IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 11, 2019, accepted July 4, 2019, date of publication July 16, 2019, date of current version July 26, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2927419

A Selectable Single-Mode Erbium Laser With Power-Flattened Output Employing Dual-Sagnac-Ring

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This work was supported in part by the Ministry of Science and Technology, Taiwan, under Grant MOST-107-2221-E-035-055 and Grant MOST-108-2221-E-035-072, and in part by the Chang Gung University, Taiwan, under Grant BMRP-740.

ABSTRACT To achieve wavelength-selectable and stable erbium-doped fiber (EDF) laser, a dual-Sagnac-ring configuration is designed to reach single-longitudinal-mode (SLM) oscillation and power-flattened output simultaneously. The presented and experimentally demonstrated EDF laser can also obtain the output power of 7.5 to 11.8 dBm in the continuous-wave (CW) tunability of 1523.0 to 1571.0 nm. Here, the power variation of lasing wavelength can be below than 1.0 dB over a wide working range of 1525.0–1565.0 nm for power-flattened output. Moreover, the 3-dB spectrum linewidth of presented EDF-based laser is measured in the range of 16.4–22.2 kHz via the Lorentzian fitting.

INDEX TERMS Fiber laser, erbium-doped fiber (EDF), single-longitudinal-mode (SLM), sagnac-ring.

I. INTRODUCTION

In the near future, erbium-doped fiber (EDF) based lasers have interested great considerations in keeping with its huge applications in optical sensor, optical communication, wavelength division multiplexing (WDM), millimeter-wave photonic, biophotonics, and spectroscopy [1]–[4]. Practically, the homogeneous broadening and spatial-hole-burning effect of EDF and a long loop cavity in EDF-based laser leads to unstable multi-longitudinal-mode (MLM) oscillation [5]. To obtain the stable continuous-wave (CW) tunability and single-longitudinal-mode (SLM) in EDF based laser, there are several related researches have been proposed to suppress the densely MLM noises, such as using compound-ring configuration [6], [7], employing Rayleigh backscattering in tapered fiber [8], applying EDF-based saturation absorber (SA) [9], designing optical self-injection technique [10], [11], utilizing Sagnac-ring architecture [12], [13] and employing Mach-Zehnder interferometer [14]. Moreover, to achieve CW wavelength-tunability, fiber Bragg grating [15], tunable bandpass filter (TBF) [16], Fabry-Perot tunable filter (FP-TF) [17] and acousto-optic tunable filter (AO-TF) [18] could be applied inside the cavity of EDF based laser for adjusting. In general, to obtain flattened output power, adjusting the bias current of pumped power, utilizing variable optical attenuator (VOA) and applying proper gain-medium in EDF laser architectures have also been studied [19], [20].

In the work, to achieve the flattened output power and SLM oscillation, a dual-Sagnac-ring scheme is proposed and used in EDF based laser. From the experimental results, the output power of 7.5 to 11.8 dBm and optical signal to noise ratio (OSNR) of 30.2 to 38.2 dB are also obtained in the presented EDF based laser. The flatter output power of 10.8 to 11.8 dBm (1.0 dB power variation) in 40 nm wavelength bandwidth from 1525.0 to 1565.0 nm can be reached. Moreover, the obtained output fluctuations of power and central wavelength are also maintained within 0.1 dB and 0.04 nm under the same wavelength range during 60 minutes observation. Here, the Lorentzian 3 dB linewidth of 16.4 to 22.2 kHz is obtained. As an experimental result, the presented dual-Sagnac-ring configuration can obtain SLM operation and flattened power output.

The associate editor coordinating the review of this manuscript and approving it for publication was Nianqiang Li.

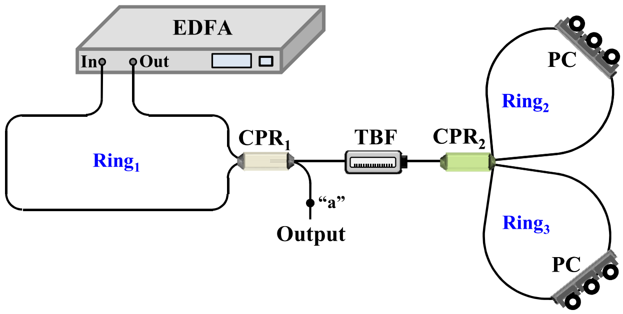

FIGURE 1. Schematic of presented wavelength-selectable EDF dual-Sagnac-ring laser.

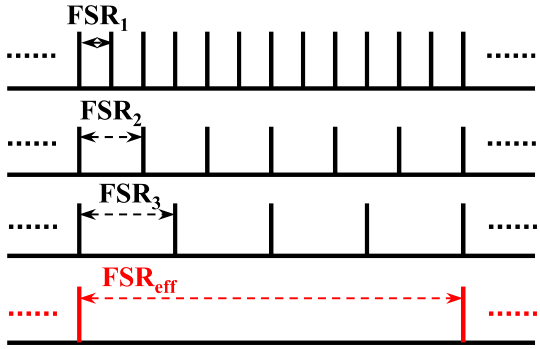

FIGURE 2. Schematic diagram of each ring's FSR output.

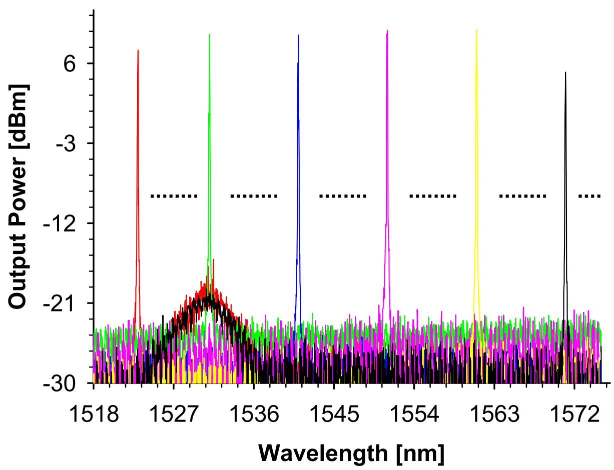

FIGURE 3. Experimental measures of optical spectrum of the lasing wavelength from 1523.0 to 1571.0 nm.

II. EXPERIMENT AND RESULTS

Experimental setup of presented stable and selectable EDF dual-Sagnac-ring laser scheme is shown in Fig. 1. In the demonstration, the commercially available C-band erbium-doped fiber amplifier (EDFA), tunable pandpass filter (TBF), two polarization controllers (PCs), 2 × 2 and 50:50 optical coupler (CPR_1) and 1 × 4 optical coupler (CPR_2) are applied to construct the presented EDF ring laser. The EDFA, having saturation output power of 13 dBm under the operation range of 1528 to 1562 nm, is utilized as gain medium. The polarization state and output power of presented EDF dual-Sagnac ring laser can be adjusted optimally by controlling the two PCs properly. Hence, while the stable lasing wavelength with optimal output power is achieved, it means that the polarization state could be retained properly in the measurement. Moreover, the TBF with 6 dB insertion loss is applied inside a laser cavity to tune different output wavelength and filter the optical noise for reaching the better optical signal to noise ratio (OSNR). The adjustable bandwidth of TBF is 60 nm is from 1520 to 1580 nm.

As displayed in Fig. 1, the 1× 4 CPR_2 is employed to create the dual-Sagnac-ring configuration. Three fiber rings ($Ring_1$, $Ring_2$ and $Ring_3$) would be produced in the presented EDF based laser. In the experiment, the cavity lengths of $Ring_1$, $Ring_2$ and $Ring_3$ are 12, 8 and 6 m, respectively. Here, the fiber length between CRP_1 and CRP_2 is 9.2 m. The three rings also have their relevant free spectrum ranges (FSRs), which denote FSR_1, FSR_2 and FSR_3 respectively. In line with the Vernier effect [6], when the FSR_1, FSR_2 and FSR_3 are met with the least common multiple of effective FSR (FSR_{eff}), the three fiber rings would cause the mode-filter for the multiply side-mode suppression. The schematic spectrum of corresponding FSR for each fiber-ring is also illustrated in Fig. 2. Here, the corresponding FSR_1, FSR_2 and FSR_3 of 17.02, 25.54 and 34.06 MHz are obtained respectively. Furthermore, the two Sagnac-rings ($Ring_2$ and $Ring_3$) also could be employed acting as the reflected mirrors with properly reflectances in the experiment [12]. Hence, the presented EDF Sagnac-ring laser scheme can be achieved the SLM operation and the flattened output power.

The fiber length of each ring is determined by the trial-and-error to achieve the SLM output and obtain the flatter output simultaneously over the available operation bandwidth. Thus, the corresponding FSR of each ring and the calculated FSR_{eff} can be achieved in this experiment.

The different output wavelength can be generated when the TBF is adjusted. In the measurement, an optical spectrum analyzer (OSA) and a power meter (PM) w are utilized to record the wavelength spectrum and output power, respectively. The higher resolution of OSA is 0.06 nm and detected power range of PM is from −50 to 23 dBm over the available bandwidth of 800 to 1700 nm. The temperature is around 25°, while the experiment is in progress. Fig. 3 presents the experimental measures of optical spectrum of lasing wavelengths from 1523.0 to 1571.0 nm. As the output wavelength shifts toward the longer wavelengths gradually, the amplified spontaneous emission (ASE) background noise of around 1530 nm could not be fully suppressed due to the gain competition. Moreover, except in the both sides of the wavelength tunability range, the observed peak power of output wavelengths are almost equalized, as shown in Fig. 3.

The output power and OSNR of presented EDF Sagnac-ring laser with an adjustable wavelength from 1523.0 to 1571.0 nm are also shown in Fig. 3. The output powers of 7.5 to 11.8 dBm are obtained. And the corresponding OSNR of the lasing wavelength is between 30.2 and 38.2 dB. The OSNR of 38.2 dB is observed at the wavelength of 1561.0 nm together with 11.8 dBm output power, as seen

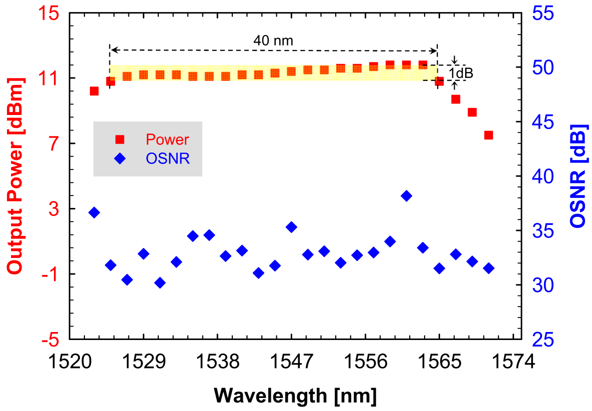

FIGURE 4. Experimental measures of output power and OSNR of each lasing wavelength from 1523.0 to 1571.0 nm.

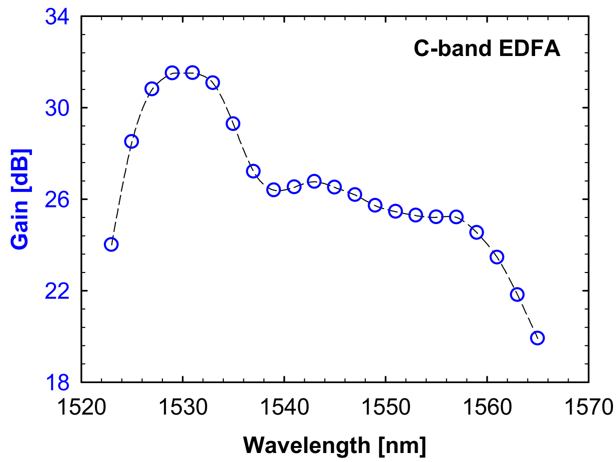

FIGURE 5. Measured gain spectrum of C-band EDFA over the wavelength range of 1523.0 to 1565.0 nm, while the input signal is set at– 10 dBm.

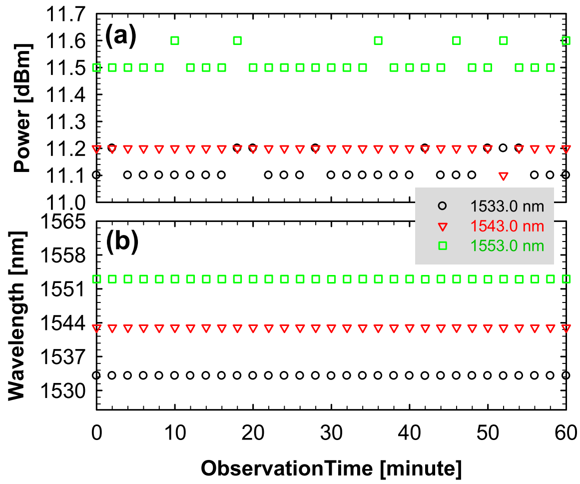

FIGURE 6. Experimental measures of the stability of (a) output power and (b) lasing spectrum at the wavelength of 1533.0, 1543.0 and 1553.0 nm, respectively.

in Fig. 4. According to the dual-Sagnac-ring configuration, in the tuning range of 1527.0 to 1563.0 nm, the observed output powers are from 11.1 to 11.8 dBm. The power variation (ΔP) of 0.7 dB is accomplished under a wavelength bandwidth of 1527.0 to 1563.0 nm. Hence, the presented EDF based laser can be obtained larger power and power-flattened output.

In the previous works [21], [22], when the OSNR of lasing wavelength could achieve >60 dB, we observe that the lower output power were obtained in their proposed EDF lasers. In the experiment, due to the larger saturation output power of EDFA and the output feature of TBF, the stronger ASE background noise is not easy to be suppressed for reaching the OSNR of >60 dB via single TBF. Hence, adding another TBF in the intracavity could filter the background noise and enhance the OSNR.

The obtained tuning range and output power of EDF based laser was limited by the gain range of the EDFA basically [6], [19]. In the demonstration, Fig. 5 presents the measured gain characteristic of C-band EDFA over the wavelength range of 1523.0 to 1565.0 nm, while the power of input wavelength is set at −10 dBm for testing. The gain values are obtained between 19.9 and 31.5 dB. Here, the observed maximum gain difference is ∼11.6 dB over the operation range. According to the proposed dual-Sagnac-ring scheme in the laser, the C-band EDF gain medium of the EDF laser could achieve the output powers of 10.8 to 11.8 dBm in the range of 1525.0 to 1565.0 nm with a flatter output curve. Therefore, the power variation of ±0.5 dB can be accomplished over the 40 nm flattened wavelength range.

Then, to verify the stability of output power for the presented EDF dual-Sagnac-ring laser, three output wavelengths of 1533.0, 1543.0 and 1553.0 nm are selected originally. As shown in Fig. 6(a), pending an observing measurement of 60 minutes, the obtained power fluctuations of three wavelengths used are below than 0.1, 0 and 0.1 dB, respectively. Furthermore, the measured wavelength variations of the three wavelengths are also smaller than 0.04, 0.04 and 0.04 nm respectively, as indicated in Fig. 6(b). Therefore, during 60 minutes observation period, the obtained maximum power output and wavelength differences of the presented EDF based laser still can be kept within 0.1 dB and 0.04 nm.

In the following, we prove the SLM characteristic of the presented EDF laser. Here, the delayed self-homodyne method is used for measurement in the experimental setup. We also use the same three wavelengths for measuring. Fig. 5 presents the measured electrical spectra of 1533.0, 1543.0 and 1553.0 nm in 500 MHz frequency bandwidth, respectively. When the dual-Sagnac-ring is exploited in the EDF laser scheme, no multiply side-mode noise is observed to attain the SLM output, as shown in Fig. 7. During 25 minutes observation, the measured results of Fig. 7 are also the same without any change.

Finally, the linewidth of presented EDF dual-Sagnac-ring laser can also be perform in this work. To evaluate the laser linewidth, a delayed self-heterodyne detection is experimented. Here, a 100 MHz RF beating signal can be generated by a phase modulator in to prove the output laser linewidth of presented EDF laser. Therefore, the experimental measures of

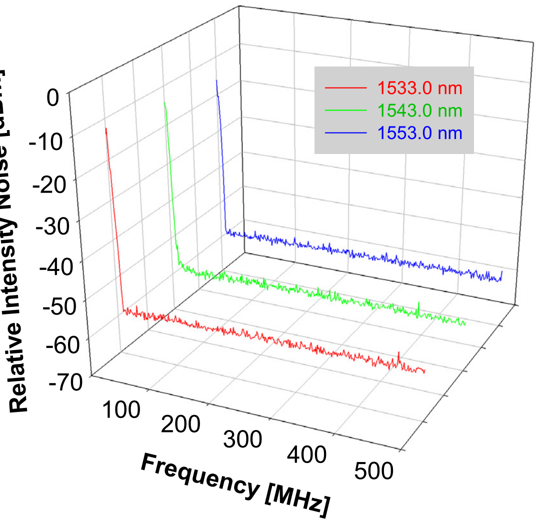

FIGURE 7. **Experimental measures of RF electrical spectra of presented EDF laser in a frequency range of 500 MHz at the wavelength of 1533.0, 1543.0 and 1553.0 nm, respectively.**

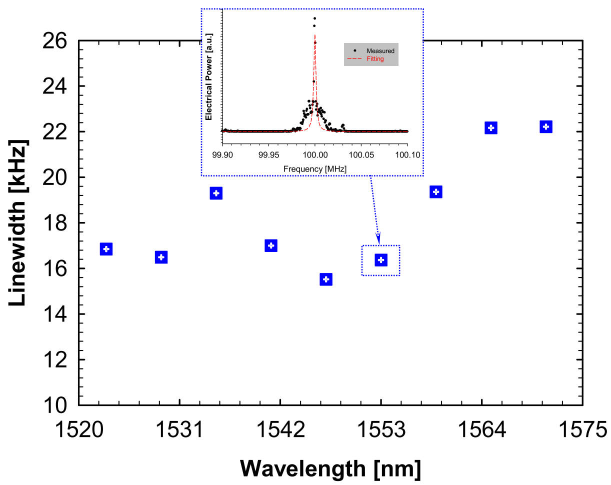

FIGURE 8. **Experimental measures of RF electrical spectra of presented EDF laser in a frequency range of 500 MHz at the wavelength of 1533.0, 1543.0 and 1553.0 nm, respectively.**

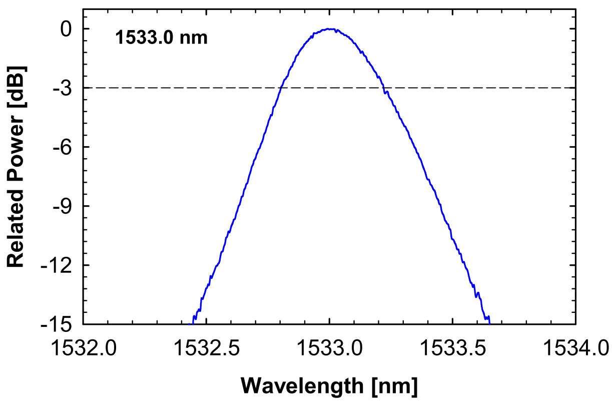

FIGURE 9. **Measured output spectrum of TBF when the wavelength location is set at 1533.0 nm.**

Lorentzian 3 dB laser linewidth from 1523.0 to 1571.0 nm are shown in Fig. 8. The insert of Fig. 6 is the measured output RF spectrum of 1553.0 nm at the original status and Lorentzian fitting, respectively. In the measurement, the 3 dB bandwidth of the commercial TBF is 0.4 nm, as plotted in Fig. 9. Hence, the obtained narrower linewidth of the proposed laser is caused by the presented dual-Sagnac-ring configuration instead of the TBF. In the measurement, the observed wavelength linewidth is between 16.4 and 22.2 kHz through the Lorentzian fitting. Moreover, the detected maximum variation of laser linewidth is 5.8 kHz over the available working range.

III. CONCLUSION

A wavelength-selectable and stable EDF dual-Sagnac-ring laser with SLM oscillation and flattened power output simultaneously was designed and experimentally demonstrated. The experimental measures of OSNRs and output powers of presented EDF based laser were between 30.2 and 38.2 dB and 7.5 and 11.8 dBm, respectively over the adjusted range from 1523.0 to 1571.0 nm. Moreover, the flattened spectrum range was obtained from 1527.0 to 1563.0 nm together with the output power from 11.1 to 11.8 dBm. The maximum variations of output power and lasing linewidth could be also below than 0.1 dB and 0.04 nm, respectively, after a precise measure of 60 minutes. Moreover, the experimental measures of wavelength linewidth of 16.4 and 22.2 kHz were accomplished via the Lorentzian fitting in the measurement. Therefore, according to the presented dual-Sagnac-ring scheme, the EDF based laser produced the SLM oscillation and implemented the flattened output within 0.7 dB power fluctuation.

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