Optical Fiber Technology 22 (2015) 52–55

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Multiwavelength thulium-doped silica fiber laser incorporating an all-fiber phase modulator

Shuo Liu, Fengping Yan *, Ting Feng, Wanjing Peng, Xiao Liang, Yan Bai

Key Lab of All Optical Network & Advanced Telecommunication of EMC, Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China

ARTICLE INFO

Article history:
Received 12 June 2014
Revised 17 September 2014
Available online 24 January 2015

Keywords:
Thulium
Multiwavelength fiber laser
Phase modulator

ABSTRACT

A novel multiwavelength thulium-doped silica fiber laser incorporating an all-fiber phase modulator is first presented in 2 μm band. In the laser cavity, a phase modulator with a modulation frequency is efficient and beneficial to overcome the mode competitions. A polarization maintaining fiber Sagnac loop mirror is used as the filter. Large number of lasing wavelengths can easily and conveniently obtained at a proper modulation frequency under room temperature. The fiber laser can achieve ten output channels within a 15 dB bandwidth from 1982 nm to 1998 nm.

1. Introduction

Thulium-doped fiber laser (TDFL) has attracted great research interest because it can operate in the eye-safe 2 μm band. Different kinds of TDFLs have been proposed by using different techniques in the recent years. Yang et al. reported a linearly polarized TDFL. This fiber laser was set up by using a 5 m polarization maintaining double cladding thulium-doped fiber (TDF) as the gain medium and a polarization beam splitter as a polarization selector [1]. Employing polarization maintaining TDF, Wang et al. proposed a tunable multiwavelength fiber laser based on polarization rotation and four-wave mixing effects [2]. Using a 1908 nm TDFL as an in-band pump source, Creeden et al. obtained 1.43 W output power at 2005 nm with 81.25% optical efficiency and 90.2% slope efficiency [3].

As for most potential applications, multiwavelength fiber laser sources have been studied significantly in recent years. At room temperature, different approaches have been used to demonstrate multiwavelength operation. Pinto et al. proposed different multiwavelength Raman fiber lasers. The random mirrors were created by cooperating Rayleigh scattering in the dispersion compensating fiber as a result of the high Raman gain [4]. Nasir et al. demonstrated a tunable multiwavelength Brillouin-erbium fiber laser. The optimization of the Brillouin pump wavelength position within the bandwidth of the self-lasing cavity modes was important to achieve the maximum stable output channels [5]. F. Xin huan et al. achieved a switchable multiwavelength erbium-doped fiber laser (EDFL). The multiwavelength operation at room temperature can be achieved by employing a highly nonlinear photonic crystal fiber to induce four-wave mixing effects [6]. The comb filters, such as two cascaded different-length long-period fiber gratings [7], a polarization maintaining fiber Sagnac loop mirror (PMF–SLM) and sampled chirped fiber Bragg grating [8], are used to achieve switchable and widely tunable multiwavelength fiber laser. Yin et al. demonstrated a stable multiwavelength EDFL using a nonlinear optical loop mirror and a twin-core fiber-based Mach–Zehnder interferometer [9]. Meng et al. studied an adjustable double-cladding Yb^{3+}-doped fiber laser using a double-pass Mach–Zehnder interferometer [10].

A implemented technique for achieving stable multiwavelength output is to add an phase modulator to the laser ring cavity to prevent the homogeneous line broadening of the gain media and gain competition among the various lasing modes excited with narrow-wavelength spacing [11]. A stable multiwavelength lasing at room temperature was realized by incorporating a semiconductor optical amplifier based on the phase modulator in the laser cavity [12]. Ahmed et al. presented a stable multiwavelength EDFL by means of the phase modulator in a linear cavity configuration. The stable multiwavelength lasing was achieved by applying any one of the waveforms of sine, square, saw-toothed, and triangular at a suitable frequency between 500 Hz to a few tens of kHz to the phase modulator [13]. Sun introduced self-lasing feedback in conventional phase-modulation-based multiwavelength fiber ring lasers, in which the number of lasing lines was increased and the differences among the lasing lines were diminished [14]. Luo et al. demonstrated a tunable and switchable multiwavelength EDFL. In this fiber laser, a phase modulator composed of a 4 m long single mode fiber (SMF) wrapped around a cylindrical piezoelectric

* Corresponding author.
E-mail address: fpyan@bjtu.edu.cn (F. Yan).

http://dx.doi.org/10.1016/j.yofte.2015.01.001
1068-5200/© 2015 Published by Elsevier Inc.

transducer (PZT), which has a resonant frequency of 23 kHz, was used to suppress the mode competition [15]. However, this method in continuous wave TDFL has not yet been reported.

In recent years, we have reported different techniques to achieve multiwavelength TDFLs [16,17]. These multiwavelength TDFLs all used a PMF–SLM as the filter, but one multiwavelength TDFL used a nonlinear polarization rotation to overcome the mode competition, the other one used a nonlinear amplifier loop mirror to overcome the mode competition. However, these methods are not satisfactory because the SMF has high loss and a low nonlinear coefficient at 2 μm band, so a high power density and a highly nonlinear fiber must be used to provide high nonlinearity. In this paper, a multiwavelength TDFL incorporating an all-fiber phase modulator is proposed and demonstrated. A phase modulator was used to overcome the mode competitions and a PMF–SLM was used as the filter. The all fiber phase modulator simplifies the fiber laser structure with low insertion loss. By adjusting the polarization controller (PC) properly, a stable multiwavelength lasing with a suitable modulation frequency applied to the phase modulator was achieved at 2 μm band.

2. Experimental setup of the proposed fiber laser

The experimental schematic of the proposed multiwavelength TDFL incorporating an all-fiber phase modulator is shown in Fig. 1A 5 m commercial double cladding TDF is used as the gain medium. The active fiber has the core diameter of 6.3 μm, the inter cladding diameter of 125 μm and the absorption is 1.4 dB/m at 793 nm. The TDF is pumped by a 793 nm pump laser diode (LD) with the maximum output power of 12 W through a 793/2000 nm fiber combiner (FC). The phase modulator is composed of a 5 m long SMF wrapped around a cylindrical PZT, which was driven by a signal waveform supplying by a waveform generator (33120A, Agilent) with tunable driving voltage, modulation waveform, and frequency. A PMF–SLM filter consists of a 50:50 coupler, a PC and a segment of PMF. A 90:10 coupler is used to provide 10% power for the laser output and 90% for the feedback inside the cavity. The laser output is monitored by an optical spectrum analyzer (YOKOGAWA AQ6375, OSA) with a resolution of 0.05 nm.

Fig. 2 shows the transmission spectrum of the PMF–SLM filter. In the measurement, a supercontinuum laser (Koheras Co., SuperK) is used as a polarized white-light source. The wavelength spacing is determined by:

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

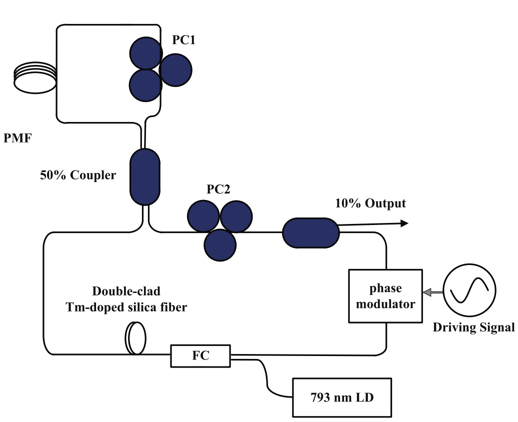

Fig. 1. The experimental setup of the proposed multiwavelength TDFL.

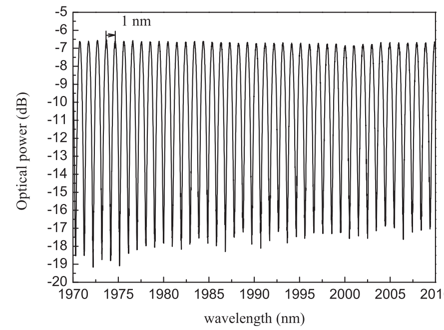

Fig. 2. The transmission spectrum of the PMF–SLM filter.

where λ is the wavelength, Δn is the birefringence and the L is the length of the PMF. We can see that the wavelength spacing of the PMF–SLM filter is inversely proportional to the birefringence and the length of the PMF. The PMF length of 5 m is corresponding to an adjacent wavelength spacing of 1 nm as shown in Fig. 2. By adjusting the PC in front of the PMF, the reflectivity of the PMF–SLM filter can be changed.

3. Experimental results and discussion

In order to achieve a multiwavelength TDFL, a phase modulator driven by the electrical signal was used to overcome the mode competitions and a PMF–SLM was used as the filter. In the experiment the pump power was fixed at 1.75 W. Figs. 3(a) and (b) show the spectra of multiwavelength operation after and before we added a modulation signal applied to the phase modulator, respectively. As shown in Fig. 3(b), without a modulation signal applied to the phase modulator, five lasing wavelengths with the optical signal-to-noise ratio (OSNR) of close to 40 dB are in operation, but the multiwavelength lasing operation could not be stable in wavelength even through by carefully adjusting the polarization state of both PC1 and PC2. That is due to the homogeneous line broadening in the TDF at room temperature and the strong mode competitions in the laser cavity. When the phase modulator was driven by a certain signal waveform, and the polarization state of both PC1 and PC2 were adjusted appropriately, a stable multiwavelength oscillation was obtained. Fig. 3(a) shows the stable multiwavelength oscillation measured by the OSA. The phase modulator with a modulation frequency of 9.27 kHz was applied in the experimental setup, and the output voltage of the waveform generator was changed to 4 V. As shown in Fig. 3(a), ten output channels was achieved within a 15 dB bandwidth from 1982 nm to 1998 nm. The channel spacing of the multiwavelength fiber laser is 1 nm, which is determined by the used PMF–SLM filter. The maximum OSNR is approximately 37 dB.

To study the stability of the laser output, the optical spectrum was measured over 60 min with an interval of 10 min, as shown in Fig. 4. During the measurement, any component in the laser system was not adjusted. No obvious fluctuations of wavelengths and output power are observed as shown in Fig. 4(a)–(f). This indicates that the fiber laser incorporating a phase modulator and a PMF–SLM filter could steadily operate in multiwavelength state at room temperature.

To investigate the output power fluctuation further, the output power variations of the six wavelengths at 1987.42 nm, 1988.42 nm, 1989.42 nm, 1990.42 nm and 1991.42 nm, are presented in Fig. 5. For all the six wavelengths lasing, the output power relative fluctuation is less than 20%. This little output power variation of the lasing can be ascribed to mode competition and hopping during the lasing. We also studied the spectrum of the multiwavelength operation with the different pump powers. In