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Feedback-Injected Erbium Fiber Laser With Selectable Tunability and Constant Single-Longitudinal-Mode Characteristic

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ABSTRACT In this investigation, a wavelength-selected single-longitudinal-mode (SLM) erbium-doped fiber (EDF) ring laser utilizing C-band EDF based gain medium over a tuning bandwidth of 1524.0 to 1573.0 nm is demonstrated experimentally. A self-injection Rayleigh backscattering (RB) is designed in the EDF ring laser configuration to suppress the multi-longitudinal-mode (MLM) oscillation and narrow the obtained linewidth. Here, the physical output features of the proposed self-injected RB EDF laser are also studied and discussed, such as the optical signal to noise ratio (OSNR), output power, and laser linewidth, respectively. Therefore, the demonstrated EDF laser not only can reach SLM output, but also can produce a flat output spectrum of 1524.0 to 1554.0 nm with 0.2 dB power variation. Moreover, the measured fluctuation of each wavelength can be kept at ±0.05 nm based on the presented self-injected RB EDF laser, while the uncertainty issue is also considered.

INDEX TERMS Fiber laser, erbium-doped fiber (EDF), Rayleigh backscattering (RB), single-longitudinal-mode (SLM), stability.

I. INTRODUCTION

In recent years, the erbium-doped fiber (EDF) lasers with the characteristics of broad tunability and single-longitudinal-mode (SLM) oscillation have been widely discussed and studied [1]–[3], due to their valuable applications in wavelength-division-multiplexing (WDM) transmission, optical fiber sensing, millimeter-wave (MMW) photonics, bio-photonics, and optical metrology [4]–[6]. Furthermore, the EDF based lasers also could reach narrow linewidth output, low phase noise and ultra-long coherent length. However, EDF-based laser would cause the unstable output feature because of the homogeneous broadening and spectral hole-burning effects. Besides, due to a longer cavity length in EDF laser, the closely multi-longitudinal-mode (MLM) oscillation and mode-hopping would be induced simultaneously [7]. Thus, the previous approaches have been proposed to suppress the MLM spikes for stable SLM operation, including utilization of the saturable absorber (SA) based filter, phase-shifted fiber Bragg grating (FBG), ultra-narrow optical filter, compound-fiber-ring method, optical injection technique and Rayleigh backscattering (RB) characteristic, respectively [8]–[13]. Furthermore, to obtain the tunability in the EDF lasers, utilization of tunable band-pass filter (TBF), narrow passband filter, variable FBG, silicon-microring-resonator (SMR) and Fabry-Perot tunable fiber (FP-TF) have been operated in the fiber ring for wavelength-selection [14]–[18].

In 2014, Zhu's group started to employ the optical injection RB effect, EDF based SA and tapered fiber in EDF ring laser schemes for generating a narrower SLM wavelength output [11], [19], [20]. However, the observed output powers of the presented RB injection EDF lasers were less than −10 dBm. To reach the SLM wavelength oscillation, they

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needed applying a variable optical attenuator (VOA) inside a ring cavity for adjusting the optimal power output to match the gain competition of erbium fiber laser. Moreover, the previous RB EDF lasers only generated single or dual wavelength output by exploiting the FBG device.

In this demonstration, we demonstrate a self-injection RB EDF laser architecture with tunable wavelength output and stable SLM operation simultaneously. To suppress the MLM oscillation in an EDF based laser, only a self-injection RB feedback design with 25 km single-mode fiber (SMF) transmission length is exploited for SLM generation. The available operation range of 1524.0 to 1573.0 nm can be obtained in the presented EDF laser for wavelength-selection. Here, the output powers of 0.2 to 3.9 dBm and optical signal to noise ratios (OSNRs) of 30.5 to 35.2 dB are achieved over the effective wavelength bandwidth, respectively. In the execution, the designed EDF laser also exhibits a flat output spectrum with 0.2 dB power change in the range of 1524.0 to 1554.0 nm. Furthermore, the observed output power and wavelength fluctuations are around 0.2 dB and ±0.05 nm, respectively, when the uncertainty issue is considered after an observation period of 40-minute. The 3-dB Lorentzian linewidth of the designed RB EDF laser are all 2 kHz in the available wavelength range. In the previous works [11], [19], [20], they only could achieve narrow linewidth output by RB injection method in the C-band range. Besides, the attained output powers were less than −10 dBm. Compared to the previous studies, the proposed self-injected RB EDF laser not only can reach a few kHz linewidth, but also can broaden the tuning range to L-band, when the C-band EDF gain medium is exploited. And the output power can be larger than 0.2 dBm in the whole operation bandwidth.

II. EXPERIMENT AND RESULTS

Fig. 1 exhibits the optical setup of presented self-injected RB EDF ring laser configuration. To construct the selectable and stable EDF laser, a commercially erbium-doped fiber amplifier (EDFA), a polarization controller (PC), a length of 25 km single-mode fiber (SMF), a 1 × 2 and 50:50 optical coupler (OCP_1), a tunable bandpass filter (TBF), and a 1 × 2 and 10:90 optical coupler (OCP_2) are exploited, respectively. In the measurement, an EDFA, having the available gain range of 1528 to 1562 nm, is regarded as the gain medium inside the ring cavity. The saturation output power of the EDFA is around 13 dBm. To achieve the wavelength tunability, a TBF is inserted in the ring loop for selection continuously. The 3-dB bandwidth and insertion loss of TBF are 0.4 nm and 6 dB, respectively, in the available wavelength range of 1510 to 1630 nm. To control the polarization direction and achieve the largest output power of arbitrarily polarized wavelength, a PC is exploited for achievement. As we know, the optical RB injection could be applied in EDF laser to narrow the linewidth and achieve the SLM oscillation simultaneously [20], [21]. We can employ an OC, a length of SMF and an OCP_2 to cause the self-injected RB signal to suppress the dense MLM effect in the proposed fiber laser configuration, as presented in Fig. 1. In addition, the output power and lasing wavelength in the presented RB EDF laser can be observed by utilizing the optical power meter (OPM) and optical spectrum analyzer (OSA), respectively, through the 10% output port of OCP_2.

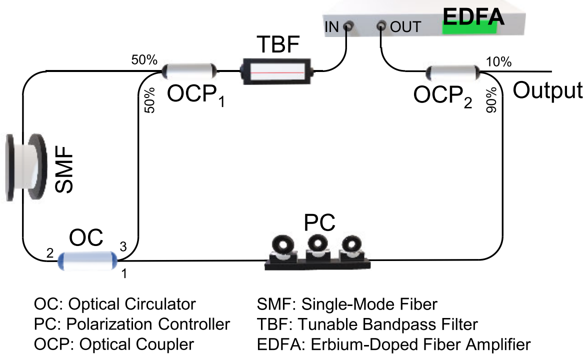


FIGURE 1. Presented self-injected RB EDF ring laser architecture.

First, to ensure the maximum tuning bandwidth of the presented self-injected RB EDF ring laser, a TBF is exploited to adjust from shorter to longer wavelengths gradually. Fig. 2 presents the observed output wavelength spectrum over the wavelengths of 1524.0 to 1573.0 nm. Here, the continuously wavelength-selected range of the EDF laser can be accomplished in the wavelengths of 1524.0 to 1573.0 nm. We select four output wavelengths of 1524.0, 1540.0, 1560.0 and 1573.0 nm for demonstration. The resolution of OSA is 0.08 nm. The measured amplified spontaneous emission (ASE) spectrum of commercial EDFA is also illustrated in the dash line of Fig. 2. Here, the higher ASE background noise around 1530 nm could be repressed to get the better side-mode suppression ratio (SMSR) for each output signal. The observed optical signal to noise ratios (OSNRs) of four wavelengths are larger than 30.5 dB, as shown in Fig. 2. Because the saturation output power of EDFA is nearly 13 dBm, the achieved OSNR of lasing wavelength will be smaller than that mentioned in the above refs. [19], [20], due to the stronger background optical noise. In addition, an avail-

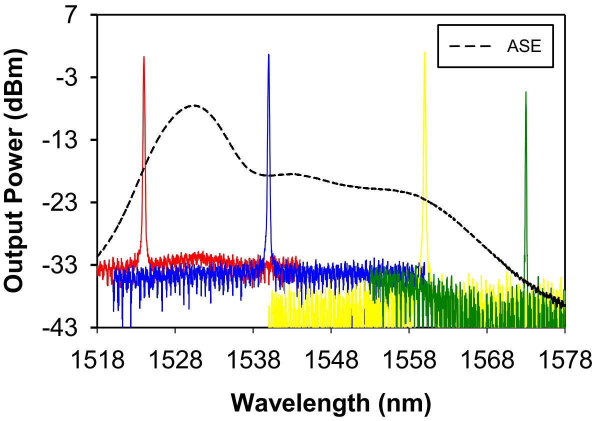


FIGURE 2. Measured wavelength spectra of presented RB EDF laser over the operation bandwidth of 1524.0 to 1573.0 nm. Dash line is the ASE spectrum of EDFA.

able bandwidth of 1524.0 to 1573.0 nm can be attained in the presented RB EDF laser based on a commercially C-band EDFA. In general, the obtained output power of lasing wavelength would be dropped gradually in both sides, due to the gain distribution of EDF. Thus, the measured peak power of 1573.0 nm is smaller than the others.

Then, we measure the output power and OSNR of the designed EDF laser over the effective wavelength bandwidth of 1524.0 to 1573.0 nm. Fig. 3 displays the output power of 0.2 to 3.9 dBm and OSNR of 30.5 to 35.2 dB over the range of 1524.0 to 1574.0 nm. In the detection, the largest output power and OSNR are attained at the wavelengths of 1529.0 and 1573.0 nm, respectively. Moreover, the presented EDF ring laser also can achieve a flat output spectrum from 1524.0 to 1554.0 nm with power difference of 0.2 dB, as seen in Fig. 3. Hence, to obtain flat output spectrum in the EDF-based laser in the previous works [22]–[24], several methods have been proposed, such as utilizing variable optical filter, applying gain-flattened EDFA, and adjusting the pump power dynamically. In our work, we only utilize the self-injected RB feedback loop with 25 km SMF in the EDF laser, nearly 30 nm flat output bandwidth with 0.2 dB power fluctuation can be achieved. Moreover, the wavelength tunability can be also extended to 1573.0 nm in L-band range by using the designed laser configuration and C-band EDFA based gain medium.

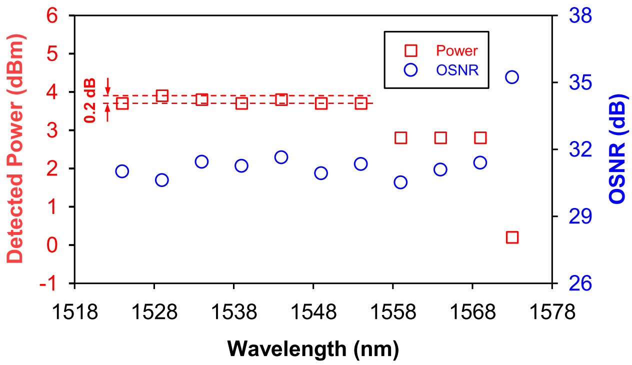


FIGURE 3. Obtained OSNR and output power versus the different wavelengths of 1524.0 to 1573. 0 nm in proposed RB EDF laser.

Next, to ensure the SLM oscillation of the presented RB EDF laser, a delayed self-homodyne detection is built for demonstration. An optical setup is assembled by a PC, two 1 × 2 and 50:50 OCPs, and a length of 26 km single-mode fiber to construct the Mach-Zehnder interferometer (MZI) architecture [8], [10], as illustrated in Fig. 4, when the red "Block" is removed. A length of 26 km SMF is put in one of the arms to form a delay line to obtain a beat wavelength. Then, the optical beat signal can be detected by a photodiode (PD) and converted to electrical signal. Then, we can observe the output electrical signal by using a 3 GHz electrical spectrum analyzer (ESA). In the measurement, we select seven output wavelengths of 1524.0, 1530.0, 1540.0, 1550.0, 1560.0, 1570.0 and 1573.0 nm for SLM observation over the whole available bandwidth. Fig. 5(a) display the observed electrical spectra of seven selected wavelengths over the frequency bandwidth of 0 to 500 MHz, respectively. We observe that the dense MLM are not measured, as seen in Fig. 5(a). In addition, when the measuring bandwidth is extended from 0 to 1 GHz, the observed electrical spectra are still without any MLM oscillation, as exhibited in Fig. 5(b). During the 40-minute observation period, the whole observed electrical spectra are also kept at the SLM operation.

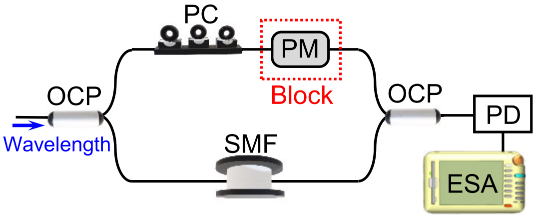
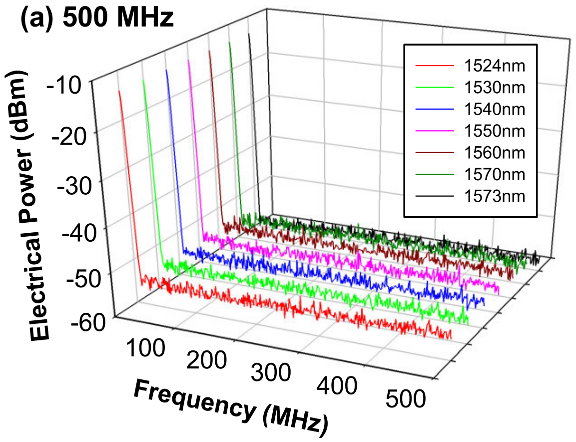


FIGURE 4. The experimental setups for delayed self-homodyne (when the Block is removed) and delayed self-heterodyne detections.



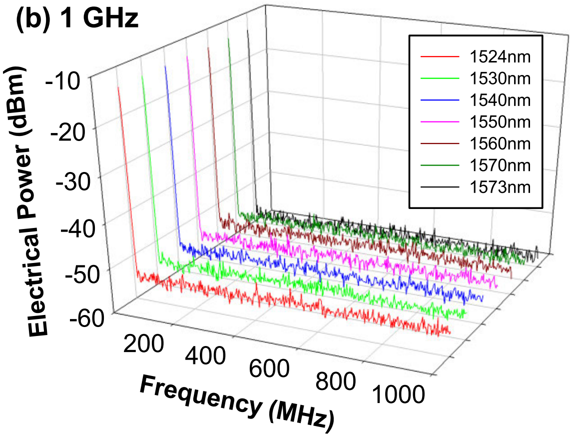


FIGURE 5. Measured electrical spectra of proposed RB EDF laser over the frequency bandwidth of (a) 0 to 500 MHz and (b) 0 to 1 GHz, respectively.

As seen in Fig. 1, the RB effect could be generated at the multiple scattering centers along the SMF. Then, the arbitrarily multiple reflections would be regarded as the distributed mirror to create the various ring cavity length and changeable mode separation at the end of SMF. Then, the RB-induced signal would enter the EDFA through the OC (port "2" to port "3") in the proposed ring laser. The EDFA permit the RB-induced light to be excited and amplified through millions of times for causing high gain and long coherence length. When the Rayleigh bandwidth is small relatively, the achieved pump wavelength in the ring cavity will become more and more narrow to reach the SLM oscillation after several million times resonance [21]. Therefore, the lasing wavelength can narrow laser linewidth and accomplish SLM output.

Then, we exploit the delayed self-heterodyne structure to determine the linewidth of presented RB EDF ring laser, when the “Block” is included in Fig. 4. To generate RF beat signal for measuring, a phase modulator (PM) is utilized in the other arm of the MZI architecture. Here, we choose the output wavelength of 1524.0 nm for linewidth measurement first. So, the measured electrical spectrum of 1524.0 nm is plotted in the blue circle of Fig. 6(a), when 280 MHz RF signal is applied on the PM. Here, the resolution and measured frequency span of ESA are 1 and 250 kHz, respectively. To obtain the real linewidth of detected signal, a Lorentzian curve can be used for fitting. Therefore, the 3-dB Lorentzian linewidth of 2 kHz can be accomplished in the presented RB EDF laser, as plotted in the red dash line of Fig. 6(a). Next, to certify the practical linewidth of the EDF laser over the available wavelength range, we also utilize the output wavelengths of 1530.0, 1540.0, 1550.0, 1560.0, 1570.0 and 1573.0 nm for measurement, respectively. Fig. 6(b) display the fitted 3-dB Lorentzian linewidth of the seven selected wavelengths over the effective bandwidth of 1524.0 to 1573.0 nm. We obtain that all the observed linewidths of seven wavelengths are around 2 kHz. Moreover, in our previous demonstration [16], the measured linewidth range of EDF laser was from 15 to 22 kHz by exploiting dual-ring cavity design. As a result, based on the proposed self-injected RB feedback scheme, the RB EDF laser not only can achieve 49 nm wavelength tunability, but also can narrow the 3-dB linewidth to 2 kHz. Due to the limited resolution of the ESA used, we believe that the measured 3-dB linewidth can be lower than 2 kHz probably. In the demonstration, using the SMF in the proposed EDF laser is an easy way to produce RB-induced signal for optical injection. The length of 25 km SMF in the presented EDF laser not only can narrow the laser linewidth, but also can extend the tuning range and flatten the power output.

Finally, to recognize the performance of output stability, we exploit the wavelength of 1524.0 nm for realization first. Originally, the 1524.0 nm wavelength with 3.8 dBm output power is employed for observing the fluctuations of power and wavelength simultaneously. During a 40-minute observation time, the power variation of 0.1 dB and wavelength change of 0 nm are measured, as illustrated in Fig. 7. In the experiment, the wavelength and power accuracies of OSA and OPM are ±0.05 nm and ±0.1 dB, respectively. Therefore, the maximum power and wavelength variations of Fig. 7 would become 0.2 (0.1±0.1) dB and ±0.05 (0 ±0.05) nm, when the uncertainty issues of the measured result and instrument are also included. Moreover, the variable temperature would induce the output fluctuation of EDF ring lasers. Hence, we execute the related measurements at room temperature to stabilize the output characteristics.

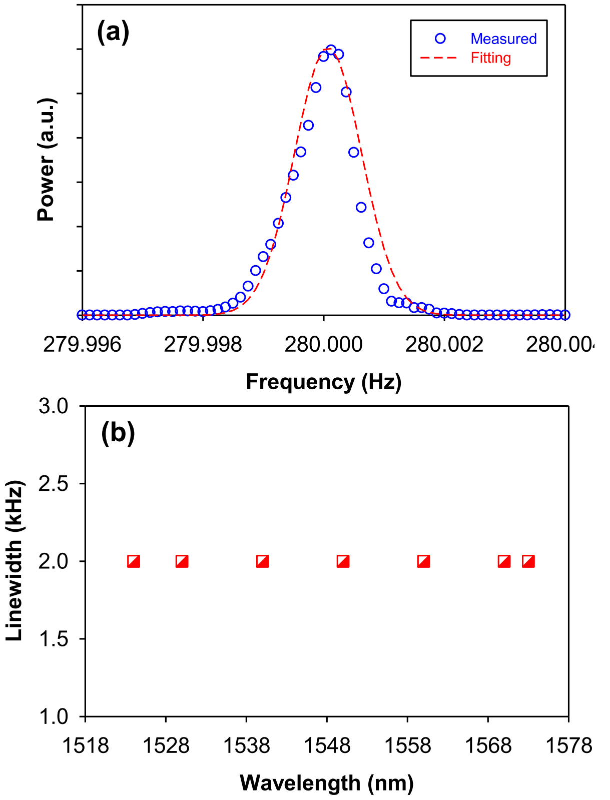


FIGURE 6. (a) Measured and fitted laser linewidth at the wavelength of 1524.0 nm. (b) Observed 3-dB Lorentzian linewidth of the seven selected wavelengths over the effective bandwidth of 1524.0 to 1573.0 nm.

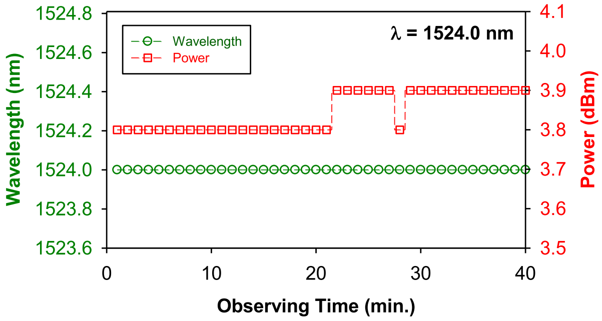


FIGURE 7. Measured fluctuations of output power and wavelength over 40 minutes observation, when the 1524.0 nm wavelength is selected for measurement.

Then, we also exploit the same selected wavelengths as mentioned above for stability examination. After a measuring period of 40-minute, the measured maximum output power variation and wavelength difference are 0.2 dB and 0 nm, respectively, among the seven wavelengths over the bandwidth of 1524.0 to 1573.0 nm, as exhibited in Fig. 8. Thus, while the uncertainty issues are also contained, the obtained power and wavelength variations would be ±0.2 dB and ±0.05 nm, respectively, over the operation bandwidth.

In the demonstration, the C band signal would pump the EDF once more, then the tuning band could be broadened to

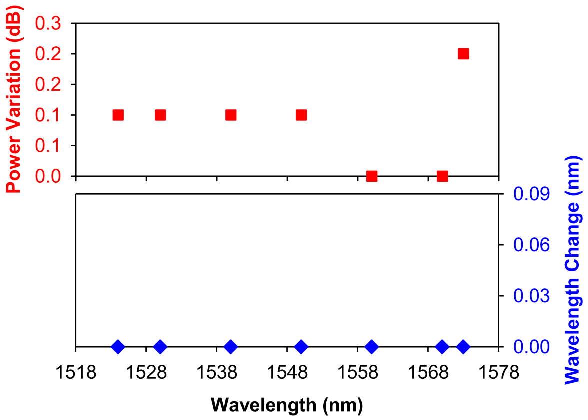


FIGURE 8. **Measured output power variation and wavelength change respectively, among the seven wavelengths over the bandwidth from 1524.0 to 1573.0 nm.**

L-band. Moreover, the operation bandwidth may be extended through RB effect, which is served as the distributed mirror to generate the different ring cavity length, under a longer SMF length. Here, the original gain range of EDFA in the proposed EDF laser structure could be suppressed and broadened to longer wavelength range under a longer SMF. Thus, the adjustable range of 1524.0 to 1573.0 nm can be achieved by using C-band erbium gain. In addition, due to the RB injection effect, the obtained output power also can be flattened over the bandwidth of 1524.0 to 1554.0 nm with 0.2 dB variation.

III. CONCLUSION

We demonstrated a self-injected RB EDF ring laser to achieve stable SLM oscillation and selectable tunability by using commercially C-band EDF based gain medium. To reach the SLM and narrow the linewidth of lasing wavelength, a self-injection RB feedback loop is proposed in the EDF laser. Here, a TBF was put inside the fiber ring to tune the various lasing wavelength over the wavelength tunability of 1524.0 to 1573.0 nm both covering C- and L-bands. The attain OSNRs and output powers of the proposed EDF laser were between 0.2 and 3.9 dBm and 30.5 and 35.2 dB over the whole tuning bandwidth, respectively. After a 40-minute observation period, the output power variation of 0.2 dB and wavelength fluctuation of ±0.05 nm was observed in the range of 1524.0 to 1573.0 nm, when the uncertainty factors were also included. Additionally, all the measured laser linewidth of the presented EDF laser were 2 kHz over the effective wavelength bandwidth.

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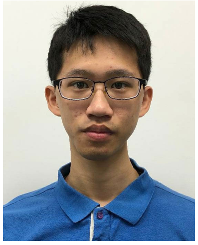

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