Northumbria Research Link

Citation: Liu, Jiandong, Liu, Juan, He, Xing-Dao, Yuan, Jinhui, Wu, Qiang and Liu, Bin (2022) Switchable multi-wavelength fiber laser based on a taper-coupled microbottle resonator. Optics and Laser Technology, 158 (Part A). p. 108819. ISSN 0030-3992

Published by: Elsevier

URL: https://doi.org/10.1016/j.optlastec.2022.108819 <https://doi.org/10.1016/j.optlastec.2022.108819>

This version was downloaded from Northumbria Research Link: https://nrl.northumbria.ac.uk/id/eprint/50417/

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: http://nrl.northumbria.ac.uk/policies.html

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)

Northumbria University NEWCASTLE

CUSTOMER SERVICE EXCELLENCE CSE UniversityLibrary

Switchable multi-wavelength fiber laser based on a taper-coupled microbottle resonator

Jiandong Liu,[1] Juan Liu,[1] Xing-Dao He,[1] Jinhui Yuan,[3] Qiang Wu[1,2,*] and Bin Liu[1,*]

[1]*Key Laboratory of Opto-Electronic Information Science and Technology of Jiangxi Province, Nanchang Hangkong University, Nanchang 330063, China*

[2]*Optical Communications Research Group. Faculty of Engineering and Environment, Northumbria University, Newcastle Upon Tyne, NE1 8ST, United Kingdom*

[3]*Research Center for Convergence Networks and Ubiquitous Services, University of Science & Technology Beijing, Beijing 100083, China*

*Corresponding authors: Bin Liu (liubin_d@126.com); Qiang Wu (qiang.wu@northumbria.ac.uk)

Abstract: A multi-wavelength erbium-doped fiber laser (EDFL) based on a taper-coupled microbottle resonator is proposed and investigated experimentally. The taper-coupled microbottle resonator has the comb filter characteristics with Q factor 2.9×10^4, which is integrated into an EDFL system. The taper-coupled microbottle resonator was packaged by ultraviolet glue, which has excellent stability of output power and wavelength at room temperature. Then, switchable dual-, triple-, quad- and quint-wavelength fiber laser states can be achieved by adjusting the polarization controller (PC). Furthermore, for dual-wavelength and triple-wavelength laser state, the position of output wavelengths also can be precisely modulated with the PC. The developed multi-wavelength EDFL has the optical signal to noise ratio as high as 40 dBm, and the wavelength shift and peak power fluctuation are less than 0.03 nm and 6 dBm.

Keywords: Fiber optic laser; Microbottle resonator; Comb filter.

1. Introduction

For the past few years, switchable multi-wavelength erbium-doped fiber laser (MWEDFL) has attracted the interest of many researchers in various potential applications, including optical fiber sensing [1,2], optical instrument testing [3], dense wavelength division multiplexing (DWDM) in communication[4], and microwave photonics [5,6]. In particular, the application of MWEDFL in DWDM is of great research value. Typically, the multi-wavelength output of MWEDFL is obtained using a multichannel filter or the nonlinear effect. The use of the latter requires high intra-cavity power and has been rarely reported [7]. As a kind of multichannel filter and passive optical device, optical fiber filter is very suitable for MWEDFL construction. Fiber filters, such as fiber Bragg grating (FBG) [8], Mach-Zenger interferometer (MZIs) and Sagnac ring filter [9-11], have been reported as wavelength selective components to achieve tunable and switchable laser emission. For example, Chang *et al.* reported a MWEDFL based on cascaded hybrid fiber filter with peak power fluctuation less than 1.93 dB and 2-4 wavelength laser output [12]. In 2019, Chang *et al.* demonstrate the single-mode-multimode-single-mode (SMS) fiber filters that can be used to achieve switchable and tunable thulium-doped fiber laser [13]. Recently Zhang *et al.* proposed a fiber filter based dual-wavelength tunable and wavelength switchable MWEDFL with output power fluctuation of multi-wavelength laser state less than 0.75 dB within 30 min [14]. Qi *et al.* proposed a new type of few mode fiber based fiber filter, which is integrated into erbium-doped fiber laser (EDFL) to realize MWEDFL capable of switching between 1–4 wavelength laser states [15].

However, the unstable mode competition caused by the homogeneous broadening of gain fiber brings great difficulties in obtaining MWEDFL with time stability [16]. In order to prevent unstable mode competition caused by gain fiber, researchers have explored many methods, such as cooling the EDF with liquid nitrogen [17], inserting a frequency shifting device [18,19], using fiber filters [20,21], adding wavelength- or intensity-dependent loss structures [22,23], and using the high nonlinear effect of fibers [24-27]. Among these techniques, additional devices need to be added within MWEDFL, significantly increasing the cost and size of the system.

The taper-coupled microbottle resonators proposed in this paper has the characteristics of inhomogeneous loss and high nonlinearity, which can not only be used as wavelength selective components, but also alleviate the mode competition caused by homogeneous gain broadening without increasing the stabilization mechanism. Therefore, the structure of the laser cavity can be simplified without the need for additional stabilization mechanisms. Meanwhile, the transmission spectrum of the taper-coupled microbottle resonators has high quality factor which is ideal for wavelength selective components. The taper-coupled microbottle resonator is integrated into an EDFL to realize switchable MWEDFL with time stability.

2. Microbottle resonators fabrication and characterization

The taper-coupled microbottle resonator is obtained by coupling a microbottle resonator and a tapered optical fiber. Firstly, a commercial welding machine (Fujikura 80C) is used to make microbottle resonator. Fig. 1 shows the detailed process. Commercial fusion splicer is used to arc discharge SMF. After repeated electrical arc discharge, a microsphere is formed at the end of the Single mode fiber (SMF). Another SMF is then aligned and fusion spliced to the microsphere to form a microbottle resonator as shown in Fig. 1(d). Meanwhile, the shape of the microbottle directly affects resonant mode characteristics and field distribution, which can be controlled by the number of arc discharge. Fig. 1(d) shows a picture of the fabaricated microbottle with a diameter of 222.67 μm. Secondly a separate SMF is tapered to very small diameter with tapering waist of 4 μm. Finally, the taper-coupled microbottle resonators needs to be formed by coupling the prepared microbottle resonators with tapered optical fiber in near field. In the coupling process, a device is needed to help optimize the coupling position and distance. The device, shown Fig. 2(a), consists of four parts: a broadband light source (BBS, SC-5-FC), an optical spectrum analyzer (OSA, YOKOGAWA AQ6370D), a microscope (GP-660V), and two translation stages. Depending on this system, the transmission spectrum can be adjusted and monitored in real time. When the coupling is optimized, the light passing through the tapered fiber will be coupled into the microvial cavity and spread in a spiral shape. After many circles of propagation around the cavity axis, it will rotate back to the previous incident dot [28]. Light oscillating back and forth between the two turning dots will form an axial mode. The structure of taper-coupled microbottle resonators is shown in Fig. 2(b).

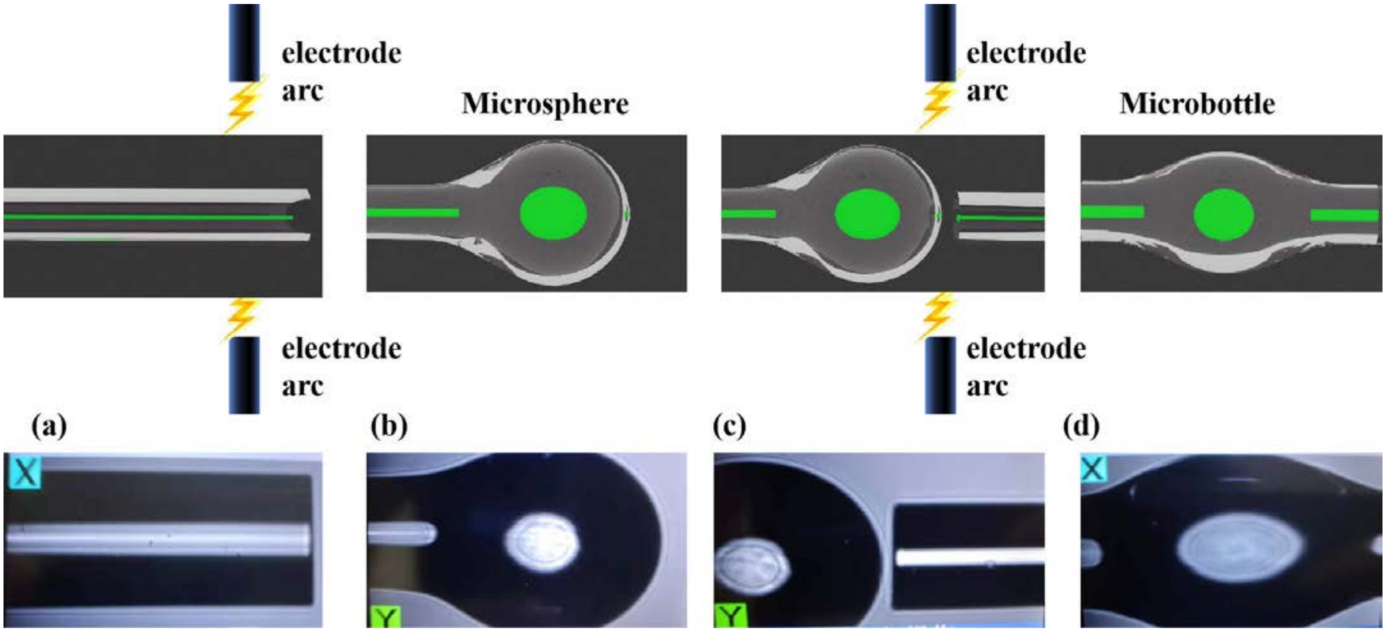

Figure 1. Preparation method of microbottle resonators: (a) the single fiber is heated via electrical arc discharge; (b) microsphere resonators formation; (c) another fiber was placed to align the microsphere; (d) Microbottle resonators.

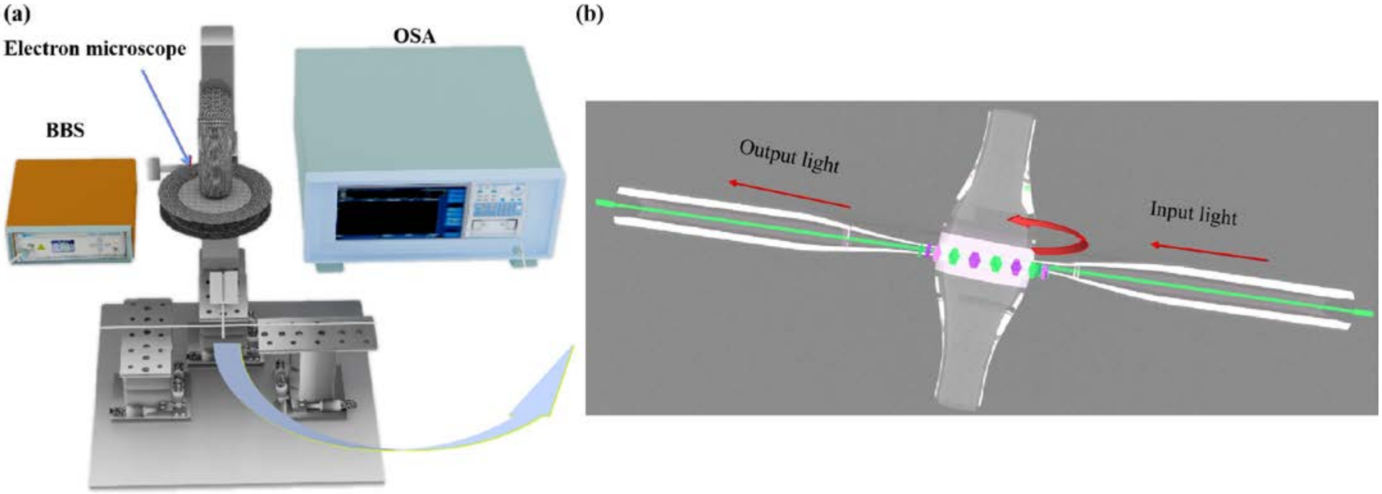

Figure 2. (a) coupling device; (b) Schematic diagram of taper-coupled microbottle resonators.

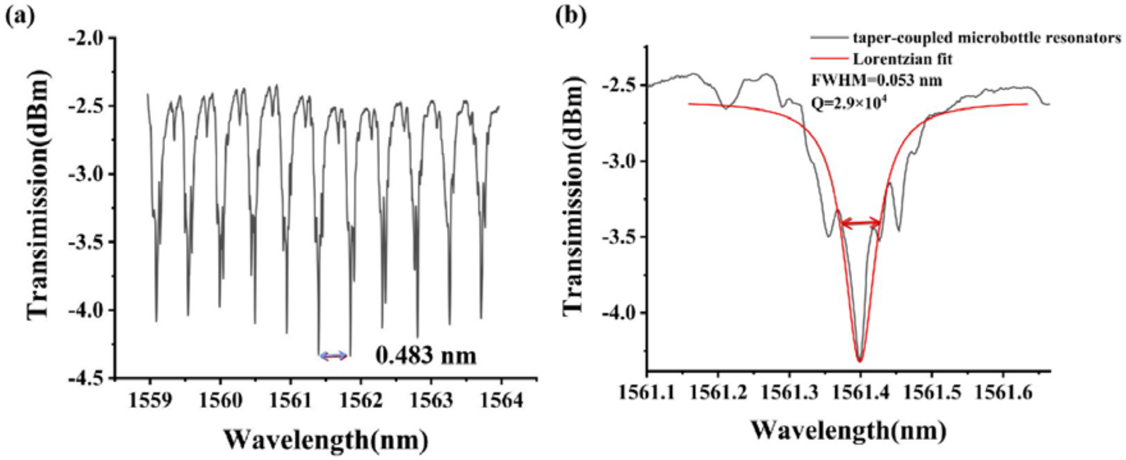

Figure 3. (a) The transmission spectrum of the taper-coupled microbottle resonators; (b) FWHM of the taper-coupled microbottle resonators

Fig. 3(a) shows measured spectral response of the taper-coupled microbottle resonator. The spectrum has comb filtering characteristics and the free spectrum range (FSR) is 0.483 nm. Lorentz function is used to fit the transmission spectrum of the cone-coupled microbottle resonator, which can be obtained in Fig. 3(b), from which it can be concluded that the specific value of the FWHM is 0.053 nm. According to the references [29], the Q-factor of taper-coupled microbottle resonators can be calculated as follows:

$$Q = \lambda / FWHM \tag{1}$$

Where λ is the resonant wavelength of taper-coupled microbottle resonators. The Q-factor is calculated as 2.9×10^4 using the above formula.

The taper-coupled microbottle resonator is fragile and unstable due to the interference of the coupling conditions caused by the surrounding vibration [30]. To make the taper-coupled microbottle resonator more robust and stable, it is packaged with ultraviolet (UV) glue. The packaging process can be described in three steps, as shown in Fig. 4(c):

(1) The first step is to fix glass2, glass3, glass4 and glass5 respectively on the glass substrate, so as to avoid the contact between the taper-coupled microbottle resonator and the glass substrate.

(2) The second step is to fix the stretched taper optical fiber on glass3 and glass5 with UV glue.

(3) In the third step, when the distance between the microbottle resonator and the taper fiber reaches the condition of near-field coupling, the tail fiber of the microbottle resonator is fixed on glass2 and glass4 with UV glue.

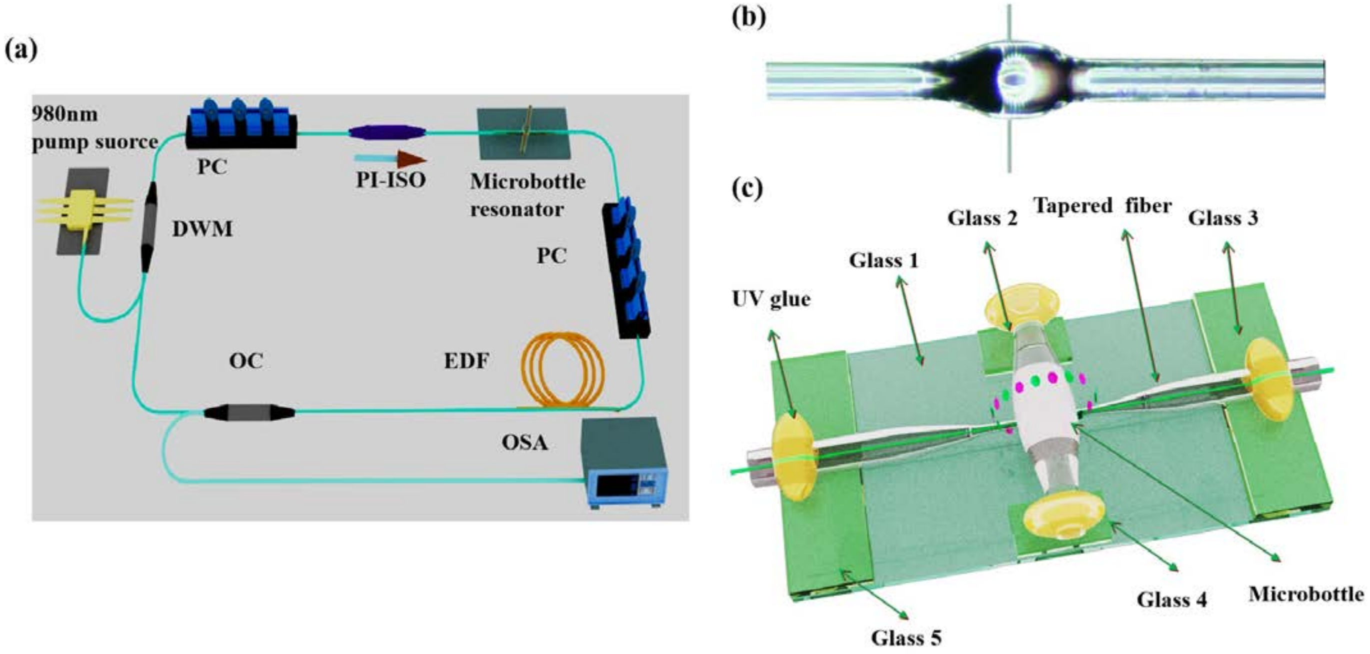

Figure 4. (a) Schematic of the proposed the MWEDFL; (b) The microscope image of taper-coupled microbottle resonator; (c) The packaging taper-coupled microbottle resonator.

The packaged taper-coupled microbottle is then integrated into an EDFL to create a MWEDFL as shown in Fig. 4(a). In the MWEDFL, a 980 nm pump source (VLSS-980-B-650-FA, VENUS) as the light source is connect into the ring cavity by a 980/1550 nm wavelength division multiplexer (WDM, WDM-1X2-980/1550-2). The WDM output port is connected to a polarization controller (PC), then to a polarization independent isolator (PI-ISO) to ensure one-way propagation of light. Then the light enters the taper-coupled microbottle resonator structure. Here we again need to add a PC. A 5-meter erbium-doped fiber (EDF, 8/125, Nufern) is connected to the back of the taper-coupled microbottle, then to a 90:10 optical coupler

(OC, WIC-1X2-1550-10/90-0-A40). Finally, the light enters the 1550 nm port of the WDM through the 90% port of the OC, forming a loop to keep most of the light propagating in the ring. The 10% port of the OC is connected to an OSA (OSA, Anritsu, MS9710C) for data analysis.

3. Experimental results and analysis

In the experiment, the taper-coupled microbottle resonators with the PC is used as a wavelength selector, which can adjust the gain and loss of wavelength in the cavity, and determine the final output position and peak power of the laser. The specific principle is that PC can be used to adjust the polarization state of the light in the cavity, thereby adjusting the polarization state of the light in the taper-coupled microbottle resonators. After the light with different polarization states passes through the taper-coupled microbottle resonators, the output polarization state changes. Therefore, different polarization states of light obtain different filtering functions. The filter function determines the gain and loss of the wavelength. When the gain of the wavelength is dominant, the laser can be emitted and formed, so as to realize the laser wavelength output at different peak values of the filter. When the power of pump source in the MWEDFL is maintained at 400 *mW*, the MWEDFL can obtain stable dual-wavelength in the laser-output spectrum by adjusting the PC. In addition, by carefully adjusting the PC, the position of the laser wavelength can be switched to obtain a number of different dual-wavelength laser states.

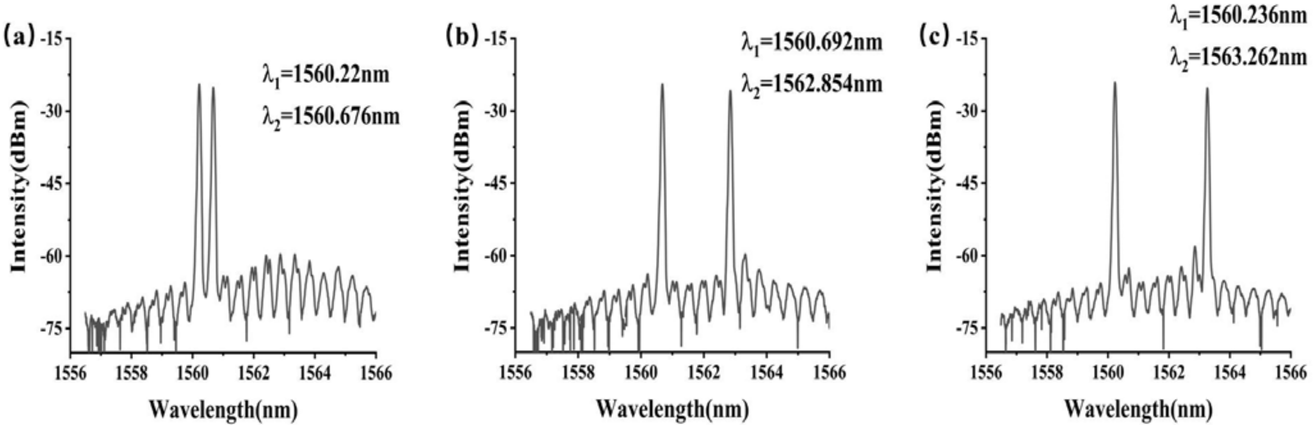

Figure 5. Different dual-wavelength laser states: (a) *state 1* of dual-wavelength; (b) *state 2* of dual-wavelength; (c) *state 3* of dual-wavelength.

Fig. 5(a), (b) and (c) respectively show three different dual-wavelength laser states. As show Fig. 5(a), the laser output spectrum is defined as dual-wavelength laser *state 1* with wavelength positions of 1560.22 and 1560.676 nm, respectively. As show Fig. 5(b), the laser output spectrum is defined as dual-wavelength laser *state 2* with wavelength positions of 1560.692 and 1562.854 nm, respectively. As show Fig. 5(c), the laser output spectrum is defined as dual-wavelength laser *state 3* with wavelength positions of 1560.236 and 1563.262 nm, respectively. The results show that the wavelength position can be changed within 3.026 nm and the optical signal to noise ratio (OSNR) is about 41 dBm in the dual-wavelength laser state.

The MWEDFL can obtain stable triple-wavelength in the laser-output spectrum by adjusting the PC. In addition, by carefully adjusting the PC, the position of the laser wavelength also can be switched to obtain a number of different triple-wavelength laser states.

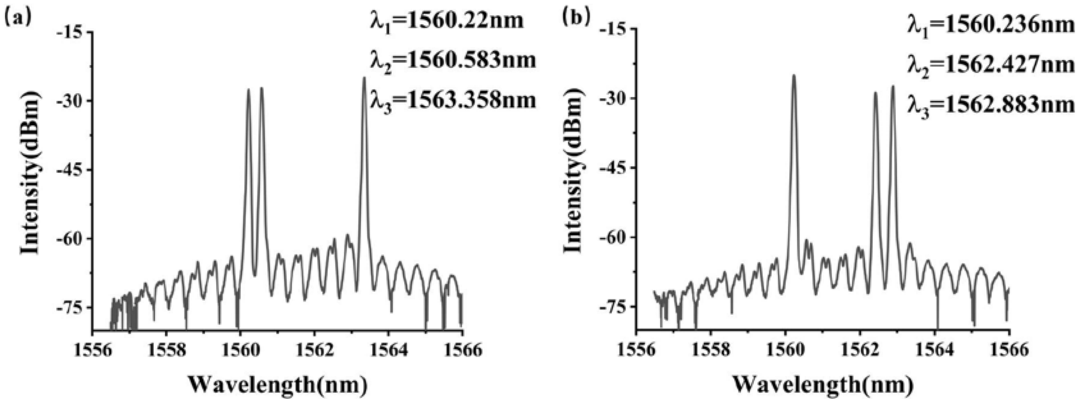

Figure 6. Different triple-wavelength laser states: (a) *state 1* of triple-wavelength; (b) *state 2* of triple-wavelength.

Figures 6(a) and (b) respectively show two different triple-wavelength laser states. As show Fig. 6(a), the laser output spectrum is defined as triple-wavelength laser *state 1* with wavelength positions of 1560.22, 1560.583 and 1563.358nm, respectively. As show Fig. 6(b), the laser output spectrum is defined as triple-wavelength laser *state 2* with wavelength positions of 1560.236, 1562.427 and 1562.883nm, respectively. Under the condition of triple-wavelength laser states, it can be concluded that the wavelength position can be changed within 3.14 nm and OSNR is about 41 dBm. However, the number of triple-wavelength laser states obtained by adjusting the PC is less than the laser states corresponding to dual-wavelength.

The power of pump source in the MWEDFL is maintained at 500 *mW*. Under the condition of proper adjustment of PC, it can be respectively realized the balance between gain and loss of dual-, triple-, quad- and quint-wavelength. Hence the number of wavelengths in the MWEDFL can be switched. Meanwhile, in order to study the stability of the MWEDFL in different laser states, the dual-, triple-, quad- and quint-wavelength state lasers are scanned within 50 min. The laser output spectra obtained are shown in Figs. 7(a)–(d), that the wavelength shift and output power fluctuation do not change significantly. It is worth OSNR of all multi-wavelength laser states is about 40 dBm. In particular, the OSNR of the dual-wavelength laser and the three-wavelength laser are all greater than 40 dB, which are 40.96 dB and 40.94 dB, respectively. However, when the power uniformity of the output laser is analyzed, the quint-wavelength laser state is obviously lower than that of dual-wavelength, triple-wavelength and quad-wavelength laser states. As shown in Fig. 7(d), the peak power of the five-wavelength laser state at 1559.764 nm is significantly lower than that at other wavelengths, about 8.339 dB lower. This phenomenon can be explained by using taper-coupled microbottle resonator as comb filters with different extinction ratios at different wavelength positions. According to Fig. 3, the extinction ratio at 1559.764 nm is relatively low. Therefore, the position with high extinction ratio corresponds to higher output laser power can be concluded in the laser output spectrum. Similarly, the lower the extinction ratio, the lower the output laser power. Because of the existence of the mode gain competition, the output power of the laser at the low extinction wavelength will be further suppressed [31]. It can also be seen from Fig. 7(d) that the wavelength interval between the quint-wavelength laser state is not exactly equal to the FSR of the taper-coupled microbottle resonator. This is attributed to spectral hole burning effect (SHB). When adjusting PC, the SHB effect will be affected, resulting in the change of the gain spectrum of the laser [31].

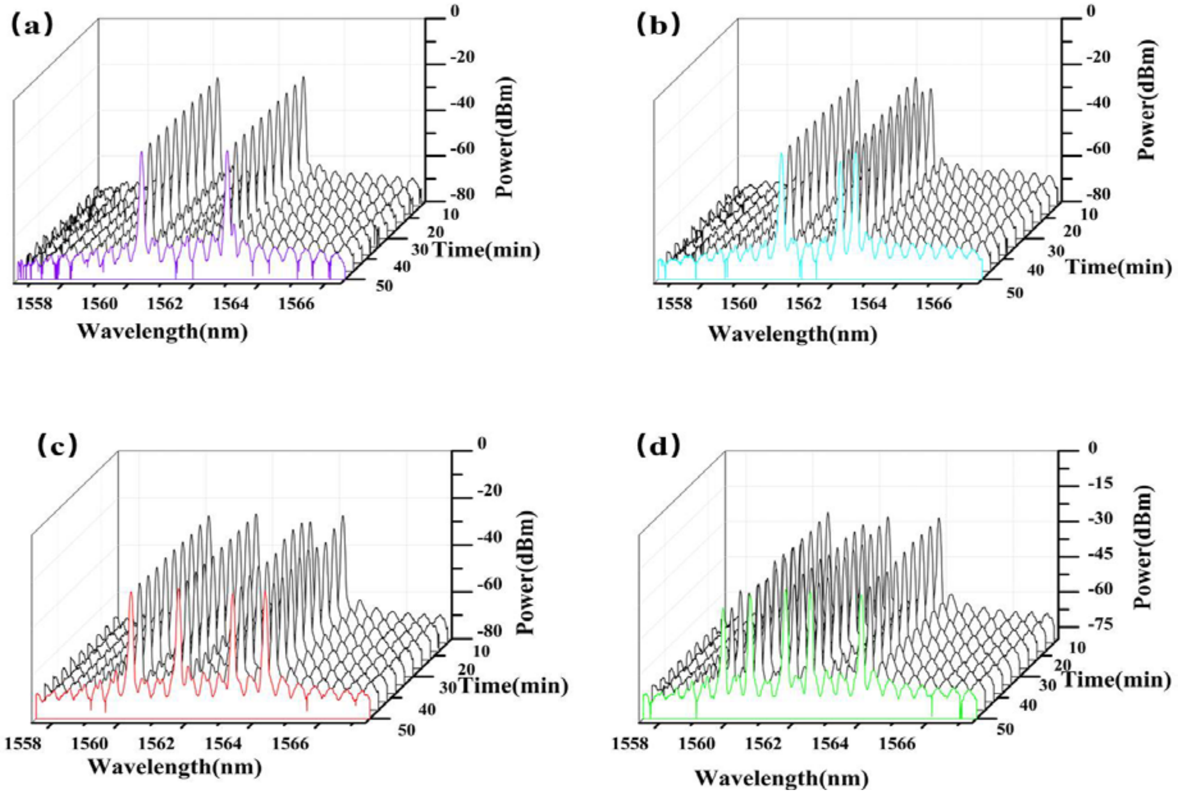

Figure 7. MWEDFL scanned within 50 min at an interval of 5 min: (a) dual-wavelength laser state; (b) triple-wavelength laser state; (c) quad-wavelength laser state; (d) quint-wavelength laser state.

The time stability of MWEDFL has an important impact on its application in DWDM. Specific wavelength drift and power fluctuation need to be understood. Therefore, on the basis of scanning the dual-, triple-, quad- and quint-wavelength state lasers at 5min intervals within 50min, the position and power of the output laser wavelength are respectively read. Fig. 8(a) shows that the wavelength drift and power fluctuation of dual-wavelength laser state, which are 0.01 nm and 0.475 dB, 0 nm and 0.324 dB at 1560.261 and 1562.884 nm, respectively. Figure 8(b) shows that the wavelength drift and power fluctuation of triple-wavelength laser state, which are 0.01 nm and 0.505 dB, 0 nm and 4.327 dB, 0 nm and 4.055 dB at 1560.279, 1562.05 and 1562.576 nm, respectively. Fig. 8(c) shows that the wavelength drift and power fluctuation of quad-wavelength laser state, which are 0.03 nm and 0.754 dB, 0.43 nm and 0.594 dB, 0.021 nm and 3.936dB, 0.021 nm and 4.579 dB at 1560.215, 1561.219,1563.268 and 1564.231nm, respectively. Fig. 8(d) shows that the wavelength drift and power fluctuation of quint-wavelength laser state, which are 0.021 nm and 6.182 dB, 0 nm and 3.858 dB, 0.03 nm and 4.518 dB, 0 nm and 1.895 dB, 0.02 nm and 1.968 dB, at 1559.764, 1560.582, 1561.659, 1562.387 and 1563.926nm, respectively. A phenomenon can be found from Fig. 7 and Fig. 8 that the more exciting spectral lines MWEDF outputs, the more obvious power fluctuation is, which is caused by mode competition. On the whole, a switchable MWEDFL can be obtained by using a taper-coupled microbottle resonators as a comb filter, but the maximum power fluctuation of the MWEDFL within 50 minutes is up to 6 dBm, which needs to be further optimized. However, our proposed MWEDFL maintains the integrity of the all-fiber system due to the packaging processing of taper-coupled microbottle resonators, so it has low requirements on the surrounding environment. It is worth noting that the maximum extinction ratio of the transmission spectrum of the taper-coupled microbottle resonators is low, which may limit the further growth of the OSNR of the MWEDFL.

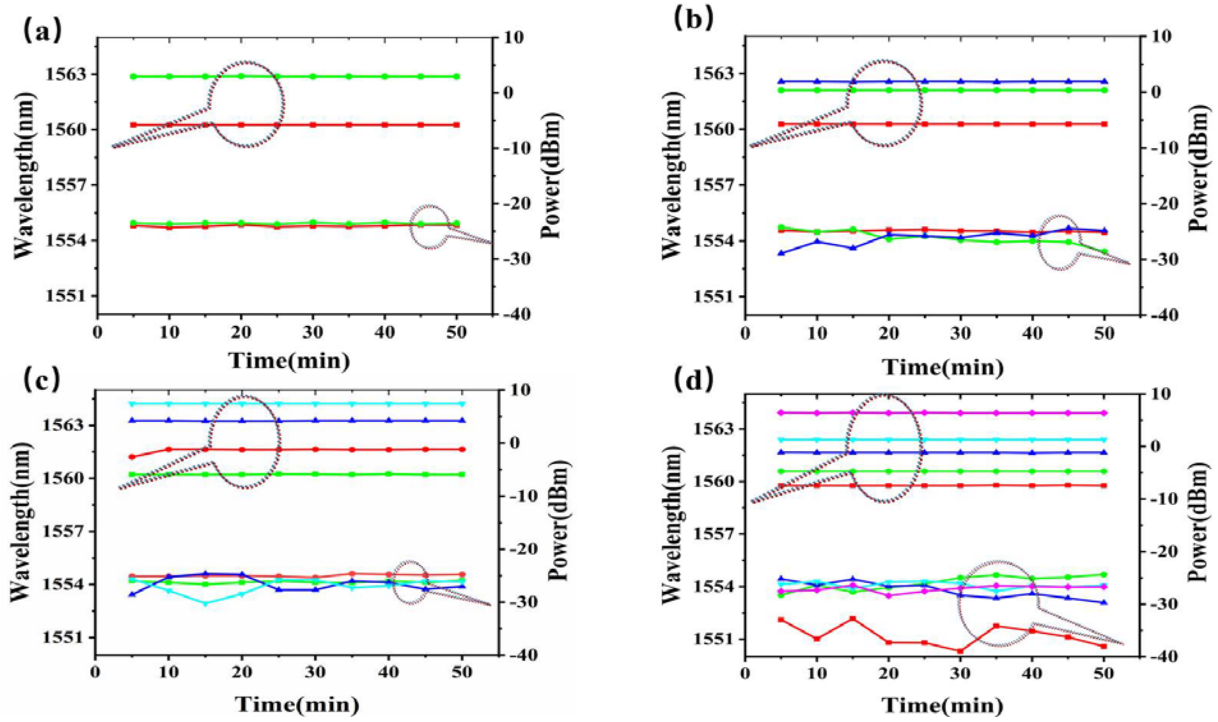

Figure 8. The wavelength drift and power fluctuation of laser with different multi-wavelength states in 50min: (a) dual-wavelength laser state; (b) triple-wavelength laser state; (c) quad-wavelength laser state; (d) quint- wavelength laser state.

4. Conclusion

In this work, a switchable MWEDFL based on the taper-coupled microbottle resonators is proposed and demonstrated. The taper-coupled microbottle resonators acted as high Q factor comb filter to select wavelength are applied in EDFL system. The stable multi-wavelength laser states of switchable dual- to quint-wavelengths can be achieved by adjusting the PC. Furthermore, the position of the output wavelength of the dual-wavelength and triple-wavelength laser can be shifted within ranges about 3.026 nm and 3.14 nm by carefully adjusting the PC, respectively. The OSNR of the MWEDFL is about 40 dBm. The system demonstrated an excellent stability at room temperature with packaging the taper-coupled microbottle resonator by ultraviolet glue. The wavelength shift and peak power fluctuation are less than 0.03 nm and 6 dBm. The developed MWEDFL has a wide range of applications in communication and optical fiber sensing.

Acknowledgements

This work was jointly supported by the Natural Science Foundation of Jiangxi Province (20212BAB202024), National Natural Science Foundation of China (NSFC) (11864025, 62175097, 62065013 and 62163029), and Key R&D Projects of the Ministry of Science and Technology of China (2018YFE0115700).

References

[1] Sungchul Kim, Jaejoong Kwon, Seungwoo Kim, and Byoungho Lee. Multiplexed strain sensor using fiber grating-tuned fiber laser with a semiconductor optical amplifier[J]. IEEE Photonics Technology Letters, 2001, 13(4):350-351.

[2] L. Talaverano, S. Abad, S. Jarabo, and M. López-Amo. Multiwavelength fiber laser sources with Bragg-grating sensor multiplexing capability[J]. Journal of Lightwave Technology, 2001, 19(4):553-558.

[3] R. Slavik and S. LaRochelle. Multiwavelength 'single-mode' erbium doped fiber laser for FFH-OCDMA testing[C]. Optical Fiber Communication Conference & Exhibit. IEEE, 2002, 245–246.

[4] Gert Sarlet, Geert Morthier, and Roel Baets. Control of widely tunable SSG-DBR lasers for dense wavelength division multiplexing[J]. Journal of Lightwave Technology, 2002, 18(8):1128-1138.

[5] Jie Sun, Yitang Dai, Xiangfei Chen, Yejin Zhang, and Shizhong Xie. Stable Dual-Wavelength DFB Fiber Laser With Separate Resonant Cavities and Its Application in Tunable Microwave Generation[J]. IEEE Photonics Technology Letters. 2006, 18(24):2587–2589.

[6] Tao Wang, Xinzhu Sang, Feijun Song, Xia Zhang, et al. Tunable microwave signal generation based on an Opto-DMD processor and a photonic crystal fiber[J]. Chinese Phys B, 2014, 23(6):064217.

[7] Xiong Wang, Pu Zhou, Xiaolin Wang, Hu Xiao, and Lei Si. Multiwavelength Brillouin-thulium fiber laser [J]. IEEE Photonics Journal, 2014, 6(1): 1–7.

[8] Xiangqiao Mao, Fengping Yan, Lin Wang, Suchun Feng, Jian Peng, Shuisheng Jian. Incorporate, switchable dualwavelength fiber laser with Bragg gratings written in a polarization-maintaining erbium-doped fiber[J]. Optics Communications, 2009, 282:93–96.

[9] Sierra-Hernandez J M, Rojas-Laguna R, Vargas-Rodriguez E, et al. A tunable multi-wavelength erbium doped fiber laser based on a Mach–Zehnder interferometer and photonic crystal fiber[J]. Laser Physics, 2013, 23(12):125103.

[10] Qianwu Zhang, Xianglong Zeng, Fufei Pang, Min Wang and Tingyun Wang. Switchable multiwavelength fiber laser by using a compact in-fiber Mach–Zehnder interferometer[J]. Journal of Optics, 2012, 14(4):233-240.

[11] H. Ahmad, M.H.M. Ahmed, M.Z. Samion, S.W. Harun. All fiber multiwavelength Tm-doped double-clad fiber laser assisted by four-wave mixing in highly nonlinear fiber and Sagnac loop mirror [J]. Optics Communications, 2020, 456:124589.

[12] Yanbiao Chang, Li Pei, Tigang Ning, Jingjing Zheng, Jing Li, Caijian Xie. Switchable and tunable multi-wavelength fiber ring laser employing a cascaded fiber filter[J]. Optical Fiber Technology, 2020, 58:102240.

[13] Yanbiao Chang, Li Pei, Tigang Ning, Jingjing Zheng. Switchable multi-wavelength fiber laser based on hybrid structure optical fiber filter[J]. Optics & Laser Technology, 2020, 124:105985.

[14] Chenfang Zhang, Jiang Sun, Shuisheng Jian. A new mechanism to suppress the homogeneous gain broadening for stable multi-wavelength erbium-doped fiber laser[J]. Optics Communications, 2013, 288:97-100.

[15] Yanhui Qi, Zexin Kang, Jiang Sun, et al. Wavelength-switchable fiber laser based on few-mode fiber filter with core-offset structure[J]. Optics & Laser Technology, 2016, 81:26–32.

[16] Dae Seung Moon, Un-Chul Paek, Youngjoo Chung. Multi-wavelength linearcavity tunable fiber laser using a chirped fiber Bragg grating and a few-mode fiber Bragg grating[J]. Optics Express, 2005, 13:5614–5620.

[17] Daoping Wei, Tangjun Li, Yucheng Zhao, and Shuisheng Jian. Multiwavelength erbium-doped fiber ring lasers with overlap-written fiber Bragg gratings [J]. Optics Letters, 2000, 25(16):1150-1152.

[18] Young-Geun Han, Thi Van Anh Tran, and Sang Bae Lee. Wavelength-spacing tunable multiwavelength erbium-doped fiber laser based on four-wave mixing of dispersion-shifted fiber [J]. Optics Letters, 2006, 31(6):697–699.

[19] Young-Geun Han and Sang Bae Lee. Flexibly tunable multiwavelength erbium-doped fiber laser based on four-wave mixing effect in dispersion-shifted fibers [J]. Optics Express, 2005, 13(25):10134–10139.

[20] Ali A. Jasim, Mohamad Dernaika, Sulaiman Wadi Harun, and Harith Ahmad. A switchable figure eight erbiumdoped fiber laser based on inter-modal beating by means of non-adiabatic microfiber [J]. Journal of Lightwave Technology, 2015, 33(2):528-534.

[21] S. Sugavanam, Z. Yan, V. Kamynin, A. S. Kurkov, L. Zhang, and D. V. Churkin. Multiwavelength generation in a random distributed feedback fiber laser using an all fiber Lyot filter [J]. Optics Express, 2014, 22(3):2839-2844.

[22] Yudong Lian, Guobin Ren, Bofeng Zhu, et al. Switchable multiwavelength fiber laser using erbium-doped twin-core fiber and nonlinear polarization rotation [J]. Laser Physics Letters, 2017, 14(5):055101.

[23] Yudong Lian, Jingbo Wang, Mengxin Yang, Yuqin Zhang, and Yuhe Wang. Multiwavelength fiber laser using erbium-doped twin-core fiber and nonlinear optical loop mirror [J]. IEEE Access, 2019, 7:152478-152482.

[24] Tao Zhu, Baomei Zhang, Leilei Shi, et al. Tunable dual-wavelength fiber laser with ultranarrow linewidth based on Rayleigh backscattering [J]. Optics Express, 2016, 24(2):1324-1330.

[25] Qi Qin, Fengping Yan, Yan Liu, et al. Multi-wavelength thulium-doped fiber laser via a polarization-maintaining Sagnac loop mirror with a theta-shaped configuration[J]. Journal of Lightwave Technology, 2021, 39(13): 4517-4524.

[26] Luna Zhang, Fengping Yan, Ting Feng, et al. Switchable multi-wavelength thulium-doped fiber laser employing a polarization-maintaining sampled fiber Bragg grating[J]. IEEE Access, 2019, 7: 155437-155445.

[27] H. Ahmad, M.H.M. Ahmed, M.Z. Samion, et al. All fiber multiwavelength Tm-doped double-clad fiber laser assisted by four-wave mixing in highly nonlinear fiber and Sagnac loop mirror[J]. Optics Communications, 2020, 456: 124589.

[28] Hou-Chang Li, Bin Liu and Qiang Wu, et al. Comparative Study on Sensing Properties of Fiber-Coupled Microbottle Resonators with Polymer Materials [J]. IEEE Sensors Journal, 2021, 21(23):26681-26689.

[29] D. Farnesi, S. Berneschi, and G. Frigenti, et al. Phoxonic glass cavities based on whispering gallery mode resonators [J]. Optical Materials: X, 2021, 12:100120.

[30] Naisi Zhu, Bufan Shi, Yuyang Guo, Bo Han, Ya-nan Zhang Polydimethylsiloxane self-assembled whispering gallery mode microbottle resonator for ethanol sensing[J]. Optical Materials, 2020, 107:110024.

[31] Maxim Bolshtyansky, Spectral hole burning in erbium-doped fiber amplifiers[J]. Journal of Lightwave Technology, 2003, 21(4):1032-1038.