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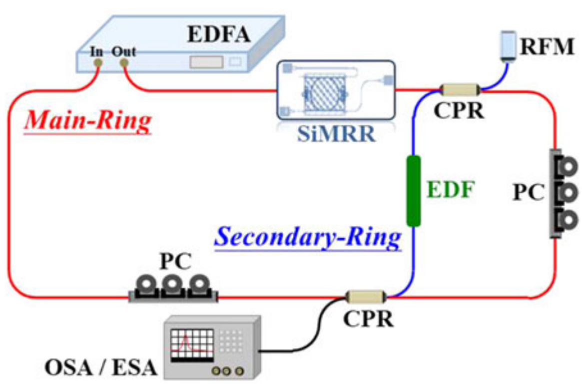

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Silicon-Micro-Ring Resonator-Based Erbium Fiber Laser With Single-Longitudinal-Mode Oscillation

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Abstract: In this paper, we propose and experimentally illustrate a wavelength-switchable erbium-doped fiber (EDF) dual-ring (DR) laser with stable single-longitudinal-mode (SLM) oscillation. In the experiment, a silicon-micro-ring-resonator (SiMRR) is applied in the proposed DR cavity for tuning different output wavelengths, when the birefringence loss is adjusted correctly. To compress the densely multilongitudinal-mode oscillations, the DR scheme together with a 2-m unpumped EDF-based saturable absorber is acted as the mode filter. The DR also can produce self-injection loop for an SLM operation. The wavelength tunability is between 1532.61 to 1557.98 nm and the measured 3-dB output linewidth is ~22.5 kHz. Moreover, the output stabilizations of the proposed SiMRR-based EDF DR laser are also analyzed and discussed.

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

1. Introduction

Stable and tunable erbium-doped fiber (EDF) lasers have many effective applications in the fields of science and engineering, such as in wavelength-division-multiplexing (WDM) communication, optics-fiber sensor, millimeter-wave (MMW) transmission system, material processing, and optical spectroscopy and instrument [1]–[5]. However, owing to the he homogeneous broadening effect of EDF and a longer fiber length of ring cavity in the EDF-based laser, it would introduce the mode-hopping and densely unstable multi-longitudinal-mode (MLM) oscillations [6]–[8]. Therefore, to overcome these issues, several related methods have been investigated to accomplish the stable single-longitudinal-mode (SLM) output of EDF-based lasers, such as using the optical injection technique [9], unpumped EDF-based saturable absorber (SA) [10], multiple-fiber-ring (MFR) based filter [11], [12], the narrow linewidth optical filter [13], and the Mach-Zehnder interferometer [14]. In order to generate different wavelength outputs, the various optical filters are utilized in fiber cavity of EDF laser for tuning, such as employing the tunable bandpass filter (TBF) [15], the fiber Fabry-Perot tunable filter (FFP-TF) [16], the silicon-based micro-ring-resonator (SiMRR) [17], and the variable fiber Bragg grating (FBG) [18].

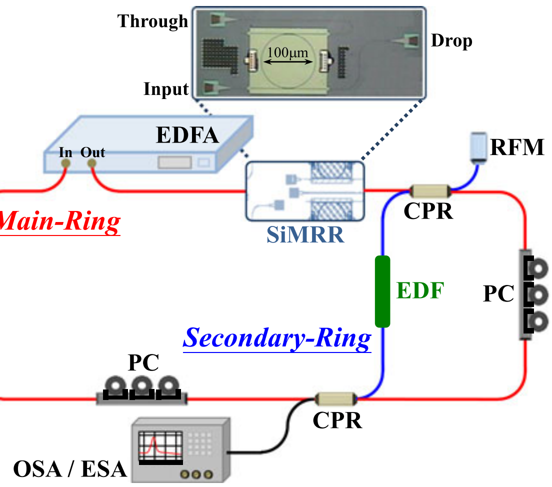

Fig. 1. Proposed SiMRR-based EDF DR laser architecture. Inset is the scanning electron microscope (SEM) graph of the SiMRR.

Furthermore, according to the recent progress of silicon photonics, using the SiMRR device to build the wavelength-tunable SLM EDF laser source is very exciting and practical. In light of the mature silicon manufacturing processes [19], [20], the SiMRR has great potential as a cost-effective filter device with a high quality factor (Q-factor) to serve as a precise and controllable free spectral range (FSR) [21].

In this paper, we propose and exhibit a SiMRR-based EDF dual-ring (DR) laser to achieve stable and wavelength-tunable SLM output. In the experiment, the SiMRR is applied in the proposed DR cavity to generate different wavelength outputs in the tuning range from 1532.61 to 1557.98 nm, while the birefringence loss of laser architecture is adapted properly. In order to obtain the stable SLM oscillation, the proposed DR configuration together with a 2 m unpumped EDF-based SA and self-injection operation can be used to compress the densely MLM fully for the SLM oscillation. There are nine lasing wavelengths of proposed EDF laser can be tuned in the same wavelength range. The measured output powers and optical signal to noise ratios (OSNRs) are between −11.0 and −9.3 dBm and 48.9 and 52.0 dB, respectively. Furthermore, the measured 3 dB linewidth of output wavelength is ∼22.5 kHz. In a short-term observation time of 30 minutes, the observed output stabilities of power and wavelength are within the variations of 0.9 dB and 0 nm, respectively.

2. Experimental Setup

Fig. 1 exhibits the proposed SiMRR-based EDF dual-ring (DR) laser architecture. The EDF laser is consisted of a SiMRR-based filter, two 2 × 2 and 50:50 optical couplers (CPRs), two polarization controllers (PCs), a reflective fiber mirror (RFM), an unpumped EDF of 2 m long, and a commercial C-band erbium-doped fiber amplifier (EDFA). In the experiment, the saturable output power and available gain of EDFA are 13 dBm and 25 dB in the effective operation range of 1528 to 1564 nm. The reflectivity of RFM is ∼95% in the wavelength range of 1530 to 1570 nm. Moreover, the inset of Fig. 1 is the scanning electron microscope (SEM) graph of the SiMRR. Here, the 193 nm deep-ultra-violet (DUV) lithography and reactive-ion etching (RIE) manners are used to fabricate the SiMRR on the silicon-on-insulator (SOI) wafer. In the structure, the top silicon layer the burial oxide (BOX) layer of SOI is 0.22 μm and 2 μm, respectively. The length and width of the input and output waveguide grating couplers (GCs) are 14 and 9 μm, respectively. The etch depth and the period of waveguide GC are 70 and 580 nm, respectively [22]. As seen in the inset of Fig. 1, the diameter of SiMRR is nearly 100 μm.

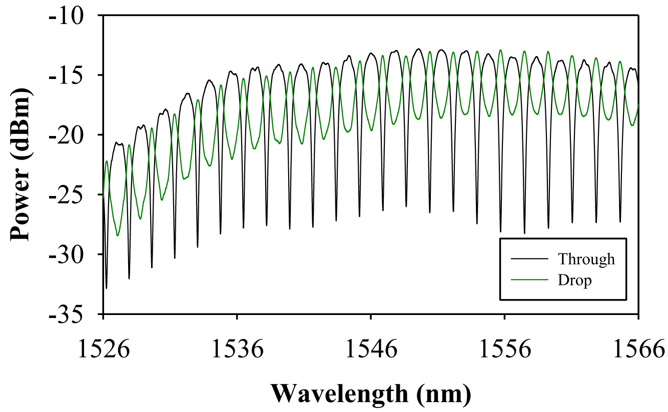

Fig. 2. Measured output spectra of the SiMRR at the drop and through ports, respectively.

In the experiment, the amplified spontaneous emission (ASE) of the C-band EDFA is used to launch into the input port of SiMRR via utilizing the silicon waveguide GC for the measurement of output characteristics. An optical spectrum analyzer (OSA) with a 0.06 nm resolution is used for measuring the output spectrum of proposed SiMRR EDF DR laser. Besides, we observe the filtering output spectra of SiMRR at the drop and through ports, respectively, as illustrated in Fig. 2. In order to connect to the single-mode fiber (SMF) and the silicon waveguide GC, the vertical coupling method with a vertical offset angle of 10° is employed for optical signal connection. Here, the waveguide GCs would result in ~10 dB coupling loss in the proposed EDF DR laser scheme. As indicated in Fig. 2, the free spectrum range (FSR) of 2.0 nm of SiMRR can be observed due to the original design.

As illustrated in Fig. 1, two CPRs, an unpumped EDF and a RFM can lead to DR architecture together with self-injection mechanism. Here, the DR scheme can generate two fiber rings, which are the main-ring (R_{main}) and secondary-ring (R_{sec}), respectively. Each fiber ring has its corresponding free spectrum range (FSR), which means the FSR_{main} and FSR_{sec} respectively. According to the Vernier effect, the least common multiple of the FSR_{main} and FSR_{sec} can result in an effective FSR (FSR_{eff}) to introduce the mode-filter influence. Besides, the unpumped EDF-based saturable absorber (SA) is also inserted in the R_{sec} to bring the ultra-narrowband auto-tracking filter. The R_{sec} can cause a self-injection loop, as illustrated in Fig. 1. In the measurement, the fiber lengths of R_{main} and R_{sec} are 20 and 22 m; hence the FSR_{main} and FSR_{sec} are 10.02 MHz and 9.29 MHz, respectively. As a result, the densely MLM of the proposed SiMRR EDF DR laser can be suppressed fully to achieve the SLM oscillation. In the measurement, two PCs can be utilized to retain the polarization state and optimize the output power of lasing wavelength. They are also employed to adjust the birefringence loss of EDF laser system.

3. Results and Discussion

To generate different output wavelength of proposed SiMRR EDF DR laser, a SiMRR is used in the laser cavity by properly controlling the birefringence loss of laser cavity. Fig. 3 shows the measured output wavelength in an operation range from 1532.61 to 1557.98 nm with a ~2.0 nm tuning interval. In the measurement, nine lasing wavelengths are observed in the proposed SiMRR DR laser. As indicated in Fig. 3, there are five lasing wavelengths cannot be obtained in the range of 1535 to 1543 nm, due to the losses of silicon waveguide GC and SiMRR in these modes conceivably. In the measurement, Fig. 4 presents the obtained output power and optical signal to noise ratio (OSNR) of each lasing wavelength in the wavelengths of 1532.61 to 1557.98 nm. Moreover, the measured output powers and OSNRs are in the ranges from −11.0 to −9.3 dBm and 48.9 to 52.0 dB, respectively. Besides, the maximum output power of −9.3 dBm is located at the wavelength 1546.19 nm with 51.2 dB OSNR.

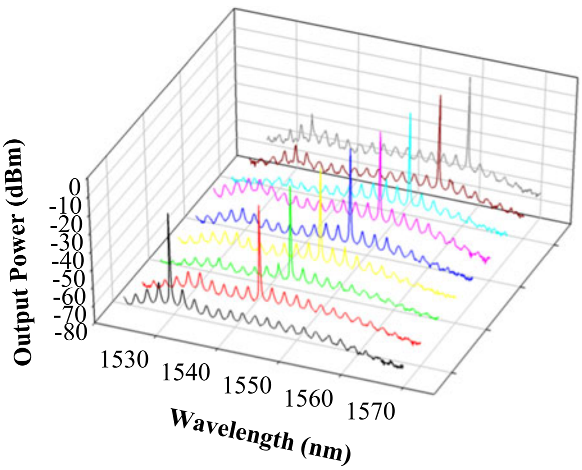

Fig. 3. Measured output wavelength of proposed EDF laser in an operation range of 1532.61 to 1557.98 nm with a ~2.0 nm tuning interval.

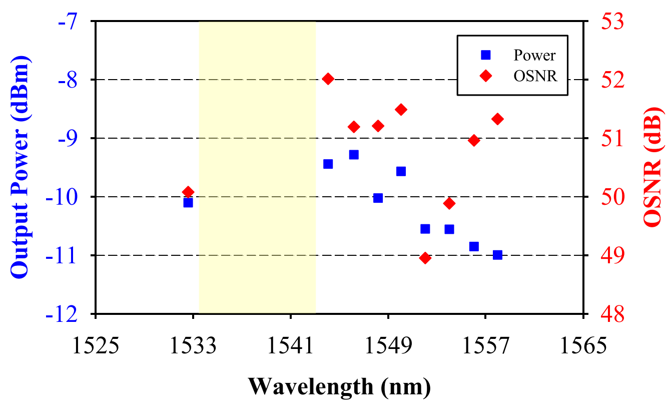

Fig. 4. Obtained output power and optical signal to noise ratio (OSNR) of each lasing wavelength in the range from 1532.61 to 1557.98 nm.

Then, to realize the output perform of proposed SiMRR EDF DR laser, the related stabilities of output power and wavelength are also executed in a short-term observation time. Here, a lasing wavelength of 1532.61 nm with −9.3 dBm output power is utilized initially for demonstration. Fig. 5 exhibits the measured output power variation and wavelength fluctuation during an observation time of 30 minutes. In Fig. 5, we observe that the measured maximum output power and wavelength instabilities are less than 0.9 dB and 0 nm, respectively. The observed results show that the proposed SiMRR EDF DR laser not only can generate different wavelength output, but also can achieve the stable output characteristic.

Next, to confirm whether the output wavelength is SLM oscillation, the delayed self-homodyne detection is utilized for measurement [6]. The experimental setup is constructed by the Mach-Zehnder interferometer (MZI) configuration, which is made of two 1×2 and 50:50 CPRs, a 65 km single-mode fiber (SMF), a PC and a 10 GHz PIN photodiode (PD). We also utilize the lasing wavelength of 1532.61 nm for the execution of SLM characteristic. Here, the optical signal is detected by using the PIN-PD and converts to electrical signal. Then, we employ the 26.5 GHz electrical spectrum analyzer (ESA, Agilent E4440A) for observing the electrical signal. Fig. 6(a) shows the observed electrical spectrum in the frequency range of 0.8 GHz, when the proposed DR scheme is applied in laser cavity. Therefore, we can obtain the stable SLM oscillation in the frequency range of 0.8 GHz without densely MLM, as shown in Fig. 6(a).

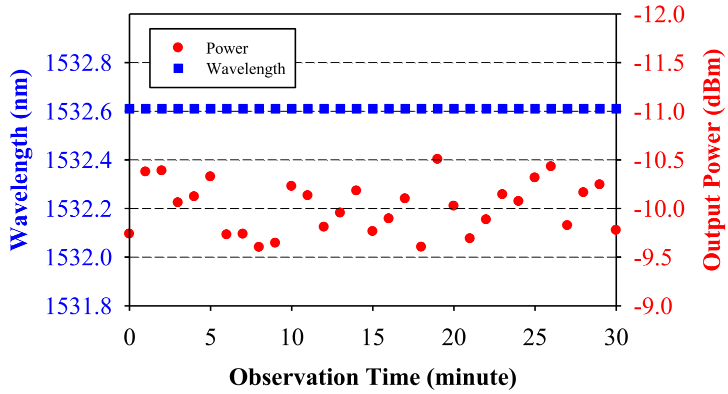

Fig. 5. Obtained power fluctuation and wavelength variation of proposed SiMRR EDF DR laser in an observation time of 30 minutes.

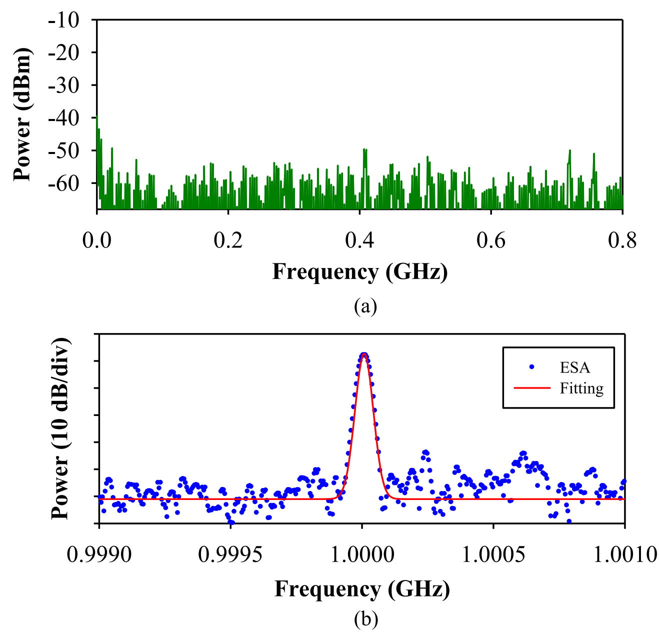

Fig. 6. Measured electrical spectra of proposed SiMRR EDF DR laser by using (a) the delayed self-homodyne and the delayed self-heterodyne detections.

To survey and realize the output linewidth of proposed SiMRR EDF DR laser, the delayed self-heterodyne detection is also employed. We utilize the same lasing wavelength of 1532.61 nm for demonstration. Therefore, the MZI configuration of the self-homodyne setup with the delay arm formed by 65 km SMF is operated. Here, the difference is in the other arm with a 10 GHz phase modulator (PM) in order to produce the beating frequency. Hence, the beating frequency is employed to verify the wavelength linewidth. Fig. 6(b) shows the measured beat frequency at the 1 GHz, when the 1 GHz sinusoidal signal is applied in PM, as plotted in the blue dot. In the measurement, the Lorentzian fitting is utilized to confirm the 3 dB output linewidth of lasing wavelength. Around 22.5 kHz linewidth of proposed SiMRR EDF DR laser is obtained, as illustrated in the red line of Fig. 6(b).

Furthermore, in our previous publications, by using the nonlinear effect of four-wave mixing, 110 GHz optical pulses based on passive mode-locking [23] and hybrid mode-locking [24] are reported by using a high power EDFA inside the fiber-laser cavity. The measured threshold to achieve nonlinear effect is about 15 dBm (without considering the losses introduced by the grating couplers and silicon micro-ring). However, the work reported here is a continuous-wave (CW) single-longitudinal-mode laser demonstration; and the EDFA used inside the fiber-laser cavity is only 13 dBm. This power lower than the nonlinear threshold.

4. Conclusion

In summary, we proposed and experimentally investigated a wavelength-tunable SiMRR-based EDF DR laser, having ~22.5 kHz output linewidth, with stable SLM oscillation. Here, to complete the SLM operation, the proposed DR scheme together with the unpumped EDF SA and self-injection method was applied as the mode-filter to compress the densely MLM fully. Furthermore, the SiMRR was used in the proposed laser cavity to generate the different output wavelengths with 2.0 nm tuning step, while the birefringence loss was adjusted correctly. In the measurement, the measured output powers and OSNRs of the proposed EDF laser were between −11.0 abd −9.3 dBm and 48.9 and 52.0 dB, respectively, in the wavelengths of 1532.61 to 1557.98 nm. There were nine lasing wavelengths could be obtained in the same wavelength range. Some wavelengths could not be generated owing to the losses of silicon waveguide GC and SiMRR in these modes conceivably. In the measurement, the maximum output power variation and wavelength fluctuation of 0.9 dB and 0 nm were obtained during a short-term observation time of 30 minutes. Moreover, during an hour observation time, the measured stabilizations of output power and wavelength were still kept within the variations.

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