Wavelength switchable and stable single-longitudinal-mode erbium-doped fiber laser based on Mach–Zehnder interferometer and tunable filter

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**ABSTRACT**

An erbium-doped fiber laser with all-fiber Mach–Zehnder interferometer (MZI) and tunable filter was proposed and experimentally demonstrated. In the designed fiber laser, 6 m C-band erbium-doped fiber was selected as a gain medium; the MZI comprised two waist-enlarged fiber bitapers. In the experiment, the laser threshold was 93 mW, whereas a switchable single-longitudinal-mode laser was realized within 1519.7–1564.6 nm by adjusting the tunable filter and the line interval was less than 2.5 nm; for single-wavelength laser, the peak power difference of each line was less than 4 dB, and the power fluctuation was less than 0.77 dB within 10-min scan time. A stable and switchable dual-wavelength laser was realized, the wavelength spacing of each dual-wavelength laser was less than 0.7 nm, the side-mode suppression ratio was more than 30.2 dB, and the power shift was less than 0.39 dB. The laser’s 3-dB linewidth was less than 0.1 nm.

**KEYWORDS**

Erbium-doped fiber laser; fiber bitaper; interferometer; Mach–Zehnder; single-longitudinal-mode; tunable filter

1. Introduction

Wavelength switchable fiber lasers have attracted significant attention in several fields, such as fiber communications, optical sensors, spectrum analysis, LADAR, and biomedicine, due to their significant advantages, such as single-longitudinal-mode output, narrow-linewidth, flexible tuning ability, stable working condition, high signal-to-noise ratio, and compact structure.\textsuperscript{[1–4]} As one of the current research subjects, the erbium-doped fiber laser (EDFL) can exit C-band lasers, and are used in many applications.\textsuperscript{[5–6]} In recent years, some techniques have been reported to realize wavelength switchable and stable EDFL, such as the Mach–Zehnder interferometer (MZI) based on photonic crystal fiber,\textsuperscript{[7–8]} Lyot–Sagnac filter,\textsuperscript{[9]} nonlinear amplifying loop mirror,\textsuperscript{[10]} hollow-core Bragg fiber,\textsuperscript{[11]} tapered fiber filter,\textsuperscript{[12]} few-mode polarization maintaining fiber loop mirror,\textsuperscript{[13]} no-core fiber,\textsuperscript{[14]} dual-ring structure,\textsuperscript{[15]} closed-loop piezoelectric ceramics,\textsuperscript{[16]} chirped fiber grating,\textsuperscript{[17]} birefringence fiber filter,\textsuperscript{[18]} tunable filter,\textsuperscript{[19]} and twin-core fiber.\textsuperscript{[20]}

As mentioned above, in the wavelength switchable EDFL, the filter was an important component and it influences laser tuning ability. However, all-fiber comb filter manufacturing is...
complex and produces weak results, and a large tuning range cannot be realized easily with the equal intervals of multi-wavelength lasers. Thus, it would be valuable to research methods of realizing stable and tunable multi-wavelength fiber lasers efficiently. The filtering comb spectrum can be realized by the methods of nonlinear effect, non-fiber components, and special optical fibers. This makes the EDFL system complex and expensive; therefore, it is useful to investigate simple and efficient methods for realizing stable and tunable multi-wavelength EDFL. In this study, a wavelength ring cavity EDFL based on MZI with waist-enlarged fiber bitapers and tunable filter is proposed and experimentally verified; in the proposed laser, wavelength switchable, tunable single- and dual-wavelength lasers can be obtained. The proposed EDFL exhibited flexible tuning capability and high stability, as well as potential for application in optical sensors, fiber communication, and spectrum analysis.

2. Experimental setup

The experimental diagram of the proposed EDFL is shown in Figure 1. The designed laser comprised 976 nm pump source, EDF, wavelength division multiplexer (WDM), optical coupler (OC), four ports circulator, polarization controller (PC), tunable filter (TF), and waist-enlarged bitapers MZI. The pump wavelength was coupled into the gain medium by the WDM. In the proposed EDFL, a circulator was used to guarantee the light transmission direction, the four ports circulator constructs a ring structure, and the MZI was inserted into the circulator as a wavelength selector. As shown in Figure 2, the light was input into circulator thought port 1, and exit from port 2, then the light was coupled into MZI and injected into the circulator from port 3, finally the light was coupled into TF, OC, PC, and WDM one after another. The MZI comprised two tapered fibers with the same size, and the maximum stripe contrast of comb filter was realized by adjusting the PC. When the designed MZI filter was used in the EDFL, lasers were generated at the

![Figure 1. Diagram of erbium-doped fiber laser.](image-url)
peak position of the comb spectrum, and wavelength switchable lasers were obtained by adjusting the TF. The optical spectrum analyzer (OSA) connected with the OC was used for output laser collection. A diagram of the proposed MZI is shown in Figure 2(a); the filter comprised two waist-enlarged tapers, the input light was separated into two beams at the first taper and transmitted into the fiber core and cladding simultaneously. Ultimately, the two light beams were concentrated at the second waist-enlarged taper. The comb spectrum wavelength spacing can be calculated using Equation (1), where $\lambda$ is the transmission wavelength, $n$ is the effective core reflection index, and $D_l$ represents different transmission lengths between two beams. The wavelength interval $\Delta \lambda$ is inversely proportional to $D_l$. When waist-enlarged fiber bitapers are used, the prominent adjusting effect can be obtained.

$$\Delta \lambda = \frac{\lambda^2}{n D_l}.$$  

3. Experimental results and analysis

In the experiment, the pump laser’s (Oclaro Inc., USA) center wavelength was 976 nm, and the maximum output power was 500 mW. The EDF’s (EDFC-980-HP; Nufern, USA) absorption coefficient was 3 dB/m. The 2×2 circulator, WDM, and OC were manufactured by the Lightcomm Co., whereas the TF was produced by the Newport Co. First, the comb filter spectrum of the two-tapered MZI was fabricated and measured. In the experiment, the waist-enlarged taper was fabricated by the fiber fusion splicer (Fujikura 60S, Japan). First, two fibers’ end surface were cut flat and put on fiber holder of splicer; then, two fibers’ core alignment mode was used, and fiber overlap length was set as $15 \mu m$ during the splicing process. In the experiment, one taper was obtained and the image is shown in Figure 2(b), after two fibers were fused, the enlarged part of the cladding and core size was 170 and 12 μm, respectively. When the two-taper distance was 3 cm long, the MZI was constructed. As shown in Figure 3, when a broadband light was injected

![Figure 2. Bitapers in-line MZI. (a) Schematic diagram of the MZI; (b) image of one waist-enlarged taper.](image)
into the filter, the transmission comb spectrum was obtained, and a wavelength spacing of 2.5 nm and maximum stripe contrast of 5 dB was obtained. The transmission spectrum of the TF was tested in the experiment and is shown in Figure 4, where the 3-dB linewidth is 1.7 nm. The OSA resolution was 0.1 nm (Yokogawa Co.).

In the experiment, the effect of filter on the output laser was investigated. When the filter was not used in the fiber laser, the laser working threshold was 88 mW, whereas the pump power was 120 mW, and 1539.9 nm single-wavelength laser was obtained by tuning the TF as shown by a black line in Figure 5; the side modes were obvious. When the filter was inserted into the cavity, the laser threshold was improved to 93 mW. When the pump power was 120 mW, the 1539.9 nm laser spectrum is shown by a red line in Figure 5; the side modes were constrained and the laser linewidth was narrow. As shown in Figure 5, the filter had a good filtering effect.

When the pump power was 150 mW, a switchable single-longitudinal-mode laser from 1519.7 to 1564.6 nm was realized by adjusting the TF, the wavelength interval was 2.5 nm, and the tuning
Figure 5. Effect of MZI filter in EDFL.

Figure 6. Single-wavelength tuning. (a) Single-wavelength laser spectrum; (b) tuning linearity and power fluctuation.
process is shown in Figure 6(a); mode jumping was not obvious during laser switching. As shown in Figure 6(b), the tuning linearity was 0.99981, the peak power difference of each laser was less than 4 dB, and the 3-dB linewidth was less than 0.1 nm.

As shown in Figure 7, the proposed EDFL produced 1556.9 and 1557.6 nm dual-wavelength lasers simultaneously by an adjusting process using the PC; when the pump power was 150 mW, the wavelength spacing was 0.7 nm and the side-mode suppression ratio (SMSR) was more than 32.7 dB. A switchable dual-wavelength laser was realized by adjusting the TF; the wavelength
spacing of every dual-wavelength laser was less than 0.7 nm, the side-mode suppression ratio was more than 30.2 dB, and the laser’s 3-dB linewidth was less than 0.1 nm as shown in Figure 8.

In the experiment, the stability of the single-wavelength laser was investigated. As shown in Figure 9(a), when the 1549.4 nm single-wavelength laser was produced, there was no show mode hopping within a 10-min scanning time at 26°C room temperature, and the EDFL exhibited a nice stability; as shown in Figure 9(b), the power fluctuation was less than 0.77 dB. Under the same test condition, when 1539.3 nm single-wavelength laser was achieved, the spectrum stability is shown in Figure 9(c) and the power shift was less than 0.45 dB as shown in Figure 9(d), and the EDFL exhibited outstanding stability. When 1556.9 and 1557.6 nm dual-wavelength lasers

Figure 9. Stability of single- and dual-wavelength laser.
were realized simultaneously, the spectrum stability is shown in Figure 9(e); as shown in Figure 9(f), the power shift was less than 0.28 and 0.39 dB, respectively, at room temperature. In the experiment, 2 hours output power fluctuation was tested, when 1549.4 nm laser was realized and pump power was 150 mW, the single-wavelength output power fluctuation was less than 1.3 dB. For the 1557 and 1557.6 nm dual-wavelength lasers, output power fluctuations were less than 1.49 and 1.73 dB, respectively.

In the above experiment, the designed wavelength switchable EDFL generated stable and continuously tuned single- and dual-wavelength laser output, thereby demonstrating the effectiveness of the proposed EDFL.

4. Conclusion

In this study, a wavelength stable and switchable EDFL based on MZI with waist-enlarged fiber bitapers and TF was proposed and experimentally demonstrated. The single-wavelength laser tuning interval was less than 2.5 nm within 1519.7–1564.6 nm tuning scope, the power difference of each line was less than 4 dB, and the single-wavelength laser power fluctuation was less than 0.77 dB within a 10-min monitoring time. When dual-wavelength lasers were produced, the wavelength interval of each group dual-wavelength was less than 0.7 nm, the SMSR was more than 30.2 dB, and the power fluctuation was less than 0.39 dB. The laser’s 3-dB linewidth was less than 0.1 nm. The proposed EDFL showed flexible tuning capability and high stability, and demonstrated potential for application in optical sensors, fiber communication, and spectrum analysis.

Funding

This work was supported by the Program for Changjiang Scholars and Innovative Research Team in University, PCSIRT [grant number: IRT-16R07]; the Importation and Development of High-caliber Talents Project of Beijing Municipal Institutions [grant number: IDHT20170510]; Young Elite Scientists Sponsorship Program by CAST [grant number: 2017QNRC001]; and QinXin Talents Cultivation Program Beijing Information Science & Technology University [grant number: QXTCP201702].

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