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Stable and Tunable Erbium Ring Laser by Rayleigh Backscattering Feedback and Saturable Absorber for Single-Mode Operation

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Abstract: This work demonstrates a high-quality erbium-doped fiber (EDF) ring laser in the L-band gain range by combining the Rayleigh backscattering (RB) feedback signal and unpumped EDF induced saturable absorber (SA) filter. The optical filter effect induced by the RB feedback injection and EDF SA could generate single-longitudinal-mode (SLM) behavior and shrink the linewidth to sub-kHz. The output linewidth, power, and optical-signal-to-noise ratio (OSNR) of the fiber ring laser were also shown within the 42 nm wavelength bandwidth of 1565.0 to 1607.0 nm. Also, the instabilities of output power and central wavelength of each lasing lightwave were analyzed with a measurement time of 45 min.

Keywords: erbium-doped fiber (EDF) laser; single longitudinal mode (SLM); Rayleigh backscattering (RB); unpumped EDF

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Citation: Liao, C.-Y.; Kao, Y.-H.; Chen, Y.-Z.; Cheng, K.-M.; Lin, C.-Y.; Wu, T.-H.; Yang, T.-Y.; Yeh, C.-H. Stable and Tunable Erbium Ring Laser by Rayleigh Backscattering Feedback and Saturable Absorber for Single-Mode Operation. *Quantum Beam Sci.* **2024**, *8*, 25. https://doi.org/10.3390/qubs8040025

Academic Editor: Simone Spampinati

Received: 8 July 2024
Revised: 4 September 2024
Accepted: 19 September 2024
Published: 2 October 2024

1. Introduction

In recent years, erbium-doped-fiber (EDF)-based lasers with tunable and constant single-longitudinal-mode (SLM) operation have garnered widespread attention. SLM EDF lasers have wide-ranging applications in wavelength-division-multiplexing (WDM) systems, optics fiber sensors, bio-photonics, optical spectroscopy, optical communication, and microwave photonics [1–4]. At present, EDF lasers are considered a brilliant source due to their better output characteristics of a broad wavelength-tuning bandwidth, narrow linewidth, and high optical-signal-to-noise ratio (OSNR) [5]. Generally, ring-based EDF lasers can avoid the gain spatial hole burning caused by the standing wave effect in a linear cavity [6]. To mitigate dense longitudinal mode competition in fiber ring laser architecture, ultra-narrow bandpass filters have been studied and applied in resonant-ring cavities by, for instance, utilizing saturable absorbers (SAs), compound ring cavities, micro-ring resonators, microfiber resonators, special fiber Bragg gratings (FBGs), Mach-Zehnder interferometer (MZI) filters, pair-based FBG Fabry–Perot filters, and Rayleigh backscattering (RB) feedback injection [7–13].

The wavelength-switchable range depends on the different gain medium ranges of erbium fiber in the S- (1480 to 1520 nm), C- (1525 to 1560 nm), and L-band (1560 to 1610 nm), respectively [5,8,14]. Moreover, to gain a broader tunable wavelength range, using two parallel EDFs or hybrid optical amplifiers has also been demonstrated [15,16]. To tune and generate various continuous-wave (CW) wavelength outputs, using the Fabry–Perot tunable filter (FP-TF), a variable FBG and tunable bandpass filter (TBF) in ring cavities were used as wavelength selectors and have become the most popular choice in EDF lasers [17,18].

Typically, in order to easily achieve SLM operation, using the Rayleigh backscattering (RB) feedback injection loop [13] or the unpumped EDF-based SA [6] in a ring cavity would be the easiest and most cost-effective way. In this paper, we combine the Rayleigh backscattering (RB) injection signal and unpumped EDF SA into an EDF ring laser structure to compress dense longitudinal mode fluctuations and shrink the wavelength linewidth. In the demonstration, a L-band erbium-based gain medium is used in the fiber ring resonator, enabling a wavelength-tunable bandwidth of 1565.0 to 1607.0 nm. The related output characteristics of power and OSNR are set at an effective wavelength range of –10.62 to 2.56 dBm and 42.19 to 55.97 dB, respectively. In addition, the RB feedback injection and EDF-SA induced effect can narrow the obtained linewidth to 400 to 800 Hz and keep the stable output of power and central wavelength within 0.58 dB and 0.044 nm during a short test time. Compared with other optical filtering technologies presented above, the proposed EDF laser, integrating the RB and EDF-SA methods, not only has a simple structure and low cost but can also achieve a narrower linewidth of sub-kHz over the L-band bandwidth.

2. Experiment and Principle

Figure 1 exhibits the EDF ring laser setup designed. In the experiment, the fiber laser consists of optical components such as a 5 m unpumped EDF, a 100 m single-mode fiber (SMF), a tunable bandpass filter (TBF), a commercial L-band erbium-doped fiber amplifier (EDFA), a 3-port optical circulator (OC), a 1 × 2 50:50 optical coupler (OCP_1), a 1 × 2 10:90 optical coupler (OCP_2), and a polarization controller (PC). EDFA, which has an effective gain range from 1568 to 1604 nm, is exploited in a ring cavity serving as a gain medium. To tune different wavelength outputs of the laser configuration, a TBF, having a tuning scale of 1510 to 1630 nm, will also be inserted in the fiber ring loop for selection. A PC is operated to change the polarization direction and realize the optimal power output for each wavelength channel.

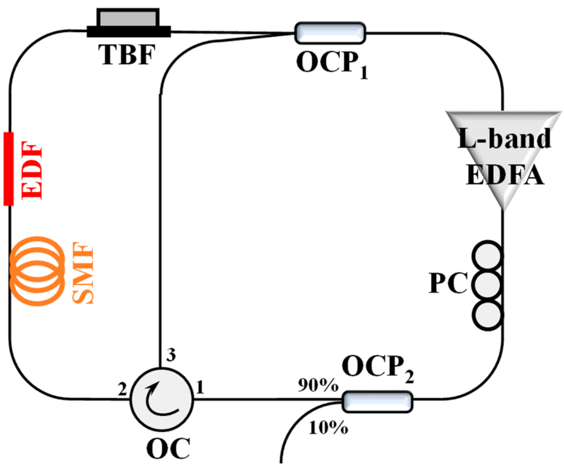

Figure 1. Proposed EDF ring architecture with RB feedback injection and EDF-SA-induced effect. OC: optical circulator; PC: polarization controller; EDF: erbium-doped fiber; OCP_1: 1 × 2 50:50 optical coupler; OCP_2: 1 × 2 10:90 optical coupler; TBF: tunable bandpass filter; SMF: single-mode fiber; EDFA: erbium-doped fiber amplifier.

To mitigate the multiple longitudinal mode vacillations, an RB feedback loop and a saturable absorber (SA) based on a 5 m unpumped EDF are added in the laser structure. The RB loop consists of a 100 m SMF, an OC, and an OCP_1. The RB feedback signal is generated by the 100 m SMF and enters the main ring cavity through OC (port 2 to port 3) and OCP_1, as displayed in Figure 1. So, the RB light is also amplified when it passes through the EDFA-based gain medium. The amplified RB signal can cause the RB light to occur again in a SMF with a greater Rayleigh coefficient. This optical set, utilizing RB, can be viewed as a permanent number of cascaded scattering cross sections. So, the scattered signal is concentrated into a weak injection to reduce the laser linewidth [13,19].

In the presented laser architecture, the generated wavelength also enters into the unpumped EDF SA with unidirectional movement. Then, a standing wave traveling down the EDF leads to a periodic composition of light intensity. So, the periodic absorption vicissitude creates a spatial periodical distinction of the refraction index and absorption coefficient. Conclusively, the standing wave will generate a narrowband dynamic Bragg grating (DBG) through the unpumped EDF to bring an ultranarrow-band auto-tracking filter for mitigating dense longitudinal mode fluctuations [6]. In general, the fiber length of an RB injection loop added in a EDF ring laser scheme was about several hundred meters long [2,19]. However, a too-long RB feedback fiber length and EDF SA length in the ring cavity will cause the power loss of the EDF laser to increase. Therefore, choosing the appropriate fiber and EDF length requires careful consideration. Thus, to reduce the fiber length of the RB feedback loop to 100 m in the proposed EDF laser, we can combine the EDF-SA-induced filter effect to achieve the SLM operation.

3. Results

Figure 2 shows the optical output spectra of six selected lasing wavelengths over the wavelength bandwidth from 1565.0 to 1607.0 nm, as the passband of TBF is changed. Moreover, Figure 2 also presents the amplified spontaneous emission (ASE) curve of L-band EDFA. The 10 dB bandwidth of the ASE band is 1573.2 to 1605.6 nm. Hence, the wavelength-tuning range achieved by the designed EDF laser is basically consistent with the gain scale of the EDFA used. The output power and OSNR of the generated wavelengths measured over the entire wavelength bandwidth of 1565.0 to 1607.0 nm are displayed in Figure 3. The output power and OSNR obtained are between −10.62 and 2.56 dBm and between 42.19 and 55.97 dB, respectively. As shown in Figure 3, as the laser wavelength moves toward longer wavelengths, the output power and OSNR obtained will gradually become smaller. The lasing wavelength with larger output power will have a higher OSNR than normal. The lasing wavelength of 1571.0 nm has a higher output power of 2.56 dBm and an OSNR of 53.79 dB. And the highest OSNR is observed at the wavelength of 1580 nm.

Then, the unstable output of power and central wavelength is also an important issue for the EDF ring laser designed. So, to verify the phenomenon, we first choose the 1565.0 nm wavelength to observe the output stability of power and the central wavelength within 45 min, as illustrated in Figure 4a. And the observed changes in the maximum output power and central wavelength of 1565.0 nm can be maintained within 0.58 dB and 0.044 nm, respectively. Furthermore, to understand the power and wavelength instability within the entire effective wavelength scale of 1565.0 to 1607.0 nm, we also record the corresponding maximum variation within 45 min of observation, as seen in Figure 4b. The maximum and minimum power and wavelength variations are between 0.048 and 0.016 nm and 0.58 and 0.13 dB, respectively, over the whole tuning bandwidth after a 45 min measurement. Hence, the RB signal and EDF-based SA in the proposed EDF ring laser provides very stable output presentation. Since the SLM output characteristics induced by RB injection and EDF SA are not affected by temperature, the output stability of the proposed EDF laser should not be affected [2]. Moreover, because the fiber length of the entire EDF ring laser is short, the chromatic dispersion effect can be ignored.

Next, to confirm the SLM capability and acquire the linewidth of the EDF laser simultaneously, a dual-arm Mach–Zehnder interferometer (MZI)-based delayed self-heterodyne architecture is applied [20]. One of the arms links to the PC and acousto-optic modulator (AOM); the other arm connects to a 75 km SMF as a delay line. A 55 MHz frequency signal is applied on the AOM to shift frequency and generate a beat signal for surveying the linewidth. Here, a 1565.0 nm output wavelength is exploited for observation first. Figure 5 displays the radio frequency (RF) beat spectrum measured within a 1 GHz frequency bandwidth at a 1 MHz resolution bandwidth. Except for the intrinsic 55 MHz shift signal of the AOM, no other beat frequencies are measured, which specifies that the presented EDF is operating in a stable SLM operation. Moreover, the inset in Figure 5 exhibits a beat signal of 55 MHz with a 2.5 kHz resolution bandwidth within a 40 kHz scale. The 1565.0 nm wavelength linewidth of the EDF laser is achieved by fitting the frequency curve measured (square symbol) to a Lorentzian profile (solid line). The 3 dB linewidth of the fitted Lorentzian spectrum is approximately 800 Hz. Then, we obtain the Lorentzian linewidth of all lasing wavelengths according to the same measurement method in the bandwidth of 1565.0 to 1607.0 nm. All 3 dB Lorentzian linewidths are achieved in a range of 400 and 800 Hz, as shown in Figure 6. A 400 Hz laser linewidth is only obtained at the wavelength of 1600.0 nm. The linewidth of other wavelengths is either 600 or 800 Hz, as illustrated in Figure 6. In previous work [2,19], the RB injection loop with fiber lengths of 120 and 660 m in an EDF ring laser provided 1.46 kHz and 2.5 kHz linewidth output, respectively. However, our proposed EDF laser structure integrating the 100 m RB feedback fiber length and 5 m EDF-based SA can achieve 400 to 800 Hz. In addition, previous studies [21,22] applied the RB feedback loop with fiber and unpumped EDF and a multiple-ring scheme to achieve SLM and narrow linewidth output, respectively. Although the output linewidth of the proposed EDF laser is not better than those of previous works, the laser architecture cost can be lower and provides an alternative fiber laser architecture for wavelength selection.

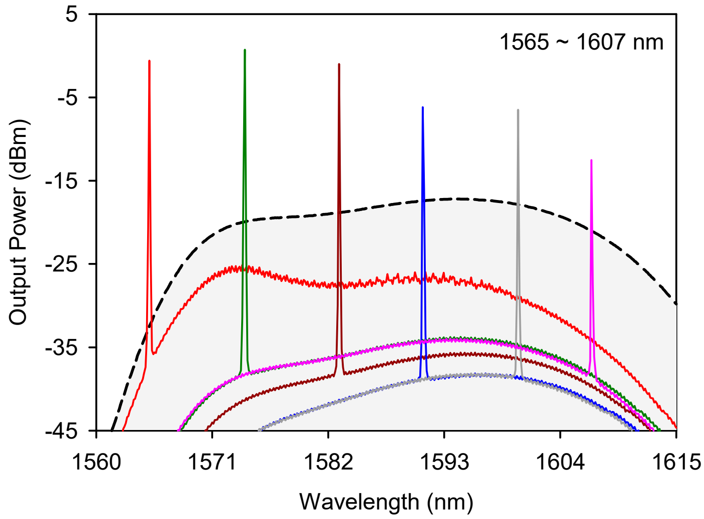

Figure 2. Observed output spectra of six chosen wavelengths over a wavelength bandwidth from 1565.0 to 1607.0 nm. The dashed line is the ASE profile of the former L-band EDFA measured.

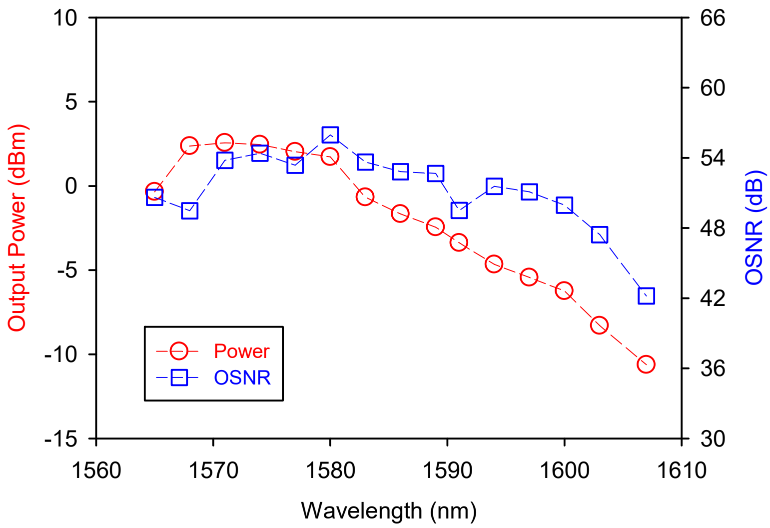

Figure 3. Output power and OSNR of each wavelength measured over the entire wavelength bandwidth of 1565.0 to 1607.0 nm.

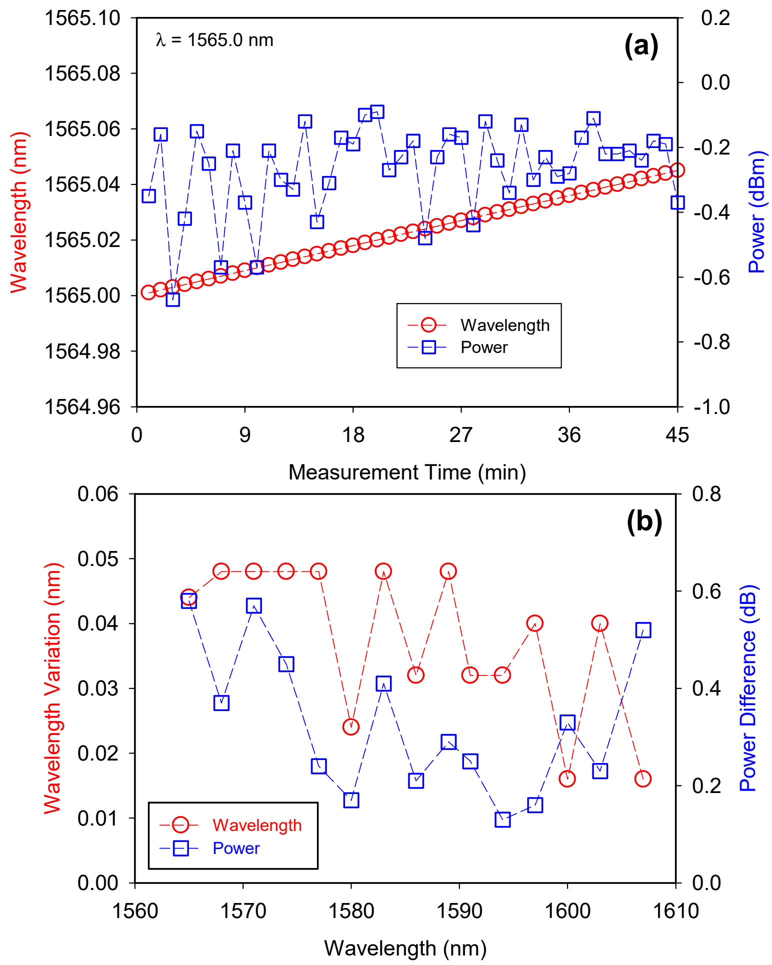

Figure 4. (**a**) Observed output stability of power and central wavelength within 45 min at the wavelength of 1565.0 nm. (**b**) Measured output stabilities of power and central wavelength of each lasing wavelength in the whole tuning bandwidth.

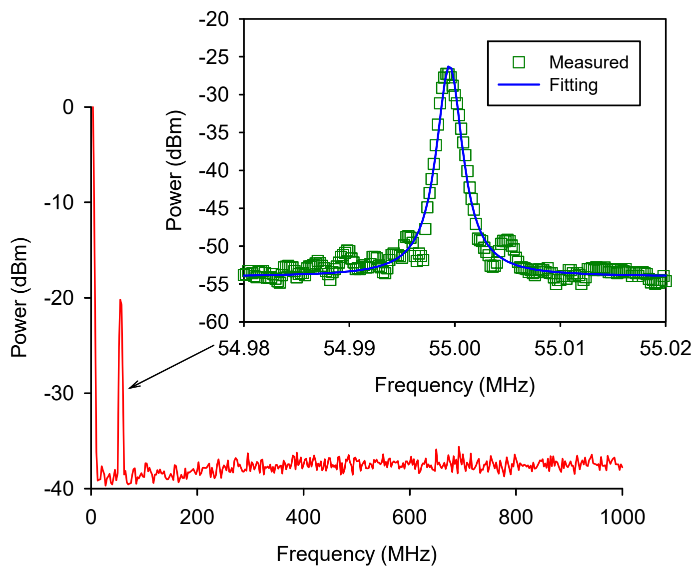

Figure 5. Electrical signal of 1565.0 nm wavelength measured via self-heterodyne setup within 1 GHz frequency bandwidth. Inset is the measured and fitted electrical spectra of 1565.0 nm over the bandwidth of 54.98 to 55.02 MHz.

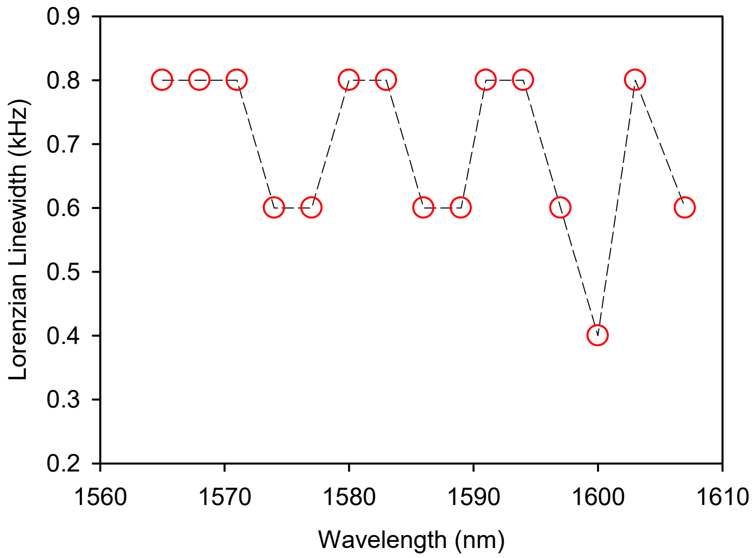

Figure 6. A graph of the 3 dB Lorentzian fitted linewidth obtained through self-heterodyne detection in the entire wavelength span of 1565.0 to 1607.0 nm.

4. Conclusions

In this study, we confirmed an EDF ring laser configuration with a stable and tunable SLM wavelength in L-band range. To achieve this target, an RB feedback signal and unpumped EDF SA filter were included in the fiber cavity to mitigate dense longitudinal modes and shrink the linewidth to sub-kHz. The output power, OSNR, and 3 dB linewidth of the EDF ring laser were obtained between −10.62 and 2.56 dBm, 42.19 and 55.97 dB, and 400 and 800 Hz, respectively, over an effective wavelength-selectable range of 1565.0 to 1607.0 nm. The largest deviations of output power and central wavelength were less than 0.58 dB and 0.048 nm over the whole wavelength-tuning bandwidth during a 45 min test. Thus, the designed EDF ring laser combining RB injection and EDF SA demonstrated excellent output accomplishment and stability according to the experimental results.

Author Contributions: Conceptualization, C.-Y.L. (Chien-Yu Liao); methodology, Y.-H.K., Y.-Z.C. and K.-M.C.; validation, C.-Y.L. (Chien-Yu Liao) and K.-M.C.; formal analysis, T.-Y.Y. and T.-H.W.; investigation, C.-Y.L. (Chun-Yen Lin); data curation, K.-M.C.; writing—original draft preparation, C.-H.Y. and C.-Y.L. (Chun-Yen Lin); writing—review and editing, C.-H.Y.; funding acquisition, C.-H.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Science and Technology Council, Taiwan, NSTC-112-2221-E-035-059-MY3.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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