Wavelength-tunable erbium-doped fiber laser based on chirped fiber Bragg grating for stretch sensing applications

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In this study, a linear cavity erbium-doped fiber laser (EDFL) incorporated with a chirped fiber Bragg grating (CFBG) and a Mach–Zehnder interferometer (MZI) for stretch sensing was proposed and demonstrated experimentally. For the designed fiber laser, the dual-stage MZI comprises two 2×2 3-dB optical couplers, with the comb interference period of 0.56 nm. The two reflection ends of the EDFL cavity constitute a CFBG with 99.96% reflectivity and the dual-stage MZI; the laser threshold is 42 mW, and 1555.73-nm single-wavelength lasing was generated. When the pump power was 150 mW, the laser signal-to-noise ratio (SNR) was 35.792 dB and the 3-dB linewidth was 0.09 nm. In the experiment, the CFBG was installed on the adjustable bracket, and the single-wavelength lasing was tuned within the range of 1555.82–1561.35 nm as the CFBG was stretched from 0 to 2.5 mm. For upload and unload stretch procedure, the lasing sensitivity was 2.19 nm/mm, linearity was 0.999, and power shifts were less than 0.138 and 0.176 dB. For lasing stability of 1559.05 and 1555.81 nm, the power fluctuation was less than 0.205 and 0.576 dB, respectively, within 10 min of monitoring time. By adjusting the polarization controller, 1555.74- and 1555.924-nm dual-wavelength lasing was realized, the SNR was more than 40.9 dB, and the peak power difference was 2.38 dB.

1. Introduction

Fiber lasers have been widely used in the fields of optical communications, material detection, spectrum analysis, fiber sensing and industry machining [1-3] because of their numerous advantages such as narrow linewidth, high signal-to-noise ratio (SNR), compact structure, and flexible wavelength tuning capability [4-6]. In recent years, fiber laser sensing techniques have been widely reported. Zhang et al. reported a narrow-linewidth ring cavity erbium-doped fiber laser (EDFL) based on Fabry–Perot (F-P) structure for temperature sensing application; the single-wavelength lasing was tuned in the range of 1573.25–1574.27 nm within 80 °C, and the sensitivity was 12.6 pm/°C [7]. Zhang et al. described an EDFL based on a cascaded Mach–Zehnder interferometer (MZI) for strain sensing, and a single-wavelength laser shift in the range of 1570.22–1559.33 nm [8]. Shi et al. reported an EDFL based on a fiber Bragg grating (FBG) and Sagnac loop for temperature sensing applications, and the resolution was 1.59×10^{-6} °C within the range of 40–80 °C [9]. Liaw et al. reported a fiber ring cavity laser based on an FBG and 1064-nm semiconductor optical amplifier, where the laser was tuned in the range of 1064.76–1075.44 nm [10]. Huang et al. reported an

FBG-based linear cavity fiber laser for temperature sensing applications, with the temperature sensing sensitivity of 15.9 pm/°C in the range of 300–1000 °C [11]. Martin-Vela et al. described an EDFL based on long-period fiber grating (LPFG) for curvature sensing, fabricated via a CO_2-laser processing method; the lasing wavelength emission shifted from 1572 to 1560 nm, and the curvature sensitivity of −42.488 nm/m was achieved [12]. Zhou et al. reported an EDFL based on a cascaded Sagnac loop and F-P for temperature sensing, with the temperature sensitivity of 10.28 nm/°C [13]. Zhang et al. reported a single-wavelength ring cavity EDFL based on photonic crystal fiber (PCF) for acetylene gas sensing, and the calculated R-squared value was 0.993 [14]. Zhang et al. described an EDFL with a single-mode–multimode–single-mode interferometer structure for hydrogen sensing, with the sensitivity of 1.23 nm/% in the concentration range of 0%–1% [15]. Sun et al. reported dual-wavelength fiber lasers based on a multimode interferometer and parallel FBGs for liquid level and temperature sensing applications, and the sensitivity values were 155.77 pm/mm/RIU and 13.8 pm, respectively [16].

As mentioned above, narrow-linewidth fiber lasers for temperature, strain, stretch, and gas sensing applications can be realized using techniques such as Sagnac

interferometer, MZI, F-P, LPFG, mismatch fiber structure, and PCF. The fiber laser spectrum characteristics are determined by the filter components, and a better filtering effect is difficult to realize with a flexible interferometer comb spectrum. Thus, it is important to establish an EDFL to realize lasing sensing applications. As a significant fiber grating, chirped FBGs (CFBGs) are widely used in the fields of fiber sensing, dispersion compensation, and optical filtering owing to the advantages of wide grating spectrum, high reflectivity, varied periods, and low loss. However, the use of a CFBG as a fiber laser wavelength selector for laser sensing applications has rarely been reported. In our study, a narrow-linewidth EDFL incorporated with a CFBG and dual-stage MZI was designed, and its stretch sensing characteristics were demonstrated experimentally.

For wavelength tunable fiber laser, comb fiber is an important component to improve laser tuning capability. For the proposed fiber laser, in order to realize narrow linewidth single-wavelength emission, all-fiber Mach-Zehnder interferometer (MZI) was used in the cavity. Our research on single-wavelength EDFL based on CFBG and dual-stage MZI has not yet been reported. In this study, the wavelength comb filter was manufacutred by MZI, and CFBG was used as reflector. The single-wavelength linear cavity fiber laser based on MZI filter and CFBG was proposed and demonstrated experimentally. Our proposed EDFL for narrow linewidth laser output was obtained, and stretch sensing applications were also realized.

2. Experimental setup

A diagram of the proposed ring cavity EDFL based on the CFBG and dual-stage MZI is shown in Fig. 1. The pump light is generated by a 976-nm laser diode and coupled into the gain medium by a wavelength-division multiplexer. The CFBG with a high reflectivity ratio was selected as one of the laser cavity ends, while the other reflector end comprises a dual-stage MZI. The proposed MZI is manufactured using two 2×2 3-dB optical couplers (OCs). A polarization controller (PC) was used to adjust the intra-cavity loss, and an optical spectrum analyzer was used to collect the output laser. As the EDFL lasing wavelength selector, the CFBG is fixed on the adjustable bracket for stretch sensing, the CFBG period changes as the grating is stretched, thus the lasing wavelength can be tuned simultaneously.
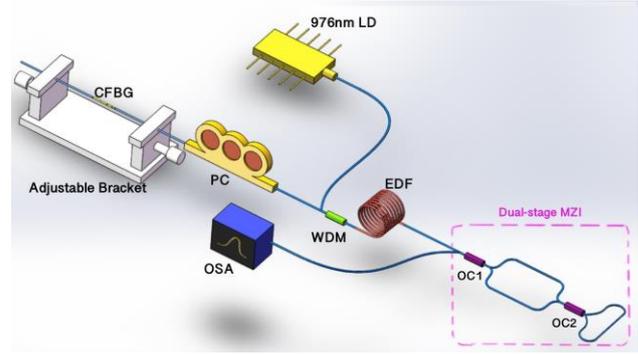

Fig. 1. Diagram of the proposed erbium-doped fiber laser (EDFL) based on a chirped fiber Bragg grating (CFBG) and Mach–Zehnder interferometer (MZI). (LD: laser diode, PC: polarization controller, WDM: wavelength-division multiplexer, OSA: optical spectrum analyzer, OC: optical coupler) (color online)

As shown in Fig. 1, the input light of the dual-stage MZI comb filter is separated into two arms along the single-mode fiber by OC1, which then converge by OC2. The two output pigtail fibers of OC2 were spliced to yield a dual-pass MZI configuration. For the MZI, the interfering power can be expressed by Equation (1). Where I_1 and I_2 mean modes intensities propagating in two beams respectively, and φ means the phase difference between I_1 and I_2. Where φ can be calculated by Equation (2)

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\varphi \qquad (1)$$

$$\varphi = \frac{2\pi n \Delta L}{\lambda} \qquad (2)$$

The MZI wavelength period can be expressed by Equation (3), where λ is the transmission wavelength, n is the effective core reflection index, and ΔL is the length difference between the two MZI arms. The wavelength period interval $\Delta\lambda$ is inversely proportional to ΔL. Compared with single-pass MZI, dual-pass MZI can exhibit half-wavelength spacing and has a superior filtering effect. Hence, we used the MZI as a comb filter in the proposed EDFL for better filtering.

$$\Delta\lambda = \frac{\lambda^2}{n\Delta L} \qquad (3)$$

In previous studies, narrow linewidth EDFL could be realized; however, fiber lasers incorporating CFBG for fiber sensing have not yet been reported. In order to realize narrow linewidth single-wavelength laser emission for stretch sensing, an all-fiber dual-stage MZI and one CFBG were used in the fiber laser cavity.

3. Experimental results and discussion

As shown in Fig. 1, the EDFL experimental system was constructed, and the pigtail fiber size of the fiber components of 9/125 μm and 4-m-long EDF was the same as those used as the gain medium. First, the single-stage MZI transmission and dual-stage MZI reflection spectra were measured and analyzed. As shown in Fig. 2, after the two OCs were fused, an abundant filtering effect was achieved, and the single-stage MZI comb spectrum interferometer interval was 1.12 nm. Compared with the single-stage MZI transmission spectrum, the dual-stage MZI comb filtering effect is intensive, and the spectrum interferometer interval is 0.56 nm. The proposed MZI has an excellent interference effect and can be used as a comb fiber in EDFL.
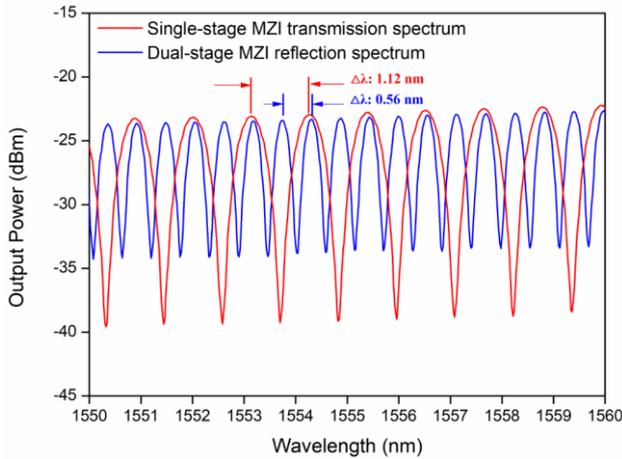
Fig. 2. Spectra of proposed MZI (color online)

When two reflection loops based on the 3-dB OC were used as the two ends of the linear laser cavity, the lasing spectrum details were collected, as shown in Fig. 3(a), numerous lasing modes were generated, and single-wavelength lasing could not be realized. In the experiment, the CFBG was fabricated by ultraviolet excimer laser through phase mask (Ibsen Co.) grating inscription technique. The CFBG reflectivity was 99.96%, the center wavelength and bandwidth were 1551.299 and 12.657 nm, respectively, and the transmission and reflection spectra are shown in Fig. 3(b). Then, the CFBG and MZI were inserted in the linear cavity EDFL to generate a stable single-wavelength laser output, as shown in Fig. 1. When the pump power was 42 mW, a 1555.73-nm single-wavelength laser was realized in the experiment. When the pump power was improved to 150 mW, as shown in Fig. 3(c), the lasing SNR was 35.792 dB, and the comb interferometer effect was apparent. Compared with lasing without CFBG and MZI, the lasing 3-dB linewidth is 0.09 nm, its spectrum detail is shown in Fig. 3(d), and a single-wavelength narrow-linewidth laser output was obtained experimentally.
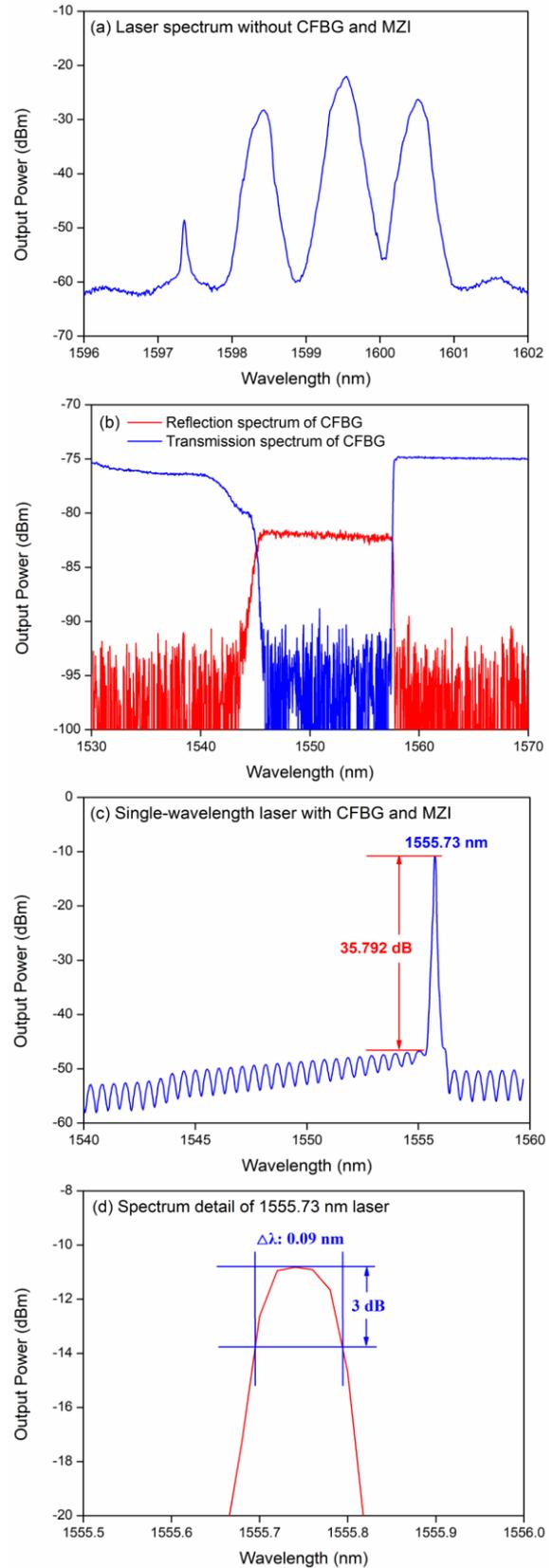
Fig. 3. Single-wavelength laser generation. (a) Laser generation without MZI and CFBG; (b) Spectrum of CFBG; (c) 1555.73- nm laser output; (d) 3-dB linewidth spectrum detail of 1555.73-nm laser (color online)

In the experiment, the single-wavelength laser stretch sensing characteristics were investigated when the pump power was 150 mW. During the 0–2.5-mm length stretch upload procedure, the laser wavelength was tuned from 1555.82 to 1561.35 nm, and the laser spectrum is shown in Fig. 4(a); mode jumping was not serious in the experiment. As shown in Fig. 4(b), the lasing sensitivity was 2.19 nm/mm, linearity was 0.999, and power shift was less than 0.138 dB. The stretch unload characteristic was tested and

the laser tuning spectrum is shown in Fig. 4(c); the wavelength was tuned from 1555.81 to 1561.35 nm. As shown in Fig. 4(d), the unload sensitivity was -2.19 nm/mm, linearity was 0.999, and power shift was 0.176 dB. During the stretch tuning procedure, the laser SNR was more than 37.648 dB. As shown in Fig. 4, the proposed single-wavelength EDFL has excellent stretch sensing capability.
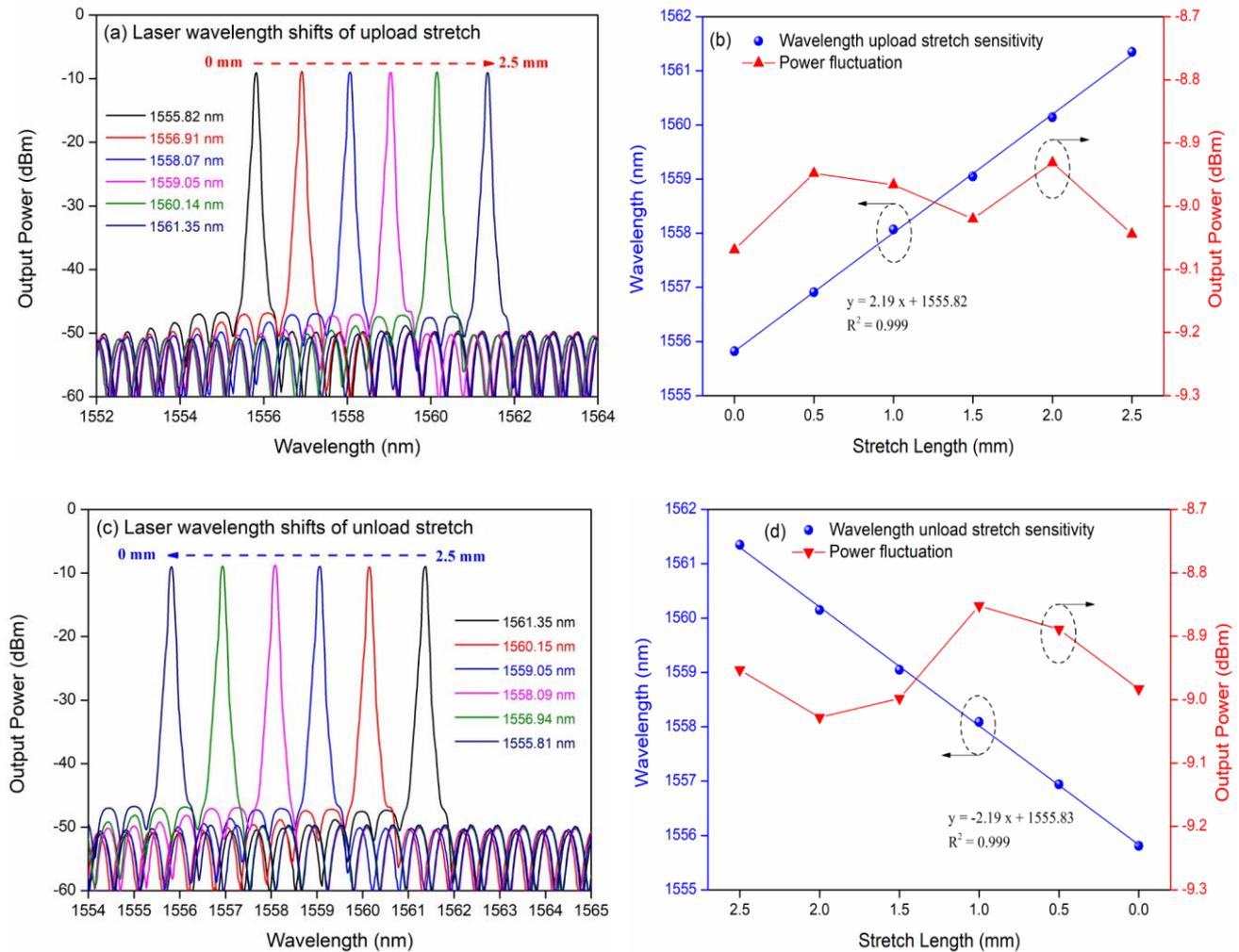

Fig. 4. Single-wavelength laser stretch sensing ability. (a) Upload stretch sensing spectrum; (b) Upload stretch sensitivity and power fluctuation; (c) Unload stretch sensing spectrum; (d) Unload stretch sensitivity and power fluctuation (color online)

In the experiment, the single-wavelength lasing output power stability was measured within 10 min of monitoring time by adjusting the stretch length. For the 1,559.05-nm laser output, as shown in Fig. 5(a), mode jumping was not apparent in the experiment, and the power fluctuation was less than 0.205 dB, as shown in Fig. 5(b).

Meanwhile, for the 1555.81-nm laser output, as shown in Fig. 5(c), the laser output was stable, and the power fluctuation was less than 0.576 dB, as presented in Fig. 5(d). Thus, as shown in Fig. 5, the proposed EDFL based on the CFBG and dual-stage MZI has excellent stability.

(a) Stability of 1559.05 nm single-wavelength laser

(b) Power fluctuation of 1559.05 nm single-wavelength laser
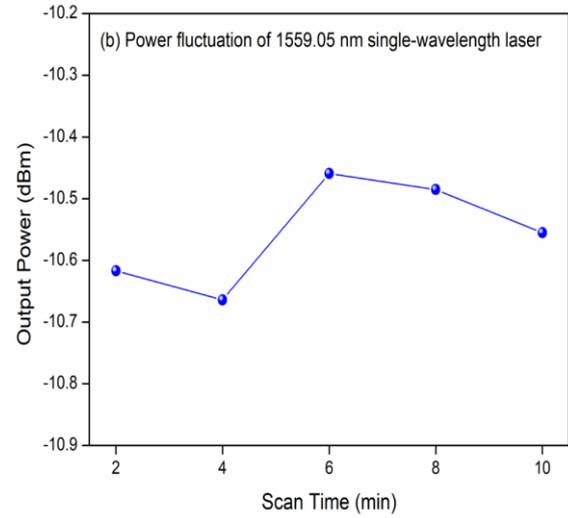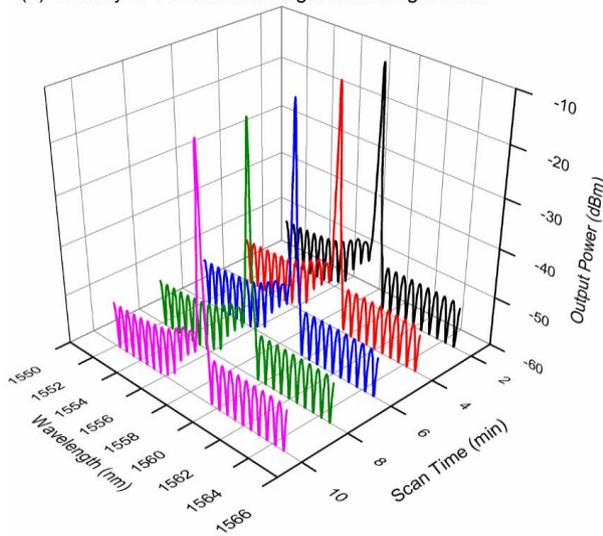
(c) Stability of 1555.81 nm single-wavelength laser

(d) Power fluctuation of 1555.81 nm single-wavelength laser
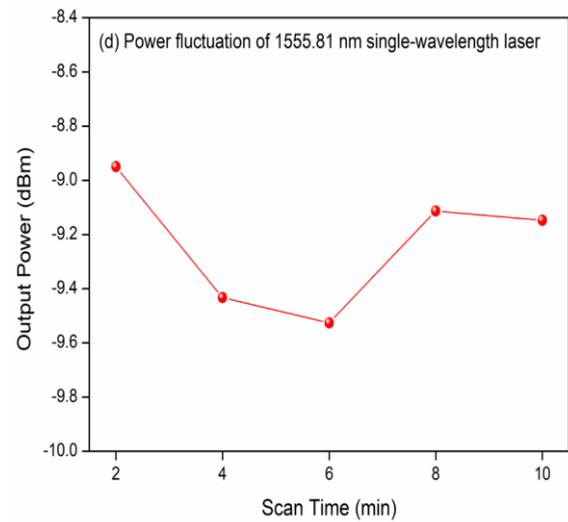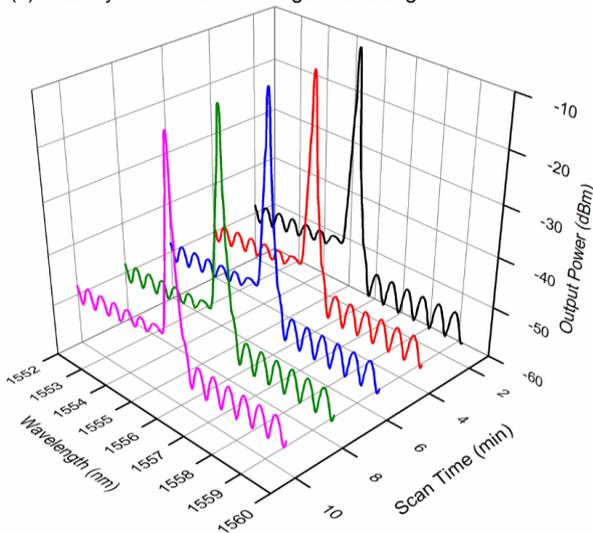
Fig. 5. Stability measurements of single-wavelength laser. (a) Stability spectra and (b) Power fluctuation of 1559.05-nm lasing; (c) Stability spectra and (d) Power fluctuation of 1555.81-nm lasing (color online)

In the experiment, a dual-wavelength laser output was realized by adjusting the PC due to polarization hole burning effect. When the intra-cavity loss is greater than the gain, the lasers cannot be generated, which will finally result changes of output wavelengths numbers. As shown in Fig. 6, 1555.74- and 1555.924-nm dual-wavelength lasing outputs were generated. The SNR was more than 40.9 dB, peak power difference of two lasing lines was 2.38 dB, and 3-dB linewidth was less than 0.09 nm.


Dual-wavelength laser output

1555.74 nm

2.38 dB

1555.924 nm
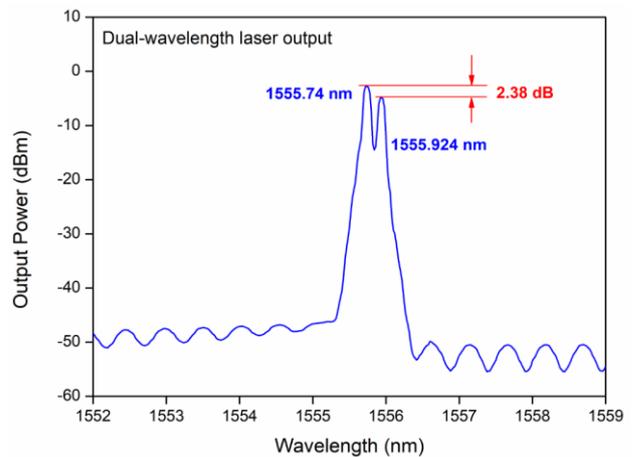
Fig. 6. Spectrum of dual-wavelength lasing output (color online)

In the above experimental demonstration, the proposed EDFL based on CFBG and MZI was realized, and a single-wavelength laser stretch sensing application was realized.

4. Conclusions

In this study, a narrow-linewidth EDFL constituting a CFBG and MZI was accomplished. The proposed dual-stage MZI comb filter interferometer was used to improve filtering effect, and the period was 0.56 nm. For the proposed EDFL, the laser working threshold was 42 mW, and single-wavelength laser stretch sensing application was realized within the length of 2.5 mm; the wavelength was tuned from 1555.82 to 1561.35 nm, the laser SNR was more than 37.648 dB, and the 3-dB linewidth was 0.09 nm. During the upload and unload stretch sensing procedure, the laser sensitivity was 2.19 nm/mm, linearity was 0.999, and power difference was less than 0.176 dB. For the single-wavelength laser output, the power fluctuation was less than 0.576 dB during a 10-min monitoring time. For the designed fiber laser, the dual-wavelength laser output could be realized by adjusting the PC, and the SNR was more than 40.9 dB. The proposed EDFL based on CFBG and dual-stage MZI shows excellent tuneable and stretch sensing capabilities, the narrow linewidth single-wavelength was realized, and can be widely used in fiber communication, fiber sensing, and spectral analysis.

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