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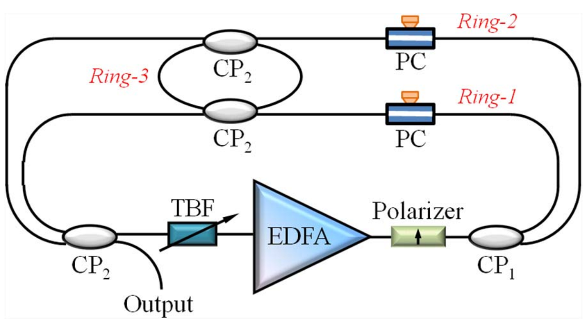

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Stable and Tunable Single-Longitudinal-Mode Erbium-Doped Fiber Triple-Ring Laser With Power-Equalized Output

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Abstract: In this demonstration, we propose and investigate a stable and tunable single-longitudinal-mode (SLM) erbium-doped fiber (EDF) ring laser structure. Here, in order to achieve the SLM output, the "eye-type" triple-ring scheme is designed in this EDF laser to suppress the densely spaced longitudinal modes. In the measurement, the output power and optical-signal-to-noise ratio (OSNR) are between 8.35 and 8.92 dBm and 33.2 and 35.7 dB, respectively, in the wavelength range of 1530 to 1560 nm. The proposed EDF laser architecture not only has free tuning step but provides stabilized and flattened output power spectrum as well.

Index Terms: Erbium-doped fiber (EDF) laser, compound-ring filter, single-longitudinal-mode (SLM).

1. Introduction

Erbium-doped fiber (EDF) lasers with wavelength tunability are attractive light sources for many important applications, such as wavelength-division-multiplexed (WDM) systems, optical spectroscopy testing, optical fiber sensors, microwave photonics, and terahertz radiation [1]–[5]. Furthermore, the fiber laser with tunability and single-longitudinal-mode (SLM) output has practical importance [6]. In general, EDF ring laser has multi-modes due to its long fiber cavity, which can be up to tens of meters [7]. Thus, the corresponding free spectral range (FSR) of ring laser lies in the megahertz range, which is several orders of magnitude less than the bandwidth of commercially available optical filter [8].

To achieve the SLM operation in EDF ring laser, several key techniques have been proposed to suppress the densely multi-longitudinal-mode (MLM), such as using an un-pumped EDF as saturable absorber filter [9]–[11], employing birefringent fiber filter [12], utilizing a Fabry–Pérot laser diode (FP-LD) [13], and applying multi-ring filter [14]. Moreover, to obtain the wavelength-tuning in fiber laser architecture, the optical tunable bandpass filter (TBF), fiber Fabry–Pérot filter (FFPF), and fiber Bragg grating (FBG) are utilized inside a fiber cavity [15]–[17].

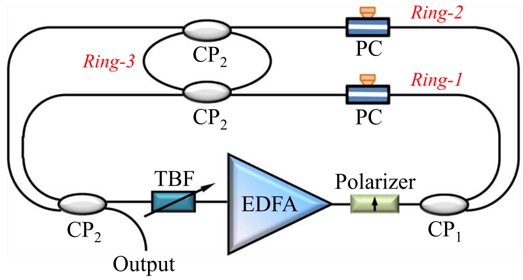

Fig. 1. Experimental setup of proposed stable and tunable SLM EDF triple-ring laser.

In this demonstration, we propose and experimentally investigate a stable and wavelength-tunable EDF laser structure with SLM output. Here, a new "eye-type" triple-ring scheme is proposed and used in the laser cavity for suppressing the MLM oscillation to achieve SLM operation. In this measurement, by adjusting the passband of TBF, the proposed laser can generate different lasing wavelengths. Experimental results show that the output powers and optical signal to noise ratios (OSNRs) of proposed fiber laser are between 8.35 and 8.92 dBm; 33.2 and 35.7 dB nm, respectively, in the operation range of 1530.0 to 1560.0 nm. The received output power difference of 0.57 dB also can be observed in the wavelengths of 1530.0 to 1560.0 nm. Hence, the proposed EDF laser can accomplish a flattened output spectrum by using triple-ring laser structure. In addition, we also perform the output wavelength and power stability measurements. The maximum fluctuations of lasing wavelength and output power are 0.04 nm and 0.5 dB, respectively, during a short-term observation time of 30 minutes.

2. Experimental Setup and Discussion

Fig. 1 is the experimental setup of proposed stable and tunable SLM EDF "eye-type" triple-ring laser, where the smaller Ring-3 is like the pupil of an eye. The proposed EDF laser consists of a commercially C-band erbium-doped fiber amplifier (EDFA), a 1×2 and 50:50 optical coupler (CP_1), three 2×2 and 50:50 optical couplers (CPs_2), two polarization controllers (PCs), an in-line fiber polarizer, and a tunable bandpass filter (TBF). In the experiment, the commercially C-band EDFA are used. The EDFA has a gain of ~28 dB, and a saturation power of 13 dBm. The noise figure and return loss are 5 dB and ≧45 dB at 1550 nm, respectively. The TBF inside a ring cavity is employed to select and generate different wavelength outputs. The tuning range and 3 dB bandwidth of TBF are 30 nm (1520 to 1560 nm) and 0.4 nm, respectively. As illustrated in Fig. 1, the four CPs can produce the triple-ring architecture (Ring-1, Ring-2, and Ring-3) for filtering MLM to complete a SLM operation. Furthermore, in order to decrease the longitudinal-mode number and mode-hopping effect, the in-line polarizer and PCs are employed. Due to the relatively long ring cavity, it would result in a change of polarization rotation. Thus, the PCs are placed inside the ring cavity in order to control the polarization state properly and obtain the maximum output power with stabilized wavelength output. These devices can also reduce the MLM and suppress mode-hopping effect [18].

By utilizing the multiple-ring configurations, a large resultant FSR could be achieved according to the Vernier effect [5]. Here, the fiber Ring-1, Ring-2, and Ring-3 cavities (see Fig. 1) would have their corresponding FSR_1 (see the green line in Fig. 2), FSR_2 (see the red line in Fig. 2), and FSR_3 (see blue line in Fig. 2), respectively. The final effective FSR (black line in Fig. 2) would be the least common multiple number of both FSRs, as schematically depicted in Fig. 2. Then, the densely spaced longitudinal modes could be suppressed and governed by the length of Ring-1, Ring-2, and Ring-3 cavities that we choose. In this experiment, the passband of the TBF would also provide further mode restriction on possible lasing mode. As a result, the triple-ring architecture of proposed EDF laser can be utilized to produce side-mode suppression easily for a stable and wavelength-tunable SLM output.

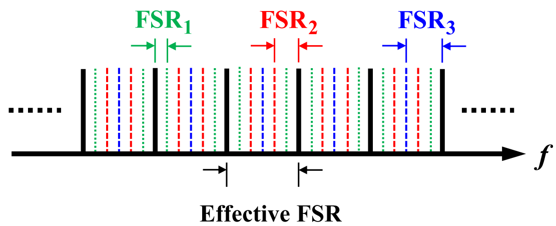

Fig. 2. Schematic diagram of mode selection in the proposed triple-ring fiber laser.

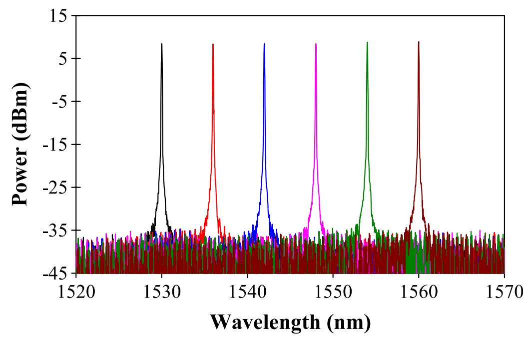

Fig. 3. Measured output wavelength of proposed fiber laser scheme with 6 nm tuning step in the wavelength range of 1530.0 to 1560.0 nm.

In the measurement, the corresponding output wavelength can be tuned when the passband of TBF is adjusted in the proposed EDF triple-ring laser. Fig. 3 presents the output wavelength of proposed fiber laser scheme with arbitrary tuning step in the wavelength range of 1530 to 1560 nm. In addition, the maximum amplified spontaneous emission (ASE) background noise around 1530 nm provided by the EDF could be highly suppressed by the proposed triple-ring fiber laser structure as shown in Fig. 3. The linewidth of the lasing wavelength is 0.06 nm measured by an optical spectrum analyzer (OSA).

Fig. 4 displays the different output powers and optical signal to noise ratios (OSNRs) in the wavelength range of 1530 to 1560 nm with a tuning step of 3 nm. Here, the measured output powers and OSNRs are between 8.35 and 8.92 dBm; 33.2 and 35.7 dB nm, respectively. In previous report [7], to accomplish the flattening spectrum of output power, the pumping power of 980 nm laser in EDFA should be adjusted dynamically. Here, the maximum output power variation of 0.57 dB is observed in the wavelengths of 1530 to 1560 nm by the proposed EDF triple-ring laser. The proposed laser can also achieve the flattened profile of output power in the tuning range without utilizing flattening technology. Furthermore, the maximum and minimum output power of is observed at the wavelength of 1536 and 1560 nm together with the OSNRs of 34.2 and 35.0 dB, respectively. In our proposed "eye-type" triple-ring scheme, we can observe that a much uniform output powers can be achieved in the wavelength range of 1530 to 1560 nm. As shown in Fig. 3, the ASE background noise around 1530 nm produced by the EDF could be highly suppressed by the proposed triple-ring fiber laser structure. As shown in Fig. 4, the output power variation is only 0.57 dB in the wavelengths of 1530 to 1560 nm by the proposed "eye-type" triple-ring laser. However, the output power variations are much higher in [7] and [19]. The stability of the laser can be further improved by reducing the reflections inside the fiber cavities. Pump power feedback control can also be used to suppress the intensity noise of the laser output [20].

Then, to understand the output stabilities of power and wavelength in the proposed EDF triple-ring laser, a short-term optical variation measurement is executed. Here, a lasing wavelength of 1541.94 nm with output power of 7.95 dBm is selected initially for the stability measurement.

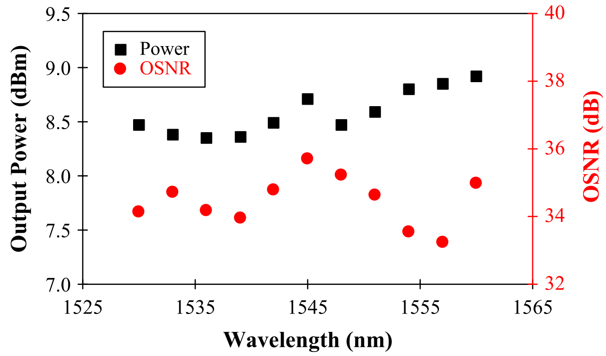

Fig. 4. Measured output powers and optical signal to noise ratios (OSNRs) in the wavelength range of 1530.0 to 1560.0 nm with a tuning step of 3 nm.

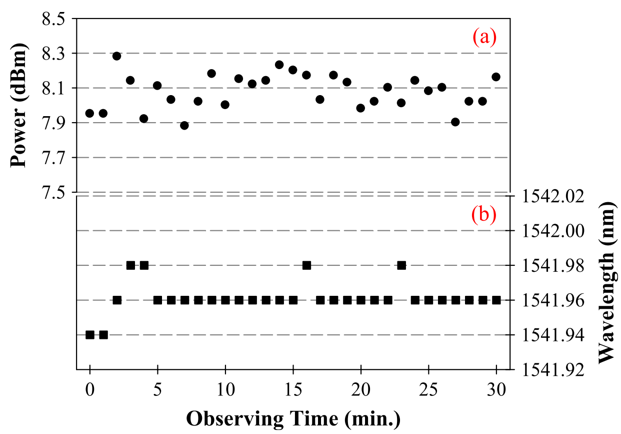

Fig. 5. Measured fluctuations of (a) output power and (b) lasing wavelength for the proposed EDF triple-ring laser.

Fig. 5(a) and (b) shows the measured fluctuations of output power and lasing wavelength for the proposed EDF triple-ring laser during an observation time of 30 minutes. As shown in Fig. 5(a) and (b), the observed maximum variations of output power (ΔP) and lasing wavelength ($\Delta\lambda$) can be kept within 0.5 dB and 0.04 nm, respectively. In addition, in more than one hour observing time, the detected output power and lasing wavelength of the proposed EDF laser are still stable under the measured variation range.

Next, to realize the SLM performance of output wavelength, the delayed self-homodyne technique is utilized for executing measurement. The measurement setup is constructed by a 2.5 GHz photodetector (PD), a PC and a Mach–Zehnder interferometer with a 25 km single-mode fiber (SMF) long, as shown in Fig. 6. We also choose the lasing wavelength of 1541.94 nm for delayed self-homodyne measurement. Hence, the single sideband (SSB) power spectrum of proposed EDF triple-ring laser can be observed by using a radio frequency (RF) 3 GHz electrical spectrum analyzer (ESA). From the measured SSB power spectrum, the densely spaced longitudinal modes could be greatly suppressed by the proposed triple-ring architecture within 1 GHz bandwidth observation, as shown in Fig. 7(a) and (b). Besides, the inset of Fig. 7 is the magnified power spectrum measurement under an observing bandwidth of 20 MHz. Here, there are no electrical spikes could be observed in the power spectrum in Fig. 7(b). In the measurement, Fig. 7 also shows that the SSB spectrum is nearly the same as the measurement baseline of the ESA. Furthermore, during one hour observation measurement, the shown SSB power spectra of ESA are very stable without any spike noises. As a result, the experimental results show

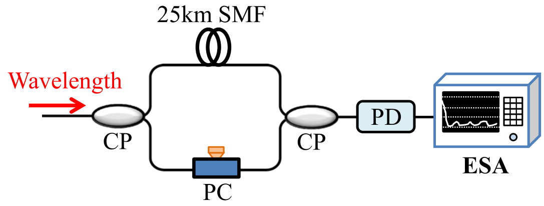

Fig. 6. Measurement setup of the delayed self-homodyne method.

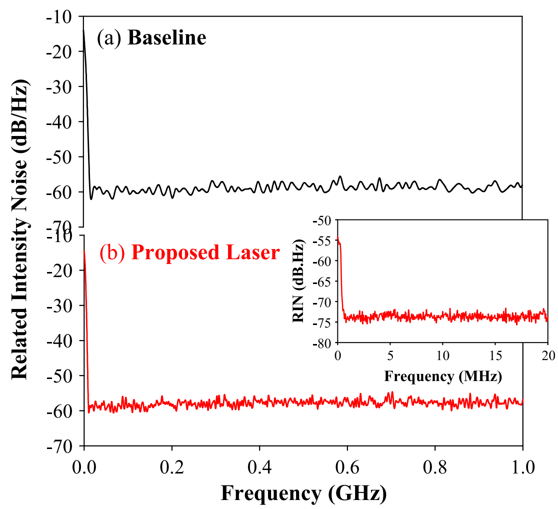

Fig. 7. Measured SSB power spectrum of the proposed EDF triple-ring laser after self-homodyne method.

that the proposed EDF triple-ring laser has good output stability and wavelength tunability with SLM output.

3. Conclusion

We proposed and experimental demonstrated a wavelength-tunable and stable SLM EDF triple-ring laser. Using the proposed "eye-type" triple-ring laser architecture, the densely MLM would be suppressed to generate a SLM output. In this measurement, by adjusting the passband of TBF, different lasing wavelengths can be tuned. Experimental results showed that the output powers and OSNRs of proposed EDF laser were between 8.35 and 8.92 dBm and 33.2 and 35.7 dB nm, respectively, in the wavelength range of 1530 to 1560 nm. The received output power difference of 0.57 dB was also obtained in the wavelength range. Therefore, the proposed EDF ring laser can also accomplish a flattened spectrum of output power by using triple-ring laser design. In addition, we also performed the stability evaluations in terms of lasing wavelength and output power. The maximum fluctuation of output wavelength and power are within 0.04 nm and 0.5 dB, respectively.

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