High power 2 μm femtosecond fiber laser

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Abstract: A high power polarization maintaining femtosecond Tm-doped fiber laser system is demonstrated. A chirped fiber Bragg grating with normal dispersion was used to compensate the anomalous dispersion from the regular fiber in the 2 μm seed oscillator to generate mode locked pulses with a pulse repetition rate of 30.84 MHz. After chirped pulse amplification, an amplified power of 78 W was obtained. The pulse was compressed by a chirped volume Bragg grating based pulse compressor. A pulse duration of 760 fs and an average power of 36 W were obtained after compressor.

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

Femtosecond pulsed laser sources operating in the 2 μm wavelength regime have many applications, including efficient high harmonic X-ray generation [1], mid-IR spectroscopy generation through optical parametric oscillators [2, 3] or supercontinuum generation [4], material processing [5], laser-induced breakdown spectroscopy [6] and eye-safe remote sensing [7]. 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 have previously been demonstrated by using various mode-locking methods [8–15]. Among these methods, soliton mode-locking technique is frequently used due to the anomalous dispersion in 2 μm regime from regular fibers and lacking of effective means to compensate it. Soliton mode-locking allows strong nonlinear phase shift in the laser cavity, which may not only make the mode-locking unstable but also bring Kelly sidebands into the optical spectrum [19, 20]. Kelly sidebands can limit the performance of the power and energy amplification, because these sidebands can be amplified more than the main pulse [9]. In our previous work, we used dispersion compensating fiber (DCF) to compensate the anomalous dispersion from regular fiber, and achieved mode-locking with near-zero dispersion in the 2 μm oscillators [16–18]. The DCF was specially made with high concentration of germanium and small mode-field diameter (MFD) and operated at normal dispersion at 2 μm. The seed laser generated pulse train at a repetition rate of 2.5 MHz, which helped to achieve higher pulse energy in the amplification stages. After further lowering the repetition rate by using a pulse picker and chirped pulse amplification, pulse energy of up to 156 μJ and average power of 15.6W were obtained [18]. A pulse duration of 780 fs was measured after pulse compression. Another method to compensate anomalous dispersion is to add a piece of fiber Brag grating (FBG) in the 2 μm oscillator. FBG was used in reference [10], but it only worked as a bandpass filter, and the mode-locking was still soliton.

In this paper, we present the most recent progress to achieve an average power of 78 W, which is the highest average power from a femtosecond Tm-doped fiber laser to the best of our knowledge. A FBG was used to replace the DCF to provide normal dispersion in the seed oscillator [16, 17]. Mode-locked pulses were generated directly from the net near-zero dispersion fiber oscillator. By removing the DCF, the total fiber length inside the oscillator was reduced dramatically, and a pulse repetition rate as high as 30.84 MHz was achieved without sidebands in the output spectrum. This high repetition rate helped to overcome nonlinear effects, such as self-phase modulation (SPM) and stimulated Raman scattering (SRS) in the high power amplification process. 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 power Tm-doped polarization maintaining (PM) large mode area (LMA) fiber amplifier were used in the laser system to boost output power to above 78 W. After pulse compression, a pulse duration of 760 fs was obtained.

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2. Experiment setup

The systematic diagram of 2 µm seed oscillator and multiple-stage power amplifiers are shown in Fig. 1. It consisted of a Tm-doped fiber laser seed oscillator, a fiber pulse stretcher, two stages of pre-amplifiers, a final stage of high power amplifier and a pulse compressor.

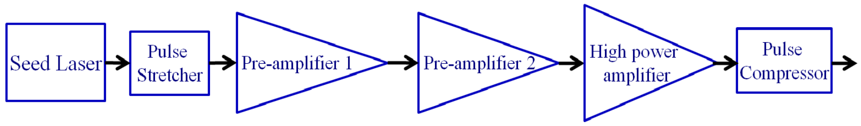

Fig. 1. Systematic diagram of 2 µm high power fiber laser system.

The structure of a high repetition rate, 2 µm, PM seed oscillator is shown in Fig. 2. The gain medium was a 2 m-long PM double cladding fiber with a fiber core diameter of 10 µm and numerical aperture (NA) of 0.15 (Nufern). The gain fiber was pumped by one multimode laser diode with central wavelength of 793 nm. A pump/signal combiner was used to couple pump power into the fiber. One end of the seed oscillator was a semiconductor saturable absorber mirror with a modulation depth of 12%, a relaxation time of 10 ps and a saturation fluence of 65 µJ (BATOP). At the other side of the laser cavity, a FBG (Teraxion) with normal dispersion of 0.52 ps^2 was used to partially compensate anomalous dispersion from regular fibers. The total fiber length is 3.25 m inside the oscillator. Regular fiber has an anomalous dispersion of –0.0849 ps^2 for 1 m length at 2 µm. Thus the total round trip dispersion from regular fiber is –0.552 ps^2 and the overall calculated dispersion has a slightly negative value of –0.032 ps^2. The FBG also worked as an output coupler. The FBG has a center wavelength of 2000 nm with a 16% reflectivity and a FWHM bandwidth of 50nm.

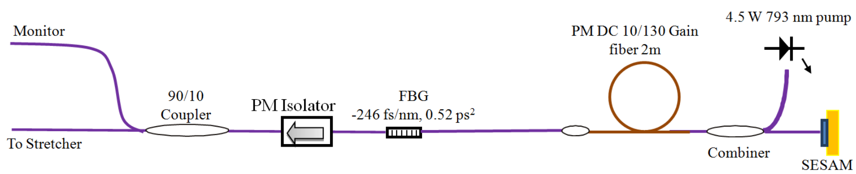

Fig. 2. Setup of 2 µm seed oscillator, the total fiber length is 3.25m.

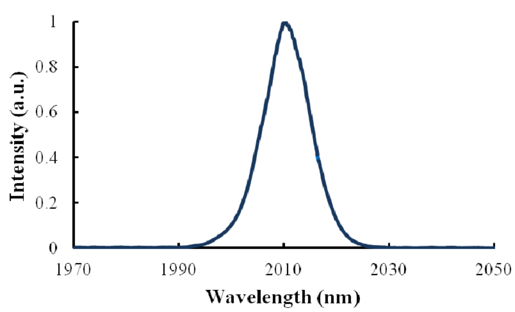

Fig. 3. Optical spectrum of seed laser.

The seed oscillator demonstrated stable self-started mode-locking with pump power of 2.4 W. An average output power of 18 mW was obtained from the main output port (to stretcher). The output spectrum was centered at 2011 nm with a spectrum bandwidth of 10.5 nm (Fig. 3). No sideband was observed in the output spectrum thus we highly suspected that the mode-locking was achieved without soliton. The pulse repetition rate was 30.84 MHz, which corresponds to 3.25 m fiber length inside the oscillator. The output coupler (FBG) was located at the point where the pulses had maximum stretching. Hence the seed oscillator

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output pulses with anomalous chirp and the pulses were further stretched by a 3 m-long regular fiber from FBG and isolator. The pulses were not intentionally compressed due to the complicated configuration of grating compressor for anomalous chirped pulses. Thus chirped pulse duration of 2.9 ps was measured.

3. Two stage pre-amplifiers

As a next step, the pulses from the output of seed oscillator were stretched by passing a spool of regular single mode fiber (SMF-28e +) with anomalous dispersion. The fiber length for the stretcher was around 650 m with a dispersion rate of around 26 ps/nm. This value was required to be consistent with the dispersion rate from chirped Bragg grating (CBG) in the pulse compressor. The stretcher elongated the pulses to a duration of around 273 ps. This stretched pulse train was amplified through two stages of pre-amplifiers. The setup of fiber stretcher and the first stage pre-amplifier is shown in Fig. 4. The constructions were similar for both stages of pre-amplifiers. The gain medium was a 2.5 m-long PM Tm-doped double cladding fiber with 10 µm core diameter. In the first stage pre-amplifier, up to 3.8 W 793 nm pump power from one pump diode was injected into the gain fiber, while in the second stage pre-amplifier, two pump diodes were used to provide up to 7.7 W pump power.

The output spectra after the first and the second stage of pre-amplifiers were plotted in Fig. 5. At the highest injected pump power of 3.8 W, 103 mW average power was obtained from the first stage pre-amplifier. No spectrum broadening effect was observed. In the second stage pre-amplifier, an average power of 1.48 W was obtained at the maximum pump power level of 7.7 W. The spectrum width was increased moderately to 12.8 nm, likely due to SPM effect.

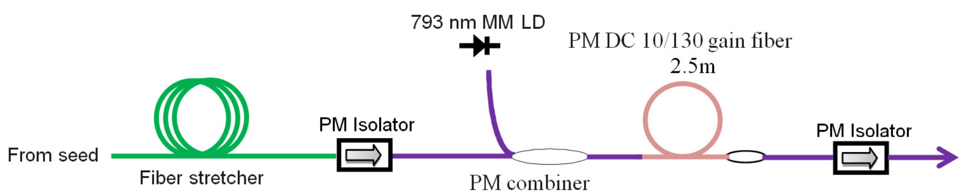

Fig. 4. First stage of amplification (pre-amplifier 1) with fiber stretcher

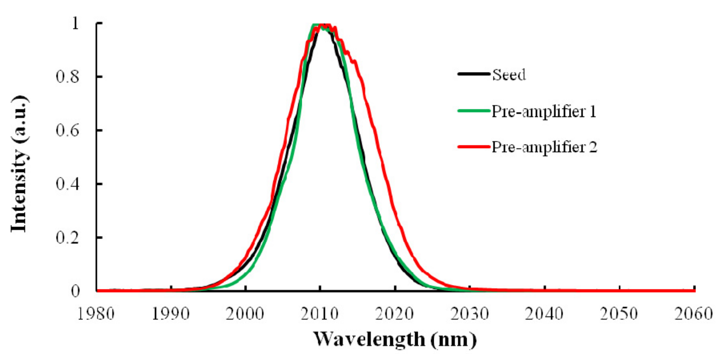

Fig. 5. Output spectra after first stage and second stage pre-amplifiers.

4. High power amplifier

Finally, the 2 µm pulse train was injected into the final stage of high power amplifier. The setup of high power amplifier is shown in Fig. 6. The gain medium was a 4.5 m-long PM Tm-doped double cladding fiber with a core diameter of 25 µm (Nufern). The gain fiber was immersed into water to avoid possible thermal damage during the high power operation. Sixteen pieces of 793 nm high power pump diodes were used to provide up to 222 W pump power. The pump diodes were divided into 4 groups with 4 pieces each. Pump beams in each group were first combined through pump combiners, and then were coupled into the gain medium through a PM pump/signal combiner (ITF). The output power as a function of pump power is shown in Fig. 7. An output power of up to 78 W (a gain of 17.2 dB) and a pulse energy of up to 2.53 μJ were obtained at pump power of 222 W with an optical slope efficiency of 32%. The output spectra at various output power levels are shown in Fig. 8(a). The spectrum bandwidth was gradually increased to 13nm, 16 nm, 18.6 nm and 21 nm at output power levels of 9 W, 27 W, 55 W and 78 W respectively. 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.

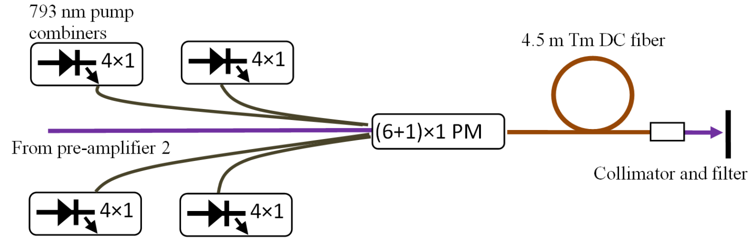

Fig. 6. Setup of high power amplifier.

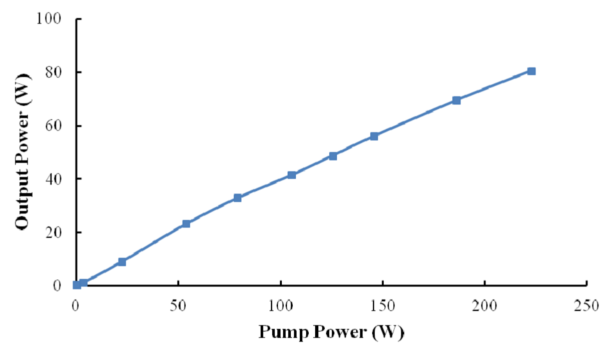

Fig. 7. Output power as a function of pump power in the final power amplifier.

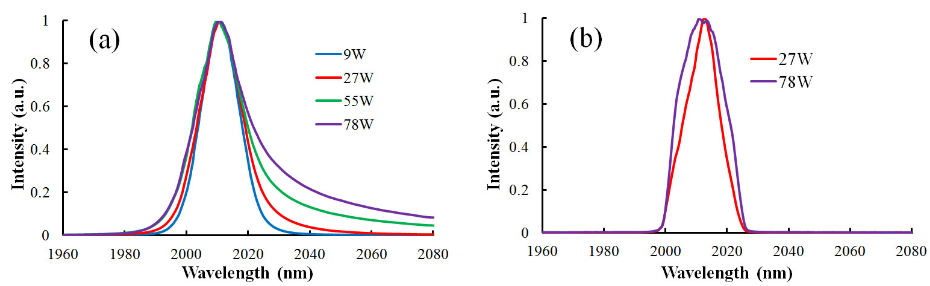

Fig. 8. (a) Spectrum with various output power levels prior to compression with the CBG; (b) Spectra of compressed pulses at two amplified power levels.

To test compression ability of amplified pulses, a chirped Bragg grating (OptiGrate) was used to compress the amplified pulses. A schematic diagram of using a CBG at a small incident angle for doubling passing is shown in Fig. 9. The CBG has a central wavelength of 2013 nm and a spectrum bandwidth of 24 nm. The dispersion rate is 26 ps/nm for double passes from CBG. A polarizer and a 1/4 waveplate at the wavelength of 2 μm were used to split the input and output beam after the CBG compressor. The CBG had a very high

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efficiency (>94%) within its spectrum bandwidth and sharp cut-offs on both longer and shorter wavelengths. Thus the overall efficiency was gradually reduced with increased average output power due to spectrum broadening. An output power of up to 36 W was obtained after compressor with input power of 78 W. Spectra after compressor at various amplified power levels are shown in Fig. 8(b). An autocorrelation trace is shown in Fig. 10(a). Assuming a $sech^2$ pulse intensity profile, the compressed pulse had a pulse duration of 790 fs at the maximum output power level. The signal to noise ratio of output pulses was always greater than 20 dB (which was limited by the oscilloscope and detectors) in this experiment. Figure 10(b) shows the output pulse train at the maximum output power level. The background signal in the output pulse train was intentionally checked, and no CW component was observed.

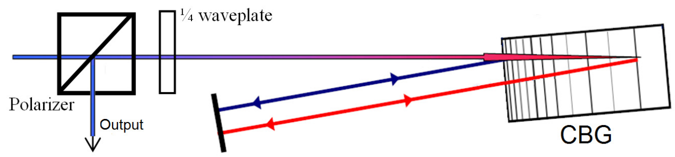

Fig. 9. Schematic diagram of a double pass CBG pulse compressor

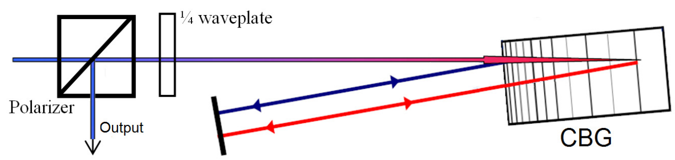

Fig. 10. (a) Autocorrelation trace of compressed pulse with amplified power of 78W (36W after pulse compressor); (b) Output pulse train with amplified power of 78W.

5. Conclusions

In conclusion, we demonstrated the highest power (78 W before pulse compressor) mode locked fiber laser at the central wavelength of 2011 nm. The laser consisted of femtosecond seed oscillator, two stage pre-amplifiers and a high energy amplifier. The femtosecond pulse train of 2 µm wavelength was generated from a near-zero dispersion fiber oscillator with a repetition rate of 30.84 MHz. Pulses were stretched by a fiber stretcher to 273 ps. The amplifiers boost the power to 78 W. After pulse compression, an average power of 36W and a compressed pulse width of 790 fs were obtained. Further scaling of power and pulse energy is ongoing in PolarOnyx.

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