All-Fiber Tm-Doped Frequency Shifted Feedback Laser

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Abstract: Ultra-simple all-fiberized 2 μm Tm-doped frequency shifted feedback mode-locked fiber lasers are demonstrated. The self-starting mode-locking is initiated by an intra-cavity acousto-optical frequency shifter. Versatile mode-locking pulse dynamics were observed by altering the pump power, cavity structure and intra-cavity polarization state, including picosecond single pulse sequence, pulse bundle state and nanosecond rectangular pulse. As short as 8 ps stable pulses and up to 12 nJ, 3 ns rectangular pulses were obtained with the aid of a nonlinear optical loop mirror. Beside the mode-locking operation, flexible Q-switching and Q-switched mode-locking operation can also be readily achieved in the same cavity. Up to 78 μJ high energy nanosecond pulse can be generated in this regime.

1 INTRODUCTION

In recent years, continuous wave as well as pulsed fiber lasers operating in the eye-safe 2 μm spectral region have attracted extensive attention owing to their numerous potential applications in areas such as remote sensing, medicine, mid-infrared frequency conversion, supercontinuum generation, and free-space communication. Various technologies have been explored in this region to produce pulses with diverse characteristics for the applications of different requirements, such as mode-locking, Q-switching and gain-switching. Generally, mode-locking is used to generate fs-ps ultrafast pulse and Q-switching and gain-switching are exploited to produce ns-μs high energy pulse. Currently, most passive mode-locking techniques exploited in the 2 μm region are based on saturable absorbers, which can be classified into two categories: real saturable absorbers and artificial saturable absorbers. The former is based on materials with saturable absorbing characteristics, such as traditional SESAM, carbon nanotube, Graphene, and various emerging low-dimension materials. The later mainly relies on the nonlinear optical effects, including nonlinear polarization rotation (NPR) and nonlinear optical loop mirror (NOLM). Although saturable absorber can also be utilized to initiate passive Q-switching operation, the performances and temporal tunabilities of passively Q-switched lasers are usually no match for actively Q-switched ones.

As far as we know, this technique has not been exploited in the 2 μm region yet. Tm-doped fiber laser can be an ideal platform for the realization of 2 μm FSF mode-locked laser. To thoroughly reveal the potential of FSF in 2 μm region, in this manuscript, we report the comprehensive investigation on all-fiberized 2 μm Tm-doped FSF mode-locked fiber laser. The characteristics of the laser were explored in two novel cavity constructions. Versatile mode-locking pulse dynamics and widely tunable Q-switching and Q-switched mode-locking operation were experimentally manifested and comprehensively analyzed.

2 EXPERIMENTAL SETUP

In the experiment, two structures were adopted to achieve mode locking based on FSF in 2 μm region. Both of them adopted the linear Fabry-Perot cavity structure, which included a fiberized AOM as the frequency shifter. The difference was that the first one was formed with a pair of fiber Bragg gratings (FBGs), while the other one was formed with an FBG and an NOLM as the cavity mirror and the additional saturable absorber. The schematic diagram of the FBG-pair-based structure is shown in Fig. 1. The FBG pair is centered at 1980 nm. The HR-FBG has a reflectivity of 99.1% and a 3 dB bandwidth of 1.3 nm. The LR-FBG has a reflectivity of 20% and a 3 dB bandwidth of 0.8 nm. A section of 2-meters-long single mode 9/125 Tm-doped fiber was employed as the gain medium. The core absorption coefficient is around 10 dB/m at 1570 nm, and the numerical aperture is 0.15. The pump light came from a 1.3 W 1570 nm home-made fiber laser. A 2000/1570 nm WDM was inserted between the pump source and the HR-FBG to prevent 2 μm backward light. The AOM frequency shifter was inserted between the gain fiber and the LR-FBG, which had frequency shift of 80 MHz and insertion loss of 2 dB. A matched 80 MHz radio frequency (RF) driver was employed to activate the AOM. The length of the passive fiber was carefully tailored to make the AOM's shift frequency (80 MHz) to be the integer harmonics of the inverse round-trip of the laser, which is a critical requirement to achieve mode-locking operation. In this case, the total cavity length was tailored to be ~6.45 m, corresponding to the fundamental cavity frequency of ~16 MHz (1/5 of the AOM's shift frequency). At the wavelength of 1980 nm, the cavity is abnormally dispersive, and the total cavity dispersion was estimated to be ~-0.98 ps2 at the wavelength of 1980 nm. It is a notable feature that this laser is all-fiber-integrated and compactly constructed, which is favorable in many practical applications.

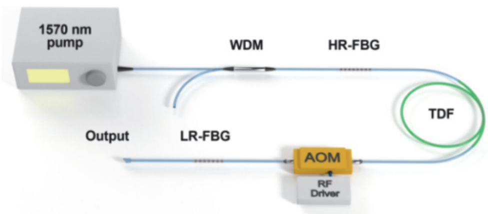

Figure 1: The schematic diagram of the FBG-pair-based FSF mode-locked fiber laser. TDF, thulium-doped fiber; WDM, wavelength division multiplexer; HR-FBG, high-reflectivity fiber Bragg grating; LR-FBG, low-reflectivity fiber Bragg grating; AOM, acousto-optical modulator; RF driver, radio frequency driver.

A commercial autocorrelator based on 2nd harmonic generation was used to measure the pulse width of output pulses with maximum measurable pulse width of 80 ps. A short Tm-doped fiber amplifier was employed to amplify the peak power of the output pulses to reach the measurement criterion of the autocorrelator. The optical spectrum was measured by a 1200 nm-2400 nm optical spectrum analyzer. The temporal characteristics were monitored with a 9 GHz InGaAs photodetector, a real-time oscilloscope (1.5 GHz bandwidth, 20 GSa/s sampling rate) and a 6 GHz radio frequency spectrum analyzer.

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

Stable single pulse mode locking could be instantly self-started from the CW regime upon the pump power was increased to around 200 mW. Single pulse operation can be maintained until the pump power was increased above 240 mW. Then the output pulse split to amplitude-even pulse bundle. Figure 2 depicts the measured temporal and spectral characteristics of the FSF mode-locked laser in the single pulse regime at the pump power of 220 mW. The output power of 7.4 mW was obtained at this pump power. Figure 2(a) shows the measured autocorrelation trace with a full width at half maximum (FWHM) of 37 ps. If a sech^2 pulse profile is assumed, the pulse width is 24 ps. The spectrum of the output pulse is shown in Fig. 2(b), which is centered at 1980 nm with a 3 dB bandwidth of 0.35 nm. Then the calculated time-bandwidth product of output pulse is 0.65, which is larger than the theoretical value for transform-limited sech^2 pulse indicating a small amount of negative dispersion in laser pulses. Figure 2(c) plots the measured pulse train with a time interval of ~62.5 ns between each pulses corresponding to a pulse repetition rate of 16 MHz, which corresponded to the estimated cavity round trip. The radio frequency spectrum measured in the span of 100 MHz (resolution bandwidth 100 Hz) is shown in Fig. 2(d). The signal-to-noise ratio of the RF spectrum is measured to be as high as 68 dB, indicating a high temporal stability. The measured autocorrelator trace and the RF spectrum manifested the single pulse operation. With the 16 MHz repetition rate and 7.4 mW average output

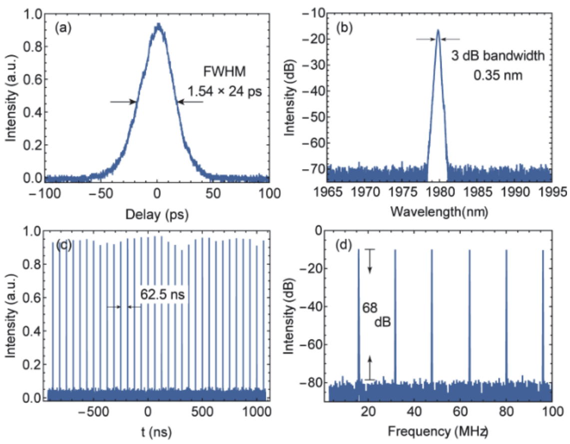

Figure 2: (a) The autocorrelator trace; (b) The optical spectrum; (c) The oscilloscope trace; (d) The RF spectrum of the output pulse under the pump power of 220 mW.

power, the pulse energy was calculated to be 0.46 nJ.

As mentioned above, limited by the peak power clamping effect, the output pulses were transformed from the single pulse state to pulse bundle state upon the pump power was increased to around 240 mW. With the increasing pump power, the number of the pulses in single pulse bundle increased accordingly, while the repetition rate of the pulse bundle remained at the fundamental frequency 16 MHz. Up to 5-pulse-bundle was formed with the pump power of 410 mW. In this case, the output average power reached 48 mW, and the corresponding energy of the pulse bundle is calculated to be 3 nJ. The inner pulse width is measured to be ~200 ps, which is limited by the bandwidth of the oscilloscope. The pulse intervals between the inner pulses are not quite stable, dither around 2.2 ns with a timing jitter of ~ 200 ps.

The various mode-locking regimes demonstrated above were based on the frequency shifting function of the AOM, where the modulator was not actually modulated. When the AOM is employed as the intra-cavity intensity modulator to switch the Q-factor of the cavity (i.e. the cavity loss), flexible Q-switching and Q-switched mode-locking operation can also be facilely achieved. In this case, the FBG-pair-based laser cavity was adopted and we used an electrical pulse generator to modulate the power of the RF driver which is linearly proportional to the insertion loss of the AOM. The repetition rate and duty cycle (laser on time/laser off time) of the modulation signal can be tuned in wide ranges, which will directly affect the characteristics of the Q-switched output pulses.

Under the modulation signal of large duty cycle (typically >50%, dependent on the repetition rate), the laser can produce Q-switched mode-locked pulses. Figure 3(a) shows the output pulse waveforms under the pump power of 1.1 W and the modulation signal of 100 kHz repetition rate, 60% duty cycle. The pulse has a Q-switched pulse envelope with 0.7 μs duration and 100 kHz repetition rate, and contains a train of ~30 mode-locked inner-pulses spaced at the laser cavity round-trip. There are also many noisy minor pulses filled in the spacing between the mode-locked inner-pulses. This phenomenon was also observed in Yb-doped FSF fiber laser (Heidt et al., 2007), as well as common Q-switched fiber lasers and gain-switched fiber lasers (Swiderski and Michalska, 2013, Eckerle et al., 2012). We believe this Q-switched mode locking regime is initiated by the combined effect of FSF and Q-switching (Heidt et al., 2007).

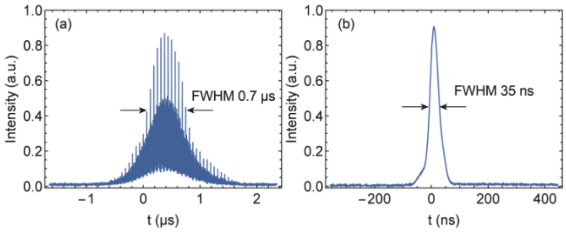

Figure 3: The oscilloscope traces of the output pulse waveforms (a) in Q-switched mode locking regime and (b) short pulse Q-switched regime.

The mode-locking sub-pulses can be eliminated by decreasing the duty cycle of the modulation signal until the laser-on time is less than the building time of the mode-locked pulses. Then the pulse waveforms become smooth and stable, indicating a regular Q-switching regime. In this regime, the repetition rate follows the modulation signal, and the pulse width is related to the repetition rate, the duty cycle and the pump power. With the repetition rate fixed at 1 kHz and the pump power at 1.1 W, the shortest pulse width 35 ns can be obtained with the duty cycle set at 1%, as depicted in Fig. 6(b). In this case, the output power reached 36 mW. The pulse energy was 36 μJ, and the peak power was nearly 1 kW. The highest pulse energy 78 μJ can be obtained under the duty cycle of 50%, and the corresponding pulse width was 47 ns, and the peak power was 1.65 kW. Under the highest pump power of 1.1 W, with the flexible adjustment of the modulation repetition rate and duty cycle, the repetition rate of the Q-switched pulses can be adjusted in a wide range (from 1 kHz to >500 kHz) and the pulse duration can be tuned from 35 ns to 770 ns.

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