-doped fiber amplifiers to boost pulse energy of ultrafast pulses were also reported [10–12]. In reference [10], thulium doped fiber amplifier was used to boost Raman shifted pulses from Er/Yb source to the energy of 31 nJ. In reference [11], regular fiber with anomalous dispersion and normal-dispersion grating stretcher was used, and maximum energy of 151 nJ was obtained. In our previous work [12], we demonstrated a high energy MOPA based on mode-locked Tm doped fiber laser oscillator and a two-stage fiber amplifier at central wavelength of 1985 nm 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 0.65 μJ with a compressed pulse width of 820 fs.

In this paper, we present the most recent progress to further increase the pulse energy to 54 μJ and shift wavelength beyond 2000 nm. To our knowledge, this is the highest energy femtosecond fiber laser ever published at 2 micron. The seed oscillator generated pulse train at central wavelength of 2024 nm with a repetition rate of 2.5 MHz. An acousto-optic modulator (AOM) was used to further 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 54 μJ. After pulse compression, pulse energy of 36.7 μJ and pulse width of 910 fs were obtained.

2. Laser oscillator and amplifier system

The systematic diagram of 2 μm seed oscillator and multiple-stage power amplifiers are shown in Fig. 1. It consisted of a 2024 nm Tm doped fiber laser seed oscillator, a fiber stretcher, a two-stage fiber power amplifier, an AOM, a final stage high energy amplifier and a pulse compressor. The AOM was used as a pulse picker.

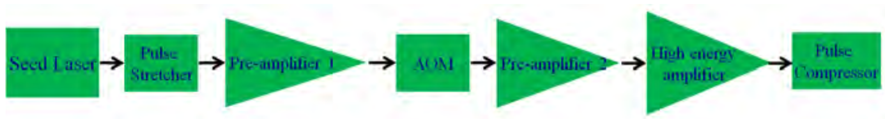

Fig. 1. Systematic diagram of 2 μm seed and power amplifier system.

The structure of seed laser oscillator was similar to Ref. [8], but tuned to operate at 2024 nm. The active gain medium was a 5 m long double clad Tm doped fiber with a core of 6 μm diameter. The gain fiber was pumped by one multimode (MM) laser diode with a wavelength of 793 nm. A piece of fiber of 30 m long with normal dispersion was used to partly compensate anomalous dispersion from regular single mode (SM) fiber and to facilitate mode locking. A semiconductor saturable absorber was used as one cavity mirror with an absorbance of 20%, a modulation depth of 12%, and a saturation fluence of 65 $\mu J/cm^2$ (commercially available by BATOP GmbH). Stable mode-locking was achieved at a repetition rate of 2.5 MHz, producing pulses with about 10 nJ energy and 8 nm spectral bandwidth centered at 2024 nm. The seed oscillator emitted pulses with anomalous chirp. The pulse duration was 2.2 picoseconds.

3. Two stage pre-amplifiers

As a next step, the pulses from the output of seed oscillator were stretched by 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

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pulses to the duration of around 320 picoseconds. The signal was weakly-polarized. A pigtailed PM isolator with one polarization blocked was spliced to the output end of the stretcher, while the pulses will be picked in polarization sensitive pulse picker (AOM) in next stage. A total loss of 9.2 dB, including all splicing loss and isolator loss, was measured. 25 mW output signal from seed after stretching was reduced to 3 mW, but it was found sufficient to suppress amplified spontaneous emission (ASE) level in pre-amplifiers.

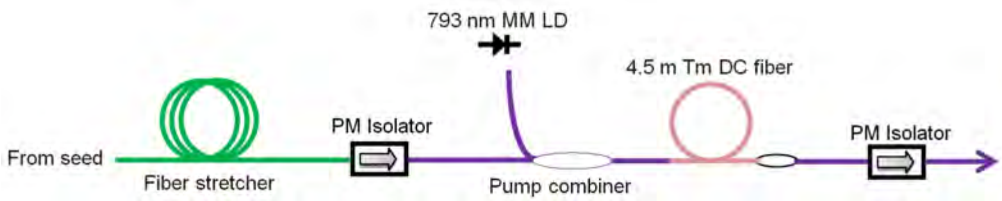

Fig. 2. First stage of amplification (pre-amplifier 1) with fiber stretcher.

Output pulses from the fiber stretcher were first 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. 2. The gain medium was a 4.5 m-long non-PM 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. Figure 3 shows the spectrum of pulses after pre-amplifier 1. The gain peak of this stage pre-amplifier was not optimized to the central wavelength of seed laser, thus it caused the center wavelength to shift 2 nm to the short wavelength side after amplification. The spectrum was slightly broadened in the first stage pre-amplifier to 9.5 nm. This broadening effect was mainly due to self-phase modulation in the gain fiber.

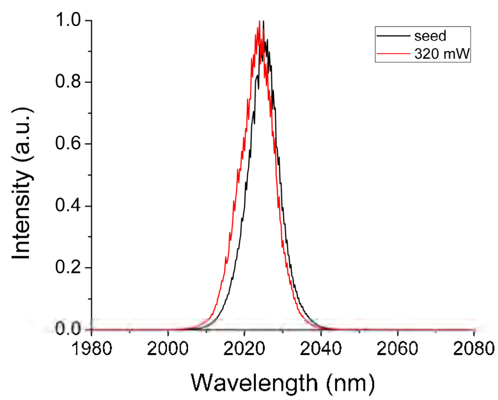

Fig. 3. Spectrum of pulses after first stage pre-amplifier.

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 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 non-PM Tm doped double clad fiber with a core diameter of 10 µm. Two multimode laser diodes provided total 4.5 W of pump power at 793 nm. The second stage amplified the pulse train up to an average power of 1.05 Watts or pulse energy of 10.5 µJ (Fig. 4) with an optical slope efficiency of 35.4%. Output spectrum at various output energy levels are shown in Fig. 5. 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 was increased to around 9.5 nm, which is mainly due to the self-phase modulation in the first stage pre-amplifier. With further increasing the pump level, the output spectrum width was increased to around 25 nm at an output level of 10.5 μJ. The fact that spectrum broadening only happened 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.

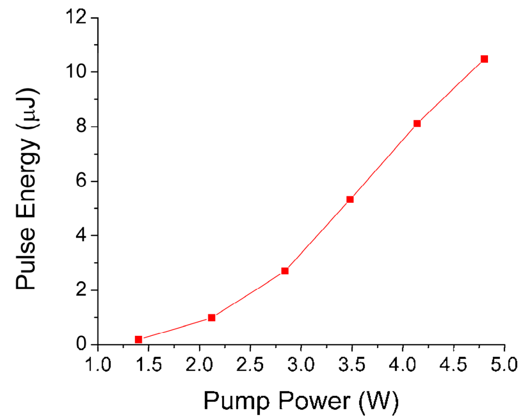

Fig. 4. Output pulse energy versus pump power of the second stage

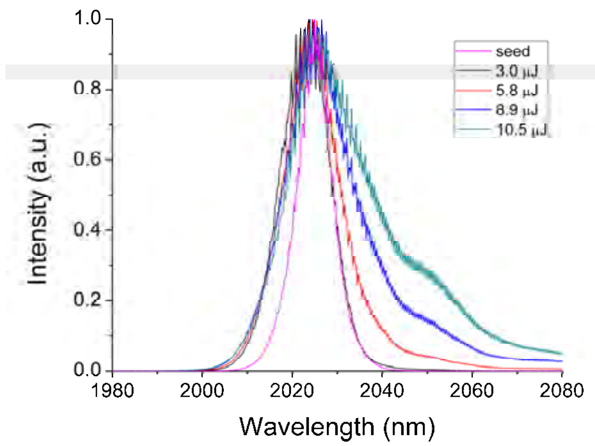

Fig. 5. Spectrum of output pulses at various pulse energy levels after pre-amplifier 2.

4. High energy amplifier

Finally, the 2 μm pulse train was injected into the final stage of high energy amplifier. The setup of high energy amplifier is shown in Fig. 6. 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 35 W 793 nm pump beam from three multimode laser diodes were coupled into the gain fiber. Maximum pulse energy of 54 μJ was obtained. It is limited only by the available pumps in our lab. By increasing the pumps, output energy over 100 μJ can be predicted. The output pulse energy as a function of pump power is shown in Fig. 7. The spectrum of output pulses at various energy levels is shown in Fig. 8. An optical slope efficiency of 18.6% was obtained in the final stage of amplification. The spectrum was moderately broadened. To test compression ability of

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amplified pulses, a conventional two-pass positive 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. The pulse energy after compression was measured up to 36.7 µJ, with 68% transmission efficiency from the pulse compressor (limited by the grating efficiencies). Assuming a $sech^2$ pulse intensity profile, the compressed pulses had duration of 910 fs (Fig. 9) with the maximum output. The pulse duration remained the similar at different pulse energy levels after the final energy amplification stage. It was slightly increased from 800 fs to 910 fs with increased pulse energy. For each energy level, pulse compressor need to be readjust to optimize the results. 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 CW component was observed.

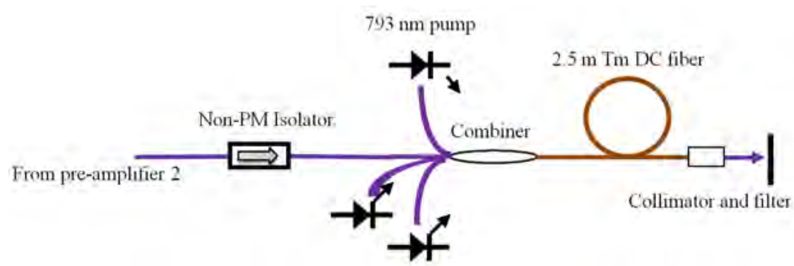

Fig. 6. Setup of high energy amplifier

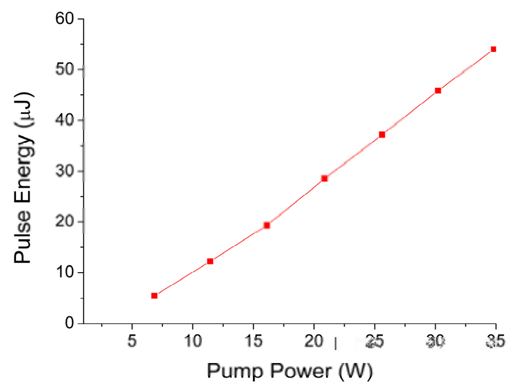

Fig. 7. Output pulse energy as a function of pump power in the final energy amplifier.

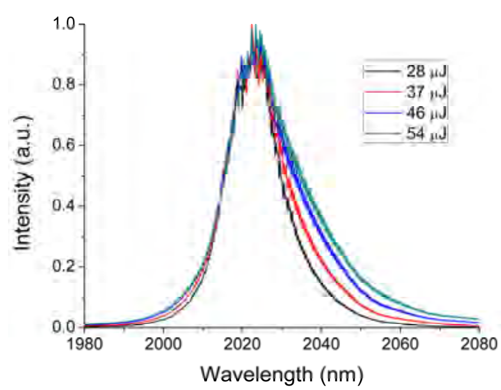

Fig. 8. Output spectrum at various pulse energy levels before compressor

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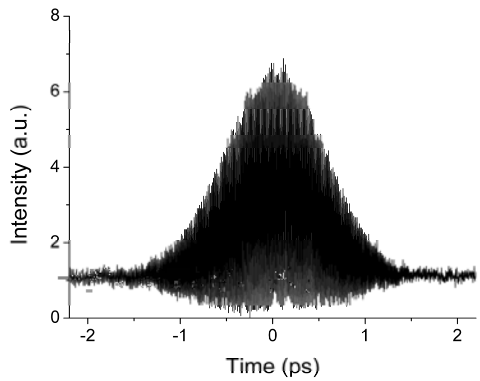

Fig. 9. Autocorrelation trace of compressed pulse with pulse energy of 54 μJ before pulse compressor.

5. Conclusions

In conclusion, we demonstrated the highest energy (54 μJ before pulse compressor) mode locked fiber laser at a wavelength of 2024 nm. The laser consisted of femtosecond 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 boost the pulse energy to 54 μJ with a compressed pulse width of 910 fs. This provides a breakthrough in developing a simple and low cost high energy mid-infrared fs fiber laser system. Current system is scalable to over 100 μJ by adding more pumps. Further scaling of the pulse energy is ongoing in PolarOnyx.

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