

# Single-Longitudinal-Mode Erbium-Doped Fiber Laser with Novel Scheme Utilizing Fiber Bragg Grating inside Ring Cavity<sup>1</sup>

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**Abstract**—In this paper, we experimentally investigate a single-longitudinal-mode (SLM) S-band erbium-doped fiber (EDF) laser with dual-ring scheme using a S-band fiber Bragg grating (FBG) inside the gain cavity to restrict the lasing mode. The proposed laser is constructed by two-ring cavities serving as the mode filters. The FBG inside the proposed laser scheme can retrieve the SLM operation. Moreover, the output performance of the proposed fiber laser is also analyzed and discussed.

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## 1. INTRODUCTION

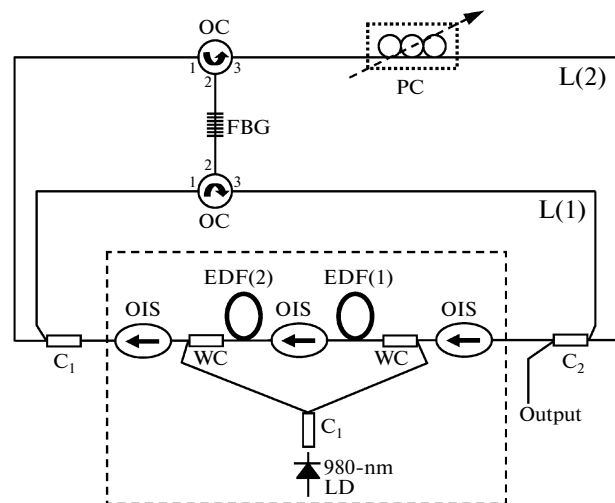
Recently, broadband wavelength-tunable fiber ring lasers are very attractive light sources, operating in the wavelength ranges of S- (1480–1520 nm), C- (1530–1560 nm), and L-bands (1560–1620 nm). They can be used in many applications, such as the high-resolution spectroscopy, passive component measurement, fiber sensor network, and wavelength division multiplexing (WDM) system backup source [1–3]. However, the fiber ring laser may have mode-hopping leading to multi-mode output due to the longer cavity length and very narrow longitudinal mode-spacing [1]. Generally, the filters are used inside the gain cavity of ring laser for lasing single-longitudinal-mode (SLM) output, such as using fiber Bragg grating (FBG), Fabry–Perot etalon filter, or fiber ring scheme filter etc. [4–7]. Moreover, the SLM fiber ring laser using saturable-absorber has also been studied to overcome the limited spectral width of the mode selection filters inside the gain cavity [8, 9].

In this study, we propose and investigate a SLM S-band erbium-doped fiber (EDF) laser with a novel ring scheme using a FBG inside the gain cavity to restrict the lasing mode. The proposed laser is constructed by two-ring cavities serving as the mode filters. By using a FBG inside the proposed laser scheme, it will retrieve the lasing wavelength at SLM. Besides, the output performance of proposed fiber laser is also discussed. Compared with our past research [10], this work doesn't need to use a shorter unpumped EDF to filter the side-mode to achieve a SLM output. In this new

proposed fiber scheme, we only use simple two-ring architecture obtaining the SLM operation.

## 2. EXPERIMENT AND DISCUSSION

Figure 1 shows the experimental setup of the proposed EDF ring laser scheme. The proposed laser is consisted of an S-band EDFA, a 1 × 2 and 50 : 50 cou-



**Fig. 1.** Proposed erbium-doped fiber ring laser scheme.  $C_1$ : 1 × 2 optical coupler;  $C_2$ : 2 × 2 optical coupler; OC: optical circulator; WC: 980/1550 nm WDM coupler; PC: polarization controller; OIS: optical isolator; EDF: erbium-doped fiber; FBG: fiber Bragg grating.

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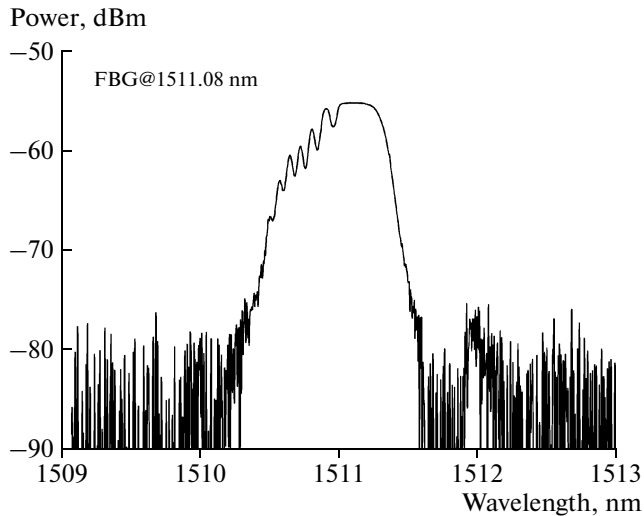


Fig. 2. Reflective spectrum of the S-band FBG at 1511.08 nm.

pler ( $C_1$ ), a  $2 \times 2$  and 50 : 50 coupler ( $C_2$ ), a FBG with the central wavelength and reflectivity of 1511.08 nm and 91% respectively, two optical circulators (OCs), and a polarization controller (PC). The  $C_1$  and  $C_2$  are used to produce to two ring scheme, as shown in Fig. 1, and the FBG is used to connect the two ring cavities via two OCs. The PC is adjusted to obtain the maximum output power and maintain the polarization state. The S-band amplifier in the experiment, with a depressed-cladding design and 280 mW pumping power, can generate the EDF gain bandwidth in the S-band window [3]. The EDF lengths of the first and second amplifier stages are 20 and 30 m long. Thus, the gain and noise figure of EDFA can reach to 32.0 and 5.7 dB at 1500 nm for input power of 25 dBm, and the saturated output power at 1500 nm can be up to 14 dBm for input power of 0 dBm. In this experiment, an optical spectrum analyzer (OSA) with a 0.05 nm resolution and a power meter (PM) are used to measure the output spectrum and output power of the proposed ring laser.

The FBG not only determines a lasing wavelength but also serves as a mode-restricting component to provide the first restriction on the possible laser modes. Figure 2 shows the reflective spectrum of FBG used at the wavelength of 1511.08 nm. Due to the combination of a FBG and proposed two ring cavities, a SLM operation in the proposed laser can be guaranteed. It is significant that the two cavities ( $L_1$  and  $L_2$ ) are served as the mode filters, as seen in Fig. 1. The two fiber cavities have the free spectral ranges (FSRs),  $FSR = c/nL$ , where  $c$  is the light speed in vacuum,  $n$  is the average refractive index of the single-mode fiber (SMF) of 1.468, and  $L$  is the fiber cavity length. In the proposed laser scheme, the cavity lengths of  $L_1$  and  $L_2$  are 54.6 and 56.5 m long. Here, the two corresponding

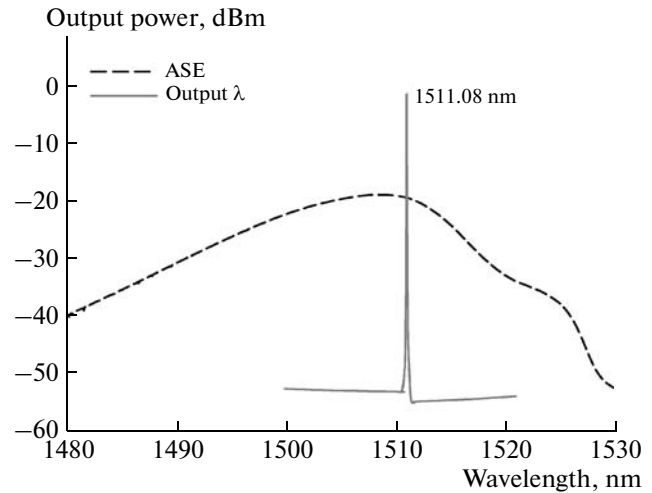


Fig. 3. Output ASE spectrum of original S-band EDFA and the lasing wavelength of proposed fiber laser at 1511.08 nm.

FSRs of ring cavities will be 3.74 and 3.61 MHz respectively. In order to realize the SLM selection of proposed fiber laser, the lasing output performance could be measured by the self-homodyne detection. The optical circuit for a measurement is consisted of a photodetector (PD) with 3 dB bandwidth of 10 GHz and a Mach–Zehnder interferometer with about 20 km long SMF.

For the laser measurement, Fig. 3 presents the original output amplified spontaneous emission (ASE) spectrum (blue dash line) of S-band EDFA used under the effective operating bandwidth of 1480 to 1520 nm. In the experiment, as seen in Fig. 1, the lasing mode can oscillate at the wavelength of

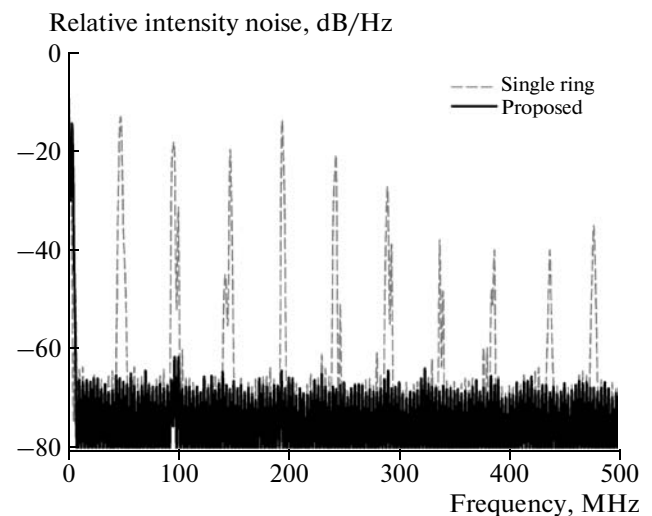


Fig. 4. Detected homodyne frequency spectra of the proposed laser using single ring and dual-ring schemes.

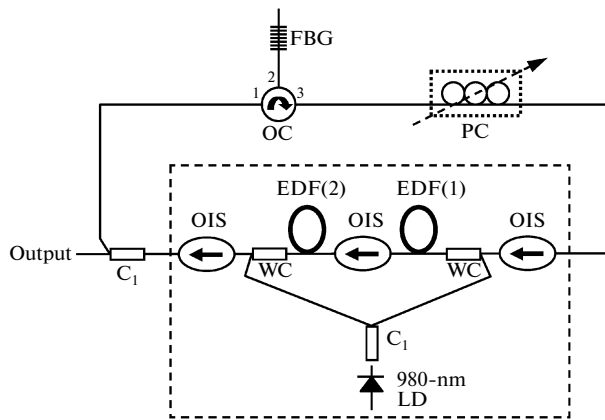


Fig. 5. Traditional single-ring scheme EDF ring laser architecture.

1511.08 nm (red solid line) when the S-band FBG is utilized in ring cavity, as also illustrated in Fig. 3. The output power and side-mode suppression ratio (SMSR) of the lasing wavelength are measured at  $-1.1$  dBm and 47.8 dB. In the proposed EDF ring laser scheme, if we want to obtain different lasing wavelengths, we can use a wavelength-tunable FBG to replace the wavelength-fixed FBG for lasing mode tuning.

As shown in Fig. 1, when the fiber cavity L1 and OC<sub>1</sub> are removed in the proposed laser scheme, the laser would result in the mode-hopping. Therefore, Fig. 4 shows the detected self-homodyne frequency spectrum of the proposed laser at the wavelength of 1511.08 nm without the first ring cavity (L1), producing a noisy and unstable output signal due to the mode-hopping, as seen in the dash line of Fig. 4. The behavior of mode-hopping can be affected by the environment disturbances of temperature and vibration. Here, when the proposed fiber laser scheme is used in the experiment, the SLM oscillation is much easier to achieve compared with traditional single-ring laser scheme, as illustrated in Fig. 5. Clearly, no beating noises are observed in RIN spectrum of the proposed laser which indicates that single frequency oscillation can be retrieved, as illustrated in solid line of Fig. 4. Thus, Fig. 4 presents a stable SLM output spectrum with side mode suppression in the measuring bandwidth of 500 MHz. In addition, after an hour observation, no spike noise and stable frequency output are observed in the RF spectrum of the proposed fiber laser.

In order to investigate the stabilities of output power and wavelength in the proposed fiber laser structure, a short-term stability of the proposed ring laser is experimented and measured as shown in Fig. 6. Here, the observation time is over 30 minutes at the lasing wavelength of 1511.08 nm with  $-1.1$  dBm out-

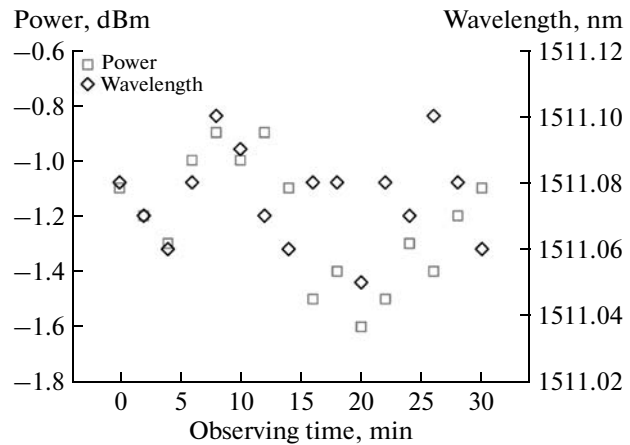


Fig. 6. Output variations of power and wavelength of the proposed ring laser at the lasing wavelength and power of 1511.08 nm and  $-1.1$  dBm initially.

put power. The output variations of power and wavelength are observed of  $<0.5$  dB and  $<0.04$  nm, respectively. Moreover, during the observation time of 60 min, the output stability of the proposed fiber laser is still kept and maintained. Furthermore, for the past studies [10–17], either they used the Brillouin pump (nonlinear effect), intra-core FBG or saturable-absorber-based filter to complete the SLM operating. However, our fiber laser only use a simple dual-ring fiber cavity design to guarantee a SLM output. Hence, the proposed fiber laser not only has simple design but also has cost-effectiveness.

### 3. CONCLUSION

In summary, we have proposed and demonstrated a single-longitudinal-mode (SLM) fiber grating-based S-band erbium-doped fiber laser with passive two ring cavities, which serve as mode filters. While a fiber Bragg grating (FBG) is used inside the proposed laser scheme, the output lasing wavelength can be guaranteed in a SLM oscillation. In the experiment, the fiber laser effectively suppresses side-mode frequencies of 0.5 GHz and provides an output power of  $-1.1$  dBm with a side-mode suppression ratio (SMSR) of 48.7 dB/0.05 nm at the wavelength of 1511.08 nm. Moreover, the power fluctuation of less than 0.5 dB and the central wavelength variation of less than 0.04 nm are observed for lasing SLM wavelength.

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