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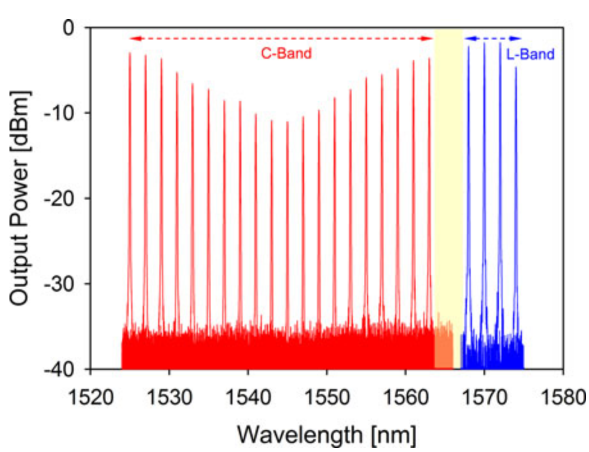

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Stable Single-Longitudinal-Mode Erbium Fiber Ring Laser Utilizing Self-Injection and Saturable Absorber

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Abstract: In this work, we demonstrate a wavelength-tunable erbium-doped fiber (EDF) ring laser with stable single-longitudinal-mode (SLM) output. Here using the self-injection method and unpumped EDF-based saturable absorber can suppress other densely side-mode to achieve SLM. Hence, the output power and optical signal-to-noise ratio of proposed EDF ring laser are between −7.1 and 2.1 dBm and 30.1 and 36.5 dB in the tuning range of 1525.0 to 1574.0 nm, respectively. According to the proposed EDF laser structure, the wavelength operation range can extend to shorter L-band from C-band. Moreover, the output stability of the proposed EDF ring laser is also executed experimentally.

Index Terms: Fiber laser, single-longitudinal-mode (SLM), erbium-doped fiber (EDF).

1. Introduction

Recently, tunable and stable single-longitudinal-modes (SLM) erbium-doped fiber (EDF) lasers are of large interests owing to their significant applications in optical communications, fiber-wireless communication, fiber sensor systems, light detection and ranging (LIDAR), and high-resolution spectroscopy [1]–[5]. Furthermore, the EDF lasers also have the beneficial features of broadband wavelength tuning range, higher output power, and narrow linewidth [6], [7]. However, the EDF ring laser has many densely multi-longitudinal-mode (MLM) due to the longer length of fiber laser cavity and mode hopping. Moreover, the output wavelength of conventional EDF ring laser with wide linewidth is unstable usually owing to the mode oscillation, competition and hopping [8]. Therefore, to complete a stable SLM output in the EDF ring laser, many relative studies have been demonstrated to suppress the MLM operation, such as utilizing a short-length of unpumped EDF-based saturable absorber (SA), compound-ring structure, Mach-Zehnder interferometer, narrow linewidth optical filter, and optical injection method [9]–[14].

In this paper, a stable and selectable SLM EDF ring laser is proposed and demonstrated. In order to reach SLM operation, the proposed self-injection scheme and a short length of unpumped EDF-based SA are used in proposed EDF ring laser to suppress the densely MLM. Besides, an optical tunable bandpass filter (OTBF) is applied in the ring cavity to generate different output wavelengths

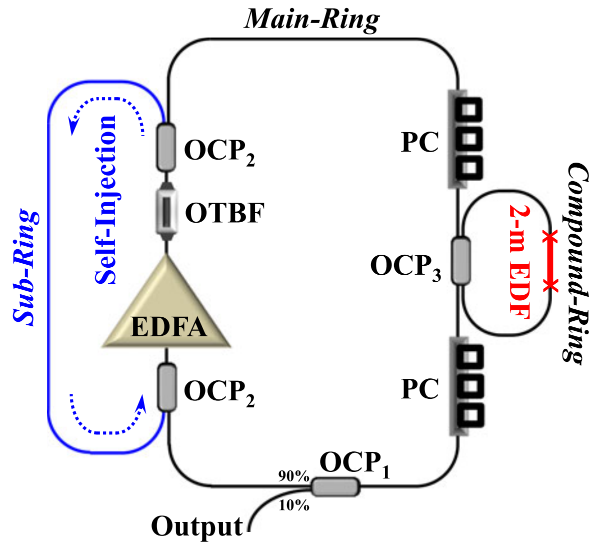

Fig. 1. Experimental setup of proposed EDF ring laser.

in the available operation range. Therefore, the observed output powers and optical signal to noise ratio (OSNR) of proposed EDF ring laser are between −7.1 and 2.1 dBm and 30.1 and 36.5 dB in the wavelength range of 1525.0 to 1574.0 nm, respectively. In addition, we also execute the output stabilities of power and wavelength during a short-term observing time of 40 minutes experimentally. The measured maximum output power fluctuation and wavelength variation of proposed EDF ring laser are within 0.6 dB and 0.03 nm respectively.

2. Experimental Setup

Fig. 1 schemes the experimental setup of proposed EDF ring laser. The proposed fiber laser is constructed by a commercially C-band erbium-doped fiber amplifier (EDFA), an OTBF, two polarization controllers (PCs), a 10:90 and 1×2 optical coupler (OCP_1), two 50:50 and 1×2 optical couplers (OCP_2), a 50:50 and 2×2 optical coupler (OCP_3), and a unpumped EDF with 2 m long. An EDFA is applied for serving as gain medium in laser cavity. Besides, the saturated power of C-band EDFA, having 25 dB gain in the range of 1528.0 to 1564.0 nm, is about 11 dBm. In order to generate different output, the passband of C-band OTBF is used in a ring cavity for tuning wavelength. The insertion loss, 3 dB bandwidth and tuning range of OTBF are 6 dB, 0.4 nm, and 40 nm (1525.0 to 1565.0 nm) respectively. Two PCs in main-ring cavity are tuned to maintain the same polarization state and also obtain the maximum output power.

As seen in Fig. 1, two OCP_2 are utilized to create the main-ring and sub-ring structures in proposed laser architecture. Here, the sub-ring can produce the self-injected feedback. The compound-ring scheme together with an unpumped EDF-based SA of 2.0 m is utilized for SLM oscillation. As plotted in Fig. 1, the three cavity rings with different fiber lengths can produce three different free spectrum ranges (FSRs), which denote FSR_{main}, FSR_{sub} and $FSR_{compound}$, respectively. Therefore, the FSR of each fiber ring can be represented

$$FSR = c/n \times L \tag{1}$$

where L is the length of ring cavity, n = 1.4682 is the effective refractive index of single-mode fiber, and c is the speed of light in vacuum. In the experiment, the fiber length of each cavity ring is chosen arbitrarily. Hence, based on the Vernier effect [15], the effective FSR of the proposed EDF laser should be the least common multiple of FSR_{main}, FSR_{sub} and $FSR_{compound}$ for producing the mode-filter effect. The fiber lengths of main-ring, sub-ring and compound-ring are 29, 18 and 4 m,

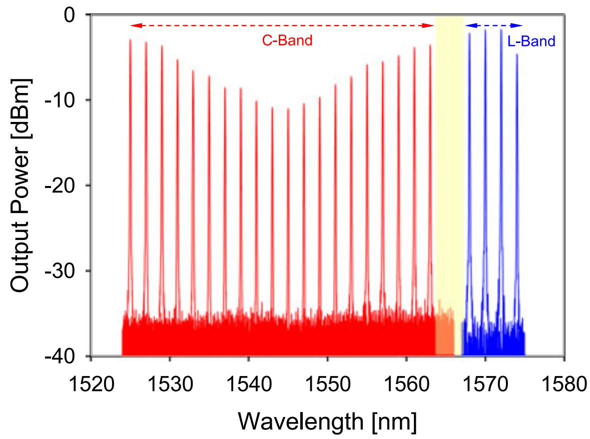

Fig. 2. Measured output wavelength spectra of proposed EDF ring laser under the different wavelengths.

respectively, as shown in Fig. 1. Therefore, the corresponding FSRs of each ring are 7.1, 11.4 and 51.1 MHz, respectively. Moreover, when two PCs are adjusted properly to controller the polarization state, the unpumped EDF-based SA would induce the ultra-narrowband auto-tracking filter due to the spatial-hole-burning [13]. As shown in Fig. 1, when the self-injected CW light is close enough to one of the longitudinal modes of laser cavity, it would diminish the gain of the other modes via cross-mode saturation [16]. Then, the other oscillation mode could be suppressed. As a result, the output mode of proposed EDF ring laser configuration can be oscillated at single frequency that undergoes the larger erbium gain and satisfies the resonance conditions to achieve SLM operation.

3. Results and Discussion

Fig. 2 plots the measured output spectra of proposed EDF laser, which is observed by an optical spectrum analyzer (OSA) with a resolution of 0.06 nm at the 10% output port of OCP_1, when the OTBF is utilized in a tuning range of 1525.0 to 1574.0 nm. In the experiment, the effective gain of proposed EDF ring laser structure can extend to the shorter range of L-band. Therefore, we can utilize another L-band OTBF (1568.0 to 1610.0 nm) to replace C-band for tuning. In the measurement, the red and blue lines show the output spectra in the wavelength ranges of 1525.0 to 1563.0 nm (C-band) and 1568.0 to 1574.0 nm (L-band), as plotted in Fig. 2. Here, a 5.0 nm gap is also observed in Fig. 2, owing to the limit of filter device. While the passband of OTBF exceeds the wavelength of 1575.0 nm, we cannot observe any lasing wavelength, due to the available gain range. The total operation range of proposed EDF laser can be operated from 1525.0 to 1574.0 nm.

Fig. 3 shows the measured output power and OSNR of proposed EDF ring laser in the different wavelengths of 1525.0 to 1574.0 nm, when a power meter (PM) is used for power measurement. In the measurement, the output powers and OSNRs are between -7.1 and 2.1 dBm and 30.1 and 36.5 dB. As depicted in Fig. 3, the minimum and maximum output power are observed at the wavelengths of 1545.0 and 1570.0 nm together with the OSNRs of 30.1 and 34.5 dB, respectively. In the experiment, due to the insufficient gain range of proposed EDF laser, the effective tuning range only can be achieved in the wavelengths from 1525.0 to 1574.0 nm ($\sim$50 nm operation bandwidth). Hence, while the central wavelength of OTBF exceeds 1575.0 nm, no output wavelength can be observed. Due to the proposed multiple-ring scheme with injection method and EDF-based SA, the effective gain of EDF laser could be shifted to the longer wavelength range. Hence, the lowest powers are found in the middle of the C-band range as shown in Fig. 3. The measured output powers of proposed EDF laser will be small relatively.

Then, the stability performance of proposed EDF laser configuration is also essential issue. Hence, a short-term observing measurement for the output power and lasing wavelength are

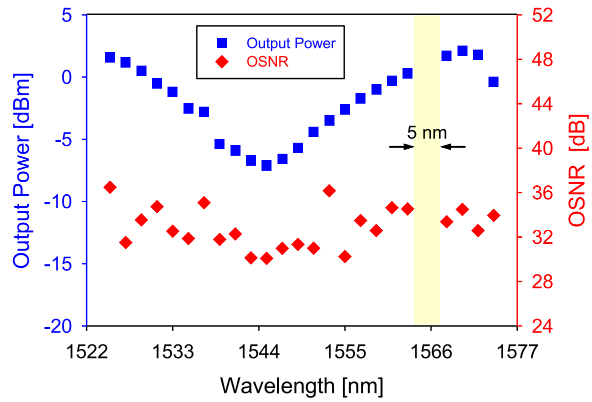

Fig. 3. Measured output power and OSNR of proposed EDF ring laser in the wavelengths of 1525.0 to 1574.0 nm, respectively.

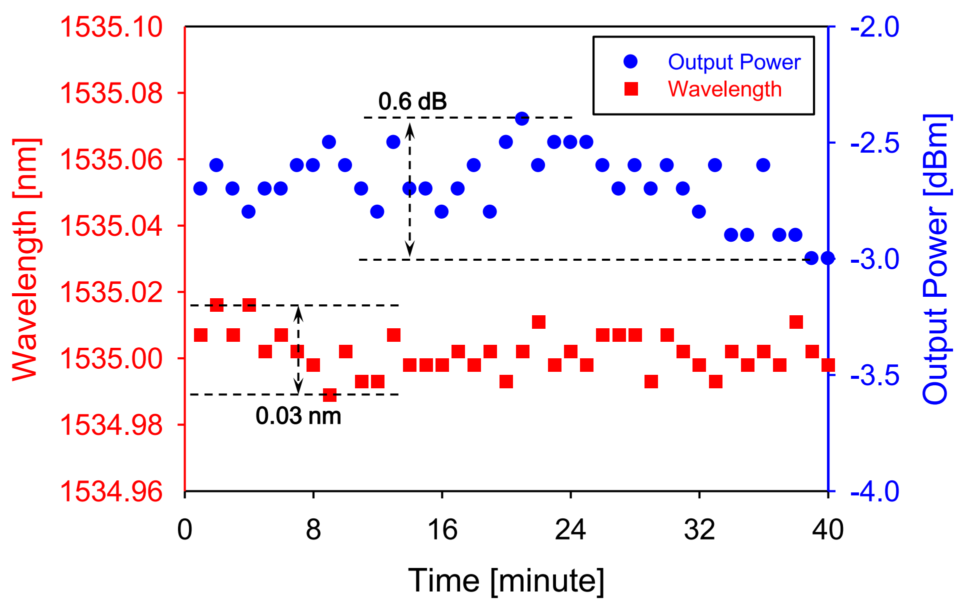

Fig. 4. Obtained power fluctuation and wavelength variation of proposed EDF laser in an observation time of 40 minutes.

experimented. Initially, a lasing wavelength of 1535.0 nm with an output power of −2.5 dBm is selected for measurement. As seen in Fig. 4, the obtained maximum power fluctuation and wavelength variation are below than 0.03 nm and 0.6 dB, respectively, in an observation time of 40 minutes. Moreover, we also apply the output wavelengths of 1545.0, 1555.0 and 1570.0 nm for the same measurements. The observed results of output stabilities are similar as mentioned above. During an hour observation, the obtained stabilities of proposed EDF laser can be still maintained within the differences. To proof the SLM oscillation of proposed EDF ring laser architecture, the delayed self-homodyne method is used for measurement [15]. In the experiment, the setup of Mach-Zehnder interferometer (MZI) has a PC and a 25 km delay line of fiber. Here, the optical output wavelength is detected by a 10 GHz PIN-based receiver (Rx) converting to electrical signal. Then, we use a 3 GHz electrical spectrum analyzer (ESA) for RF spectrum observation. To realize the SLM performance of proposed laser, the tested wavelengths of 1535.0, 1545.0, 1555.0 and 1570.0 nm are chosen for demonstrations respectively. Fig. 5(a)–(d) present the clear electrical spectra of proposed EDF ring

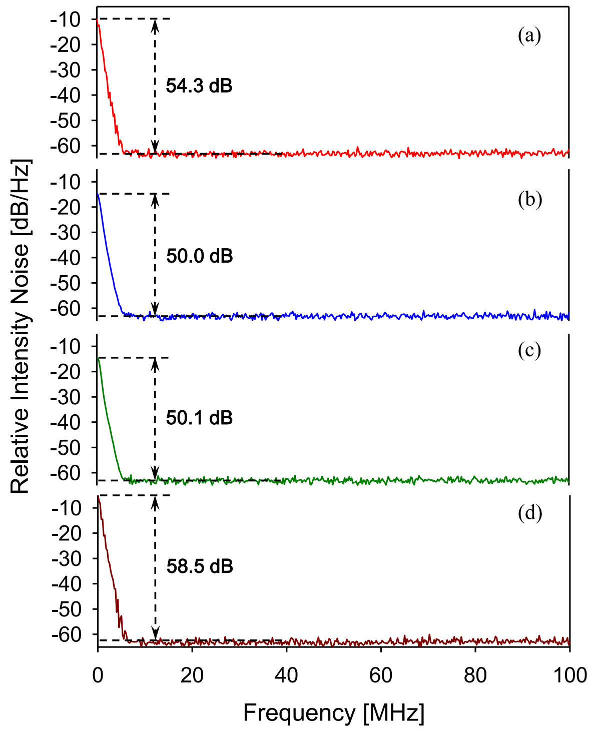

Fig. 5. Measured electrical spectra of proposed EDF ring laser for the four wavelengths of (a) 1535.0, (b) 1545.0, (c) 1555.0 and (d) 1570.0 nm under the observing bandwidth of 100 MHz, respectively.

laser for the four tested wavelengths under the observing bandwidth of 100 MHz, respectively. The other oscillation modes can be suppressed together with stable SLM spectrum output, as presented in Fig. 5(a)–(d). Furthermore, the measured relative signal to noise ratio of each tested wavelength can be greater than 50 dB as shown in Fig. 5(a)–(d) In the observation time of one hour, the stable SLM output of proposed EDF laser can be still continued without spike noise. Moreover, when we expand and narrow the measured frequency bandwidth to 1 GHz and 10 MHz for measurement respectively, the observed electrical spectra are still without other side-mode.

In this work, when we remove the 2 m EDF in compound-ring scheme, some side modes are measured in the electrical spectrum. Here, if the proper coupling loss and FSRs of proposed EDF laser are used, then the SLM also can be obtained. Hence, to solve the MLM issue effectively with multiple-ring-cavity, using the compound-ring scheme with an unpumped EDF-based SA can suppress the MLM easily. Compared with the previous works [15], [17], the proposed EDF compound-ring laser not only can achieve SLM oscillation, but also can accomplish the tuning range from C-band to L-band (1525.0 nm to 1574.0 nm), when the C-band EDFA is used in a laser cavity.

4. Conclusion

In summary, we proposed and demonstrated a wavelength-selectable EDF ring laser with stable SLM output. In this experiment, to complete stable SLM operation, the proposed self-injection scheme and an unpumped EDF-based SA were used in proposed EDF ring laser to suppress the MLM. Here, the observed output powers and optical signal to noise ratio (OSNR) of proposed EDF ring laser were between −7.1 and 2.1 dBm and 30.1 and 36.5 dB in the wavelength range of 1525.0 to 1574.0 nm, respectively, when the OTBF was applied. In addition, the output stabilities of power and wavelength during were also performed in a short-term observing time of 40 minutes. The maximum output power fluctuation and wavelength variation of proposed EDF ring laser were below than 0.6 dB and 0.03 nm, respectively. As a result, the proposed EDF ring laser architecture not only can complete stable SLM output, but the tuning range also can reach to the shorter L-band from C-band.

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