2 µm femtosecond fiber laser at low repetition rate and high pulse energy

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Abstract: In the paper, a 2 µm high energy fs fiber laser is presented based on Tm doped fiber at a low repetition rate. The seed laser was designed to generate pulse train at 2 µm at a pulse repetition rate of 2.5 MHz. The low repetition rate seed oscillator eliminated extra devices such as AO pulse picker. Two-stage fiber amplifier was used to boost pulse energy to 0.65 µJ with chirped pulse amplification.

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 short pulses are very promising tools for investigation of ultrafast processes in physics and chemistry [1–4]. A pump-probe technique often allows getting information about phenomena which is unreachable by any other methods. Multi-photon fluorescence spectroscopy allows investigating biological materials with spatial resolution below diffraction limit. High energy short pulse light detection and ranging (LIDAR) are widely used for distant diagnostics of atmosphere and other gases and liquids. Short pulses material processing gives new methods to create new devices and components of micro- and nano-sizes. Every year, it brings more and more applications for femtosecond laser optics [1–4]. Thulium 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 attracting growing interest because many molecular absorption lines are located in this spectral region.

Several methods were used to generate passive mode locking femtosecond pulses for Tm doped fiber lasers: nonlinear polarization rotation [5], exotic nonlinear elements like carbon nanotube [6], and saturable absorbing mirrors, which are obviously most convenient and

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reliable components and very popular in other wavelength regions, but in 2 μm region are still very rare. In reference [7], thulium doped fiber amplifier was used to boost Raman shifted pulses from Er/Yb source to the energy of 31 nJ. The initial stretching of the pulses was provided by a piece of normal dispersion fiber, and compression was occurred directly in Tm-doped fiber of amplifier. Regular fiber with anomalous dispersion and grating normal-dispersion stretcher was used in reference [8]. The compression ratio of grating stretcher can be made essentially higher than that in short piece of Tm doped fiber and maximum energy of 151 nJ was obtained in the work.

In this paper, we present a laser system for generation of low repetition pulse train and amplificationit to energy of 0.65μJ. In our work, we were able to combine all the state-of-the-art solutions. A sequence of mode locking pulse train was directly generated in Tm doped fiber seed oscillator. The mode locked seed laser used semiconductor saturable absorber mirror and long all-fiber cavity to reduce low pulse repetition rate of lasing and to reach higher pulse energy by chirped pulse amplification. To simplify design of the compressor, we used a spool of fiber with normal dispersion in 2 μm region to stretch pulses before amplification. Two stages of double cladding Tm doped fiber amplification were used in the laser to boost output power. Normal dispersion fiber stretcher was also used in reference [9], but there were no results on pulse compression after amplification. In this paper, we present all results on the low pulse repetition rate seed oscillator and chirped amplification.

2. Seed laser

The schematic diagram of seed laser oscillator is shown in Fig. 1. The laser active medium was 5 m long double clad Tm doped fiber with a core of 6 μm diameter and a 0.23 numerical aperture (NA). The gain fiber was pumped by one multimode (MM) laser diode with a wavelength of 793 nm. An MM signal/pump combiner was used to couple pump power into the fiber. Such a pumping scheme had obvious advantage of using high power and inexpensive multimode laser diodes with wavelength matched Tm strong absorption band. The central wavelength of the laser was close to our target of 2 μm without any filter.

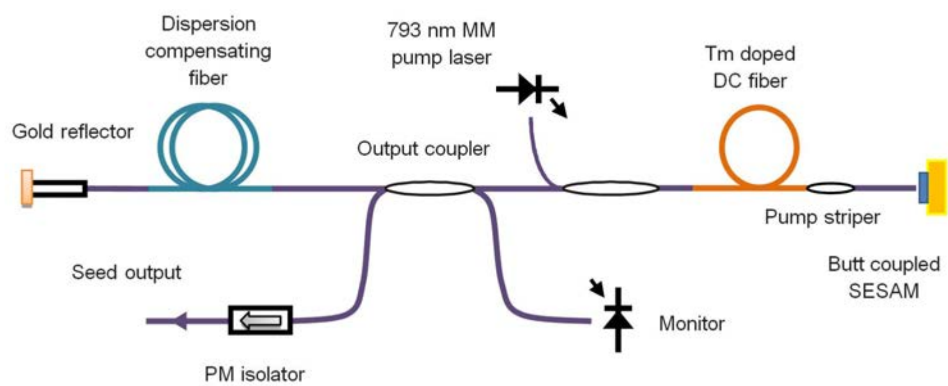

Fig. 1. Schematic diagram of the seed laser oscillator.

As shown in Fig. 1, one mirror of the cavity was a semiconductor saturable absorber mirror with a modulation depth of 20%, a relaxation time of 500 fs, and a saturation fluence of 35 μJ/cm^2 (commercially available by BATOP GmbH). The other cavity mirror was a fiber pigtailed gold reflector. A piece of fiber of 30 m long with normal dispersion of −12 ps/nm/km was used to partly compensate positive dispersion of + 40 ps/nm/km from regular fiber and to facilitate mode locking. The net dispersion of the cavity was reduced to be the value of −0.085 ps^2. The dispersion compensating fiber (DCF) had high concentration of germanium and small mode-field diameter (MFD) and operated at normal dispersion. Output

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couplers with various coupling coefficients ranging from 15% to 85% were used. High coupling ratio helped to gain significantly high output signal power. Stable single pulse mode locked generation was obtained.

The seed oscillator demonstrated stable self-started mode locking regime with 700 mW of pumping. The fluctuation of pulse amplitudes was within 3%. The output coupler was located at the point where the pulses had maximum stretching. Hence the seed oscillator emitted pulses with anomalous chirp and duration of 2.6 ps as shown in Fig. 2. The output spectrum had a bandwidth of 8 nm corresponding 0.55 ps duration in transform-limited pulses. The output pulses were used in further amplification process, so we didn't compensate the chirp at this part of the laser. Good single pulse regime of the seed was observed with output power up to 25 mW (with 85% output coupling coefficient). Total cavity length was 40 meters, which corresponds of 2.5 MHz pulse repetition rate. Such low repetition frequency eliminates a necessity to use a pulse picker and is quite convenient for achieving high pulse energy.

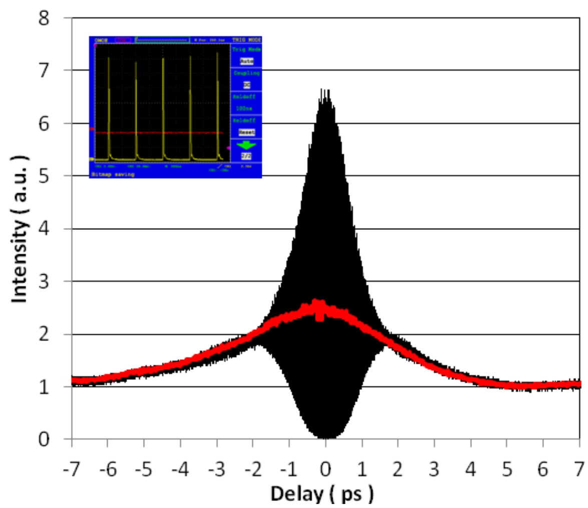

Fig. 2. Autocorrelation trace of the seed output.

The seed emitted weakly-polarized signal. A pigtailed PM isolator with one polarization blocked was spliced to the output of the seed, while the pulses will be finally compressed in polarization sensitive pulse compressor.

As a next step, the pulses from the output of seed oscillator were stretched by a spool of fiber with normal dispersion. The stretcher elongated the pulses to the duration of 40 psec. The fiber with normal dispersion was chosen due to simple configuration of anomalous grating compressor. Due to initial chirp of the pulses, they were compressed at the first meters of the stretching fiber, so some spectrum broadening mainly due to self-phase modulation was observed as shown in Fig. 3. The high numerical aperture stretching fiber had significant fundamental absorption near 2 μm and high splicing loss to regular fiber. We measured total loss of 13 dB including splicing loss of 1.5 dB for two splices. 10 mW output signal from seed after stretching reduced to 0.5 mW, but it was found to be sufficient for high output power with low amplified spontaneous emission (ASE) level.

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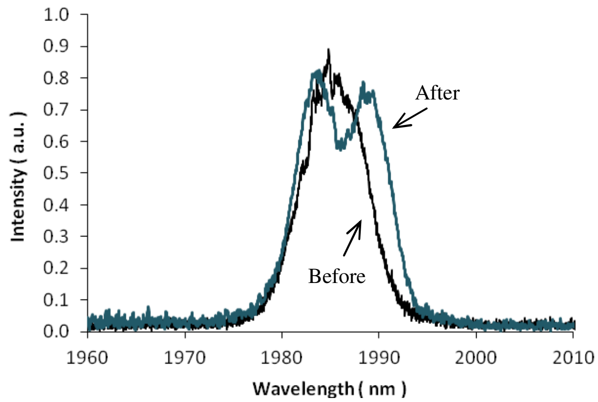

Fig. 3. Optical spectrum of seed laser before and after stretcher.

3. Two-stage amplifier

Output pulses from the seed laser were amplified in two-stage amplifier. Construction of both stages was similar, but in the first stage Tm doped double clad fiber with 6 µm core was used, while for the second stage we utilized 10 µm core fiber to decrease length and reduce nonlinear effects. The setup of the first stage amplifier is shown in Fig. 4. The gain medium was a 5 m-long Tm doped double clad fiber with a diameter of 6 µm. Maximum average power of 450 mW was measured after first stage with noticeable broadening of pulse spectrum at high level of pumping (Fig. 5). To minimize the effect of nonlinear spectrum deterioration the output power of the first stage was limited to 115 mW.

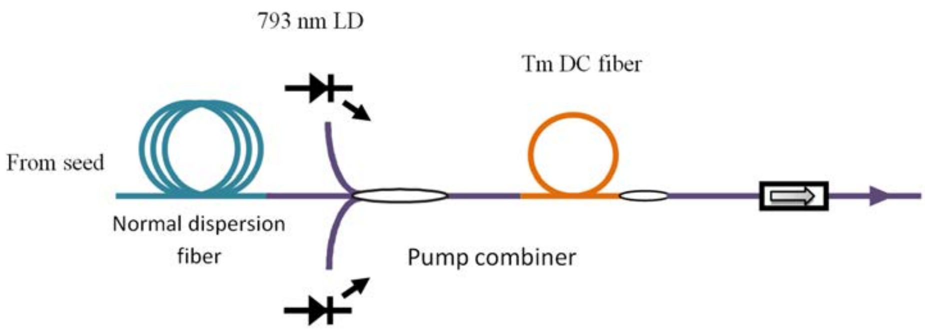

Fig. 4. First stage of amplification with pulse stretcher.

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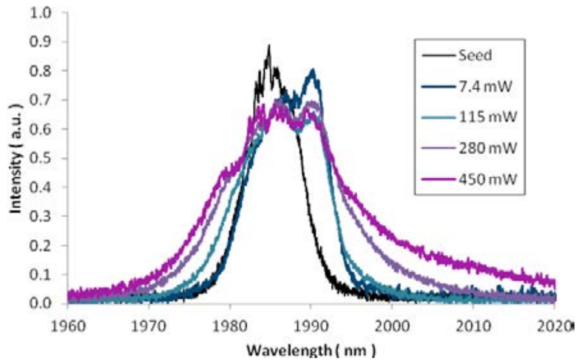

Fig. 5. Spectrum of pulses after first stage for different levels of output power.

The second stage of amplification was assembled in the similar way by using a 5.5 m-long Tm doped double clad fiber with a core diameter of 10 µm and a pump combiner with 6 pump inputs. Three multimode laser diodes provided total 7 W of pump power at 793 nm. In this experiment, we used only three pump diodes and left three pump inputs free for future enhancements. The second stage amplified the pulse train up to average power of 1.6 Watts or pulse energy of 0.65 µJ (Fig. 6).

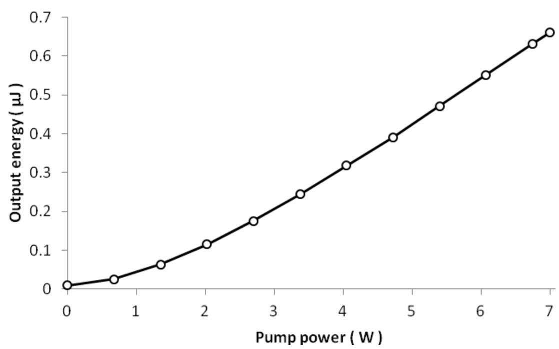

Fig. 6. Output pulse energy versus pump power of the second stage.

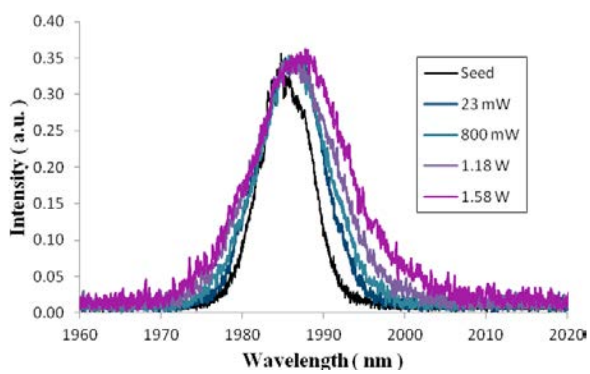

Fig. 7. Spectrum of output pulses.

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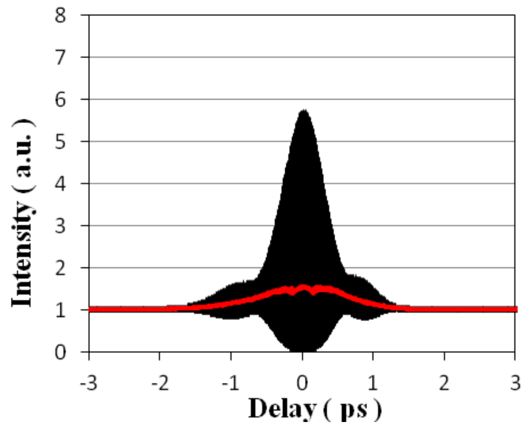

Fig. 8. Autocorrelation trace of compressed pulse.

Spectrum of output pulses was moderately broadened, but still acceptable for high quality compression (Fig. 7). Pulse spectrum can be improved by shortening of active fiber. For the second stage we used active fiber of excessive length for higher energy experiments. Further power increasing can be possible by using large mode area (LMA) fibers with 20-25 um core diameter and shorter lengths. Such a fiber can be used for pulse energies scaling to over 10 μJ. To test compression ability of amplified pulses, traditional two-pass compressor was built using two 830 lines/mm gold coated gratings. The compressed pulses had duration of 820 fs and quadratic chirp due to uncompensated third order dispersion (Fig. 8).

4. Conclusions

In conclusion, we demonstrated high energy mode locked laser at a wavelength of 2 μm. The laser consisted of femtosecond seed and a two-stage all-fiber amplifier. The seed laser generated pulse train at a repetition rate of 2.5 MHz and the amplifiers boost the pulse energy to 0.65 μJ with a compressed pulse width of 820 fs. This provides a breakthrough in developing a simple and low cost high energy fs fiber laser system. Further scaling the pulse energy is ongoing in PolarOnyx.

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