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Tunable and switchable thulium-doped fiber laser utilizing Sagnac loops incorporating two-stage polarization maintaining fibers

Wei He, Lianqing Zhu *, Mingli Dong, Fei Luo

Beijing Engineering Research Center of Optoelectronic Information and Instruments, Beijing Information Science and Technology University, Beijing 100192, People's Republic of China

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A B S T R A C T

A ring cavity thulium-doped fiber laser incorporating a Sagnac loop is proposed and experimentally demonstrated. In the designed fiber laser, a 0.4-m-long thulium-doped fiber is selected as the gain medium; the Sagnac loop is composed of two-stage polarization maintaining fibers of lengths 1 m and 2 m, respectively; and one broadband reflection mirror is used as the wavelength reflector. In the experiment, the lasing threshold is 135 mW, and by adjusting the polarization controller, a tunable and stable single-wavelength laser can be realized. The line interval is less than 3 nm within 1832–1865 nm, the power difference of each line is less than 1.111 dB, and the side-mode suppression ratio is larger than 44.7 dB. When 1848.4 and 1846.4 nm single-wavelength lasers are realized, the peak power fluctuation is less than 0.18 dB and 0.206 dB, respectively, within 10 min of scan time. A tunable and stable dual-wavelength laser can be realized by adjusting polarization controller; the power difference is less than 3.68 dB, and the side-mode suppression ratio is more than 35.04 dB. When 1844 and 1863.2 nm lasers are obtained simultaneously, the power shift is less than 0.6 dB and 0.95 dB, respectively, at room temperature. By changing the polarization state, tunable triple-wavelength lasing can be achieved ultimately, and the side-mode suppression ratio is larger than 41 dB.

1. Introduction

Multi-wavelength thulium-doped fiber lasers (TDFLs) exhibit important advantages, including narrow linewidth, flexible tuning ability, stable function, high signal-to-noise ratio, and compact structure, and have therefore attracted considerable attention in fields such as fiber communications, optical sensors, optical detection, spectrum analysis, and biomedicine [1–6]. Some techniques for realizing multi-wavelength fiber lasers have recently been reported. In 2015, Gong et al. [7] reported a tunable multi-wavelength TDFL based on the Sagnac loop; the pump wavelength of the proposed TDF was 1.57 μm, and a tunable one-, two-, three-, and four-wavelength fiber laser was realized. Huang et al. [8] reported an all-fiber multi-wavelength TDFL incorporating the Sagnac loop and a germania-doped fiber. In the designed laser, 36 lasing lines with wavelength spacing of 0.86 nm could be achieved, and power fluctuation was less than 1.6 dB. Liu et al. [9] designed a multi-wavelength TDFL incorporating the Sagnac loop and an all-fiber phase modulator, and this laser could achieve ten lines within a 15-dB bandwidth of wavelengths from 1982 to 1998 nm. In 2014, Zhang et al. [10] realized an all-fiber multi-wavelength TDFL using a Mach–Zehnder interferometer, in which stable four-wavelength lasing was achieved and power fluctuation was less than 1 dB. Ma et al. [11] designed a tunable multi-wavelength TDFL based on a multimode interference filter with large no-core fiber; for the proposed TDFL, the tuning range was 45.18 nm and the side-mode suppression ratio was more than 40 dB. In 2013, Peng et al. [12] reported a multi-wavelength TDF based on a nonlinear amplifier loop mirror, and 42 lines with wavelength spacing of 0.33 nm within 10-dB bandwidth were simultaneously realized. Saidin et al. [13] reported an all-fiber, switchable, dual-wavelength thulium–bismuth codoped fiber laser using a single fiber Bragg grating (FBG); in the proposed fiber laser, the wavelength spacing was 0.89 nm and the signal-to-noise ratio was more than 45 dB.

As mentioned above, multi-wavelength TDFLs could be realized by various methods including nonlinear amplifier loops, Mach–Zehnder interferometers, Sagnac loops, and frequency mixing technology. Thus, it would be valuable to research simple and efficient methods for realizing stable and tunable multi-wavelength TDFLs. In the paper, a multi-wavelength ring cavity TDFL based on the Sagnac loop incorporating two-stage polarization-maintaining fibers (PMFs) was realized. In the proposed laser, tunable and stable single- and dual-wavelength lasers

* Corresponding author.
E-mail address: zhulianqing@sina.com (L. Zhu).

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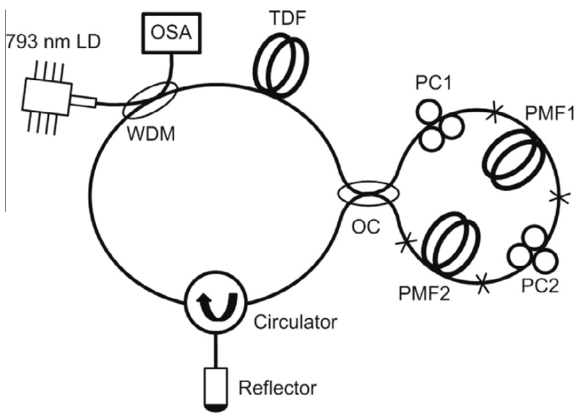

Fig. 1. Schematic diagram of the TDFL.

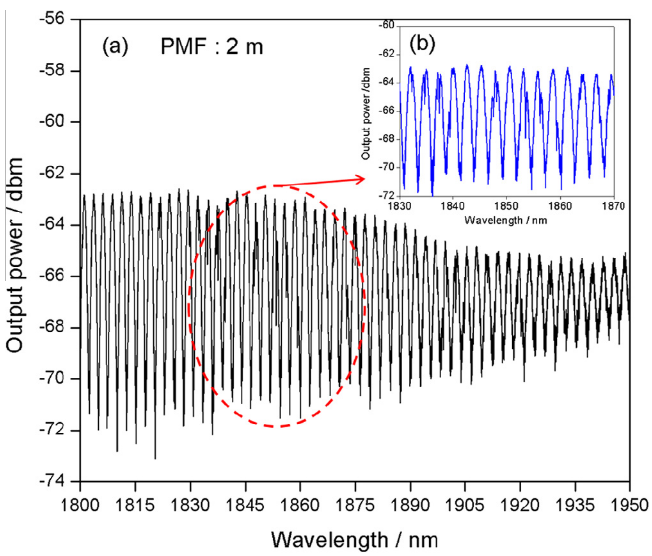

Fig. 2. Comb spectrum when single PMF was used. (a) Within 1800–1950 nm; (b) within 1830–1870 nm.

were realized, and a tunable triple-wavelength laser could also be obtained.

2. Experimental setup

The experimental diagram of the proposed TDFL is presented in Fig. 1. The designed laser was composed of a pump source, TDF, wavelength division multiplexer (WDM), 3-dB coupler, PMF, circulator, polarization controller (PC), and broadband reflection mirror (BRM). The pump wavelength was 793 nm, the pump light was coupled into the TDF by the WDM, and a 0.4-m-long TDF was selected as the gain medium. The Sagnac loop was composed of a two-stage PMF, an optical coupler (OC), and two PCs. PMF1 and PMF2 were both the same panda PMF of lengths 2 m and 1 m, respectively. The BRM connected to the circulator served as the wavelength selector. The optical spectrum analyzer (OSA) connected to the WDM was used to collect the output laser. As shown in Fig. 1, the comb filter effect could be realized by adjusting the PC, after splicing the Sagnac loop in the ring cavity. When the one-stage PMF was used in the Sagnac loop, the comb spectrum wavelength spacing can be calculated by Eq. (1), where λ is the transmission wavelength, Δn is the birefringence, and L represents the PMF length. The wavelength interval $\Delta\lambda$ is inversely proportional to L. By using cascaded PMFs, when optimum fiber length proportion of PMF1 and PMF2 is 2:1, the maximal side mode suppression ratio (SMSR) of Sagnac loop transmissivity is realized. When the two-stage PMFs were inserted into the Sagnac loop, a prominent adjusting effect could be obtained. For the proposed two-stage Sagnac filter, the filter design methods can be expanded, a greater filtering effect can be achieved, and more accurate tuning ability can be realized.

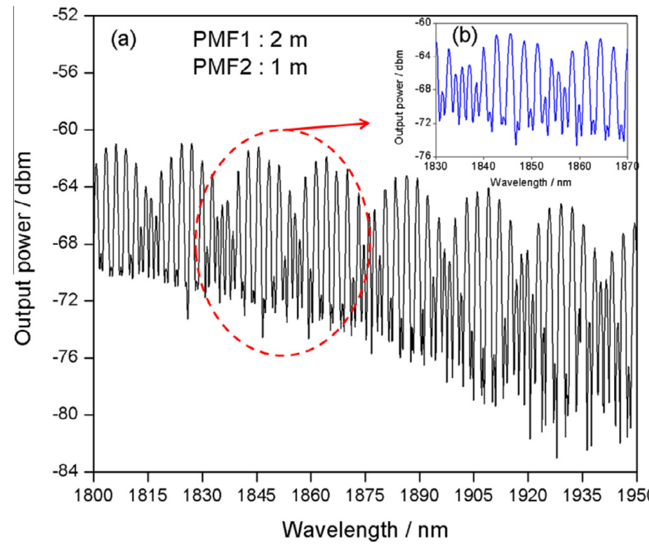

Fig. 3. Comb spectrum when two-stage PMFs was used. (a) Within 1800–1950 nm; (b) within 1830–1870 nm.

$$\Delta\lambda = \frac{\lambda^2}{\Delta n L} \quad (1)$$

3. Experimental results and discussion

In the experiment, the center wavelength of the pump laser (Lumics) was 793 nm, and the maximum output power was 250 mW. The absorption coefficient of the TDF (SM-TSF-9/125, Nufern) was 27 dB/m. The circulator, the 2×2 WDM, and OC were manufactured by Advanced Fiber Resources (AFR) Co. First, the comb filter spectrum of the Sagnac loop was measured. As shown

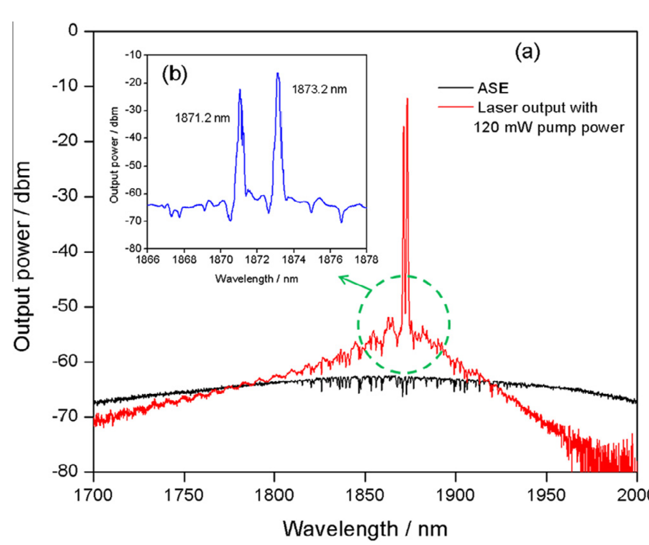

Fig. 4. Output spectrum without Sagnac loop. (a) Within 1700–2000 nm; (b) within 1866–1878 nm.