Short-wavelength-band tunable high-power Tm-doped fiber laser

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ABSTRACT

In this work, we realized broadly tunable mode-locking operation from 1730 nm to 1815 nm in normal dispersion regime employing an acousto-optic tunable fiber (AOTF) in a Tm-doped dispersion-managed fiber laser. The AOTF worked as a multifunctional component in laser cavity suppressing undesired wavelength lasing and introducing a frequency shifting, which improved the stability of laser operation. The hybrid mode-locking incorporated by nonlinear polarization rotation (NPR) effect and frequency shifting effect ensured self-starting stable pulsed operation. The pulse spectral widths ranged from 17 nm to 25 nm. The stretching-free direct amplification in two-cascaded fiber amplifier enabled power scaling up to 310 mW and pulse energy of 19 nJ. Pulse duration was compressed down to 282 fs by a pair of gratings. The seed laser is further optimized. The optimized seed laser enhances output power about 5 times. The laser system was designed for multiphoton imaging of bladder cancer in the third biological window to demonstrate the recently discovered nonlinear effect resulting in improvement of signal contrast at the deeper tissue level.

Keywords: mode-locking Tm-doped fiber laser, third biological window, multiphoton imaging

1. INTRODUCTION

The wavelength band of 1.7 μm-1.8 μm carriers enormous potential for laser-induced technology enabling the game change for a diverse list of applications (multiphoton bioimaging, gas sensing, polymer welding). Remaining undiscovered for many years, it has just recently attracted wide researchers' interest following up the very first success in the implementation of short-wavelength-band operation in Tm-doped fiber laser [1,2]. One of the biggest challenges for this wavelength range is a low gain coefficient in comparison to commonly studied wavelength band from 1.8 μm to 2 μm resulting in dominance of laser regime at longer wavelengths. Different methods have been put forward to suppress high gain at longer wavelengths in the short-wavelength-band operation, such as introducing bending loss and using spatial filter [3, 4]. In the early years, researchers focused on continuous-wave (CW) and single-frequency operation [5]. Later, the attention shifted towards the realization of the pulsed operation and wide tunability by using different approaches [6,7]. However, all demonstrated so far tunable Tm-doped mode-locked lasers were working at the conventional soliton regime. As a result, the output pulse energy is limited by the soliton area theorem and the soliton pulses are not suitable for further amplification due to the pronounced dispersive waves background. In this work, using a cavity incorporating both nonlinear polarization rotation (NPR) and frequency shifting mode-locking techniques, we realized a widely (1730 nm to 1815 nm) tunable Tm-doped fiber laser operating in normal dispersion regime with spectral width up to 25 nm. Positively highly chirped pulses were further directly amplified without stretching in a cascaded fiber-based amplifier resulted in an output power up to 310 mW, corresponding to a pulse energy of 19 nJ. Using a pair of grating, the pulse duration was compressed down to 282 fs.

2. EXPERIMENT AND RESULTS

The experimental setup is shown in Figure 1. Self-made master oscillator power amplifier (MOPA) at 1.55 μm was used as pump source. An acousto-optic tunable fiber (AOTF) was used as a versatile device in the cavity. It worked as a tunable spectral filter, polarizer and frequency shifter. At 1800 nm, the AOTF had a transmission bandwidth of ~12 nm. Frequency shifting effect applied by AOTF can stabilize the pulse generation additionally. Two quarter waveplates and one half waveplate inserted near AOTF control polarization evolution in the cavity and enabled NPR caused pulse generation. The free space coupling efficiency of diffracted +1 order light is ~70%. One fusion coupler with a splitting ratio of 20/80 coupled 20% power out of the laser cavity. 7.4 m DCF was used to shift the laser operation into a normal dispersion regime. The cavity is composed of ~11.7 m fiber and 30 cm free space. The estimated net cavity dispersion is $0.016 ps^2$.

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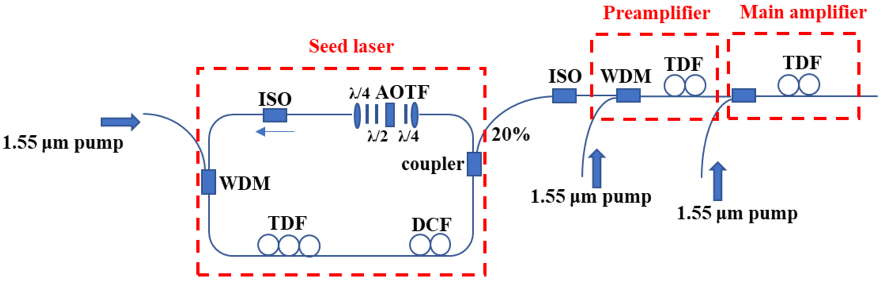

Figure 1. Experimental setup. WDM: wavelength division multiplexer; TDF: Thulium doped fiber; DCF: dispersion compensation fiber; AOTF: acousto-optic tunable filter; λ/4: quarter waveplate; λ/2: half waveplate; ISO: isolator.

By varying the driving frequency of AOTF, the laser wavelength was tuned from 1730 nm to 1815 nm, as shown in Figure 2(a), with average output power up to 3.7 mW and spectral full widths up to 25 nm. The seed signal was further amplified without stretching in two-cascade single-mode amplifier system built of commercial fibers. The Figure 2(b,c) showed an example of stretching-free amplification at 1780 nm with a maximum achieved output power of 310 mW. A pair of grating with a groove density of 1000 lines/mm was used to compress pulse after the main amplifier, resulting in a pulse duration of 282 fs with insignificant pulse distortion caused by nonlinearity (Figure 2c). Further power enhancement was limited the available pump power.

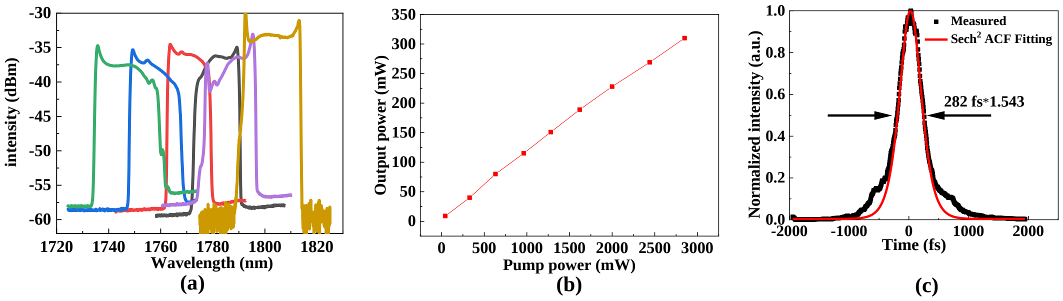

Figure. 2 (a) Output spectra from laser cavity in widely wavelength-tuning operation regime; (b) Power performance of main amplifier at 1780 nm; (c) Autocorrelation trace of compressed laser pulse.

We have optimized the seed laser by shortening the cavity length, tailoring net cavity dispersion and minimizing loss in the cavity. With a shortened cavity composing of 9.37 m fiber and 41.3 cm free space, an estimated net cavity dispersion of 0.0044 ps^2 and improved free space coupling efficiency of ~80%, the output power is enhanced by ~5 times. The wavelength tunability is shown in Figure 3(a). At 1780 nm, the output average power is 16.8 mW and the obtained spectrum has a full width of 33 nm. The spectra have wider full width. However, the spectra are more structed due to nonlinearity caused phase shift. By using the retrieved spectrum and phase generated by FROG measurement, we illustrate that the highly modulated spectral peak on the right edge of spectrum generates extended pulse wing, as shown in the filled part of Figure 3(b,c). The extended pulse wing inevitably deteriorates pulse quality and restricts pulse compressibility. Figure 3(d) shows the measured spectrogram and the retrieved spectrogram with a great agreement. Using a pair of grating with groove density of 711 lines/mm, the pulse duration at 1780 nm can be compressed to 282 fs, as shown in Figure 3(e). It is noteworthy that the pedestal is negligible.

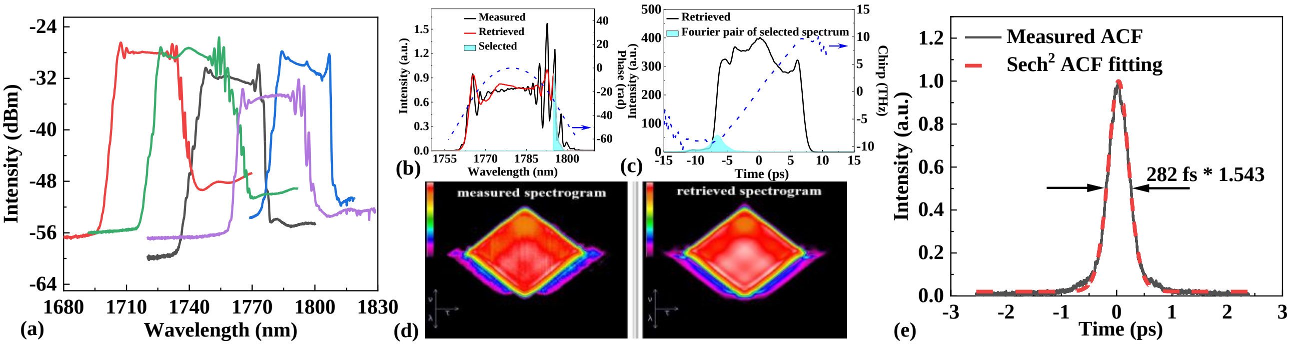

Figure. 3 Laser performance of the optimized cavity. (a) Wavelength tunability; (b) Measured spectrum and FROG retrieved spectrum with phase at 1780 nm; (c) Corresponding retrieved pulse profile with chirp; (d) Measured and retrieved spectrograms of FROG; (e) Measured autocorrelation figure (ACF) and hyperbolic ACF fitting of the compressed pulse.

3. CONCLUSION

In conclusions, we have demonstrated a widely tunable laser operated in normal dispersion regime in 1730-1815 nm wavelength range. The further stretching-free two-cascaded amplification of the seed pulses resulted in enhancement of the average power up to 310 mW with compressed pulsed duration down to 282 fs. The system has a great potentiality for further power scaling with a large-mode area fiber amplifier and more powerful pump sources. This laser operation will be explored for multiphoton imaging in the third-biological window with deep tissue penetration with high resolution.

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