OPTOELECTRONICS LETTERS Vol.10 No.6, 1 November 2014

A switchable dual-wavelength erbium-doped fiber laser based on saturable absorber and active optical fiber ring filter*

ZHU Lian-qing (祝连庆)[1], CHEN Qing-shan (陈青山)[1], ZHAO Ran-ran (赵冉冉)[1], LOU Xiao-ping (娄小平)[1], and HE Wei (何巍)[1,2]**

1. Beijing Key Laboratory of Optoelectronic Measurement Technology, Beijing Engineering Research Center of Optoelectronic Information and Instrument, Beijing Information Science & Technology University, Beijing 100192, China

2. School of Instrument Science and Optoelectronics Engineering, Hefei University of Technology, Hefei 230009, China

(Received 19 September 2014)

A dual-wavelength erbium-doped fiber laser (EDFL) with outstanding stability is presented. In the fiber laser system, two nested active optical fiber ring filters are configured to improve the comb spectrum performance, a saturable absorber is employed to form a gain grating for both filtering and frequency stabilizing, two cascaded fiber Bragg gratings (FBGs) are utilized to achieve dual-wavelength output, and a variable attenuator is arranged to adjust output power. Experimental results illustrate that the peak wavelength drift is less than 3 pm, and a good linear relationship between output power and pump power is realized.

Document code: A **Article ID:** 1673-1905(2014)06-0434-5

DOI 10.1007/s11801-014-4166-8

Dual-wavelength erbium-doped fiber laser (EDFL) can be widely used in such applications as optical fiber sensing, optical testing, optical fiber communication and wavelength division multiplexing (WDM)[1-4] because of its advantages[5-8]. J. H. Han et al[9] use two fiber Bragg gratings (FBGs) with different center wavelengths to achieve double-wavelength output, whose wavelength spacing is within 1 nm, but as a result of the wide reflection spectrum of fiber grating, the longitudinal mode of the laser output is relatively dense, which affects the stability of the laser output[10]. D. S. Moon et al[11] put two FBGs into a Sagnac loop, so as to improve the stability of the cascaded grating dual-wavelength laser. X. Liu et al[12] adopt a comb filter composed of two cascaded long period fiber gratings with different lengths to stabilize the laser output. On the basis, a variety of filtering and frequency stabilizing structures, for example, compound cavity[13], saturable absorber (SA)[14,15], Fabry-Perot (F-P) filter[16,17], optical fiber feedback ring[18] and high fineness comb filter structure[19], can be added into the system to improve the stability of the laser output.

In this paper, a dual-wavelength EDFL incorporating an active optical fiber ring filter structure is presented, in which an SA and an active optical fiber filter are combined to effectively suppress the undesirable longitudinal modes. The active ring filter consists of a 2×2 fused taper type coupler and a 2 m-long active optical fiber. Switchable output between two wavelengths is achieved. The power property and stability of the system are analyzed. The experimental results show that the peak wavelength drift of the system is less than 3 pm, and the output laser light power is in good linear relationship with the pump light power.

The experimental setup of the switchable dual-wavelength EDFL consists of four parts as shown in Fig.1. In the adopted circular cavity structure, a 976 nm laser diode (LD) from Oclaro Company is used as the pump source, and the pump light is coupled through a WDM device into a 7.8 m-long erbium-doped fiber (EDF1), as shown in the dashed block I of Fig.1. An optical circulator makes the laser in a travelling wave state, and the port 2 of the optical circulator is connected with two FBGs (FBG1 and FBG2). The reflection wavelengths are 1 535 nm and 1 540 nm, respectively, and the reflectivity is 98%. By adjusting a variable attenuator (VA), switchable laser outputs of 1 535 nm and 1 540 nm can be achieved, as shown in the dashed block III of Fig.1. A 1×2 fused taper type coupler (Coupler1) shown in the

---

* This work has been supported by the Transformation and Industrialization of Scientific and Technological Achievements (Nos.PXM2013_014224_000077 and PXM2012_014224_000019), and the Open Foundation of Beijing Engineering Research Center for Optoelectronic Information and Instrument (No.GD20130006).

** E-mail: zhulianqing@sina.com

dashed block IV of Fig.1 is used to output laser, whose splitting ratio is 10:90. The 10% terminal is monitored by an optical spectrum analyzer (OSA, Yokogawa AQ6370c 600–1 700 nm), and the resolution is 0.02 nm. In the dashed block III of Fig.1, a 2 m-long active optical fiber as an SA is fusion spliced between FBG1 and the optical circulator to suppress the wavelength drift. As shown in the dashed block II of Fig.1, an active optical fiber ring filter is incorporated through Coupler2 to implement the filtering effect and further improve the stability.

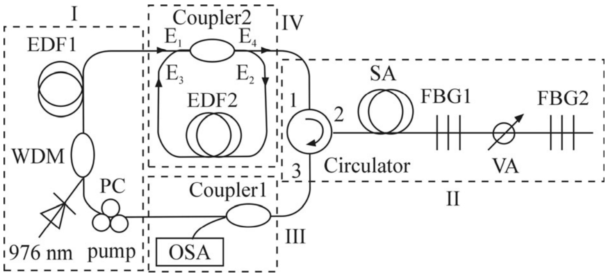


Fig.1 Experimental setup of the switchable dual-wavelength EDFL

The free spectral range (FSR) is inversely proportional to the cavity length according to the principle of ring cavity laser as

$$FSR=\frac{c}{nL}, \tag{1}$$

where L is the total cavity length, n is the average refractive index of the fiber which is assumed as 1.446, and c is the speed of light in vacuum.

For the two wavelengths, the total cavity lengths are approximately 21 m and 22 m, corresponding to two FSRs of 9.879 MHz and 9.430 MHz, respectively. Because the FSR is proportional to longitudinal mode spacing, the smaller the FSR, the denser the longitudinal modes of the laser output, the more apparent the mode jump phenomenon, and the more considerable the wavelength drift of the output laser light. The primary circular cavity can be incorporated with optical FBG as the cavity mirror to apply the effect of energy feedback and frequency selecting, which can not only decide the dual-wavelength output, but also act as a mode limiting element by providing preliminary selection for possible lasing modes. However, due to the wide bandwidth of optical FBGs, an SA can be added in the laser to filter and stabilize frequency. Here an un-pumped EDF segment with length of 2 m is added as the SA. In this segment, the incident and reflected light waves encounter with each other and produce mixing interference, developing a periodic interfered light intensity distribution, by which the caused gain saturation forms a gain grating in the doped fiber. The investigations already carried out in Ref.[15] indicate that this gain grating has a certain filtering and frequency stabilizing effect. However, in common doped fiber, the random variation in the polarization states of these two light waves can degrade the contrast of the interfered intensity distribution, which leads to that the gain grating is unstable, so for achieving effective filtering and frequency stabilizing, a relatively long fiber is usually needed, and the polarization state is necessary to control. Nevertheless, too long un-pumped doped fiber will cause an over-strong absorption, it is not easy to accurately control the polarization state, and the effect of filtering and frequency stabilizing could be limited. For these reasons, the experimental setup is fusion spliced with an active optical fiber ring filter in the ring cavity structure to suppress the wavelength drift and to realize filtering.

According to Vernier principle[20], if the lengths of primary and secondary rings are assumed to satisfy

$$\frac{L_m}{L_n}=\frac{2m}{2n+1}, \tag{2}$$

where L_m and L_n are the lengths of the primary and secondary rings, m and n are positive integers with no common factors, the effective FSR can be given by

$$FSR=2mFSR_m=(2n+1)FSR_n\,. \tag{3}$$

It means that the effective FSR of an EDFL in multiple ring cavity form is the least common multiple (FSR_m, FSR_n) of the primary and secondary ring cavities. In the experimental setup, the secondary ring cavity is the active optical fiber ring filter shown in the dashed block II of Fig.1, which is composed of a 2×2 50:50 fused taper coupler (Coupler2) and an active optical fiber (EDF2). If the length of the active optical fiber ring filter is 3 m, according to Eq.(1), the FSR is 69.156 MHz, which can increase the FSRs of two wavelengths mentioned above. Compared with the single ring cavity structure, the modes of the multiple-ring-cavity EDFL are more significantly suppressed.

The splitting ratios of the 3 dB Coupler2 are 50:50 for 1 550 nm and 10:90 for 976 nm, which enables that 10% of the pump power enters the secondary ring at port E_1, and a gain g and a time delay τ are obtained after it passes through EDF2. The time delay is calculated as 0.091 ns according to[19]

$$\tau=\frac{2\pi}{FSR}\,. \tag{4}$$

This portion of pump light then enters Coupler2 at port E_3 and returns to the primary ring cavity at port E_4.

The transmission function T of the filter is given as

$$T=\frac{r}{1+g^2(1-r)-2g\sqrt{1-r}\cos(\omega\tau)}\,. \tag{5}$$

Assuming that the coupling factor is r=0.5 and the gain is g=1.2, the transmission of the active optical fiber ring filter can be simulated as shown in Fig.2. It can be seen from Fig.2 that the frequency response of the filter is a comb spectrum. Therefore, theoretically, the filter can act as a mode jump inhibitor so as to improve systematic stability.

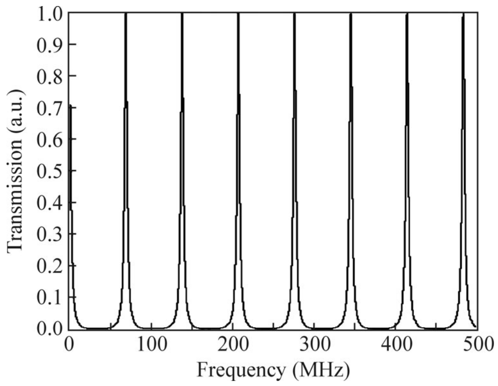


Fig.2 Transmission of the active optical fiber ring filter

The 976 nm LD is firstly used to pump a gain fiber with length of 7.8 m directly. The port 2 of the circulator is connected with FBG1 and FBG2. It is observed by a spectrometer that the system generates laser light at 1 540 nm when the pump power reaches 58 mW, and the spectrum is shown in Fig.3. By adjusting the VA, single wavelength output can be switched between 1 535 nm and 1 540 nm. Because there are a lot of longitudinal modes in the reflection spectrum of the FBGs, and these longitudinal modes circulate in the ring cavity, one part of the modes forms the laser output, while the other part becomes the noise affecting the stability of the laser output.

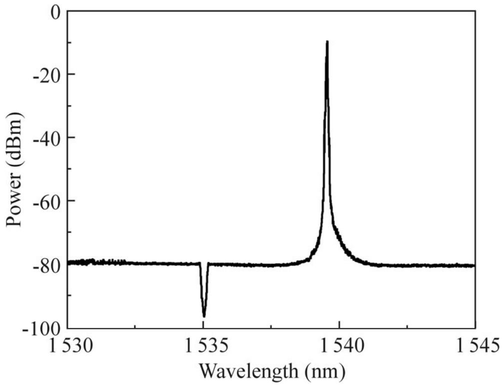
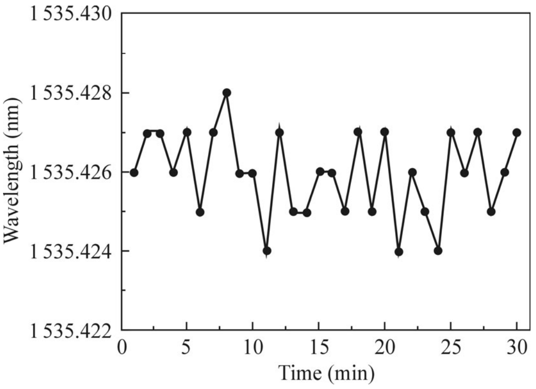
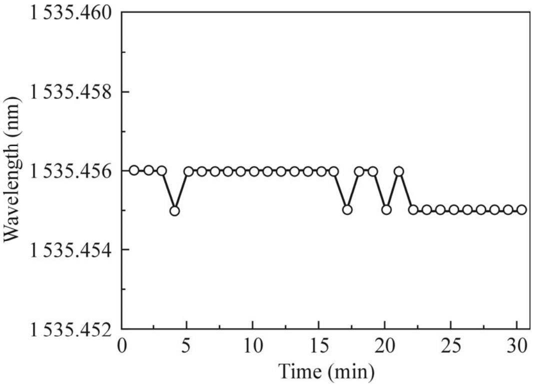


Fig.3 Spectrum of laser output at 1 540 nm

After adding the 2 m SA, the peak drifts of these two wavelengths are both approximately 5 pm. On this basis, when the active optical fiber ring filter is incorporated, the peak wavelength drift of 1 535 nm becomes less than 2 pm, and that of 1 540 nm becomes less than 3 pm. The wavelength stabilities with and without the active optical fiber ring filter at 1 535 nm and 1 540 nm are shown in Figs.4 and 5, respectively. It indicates that the active optical fiber ring filter further improves the wavelength stability.

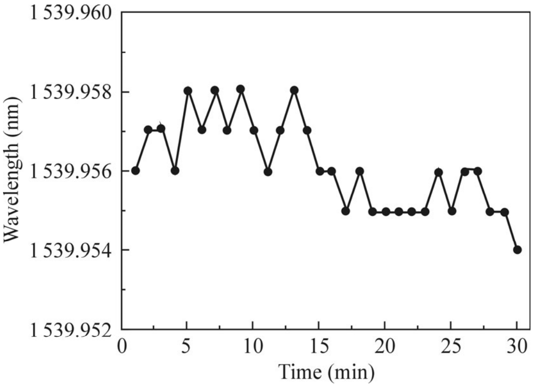


(a) Before filter

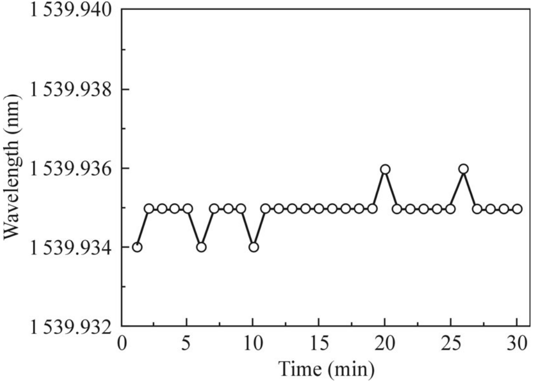


(b) After filter

Fig.4 Stabilities of 1 535 nm with and without the active optical fiber ring filter



(a) Before filter



(b) After filter

Fig.5 Stabilities of 1 540 nm with and without the active optical fiber ring filter

The output power versus the pump power for the system is shown in Fig.6. It can be seen that for both 1 535 nm and 1 540 nm, the output laser power is in good linear relationship with the pump power, and the maximum output powers are 1.35 mW and 1.52 mW, respectively. The power stability of laser is measured with a pump power of 145 mW, which is shown in Fig.7. For 1 535 nm and 1 540 nm, peak power variations are less than 0.010 mW and 0.012 mW, respectively.

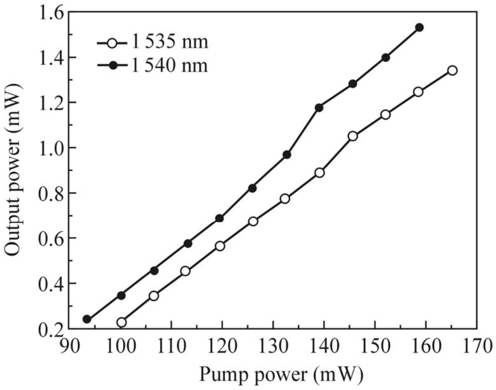
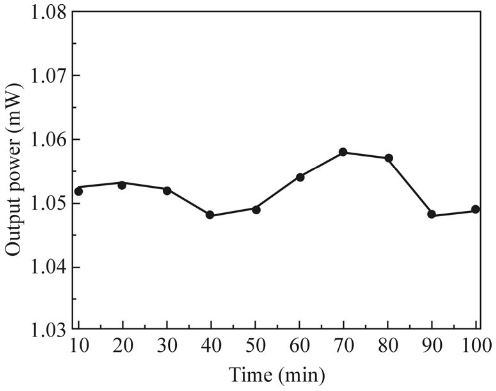
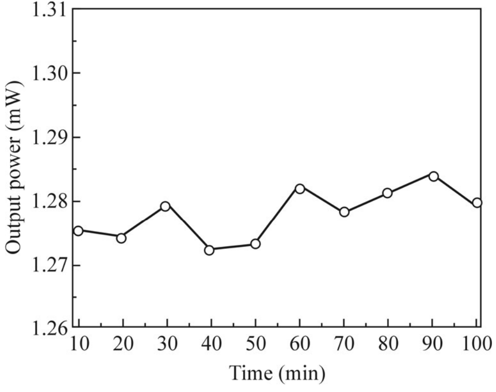


Fig.6 Output power versus pump power



(a) 1 535 nm



(b) 1 540 nm

Fig.7 Power stabilities of the laser for 1 535 nm and 1 540 nm with pump power of 145 mW

After the active optical fiber ring filter is added into the ring cavity, the threshold pump power of the system is 87 mW when the laser works in single longitudinal mode state with a central wavelength of 1 540 nm. When the pump power is increased to be 113 mW, the output laser powers of 1 535 nm and 1 540 nm shown in Fig.8(a) and (b) can be adjusted separately by the VA. The powers of these two wavelengths can also be adjusted by the VA to be nearly equal as shown in Fig.8(c). It indicates that the output of the fiber laser configuration can be switched between two wavelengths.

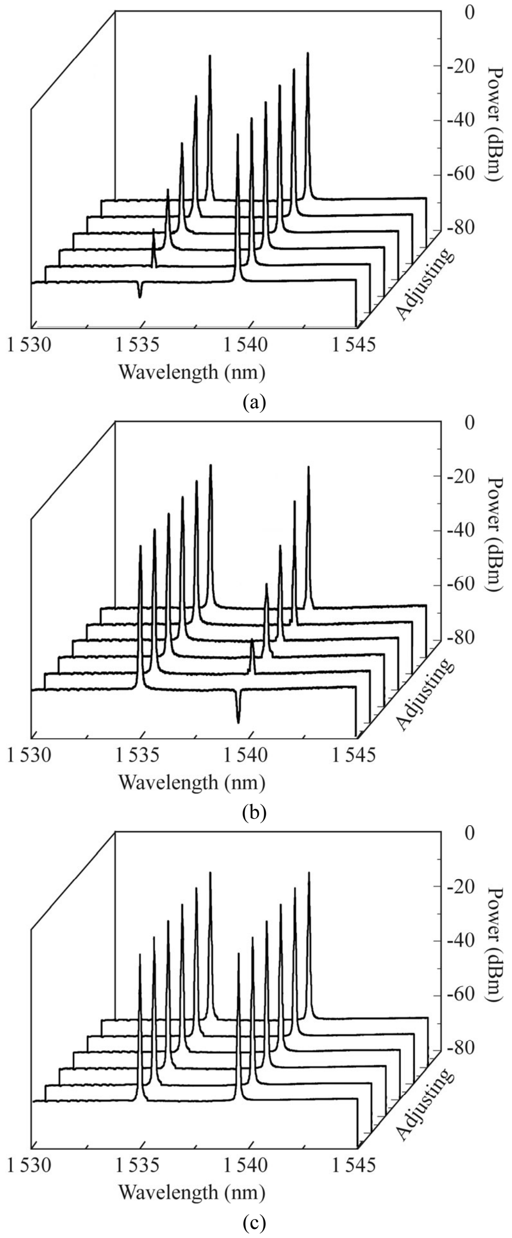


Fig.8 Adjustment of the output laser power for (a) 1 535 nm and (b) 1 540 nm, and (c) the power of both wavelengths to be nearly equal

A switchable dual-wavelength EDFL incorporating an active optical fiber ring filter is demonstrated with stable output power for both wavelengths. Experimental results show that the output laser wavelength drift phenomenon is effectively suppressed to be 2–3 pm. The output power and the pump power are in a good linear relationship. For the wavelengths of 1 535 nm and 1 540 nm, the peak power variations are less than 0.010 mW and 0.012 mW, and the output powers of the laser are 1.34 mW and 1.53 mW, respectively. The demonstrated fiber laser has the advantages of compact structure, flexible wavelength selection and stable laser output, so it has promising application prospect.

For the purpose of further improving the demonstrated system, the gain fiber with higher doping concentration can be adopted to increase the output power, and more FBGs can be cascaded to generate laser output with more wavelengths.

References

[1] Ryun Kyung Kim, Suho Chu and Young-Geun Han, IEEE Photonics Technology Letters **24**, 521 (2012).

[2] Dai Y., Sun Q., Tan S., Wo J., Zhang J. and Liu D., Optics Express **20**, 27367 (2012).

[3] Yi Dai, Qizhen Sun, Jiejun Zhang, Jianghai Wo and Deming Liu, Tunable Dual-Wavelength Double-Ring Fiber Laser and Its Application in Highly Sensitive Temperature Sensing, Conference on Lasers and Electro-Optics, JW2A.75 (2012).

[4] Yu Yao, Xiangfei Chen, Yitang Dai and Shizhong Xie, IEEE Photonics Technology Letters **18**, 187 (2006).

[5] Xiangfei Chen, Zhichao Deng and Jianping Yao, IEEE Transactions on Microwave Theory and Techniques **54**, 804 (2006).

[6] Shilong Pan and Jianping Yao, Optics Express **17**, 5414 (2009).

[7] S. Rota-Rodrigo, R. A. Perez-Herrera, M. Fernandez-Vallejo and M. López-Amo, Applied Physics B **106**, 563 (2012).

[8] Cheng X. S., Hamida B. A., Naji A. W., Arof H., Ahmad H. and Harun S. W., IET Optoelectronics **6**, 127 (2012).

[9] Jae-Ho Han, Optik-International Journal for Light and Electron Optics **121**, 2266 (2010).

[10] Maestre H., Torregrosa A. J., Fernandez-Pousa C. R., Pereda J. A. and Capmany J., IEEE Journal of Quantum Electronics **47**, 1238 (2011).

[11] Cao Y., Lu N. and Tong Z., Optoelectronics Letters **9**, 434 (2013).

[12] Xuesong Liu, Li Zhan, Shouyu Luo, Yuxing Wang and Qishun Shen, Journal of Lightwave Technology **29**, 3319 (2011).

[13] Yun L., Liu X. and Mao D., Optics Express **20**, 20992 (2012).

[14] Wang Z. T., Chen Y., Zhao C. J., Zhang H. and Wen S. C., IEEE Photonics Journal **4**, 869 (2012).

[15] Suchun Feng, Shaohua Lu, Wanjing Peng, Qi Li, Chunhui Qi, Ting Feng and Shuisheng Jian, Optics & Laser Technology **45**, 32 (2013).

[16] He X., Fang X., Liao C., Wang D. N. and Sun J., Optics Express **17**, 21773 (2009).

[17] Fangfang Weia, Xiufeng Yanga, Zhengrong Tonga, Ye Caoa and Honggang Panb, Optik-International Journal for Light and Electron Optics **123**, 1026 (2012).

[18] Jianguan Tang and Junqiang Sun, Optical Fiber Technology **16**, 299 (2010).

[19] Pan S. and Yao J., Optics Express **17**, 12167 (2009).

[20] Yeh C. H., Shih F. Y., Chen C. T., Lee C. N. and Chi S., Optics Express **15**, 13844 (2007).