

Wavelength tunable erbium-doped fiber laser based on all-fiber bitaper Mach–Zehnder interferometer incorporating photonic crystal fiber in ring cavity

WEI WEI, YANG WANG, GAOLIN QIN, JUNFA DUAN*

School of Mechanical Engineering, North China University of Water Resources and Electric Power, Zhengzhou 450045, China

The wavelength-switchable and stable erbium-doped fiber laser (EDFL) based on a Mach–Zehnder interferometer (MZI) was designed and experimentally demonstrated. For the proposed fiber laser, a bitaper MZI was manufactured using extrusion splicing photonic crystal fiber (PCF) and single-mode fiber to generate the comb filter effect. In the experiment, an erbium-doped fiber with a length of 3 m was used as the laser gain medium in the cavity. The laser threshold was 95 mW, and a laser output of 1563.06 nm was obtained. Single-wavelength tunable lasing from 1561.22 to 1563.34 nm with a minimum tuning space of 0.08 nm was realized. The power fluctuation was lower than 3.261 dB, and the signal-to-noise ratio (SNR) exceeded 28.535 dB. By tuning the polarization conditions, dual-, triple-, and quadruple-wavelength lasers with power fluctuations lower than 0.23, 2.94, 6.77 dB, respectively, were realized in the experiment. The 3 dB linewidth for the laser was less than 0.06 nm. The results indicate that single-, dual-, triple-, and quadruple-wavelength-tunable lasers can be realized using the proposed fiber laser.

(Received April 7, 2022; accepted December 5, 2022)

Keywords: Erbium-doped fiber laser, Mach–Zehnder interferometer, Wavelength tunable, Photonics crystal fiber

1. Introduction

Wavelength-tunable erbium-doped fiber laser (EDFL) is widely used in optical communications, industrial fabrication, spectrum analysis, and fiber sensing [1–5] owing to its many advantages, such as flexible wavelength tuning capability, high signal-to-noise ratio (SNR), narrow linewidth, and high stability [6–8]. The EDFL has been widely used in the C+L communication wavelength band, making wavelength-tunable EDFL an active research topic.

Recently, a comb filter, nonlinear loop, and special fiber grating were designed to realize wavelength-tunable EDFLs. Chen et al. reported a tunable single-mode erbium fiber laser based on dual-ring Sagnac loops; the power fluctuation was less than 0.9 dB, and the wavelength tuning ranged from 1528 to 1562 nm [9]. Cheng et al. reported a quadruple-wavelength EDFL incorporating chirped fiber grating and Sagnac loop. The narrow linewidth of the proposed fiber laser was less than 0.28 nm, and the SNR exceeded 20 dB [10]. Zhao et al. designed a fused taper fiber-based Mach–Zehnder interferometer (MZI) for multiwavelength EDFL laser generation. The minimum wavelength interval was 0.5 nm, and the SNR was larger than 35 dB [11]. Yan et al. reported a wavelength tunable linear cavity EDFL using Sagnac rings embedded with FBGs. The wavelength tuning range of the

proposed fiber laser was 1.2 nm, the SNR exceeded 52 dB, and single-, dual-, and triple-wavelength lasers could be realized [12]. Guzman–Chavez et al. reported a thermal sensitive filter-based multi-wavelength tunable fiber laser. A sextuple-wavelength emission could be realized, and tuning scope ranged from 1527.52–1534.40 nm [13]. Wang et al. reported a tunable EDFL incorporating double superimposed fiber Bragg grating (FBG). The 3 dB linewidth of this fiber laser was less than 0.02 nm, power fluctuation was less than 1.25 dB, and the maximum tunable range was 5.796 nm [14]. Bender–Perez et al. reported a spherical micro-ball Fabry–Perot interferometer filter for EDFL tunable wavelength laser output. The tunable single laser emission range was 1556.85–1569.72 nm, and the laser linewidth was less than 0.1 nm [15]. Zhou et al. reported a wavelength-tunable EDFL based on polarization hole burning and the Sagnac loop. The linewidth of the designed fiber laser was less than 0.02 nm. Chang et al. reported a ring cavity fiber laser using few mode fiber-based cascaded comb filter for tunable multi-wavelength laser emissions. For this fiber laser, single-, dual-, triple-, and quadruple-wavelength laser outputs could be realized, the SNR exceeded 30 dB and the tuning scope was 10 nm [16].

As mentioned previously, the Sagnac loop, MZI, Fabry–Perot structure, nonlinear effect, fiber grating, and non-optical fiber components are selected as comb filters

to improve the wavelength tuning capability of EDFL. The fabrication procedure of the comb filter is complex and its structure is fragile, making the entire EDFL system is complex. In addition, it is difficult to realize high-resolution lasing wavelength tuning for some of the proposed fiber lasers. The designed comb filter determines the laser-tuning ability. It is crucial to fabricate a compact all-fiber comb filter to improve the fiber laser tuning capability with a high resolution.

In this study, an all-fiber bitapered MZI based on photonic crystal fiber was designed and manufactured, and it was fabricated using extrusion splicing photonic crystal fiber (PCF) and single-mode fiber (SMF), the MZI was used in the L-band EDFL ring cavity. During the experiment, tunable and stable single-, dual-, and triple-wavelength lasers could be realized, and quadruple-wavelength laser outputs were ultimately obtained.

2. Operation principle

A schematic of the designed fiber laser is shown in Fig. 1. The pump power is supported by a laser diode (LD) with a center wavelength of 976 nm, and the pump light is coupled into the L-band erbium-doped fiber (EDF) by a wavelength division multiplexer (WDM). The EDF is adopted as the gain medium. A fiber circulator was selected in the ring cavity to ensure the transmission direction, and a broadband reflection mirror (BRM) was used as a reflector to improve the working efficiency of the fiber laser. The proposed comb filter, PCF-MZI, was inserted into the ring cavity to improve the laser-tuning capability. An optical coupler (OC) was used; 10% of the output export was connected to an optical spectrum analyzer (OSA), and 90% of the export was connected to the WDM to generate a ring cavity structure. A polarization controller (PC) was used to adjust the fiber laser intra-cavity loss.

The principle of the proposed bitapered PCF-MZI is shown in Fig. 1, where the waist-enlarged bitaper structure is fabricated using extrusion splicing PCF and SMF techniques. The input light is transmitted in the core of the SMF and directed into the PCF by taper 1. The higher-order modes are stimulated and transmitted in the core and micro-hole structure of the PCF. The light is coupled into the SMF by taper 2; thus, the MZI structure is realized. Because of different lengths of light transmitting at core and micro-hole parts, the optical path difference, Δl , of light in PCF is generated, and the comb wavelength interval, $\Delta\lambda$, can be expressed as $\Delta\lambda = \lambda^2/n\Delta l$, where n is the core reflection index. For the proposed MZI, the comb filter can be realized. Additionally, the lasers can be generated at the peak position of the comb spectrum after the MZI is inserted into the ring cavity, and the unnecessary modes can be filtered. With a certain erbium doped fiber

gain profile, wavelength adjustable-spacing and number switching can be realized through adjusting PC, because that will result intensity dependent loss of fiber laser, thus, the intra-cavity loss of proposed fiber laser was changed. When the intra-cavity loss is more than the EDF gain, lasers cannot be generated, on the contrary, the lasing wavelength and number of output wavelengths can be restrained.

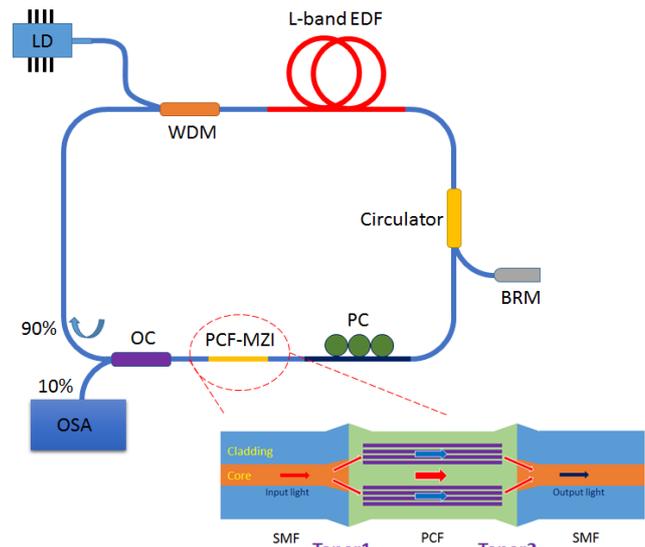


Fig 1. Principle of the proposed EDFL (color online)

3. Experimental results and discussion

In the experiment, the LD center wavelength was 976 nm (Oclaro Co.), which was used to support the pump power; the pigtail fiber of the LD was 9/125 μm . A 4 m long single-mode L-band EDF (EDFL-980-HP, Nufern) was used as the gain medium for the ring cavity. The working wavelength of the WDM was 976/1550 nm, and the circulator, PC, and OC pigtail fibers were in single-mode. The reflection ratio of the BRM was 90%. An OSA (6370, Yokogawa Co.) was used to collect the spectrum signals. The single-mode PCF core and cladding diameters were 9 and 125 μm , and the coating diameter was 245 μm . The all-fiber taper was manufactured using the extrusion-splicing method through a fusion splicer. The SMF and PCF fiber ends were cut flat, then two fibers were fused with an overlap length of 10 μm , and a fiber waist-enlarged taper could be realized. An image of the fiber taper is shown in Fig. 2(a). The cladding part of the taper was 167 μm , and the length of the bitaper was 3.5 cm. The MZI transmitted light source profile is shown in Fig. 2(b). An obvious comb spectrum was generated in the experiment.

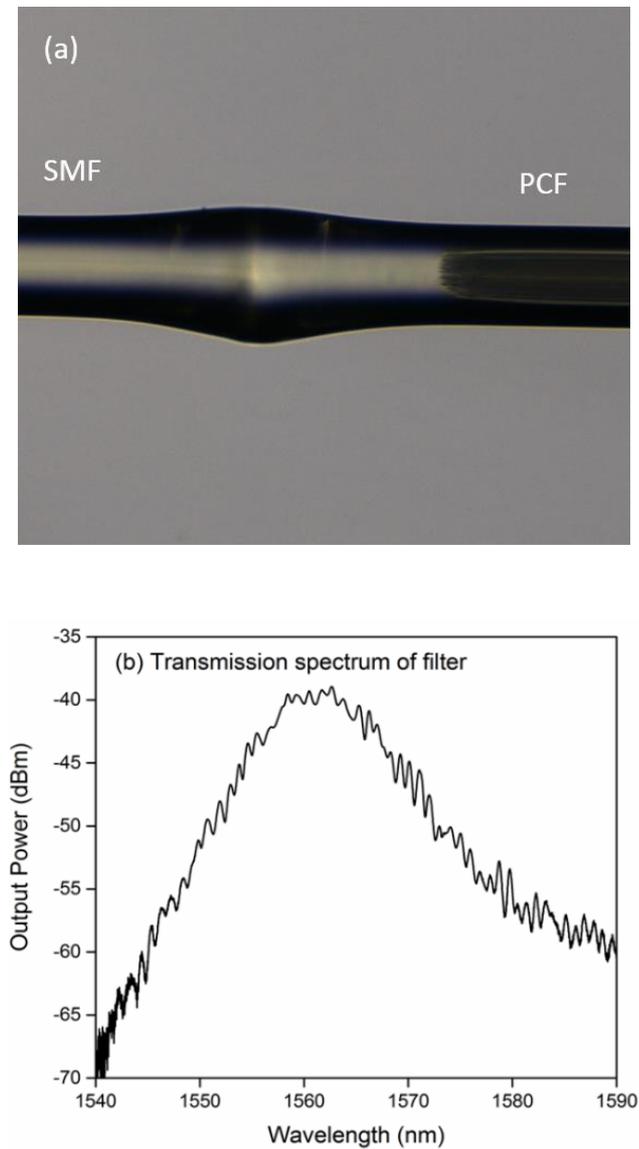


Fig. 2. All-fiber bitaper MZI. (a) Image of the fiber taper; (b) Transmitted light source profile of the MZI

In the experiment, the proposed MZI was inserted into the ring cavity as a comb-filter. When the pump power was 95 mW, a laser emission of 1563.06 nm was obtained. As the pump power increased to 200 mW, the single-wavelength lasing spectrum was obtained, as shown in Fig. 3(a); the SNR is larger than 25.539 dB. The detailed spectrum of the laser is shown in Fig. 3(b). As is evident, the 3 dB linewidth is 0.05 nm.

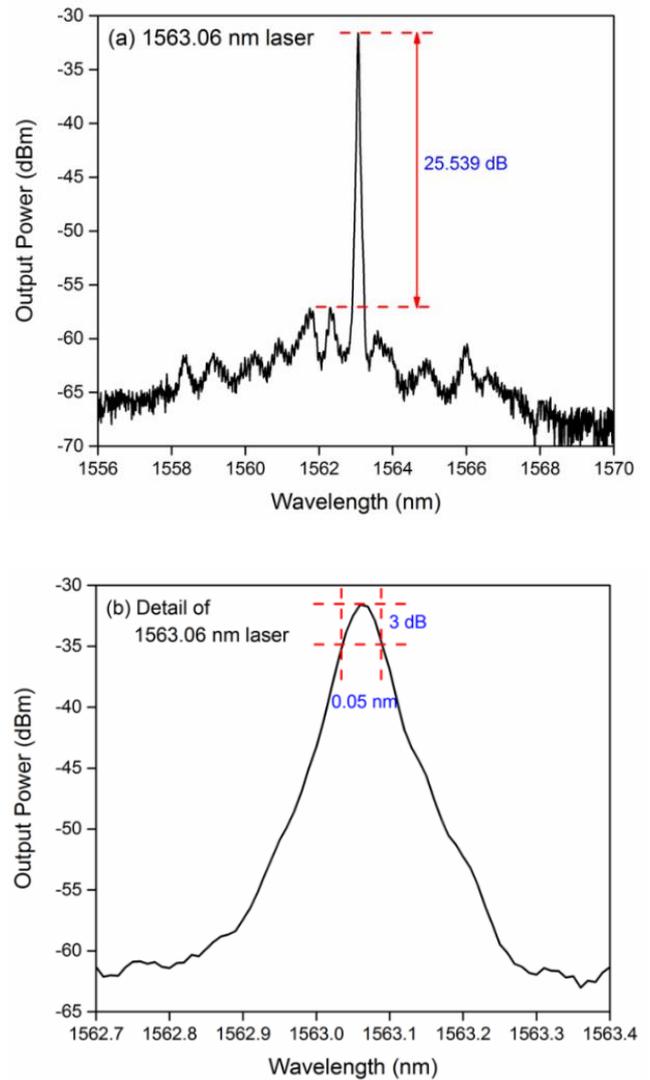


Fig. 3. Laser output of 1563.06 nm. (a) Spectrum ranging from 1556 to 1570 nm; (b) Spectrum ranging from 1562.7 to 1563.4 nm

By adjusting the PC, the intra-cavity loss was changed, and a single-wavelength tunable laser output could be realized. The single-wavelength laser could be tuned from 1561.22 to 1563.34 nm when the pump power was 250 mW and the SNR exceeded 28.535 dB; the spectra are shown in Fig. 4(a). As shown in Fig. 4(b), the minimum laser wavelength spacing is 0.08 nm, and the peak power differences are less than 3.261 dB. For the single-wavelength laser output, the 3 dB linewidth is less than 0.05 nm.

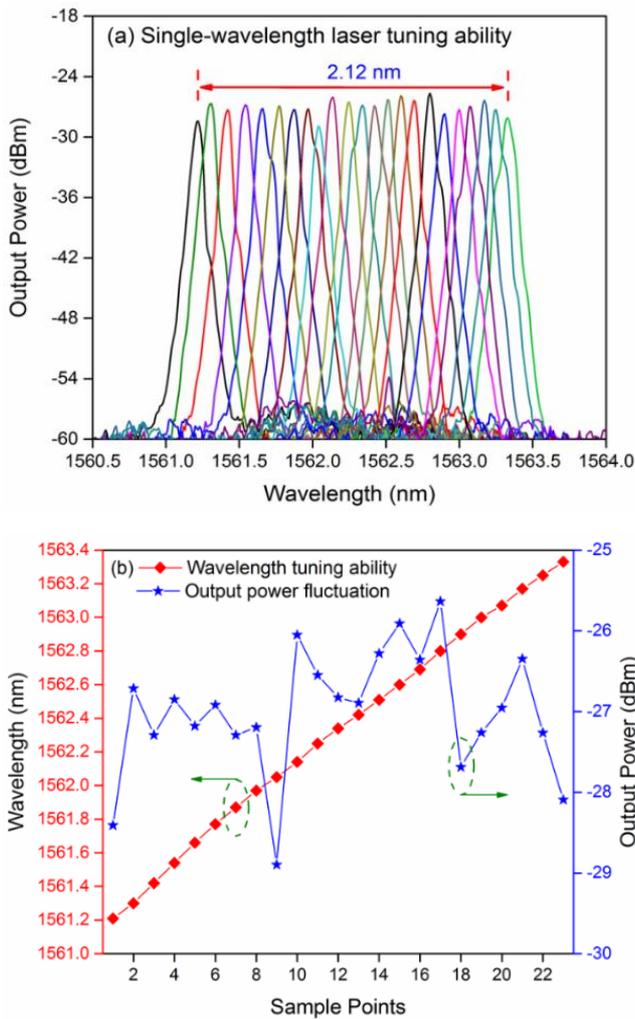


Fig. 4. Tunable single-wavelength lasers realization. (a) 1556.84 nm and 1560.07 nm dual-wavelength laser output, (b) Single-wavelength laser tuning spectrum (color online)

In the experiment, a tunable dual-wavelength laser output was realized by adjusting the PC, and the spectra of four different dual-wavelength laser emissions are shown in Fig. 5, with wavelength spacings of 0.57, 0.76, 1.01, and 1.58 nm. The peak power difference was less than 2.3 dB, and the SNR exceeded 26.132 dB during tuning procedure.

When the pump power was 250 mW, two different groups of triple-wavelength lasers was generated by adjusting PC, as shown in Fig. 6(a). The SNR exceeded 23.07 dB. As is evident from Fig. 6(b), the quadruple-wavelength laser emission was realized, and peak power difference was less than 5.25 dB; the SNR exceeded 20.4 dB. For triple- and quadruple-wavelength lasers, the 3 dB linewidth was less than 0.06 nm.

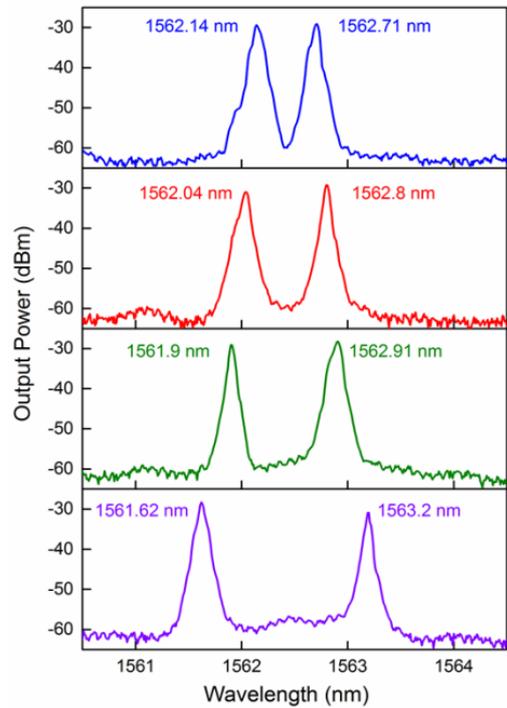


Fig 5. Tunable dual-wavelength tuning output (color online)

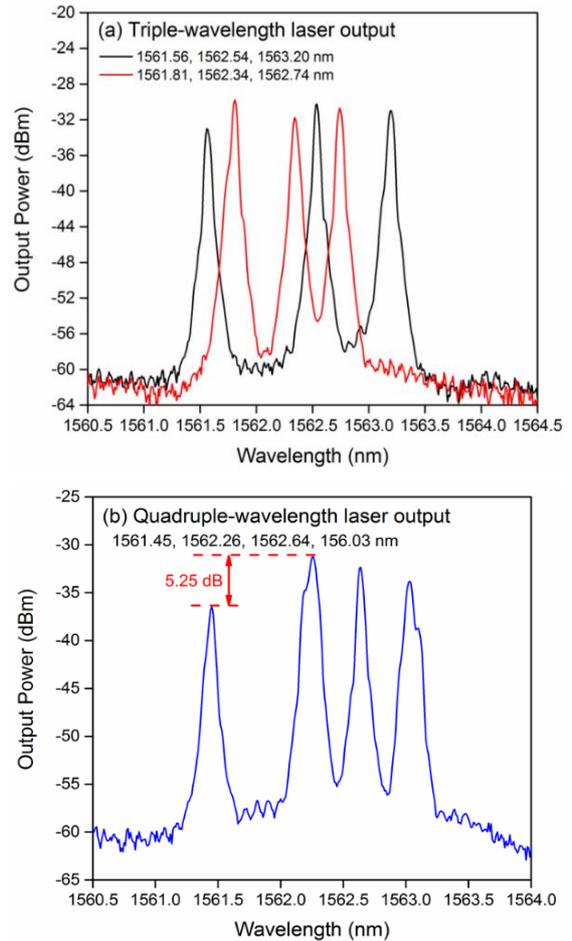


Fig. 6. Tunable triple- and quadruple-wavelength tuning output. (a) Triple-wavelength output; (b) Quadruple-wavelength output (color online)

Subsequently, the laser stability of the single-, dual-, and triple-wavelength laser outputs was tested. For a single-wavelength output of 1562.46 nm, the spectrum stability is shown in Fig. 7(a). During the 16 min monitoring time, the power fluctuation was less than 0.23 dB. For laser outputs corresponding to wavelengths of 1562.14 and 1562.71 nm, the mode shifting was not shown in the monitoring time, and power shifts were less than 1.49 and 2.94 dB respectively, as shown in Fig. 7 (c and d). As shown in Fig. 7(e), stable triple-wavelength laser outputs of 1561.56, 1562.54, and 1563.2 nm were realized, and their peak power fluctuations were 2.32, 3.27, and 6.77 dB, respectively. Owing to the proposed MZI, the single-, dual-,

and triple-wavelength laser stabilities were good at a room temperature of 26 °C. The experiment demonstrated that the ring cavity EDFL based on a bitaper MZI could excite stable and tunable multiwavelength laser outputs.

In the above experiment, the proposed PCF-based bitaper MZI was manufactured and used as a comb filter in the EDFL, which could generate stable single-, dual-, triple-, or quadruple-wavelength laser outputs. In our next study, Fabry-Perot or Mach-Zehnder polarization-maintaining fiber-based comb filter combined with proposed MZI filter will be selected to improve filtering effect for generating high stability laser output.

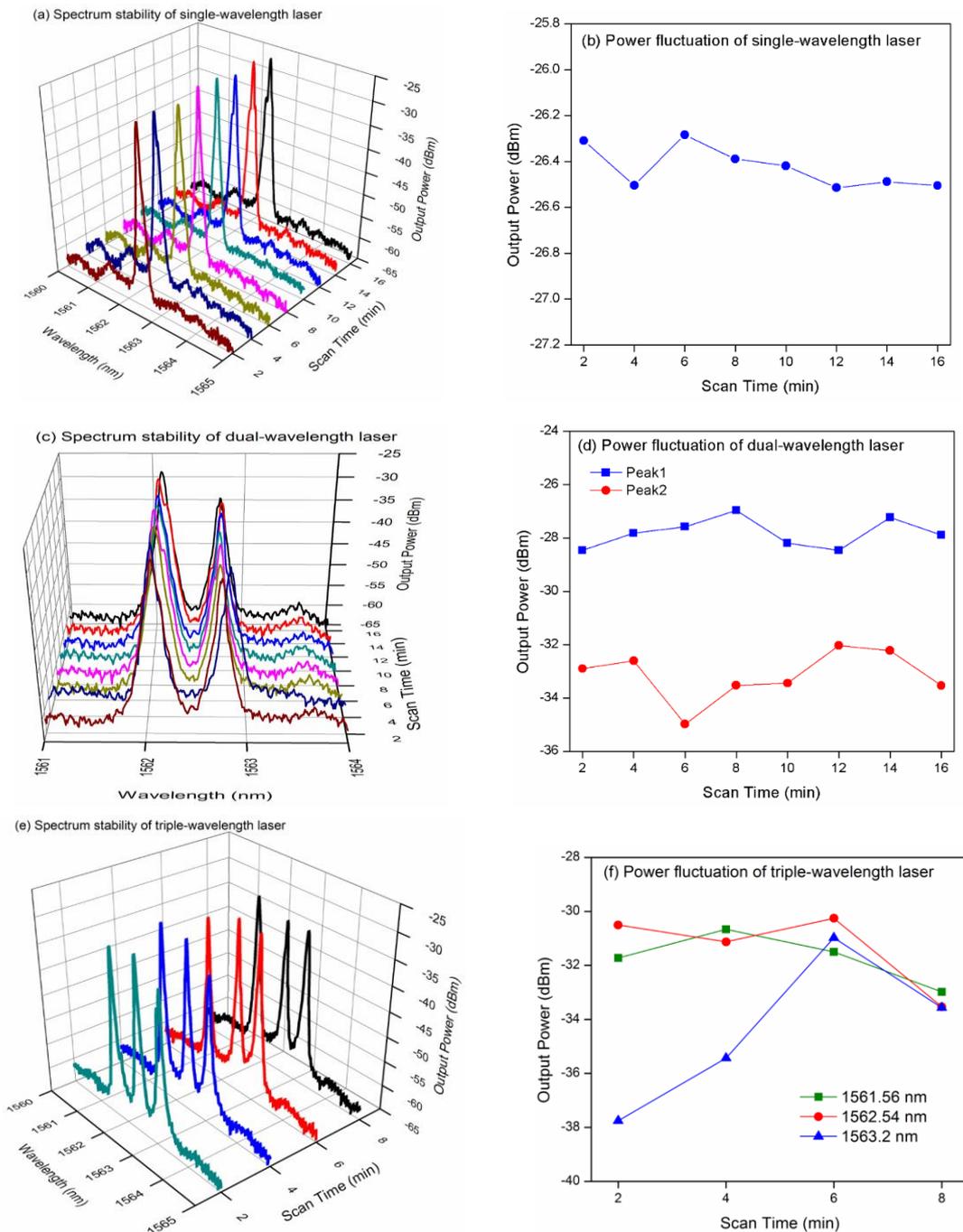


Fig. 7. Stability of laser emission. (a) Single-wavelength spectrum; (b) Single-wavelength power fluctuation; (c) Dual-wavelength spectrum; (d) Dual-wavelength power fluctuation; (e) Triple-wavelength spectrum; (f) Triple-wavelength power fluctuation (color online)

4. Conclusions

In this study, a tunable and stable single-, dual-, and triple-wavelength EDFL based on an all-fiber PCF-based MZI is proposed and experimentally demonstrated. The waist-enlarged bitaper MZI was fabricated using extrusion-splicing PCF and SMF. For the proposed fiber laser, the single-wavelength laser tuning range was 1561.22–1563.34 nm with a minimum tuning space of 0.08 nm. For the tunable dual-wavelength laser output, the wavelength spacing was tuned to 0.57, 0.76, 1.01, and 1.58 nm. The power stabilities for the single-, dual-, and triple-wavelength lasers were less than 0.23, 2.94, and 6.77 dB, respectively, and the 3 dB linewidth is less than 0.06 nm. Additionally, the SNRs exceeded 28.535, 26.132, 23.07, and 20.4 dB respectively. This indicates that the proposed EDFL can produce quadruple-wavelength lasers and exhibits flexible tuning capability and high stability.

Acknowledgements

Funding: This study was supported by the Program of the National Natural Science Foundation of China (grant number 51976012).

References

- [1] J. Q. Cheng, T. B. Wang, G. J. Chen, *Laser Phys.* **31**, id.095102 (2021).
- [2] H. Ahmad, N. F. Azmy, S. N. Aidit, M. Z. Zulkifli, *Microw. Opt. Technol. Lett.* **62**, 3363 (2020).
- [3] Y. Zhang, X. Q. Bu, *Optik* **219**, 165005 (2020).
- [4] K. Gao, Y. Z. Liu, W. C. Qiao, Y. Z. Song, X. Zhao, A. M. Wang, T. Li, *Opt. Lett.* **47**, 5 (2022).
- [5] S. Marrujo-García, L. A. Herrera-Piada, I. Hernández-Romano, D. A. May-Arrijoja, V. P. Minkovich, M. Torres-Cisneros, *Opt. Fiber Technol.* **67**, 102739 (2021).
- [6] J. W. Liu, Z. R. Tong, W. H. Zhang, J. X. Li, Y. T. Li, *Optik* **241**, 167015 (2021).
- [7] H. Q. Merza, S. K. Al-Hayali, A. H. Al-Janabi, *Infrared Phys. Technol.* **116**, 103791 (2021).
- [8] Y. Lu, X. G. Jiang, F. H. Chen, C. L. Lu, S. L. He, *Appl. Sci. Basel* **11**, 2073 (2021).
- [9] Y. C. Chen, C. H. Yeh, W. P. Lin, L. H. Liu, H. S. Ko, Y. T. Lai, C. W. Chow, *Phys. Scripta* **97**, 025501 (2022).
- [10] J. Q. Cheng, W. J. Zheng, Z. F. Liu, J. Q. Zhang, P. G. Yan, *J. Russ. Laser Res.* **42**, 190 (2021).
- [11] Q. Zhao, L. Pei, Z. L. Ruan, J. J. Zheng, J. S. Wang, M. Tang, J. Li, T. Ning, *Chin. Opt. Lett.* **20**, 011402 (2022).
- [12] G. X. Yan, W. H. Zhang, P. Li, Q. H. Jiang, M. Wu, Z. R. Tong, X. Wang, *Laser Phys.* **32**, 075104 (2022).
- [13] A. D. Guzman-Chavez, E. Vargas-Rodriguez, L. Martinez-Jimenez, B. L. Vargas-Rodriguez, *Opt. Commun.* **482**, 126613 (2021).
- [14] F. Wang, Y. K. Liu, W. H. Bi, *Optik* **246**, 167777 (2021).
- [15] C. E. Bender-Pérez, A. A. Castillo-Guzmán, R. I. Alvarez-Tamayo, *Laser Phys.* **31**, 033001 (2021).
- [16] Y. B. Chang, L. Pei, T. G. Ning, J. J. Zheng, J. Li, C. J. Xie, *Opt. Fiber Technol.* **58**, 102240 (2020).

*Corresponding author: duanjunfa@126.com