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Wavelength-Tunable Mode-Locked Thulium-Doped Fiber Laser Based on Nonlinear Amplifying Loop Mirror

Xiaoling Peng [1, a,] *,Shihai Zhang, Lingyu Zhu[1] and Yutao Yan[1]

Department of Electronic Information Engineering, Leshan Vocational and Technical College, Sichuan, China

[a]978934326@qq.com

Abstract: In this paper, a wavelength-tunable mode-locked thulium-doped fiber laser based on nonlinear amplifying loop mirror is reported. When the pump power is continuously increased, the center wavelength can be adjusted from 1992.86 to 2003.06nm, and the maximum 3dB bandwidth is 18.28nm. The repetition frequency of both the time domain waveform and the spectrum is 5.32MHz, which is consistent with the theoretical value. And the pulse signal-to-noise ratio reaches 60dB, indicating that the mode-locked fiber laser has good stability. In addition, the maximum single pulse energy reaches 64.2nJ, which is much larger than that of the traditional negative dispersion mode-locked fiber laser.
Keywords: nonlinear amplifying loop mirror; thulium-doped fiber laser; wavelength tunable.

1. INTRODUCTION

Compared with solid-state lasers, fiber lasers have the characteristics of good heat dissipation, simple structure, high light-to-light conversion rate and high stability [1]. Therefore, fiber laser is widely used in various fields such as industrial processing, laser surgery, photoelectric countermeasures and radar sensing [2, 3]. In recent years, 2μm thulium-doped fiber lasers have been extensively studied at home and abroad. Compared with 1μm and 1.5μm short wavelength band, 2μm band of thulium-doped fiber laser research starts late, detection technology and manufacturing process is not yet mature, and the mainstream technology is in foreign countries, so there are a few studies on the 2μm mode-locked thulium-doped fiber laser in China. At present, the mode-locking technology of 2μm fiber laser mainly focuses on two major aspects: real saturable absorbers and artificial saturable absorbers [4]. Compared with the real saturable absorber, the nonlinear amplifying loop mirror (NALM) of the artificial saturable absorber is simple in structure and easy to operate. Since there is no material limitation, it can withstand higher damage threshold and realize full all-fiber structure.

In 2013, Rudy et al. reported an amplified “8” cavity mode-locked thulium-doped fiber laser, and obtained mode-locked pulses with a pulse width of 1.5ps, single-pulse energy of 63pJ, repetition frequency of 10.4MHz, spectral bandwidth of 3nm and central wavelength of 2034nm [5]. In 2015, Jin et al. from the national university of defense technology reported that NALM thulium holmium co-doped mode-locked fiber laser. By adjusting the polarization state, a large range of tunable three-wavelength mode-locked pulses with tunable wavelength ranging from 1935 to 1965nm can be obtained, with a repetition frequency of 6.1MHz and a pulse width of nanoseconds [6]. In 2016, lauterio-cruz et al. of the Mexican optical research center reported that the NALM double-clad erbium-ytterbium co-doped fiber laser, and obtained noise-like mode-locked pulses with a single-pulse energy of 300nJ, a 3dB spectral bandwidth of 18nm and a red shift in the spectrum [7]. In 2018, wang et al. reported the thulium holmium co-doped fiber mode-locked laser based on NALM, and obtained multi-soliton mode-locking pulses with a central wavelength of 1923.21nm, a spectral bandwidth of 1.03nm, and a slope efficiency of 0.7% [8].

In this paper, SMF-1950 fiber with low loss transmission is adopted to ensure that the laser can accumulate enough nonlinear phase shift difference in the resonator cavity to obtain stable mode-locking pulse. When the pump power is continuously increased, the wavelength adjustable range is 1992.86~2003.06nm, the 3dB bandwidth is above 15nm, and the maximum bandwidth reaches 18.28nm, the maximum single-pulse energy reaches 64.2nJ, which is far greater than the energy of traditional negative dispersion mode-locked fiber laser. In addition, the repetition frequency is 5.32MHz, and the pulse signal-to-noise ratio (SNR) reaches 60dB, indicating that the mode-locked fiber laser has good stability.

2. EXPERIMENTAL SETUP

The schematic diagram of the experimental device of the NALM mode-locked thulium-doped fiber laser is shown in figure 1. The ring loop on the left is an NALM, and the ring loop on the right is a unidirectional loop. The left and right ring loops are connected by a 50:50 four-port coupler (OC) to form an "8" cavity structure. A 4.5m long single mode double cladding thulium-doped fiber (TDF) is used as the gain medium. The gain fiber is pumped by a fiber-pigtailed 793 nm laser diode (LD) via a (2+1)×1 signal-pump combiner. A 20-meter long SMF-1950 single-mode fiber made by Nufern is also added to the left loop. The central wavelength of SMF-1950 fiber is 1950nm. Compared with other ordinary single-mode fiber, it has lower transmission loss and bending loss in the 2-μm band, which can further reduce the loss of fiber laser. The isolator (ISO) is added in the right ring loop to make the signal light transmit in one direction, so as to eliminate the backscattered light wave in the ring loop. The coaxial polarization controller (PC) is also added in the right ring to adjust the polarization state. In addition, the cavity length of the entire laser resonator is about 38.6 meters. Since the dispersion value of the gain fiber and other single-mode fiber is negative at the 2-μm band, the net dispersion value of the entire resonator is negative, and the laser works in the anomalous dispersion region.

The output characteristics of the fiber laser mainly use spectrum analyzer (Yokogawa; AQ6375B), 1GHz digital oscilloscope (Teledyne Lecroy; WaveRunner610Zi), 3GHz spectrum analyzer (Rohde & SchwarzFSL3) and 12.5GHz high-speed photodetector (EOT ET-5000F).

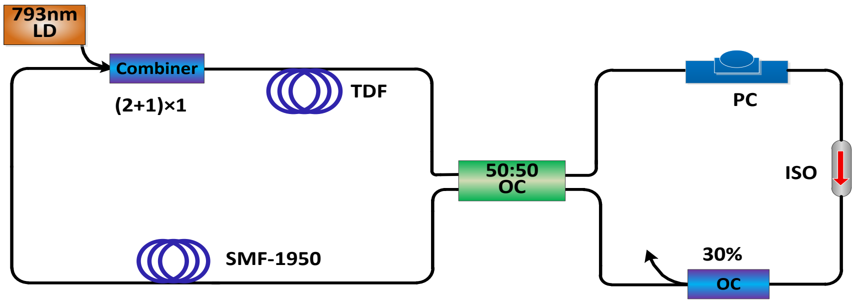

Figure 1 Schematic diagram of experimental device for NALM mode-locked thulium-doped fiber laser

3. EXPERIMENTAL RESULTS

In the experiment, when the pump power was increased to 1.3 W, the self-starting continuous wave was realized by slightly adjusting the PC. Then continue to increase the pump power to get a stable mode-locked pulse. Figure 2(a) shows the mode-locked pulse train with a cavity round-trip time of 187.97 ns, that is, the repetition frequency of the mode-locked pulse is 5.32 MHz. Figure 2(b) is a time-domain pulse sequence diagram over a wide range (50μs), and it can be seen that the pulse waveform is flattened without a modulation phenomenon or missing portion in the wide range. Moreover, it is found that when the pump power is continuously increased, the repetition frequency remains unchanged, only determined only by the cavity length, which is a typical mode-locked pulse phenomenon.

As shown in Figure 3, when the pump power is different, the 3dB bandwidth of the spectrum has normal fluctuations, but the 3dB bandwidth is above 15nm, and the maximum bandwidth is 18.28nm, which is much larger than the traditional soliton mode-locking. Compared with the traditional soliton mode-locking, the 3dB bandwidth of the noise-like mode-locked pulse is larger, and the smooth spectrum and the wide 3dB bandwidth are typical characteristics in the noise-like mode-locking [9]. In addition, it was found in the experiment that increasing the pump power, the wavelength appears tunable. That is, the center wavelength shifts toward the long wavelength direction as the pump power increases. As shown in Figure 3 (a), (b), (c) and (d), the spectrum is obtained when the pump power is 2.50, 5.50, 8.00, and 12.00 W, respectively. The corresponding center wavelength is 1992.86, 1995.89, 1998.25, 2003.06nm, and their corresponding 3dB bandwidth are 16.13, 15.92, 16.72, 17.18nm.

In order to explore the stability of the mode-locked fiber laser, the fiber laser was tested with a spectrum analyzer. Figure 4(a) shows the fundamental frequency of the mode-locked pulse with a scan accuracy of 1 kHz. It can be seen that the repetition frequency is 5.32MHz, which is consistent with the results measured by the oscilloscope. In general, it should be noted that the noise-like mode-locking pulse stability is not very good, and its SNR is mostly 40~50dB. However, in this paper, the SNR is as high as 60dB, indicating that the fiber laser has good stability. A noise-like mode-locked pulse with a high SNR is also reported in reference [10], but it studies the nonlinear optical loop mirror structure, which is somewhat different from this paper. Figure (b) is a radio frequency (RF) diagram with a scan range of 500MHz. It can be seen that the fundamental and harmonic spectral components have high signal-to-noise ratios, and there is no modulation phenomenon, indicating that the laser operates in a stable mode-locked state.

The average output power of the NALM fiber laser was tested with an optical power meter at room temperature. As shown in Figure 5, the laser pumping threshold is 1.30W. As the power continues to increase, the average output power of the laser increases linearly. When the pump power is 12.00W, the maximum average output power is 341.3mW. From the average output power and repetition frequency, the maximum single pulse energy can be calculated to reach 64.2 nJ, which is much larger than the traditional negative dispersion mode-locked fiber laser.

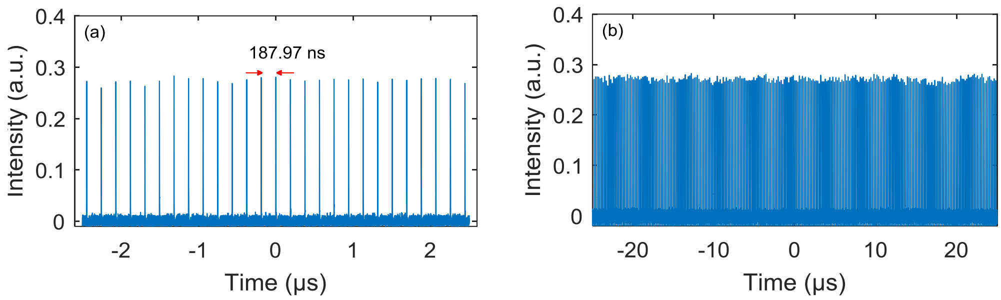

Figure 2 Oscilloscope trace of the pulse-train. (a): mode-locked pulse sequence diagram. (b): mode-locked pulse sequence diagram within 50μm

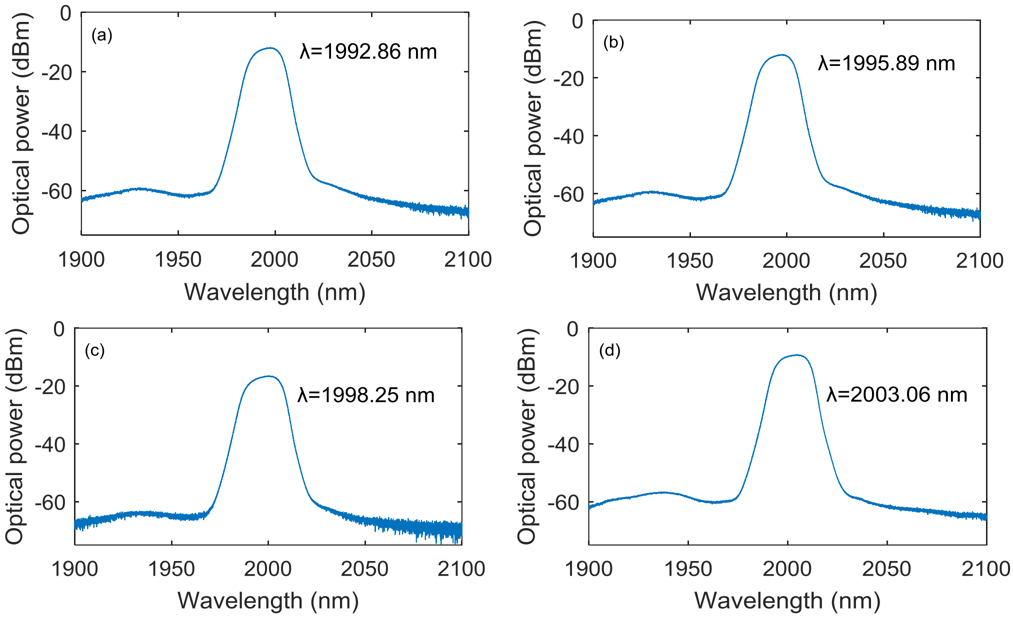

Figure 3 Optical spectrum at different pump powers. (a): pump power is 2.50W. (b): pump power is 5.50W. (c): pump power is 8.00W. (d): pump power is approximately 12.00W

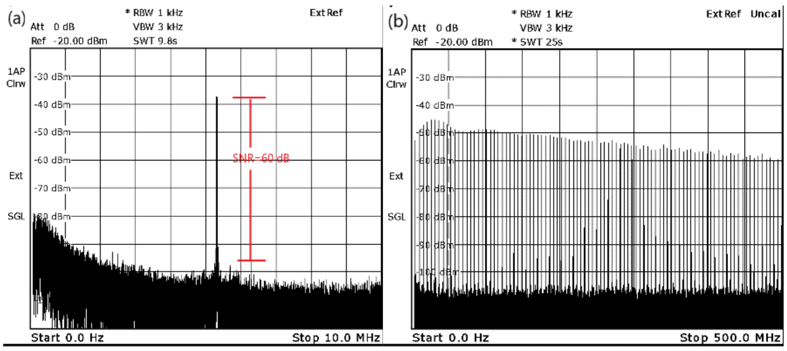

Figure 4 RF diagram. (a): base RF spectrum. (b) RF spectrum with a span of 500 MHz

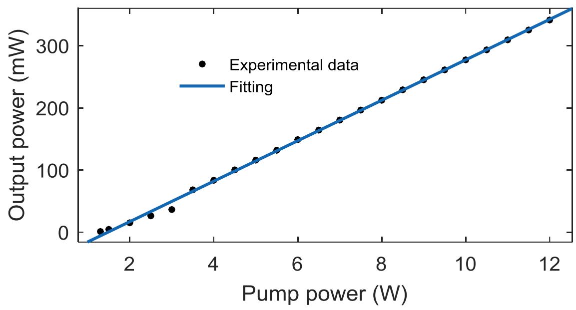

Figure 5 Average output power versus pump power

4. CONCLUSION

In this paper, a high stability wavelength-tunable NALM mode-locked thulium-doped fiber laser is reported. The SNR of mode-locked pulse reaches 60dB, and the repetition frequency is 5.32MHz which is consistent with the theoretical value. When the pump power is increasing, the spectrum appears red-shifted, and the wavelength can be adjusted from 1992.86 to 2003.06nm. The maximum 3dB bandwidth reaches 18.28nm, which is much larger than the traditional soliton mode-locking. And the spectrum is very smooth, which is typical of noise-like mode-locking. And the maximum single pulse energy reaches 64.2nJ, which is much larger than that of the traditional negative dispersion mode-locked fiber laser.

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