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Communication

L-Band Wavelength-Selectable Erbium Laser with Stable Single-Frequency Oscillation

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Abstract: In this presentation, we demonstrate an erbium-doped fiber (EDF) laser by a compound-ring structure to reach the output performances of narrow linewidth, stable single-longitudinal-mode (SLM) and high optical signal to noise ratio (OSNR) in the L-band bandwidth of 1563.0 to 1613.0 nm. Based on the Vernier effect through the compound-ring design, the substantial multi-longitudinal-mode (MLM) noises can be mitigated fully. Furthermore, the relative optical output features of the fiber laser are also performed experimentally.

Keywords: fiber laser; erbium-doped fiber (EDF); compound-ring; single-longitudinal-mode (SLM); L-band tunability

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1. Introduction

In recent years, stabilized single-longitudinal-mode (SLM) erbium-doped fiber (EDF) lasers have been investigated and studied for more common applications, such as optical sensors, optical communications, RF-photonics, bio-photonics, time and frequency transfer, and high-resolution spectroscopy [1–5]. This is because EDF-based lasers have output deeds of high optical signal to noise ratio (OSNR), anti-electromagnetic interference, narrow linewidth and high stability [6,7]. Furthermore, due to the growth and requirements of cloud networks, data centers, big data and 5G/6G transmission systems, the traditional C-band bandwidth is not enough to satisfy subscribers. So, the development of the L-band operation band will be an important issue for EDF-based lasers. Because of the homogeneous broadening behavior and longer fiber length of the ring cavity of the EDF laser configuration, multi-longitudinal-mode (MLM) oscillations are induced. To reduce the multiple MLM noise of the EDF-based laser structure, utilizations of the multiple-ring design [7–9], ultra-narrow optical filters [10], saturable absorbers (SA) of unpumped EDF [11,12], the Rayleigh backscattering (RB) effect [3,13], the optical self-injection technique [14] and the Mach–Zehnder interferometer (MZI) method [15] have been experimentally demonstrated for single-longitudinal-mode (SLM) output.

Actually, most EDF lasers are operated in the C-band scale of 1530 to 1560 nm. To expend the available wavelength-tuning bandwidth, the S- or L-band EDFs can be exploited in the fiber cavity as a gain medium [16,17]. Moreover, to generate the various wavelength outputs of the EDF laser, the Fabry–Perot tunable filter (FP-TF) [16], variable fiber Bragg grating (FBG) [18], tunable bandpass filter (TBF) [19] and MZI-based filter [20] have been applied in the fiber cavity for tuning.

In this work, an L-band EDF compound-ring laser with wavelength-swept and stable SLM action is demonstrated. To mitigate the multiple MLM oscillations, a compound-ring configuration with three fiber rings is presented to cause a mode-filter function in line with the Vernier effect. In the experiment, the detected output power and OSNR of each tuning wavelength are between −10.8 and 0 dBm and 64.5 and 74.4 dB, respectively, under the wavelength-swept bandwidth of 1563.0 to 1613.0 nm. The 3 dB Lorentzian linewidth of 2 to 3 kHz of the EDF laser is achieved over the entire wavelength-swept range. In addition, the output stabilities of power and center wavelength are maintained in the ranges of 0.01 to 0.37 dB and 0 to 0.048 nm through a measuring time of 40 min in the whole wavelength scale, respectively. Therefore, the presented compound-ring L-band EDF laser can not only achieve the stable SLM, narrow linewidth output and high OSNR, but also can reach high output stability.

2. Proposed Erbium Laser Architecture

Figure 1 exhibits the proposed selectable and stable L-band EDF laser structure based on the multiple-ring design. The experimental setup is composed of a commercial L-band erbium-doped fiber amplifier (EDFA), two polarization controllers (PCs), an L-band tunable bandpass filter, four 2 × 2 and 50:50 optical couplers (OCP_1s) and a 1 × 2 and 10:90 optical coupler (OCP_2). The saturated output power of 10 dBm is achieved in the L-band EDFA under the operative gain scale of 1568 to 1604 nm. The insertion loss and 3 dB bandwidth of the L-band TBF are 6 dB and 0.4 nm (50 GHz). When the passband of TBF is tuned in the ring cavity, the changed output wavelength can be generated. To obtain optimal power output of lasing wavelength, two PCs are applied in the EDF ring laser for adjusting properly. The output wavelength of the fiber laser is observed from the 10% output port of an OCP_2 through the optical spectrum analyzer (OSA, Anritsu, Atsugi, Japan, MS9740B).

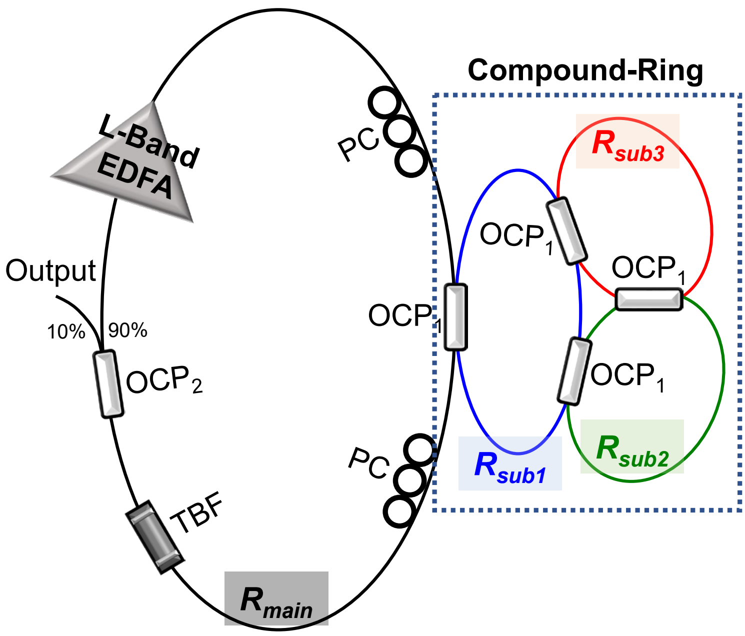

Figure 1. Experimental setup of designed L-band EDF laser with compound-ring configuration.

As seen in Figure 1, the OCP_2 of the presented EDF laser can be circled to construct a main ring (R_{main}). Four OCP_1s are exploited to generate the compound-ring configuration, which causes three sub-rings of R_{sub1}, R_{sub2} and R_{sub3}, respectively. Actually, each ring produces its equivalent free spectrum range (FSR), which is stated by the expression FSR = c/(n·L), where c, n and L are the speed of light in vacuum (c = 3 × 10^8 m/s), average index of fiber (n = 1.468) and fiber length, respectively. In the demonstration, four different fiber rings can be set in the presented EDF laser architecture to produce an effective and wide FSR_{eff} in line with the Vernier effect to create the mode-filter function [21]. Then, the multi-longitudinal-mode (MLM) induced by the main ring can be suppressed according to the wide FSR_{eff} based mode-filter. Here, the measured fiber lengths of R_{main}, R_{sub1}, R_{sub2} and R_{sub3} are 31, 8, 5 and 4 m, respectively. Therefore, the calculated FSR_{main}, FSR_{sub1}, FSR_{sub2}

and FSR_{sub3} are 6.59, 25.54, 40.87 and 51.09 MHz, respectively. Then, the FSR_{eff} of 53.33 GHz will be achieved when the compound-ring of FSR_{sub1}, FSR_{sub2} and FSR_{sub3} reaches the least common multiple. As mentioned above, the achieved FSR_{eff} of the compound-ring scheme is larger than the 3 dB bandwidth (50 GHz) of the TBF. Thus, the applied compound-ring can guarantee the SLM operation in the EDF laser.

3. Experiment and Results

To comprehend the optical output characteristic of the proposed compound-ring EDF laser, Figure 2 displays the observed spectrum of each lasing wavelength in the wavelength-swept bandwidth from 1563 to 1613 nm, while the TBF is adapted appropriately. The measured wavelength also shows better optical signal to noise ratio (OSNR) output. As seen in Figure 2, due to the designed compound-ring structure, the optical background noise can be blocked fully to achieve higher OSNR output. Here, Figure 3 presents the detected output powers and OSNRs of the fiber laser under the different tuning wavelengths. The detected output power and OSNR ranges of the EDF ring laser are in the scales of −10.8 to 0 dBm and 64.5 to 74.4 dB, respectively. The greatest output power and OSNR are observed at the wavelengths of 1578.0 and 1599.0 nm, respectively. In addition, the OSNR of >70.4 dB can be achieved in the tuning scope of 1563 to 1608 nm. As the generated wavelength travels to the longer wavelengths, the found output power and OSNR slowly decrease, as seen in Figure 3. Since the commercial EDFA already has an optical isolator inside, the directionality of lightwave transmission is limited. Thus, the damage behavior can be avoided in the proposed EDF laser.

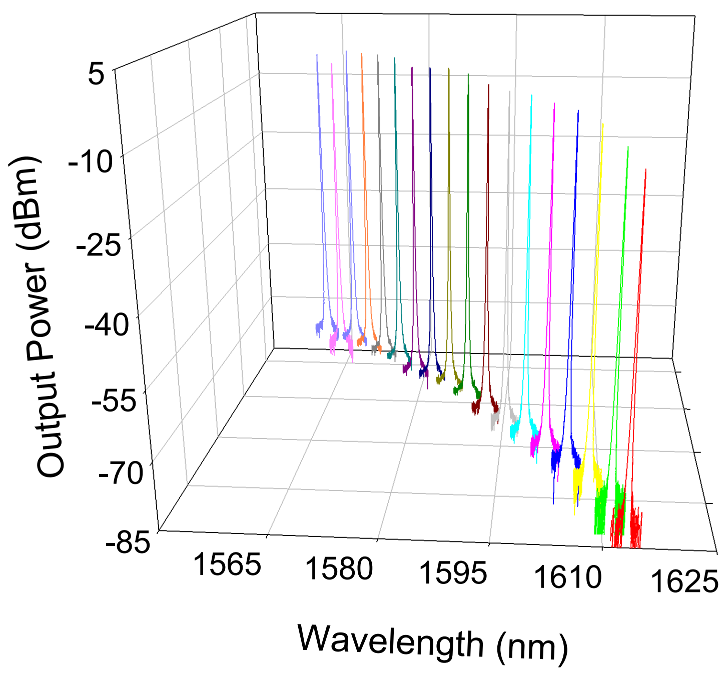

Figure 2. Observed output spectrum of each lasing lightwave of the EDF laser over the bandwidth of 1563.0 to 1613.0 nm.

Then, to check that the obtained wavelength of the compound-ring EDF laser has the SLM oscillation, the delayed self-homodyne process was constructed for the demonstration [13]. Thus, the Mach–Zehnder interferometer (MZI), which is composed of a PC, two 1 × 2 and 50:50 OCPs, and a length of 50 km fiber, was applied in the experiment. One arm of the MZI was connected to a PC, and the other was linked to the 50 km fiber as the delay line. Here, an output wavelength of 1613.0 nm was selected initially in the setup for SLM observation. The 1613.0 nm beat wavelength entered a photodiode (PD) for changing to an electrical signal and was measured through an electrical spectrum analyzer (ESA, Agilent, E4403B). Figure 4 indicates the obtained electrical spectrum of relative intensity noise (RIN) over the frequencies from 0 to 1 GHz. We observe that no MLM oscillations can be measured for SLM output when the compound-ring induced mode-filter effect is exploited, as shown in Figure 4. Moreover, when we narrowed the spectrum observation range from 0 to 20 MHz, the received RF spectrum was still maintained at the SLM status, as displayed in the inset of Figure 4.

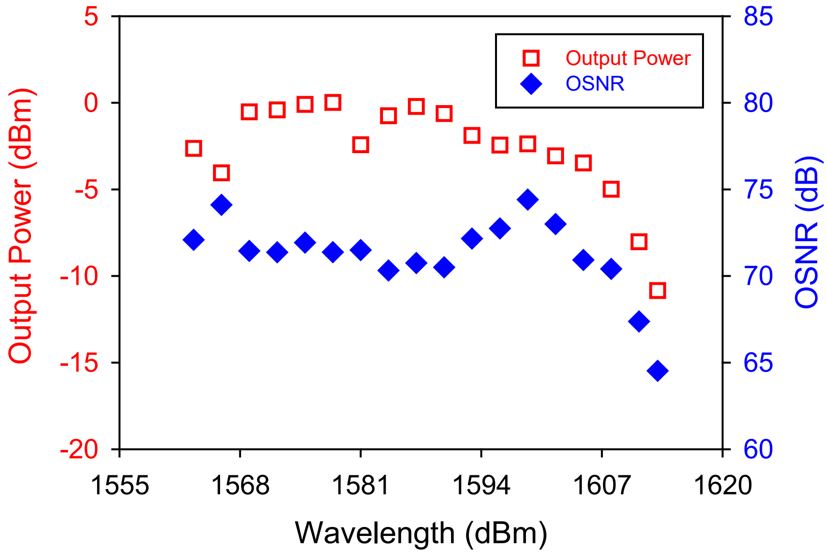

Figure 3. Observed output wavelength and OSNR of the presented EDF compound-ring laser in the achievable bandwidth of 1563.0 to 1613.0 nm.

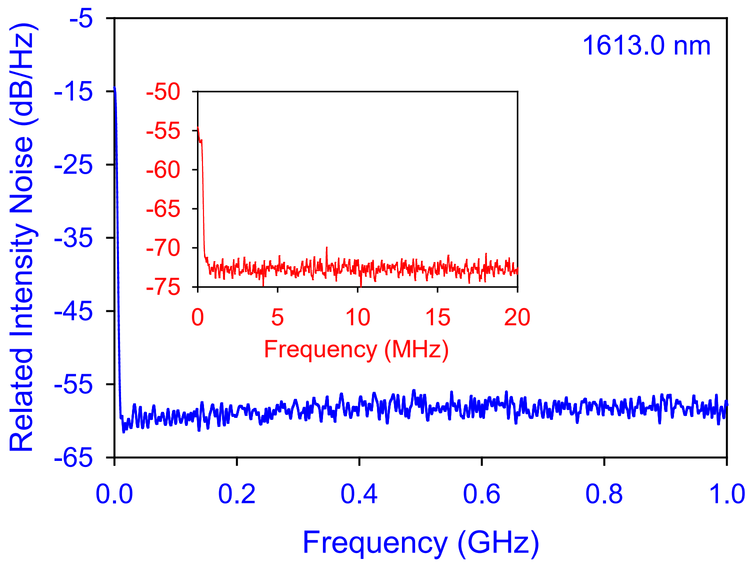

Figure 4. Measured electrical RIN spectrum of 1613.0 nm wavelength in the frequency scope of 0 to 1 GHz. Inset is an observation zoomed in on the spectral range of 0 to 20 MHz.

Afterward, a self-heterodyne detection can be used to measure the wavelength linewidth via the same MZI configuration [13]. Here, we used an optical modulator in the MZI setup to produce a 250 MHz frequency shift for the beating signal. An output wavelength of 1581.0 nm was chosen for detection initially. The observed spectrum of frequency linewidth at 1581.0 nm wavelength is seen in the green square symbol of Figure 5a over the frequency bandwidth of 249.99 to 250.01 MHz with 1 kHz resolution bandwidth. To determine the actual linewidth of 1581.0 nm wavelength, the Lorentzian function can be applied for fitting, as seen in the red line of Figure 5a. Here, the 3 dB Lorentzian linewidth of 1581.0 nm wavelength is about 2 kHz. We measured the 3 dB Lorentzian linewidth of output wavelength with 9 nm tuning interval in the tunable scope of 1563.0 nm to 1613.0 nm, as illustrated in Figure 5b. The obtained wavelength linewidth of the EDF compound-ring laser is between 2 and 3 kHz in the entire tunability range. The observed linewidth variation is 1 kHz over the whole tunable-wavelength scale.

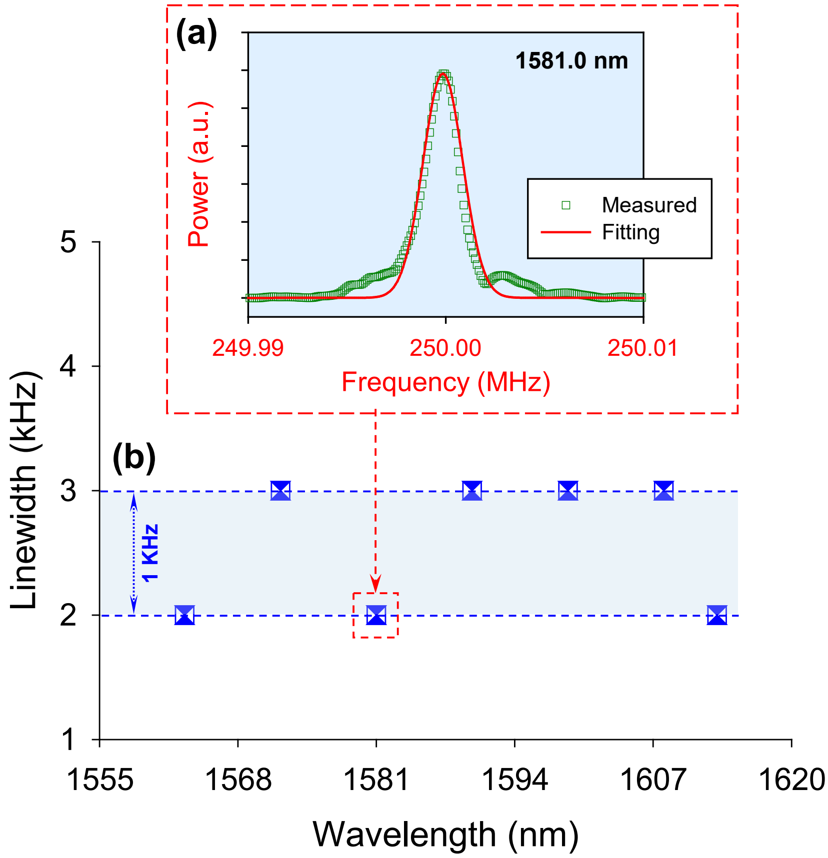

Figure 5. (**a**) Observed linewidth spectra of measured data and Lorentzian fitting at the wavelength of 1581.0 nm. (**b**) Obtained 3 dB Lorentzian linewidth over the tuning range of 1563.0 to 1613.0 nm.

Due to the commercial L-band EDFA as gain medium in the ring laser structure, we could not adjust the pump power of the laser diode to determine the laser threshold in the measurement. However, the multiple MLM oscillation of the presented laser can be suppressed significantly by the multiple-ring and reach the linewidth of 2 to 3 kHz under the original operating condition. Furthermore, the multiple-ring laser also can achieve a higher OSNR.

Finally, to further examine the actual stability of the EDF ring laser, the differences in the center wavelength and the output power were measured by the OSA and power meter. In the experiment, we selected eighteen wavelengths in the scale from 1563.0 to 1613.0 nm with even wavelength spacing for stability observation. The largest output power and center wavelength oscillations of the laser were obtained between 0.01 and 0.37 dB and 0 and 0.048 nm after an observing time of 40 min, respectively, as shown in Figure 6a,b. The 0.37 dB power variation and 0.048 nm wavelength change are at the generated wavelengths of 1584.0 nm and 1566.0 nm, respectively. Consequently, the demonstrated simple compound-ring can not only suppress the MLM noise and narrow the linewidth, but also can reach high OSNR and stable output performances.

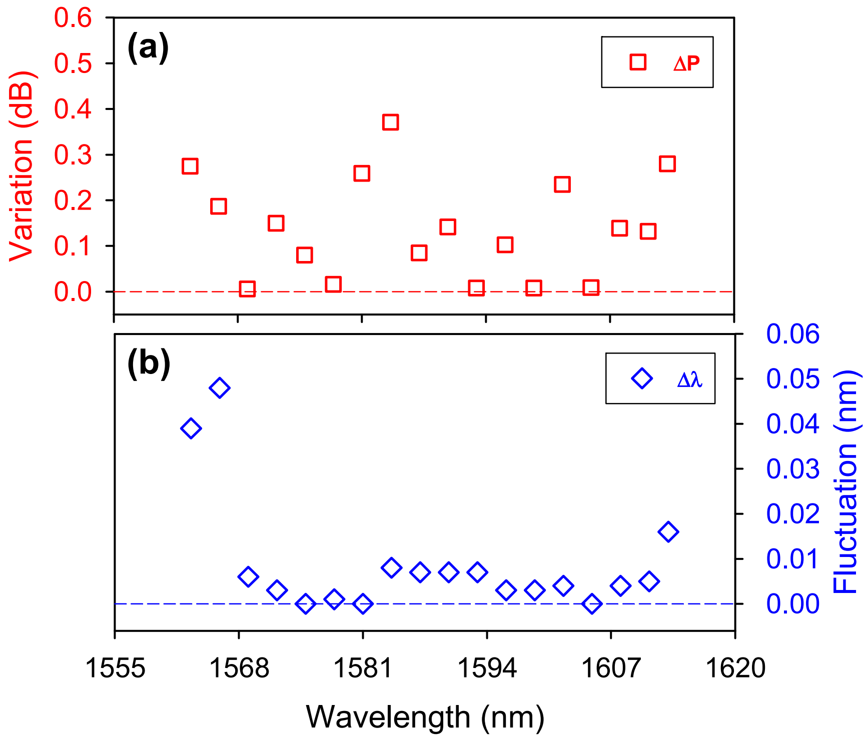

Figure 6. Measured largest fluctuations of (**a**) output power and (**b**) center wavelength in the whole tuning range of 1563.0 to 1613.0 nm.

In previous works [22,23], two compound-ring based architectures were applied in EDF lasers to achieve the SLM oscillation in the C- and part of the L-band range. The linewidth and OSNR of the two EDF lasers were between 2 and 3 kHz and 58.2 and 64.9 dB, respectively. In this study, a sub-ring structure with triple-ring design is added in the presented L-band EDF laser. Compared with the references [22,23], the fiber ring laser design is simple and easy to implement for reaching higher OSNR and similar linewidth scales of 64.5 to 74.4 dB and 2 to 3 kHz over the tunability of 1563.0 to 1613.0 nm, respectively.

4. Conclusions

We investigated an L-band wavelength-swept EDF compound-ring laser with stable SLM performance. To decrease the MLM oscillation for SLM output, the mode-filter caused by the compound-ring configuration through the Vernier effect was demonstrated here. Thus, the wavelength tunability of the proposed L-band EDF laser was achieved between 1563.0 and 1613.0 nm. The received output power and OSNR were also found in the scales of −10.8 to 0 dBm and 64.5 to 74.4 dB in the total wavelength-tuning range, respectively. Furthermore, the SLM oscillation and the Lorentzian linewidth of 2 to 3 kHz were also confirmed by applying the designed triple-ring scheme. The greatest output fluctuations of power and center wavelength of each lasing lightwave were observed in the ranges of 0.01 to 0.37 dB and 0 to 0.048 nm through a 40 min measurement, respectively, in the whole wavelength bandwidth. Therefore, the presented L-band SLM EDF laser structure reached the high OSNR, narrow linewidth and stable output stability in the tunability scale of 1563.0 to 1613.0 nm via the simple design of the compound-ring configuration.

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

References

1. Zhang, L.; Tian, Z.; Chen, N.K.; Han, H.; Liu, C.N.; Grattan, K.T.; Rahman, B.M.A.; Zhou, H.; Liaw, S.K.; Bai, C. Room-temperature power-stabilized narrow-linewidth tunable erbium-doped fiber ring laser based on cascaded Mach-Zehnder interferometers with different free spectral range for strain sensing. *J. Lightwave Technol.* **2020**, *38*, 1966–1974. [CrossRef]
2. Yan, Z.; Li, X.; Tang, Y.; Shum, P.P.; Yu, X.; Zhang, Y.; Wang, Q.J. Tunable; switchable dual-wavelength Tm-doped mode-locked fiber laser by nonlinear polarization evolution. *Opt. Express* **2015**, *23*, 4369–4376. [CrossRef] [PubMed]
3. Yeh, C.-H.; Liu, L.-H.; Ko, H.-S.; Lai, Y.-T.; Chow, C.-W. A selectable single-frequency erbium fiber laser with Mach-Zehnder interferometer and Rayleigh injection scheme. *IEEE Photonics J.* **2022**, *14*, 1532904. [CrossRef]
4. Dong, X.; Su, L.; Shum, P.; Chung, Y.; Chan, C.C. Wavelength-selective all-fiber filter based on a single long-period fiber grating and a misaligned splicing point. *Opt. Commun.* **2006**, *258*, 159–163. [CrossRef]
5. Yang, C.; Guan, X.; Zhao, Q.; Lin, W.; Li, C.; Gan, J.; Qian, Q.; Feng, Z.; Yang, Z.; Xu, S. 15 W high OSNR kHz-linewidth linearly-polarized all-fiber single-frequency MOPA at 1.6 μm. *Opt. Express* **2018**, *26*, 12863–12869. [CrossRef]
6. Lin, Y.Z.; Yen, P.M.; Huang, B.W.; Yeh, C.H.; Chow, C.W.; Hsu, W.H.; Wang, B.Y.; Chen, J.H. Applying self-injection and dual-ring based fiber laser for wide tunability and stable single-frequency output. *Opt. Laser Technol.* **2021**, *137*, 106804. [CrossRef]
7. Wei, D.; Feng, T.; Sun, W.; Yan, F.; Yao, X.S. Widely wavelength-swept single-longitudinal-mode fiber laser with ultra-narrow linewidth in C+L-band. *IEEE Photonics J.* **2022**, *14*, 7134810. [CrossRef]
8. Zhang, J.; Yue, C.Y.; Schinn, G.W.; Clements, W.R.; Lit, J.W. Stable single-mode compound-ring erbium-doped fiber laser. *J. Lightwave Technol.* **1996**, *14*, 104–109. [CrossRef]
9. Ummy, M.A.; Bikorimana, S.; Dorsinville, R. A novel technique for designing high power semiconductor optical amplifier (SOA)-based tunable fiber compound-ring lasers using low power optical components. *Appl. Sci.* **2017**, *7*, 478. [CrossRef]
10. Razak, N.F.; Ahmad, H.; Zulkifli, M.Z.; Muhammad, F.D.; Munajat, Y.; Harun, S.W. Single mode EDF fiber laser using an ultra-narrow bandwidth tunable optical filter. *Optik* **2017**, *126*, 179–183. [CrossRef]
11. Han, J.H.; Yang, Y.; Kang, J.U. Linewidth broadening in single-mode sub-kHz fiber ring laser with unpumped Er-doped Sagnac loop. In Proceedings of the Quantum Electronics and Laser Science Conference 2007, Baltimore, MD, USA, 6–11 May 2007; p. JWA72.
12. Chen, X.; Xian, L.; Li, H. Single-longitudinal-mode Brillouin fiber laser incorporating an unpumped erbium-doped fiber loop. In Proceedings of the CLEO: 2011-Laser Science to Photonic Applications 2011, Baltimore, MD, USA, 1–6 May 2011; p. CTuI2.
13. Zhu, T.; Zhang, B.; Shi, L.; Huang, S.; Deng, M.; Liu, J.; Li, X. Tunable dual-wavelength fiber laser with ultra-narrow linewidth based on Rayleigh backscattering. *Opt. Express* **2016**, *24*, 1324–1330. [CrossRef]
14. Yeh, C.H.; Chow, C.W.; Shih, F.Y.; Wang, C.H.; Wu, Y.F.; Chi, S. Tunable dual-wavelength fiber laser using optical-injection Fabry-Perot laser. *IEEE Photonics Technol. Lett.* **2008**, *21*, 125–127. [CrossRef]
15. Niu, P.; Jiang, J.; Wang, S.; Liu, K.; Ma, Z.; Zhang, Y.; Chen, W.; Liu, T. Optical fiber laser refractometer based on an open microcavity Mach-Zehnder interferometer with an ultra-low detection limit. *Opt. Express* **2020**, *28*, 30570–30585. [CrossRef]
16. Yeh, C.H.; Lee, C.C.; Chi, S. A tunable S-Band erbium-doped fiber ring laser. *IEEE Photonics Technol. Lett.* **2003**, *15*, 1053–1054.
17. Mao, Q.H.; Feng, S.J.; Liu, W.; Lit, J.W. Bistability-mapping for L-band dual-wavelength erbium-doped fiber laser by using fiber loop mirror with polarization controller. *IEEE Photonics Technol. Lett.* **2006**, *18*, 1973–1975. [CrossRef]
18. Haramoni, N.; Paterno, A.S.; Goedtel, A.; Soares, G.R.; Silva, J.C.; Kalinowski, H.J. Hybrid wavelength-time-domain interrogation system for multiplexed fiber Bragg sensors using a strain-tuned erbium-doped fiber laser. *IEEE Sens. J.* **2008**, *8*, 1061–1066. [CrossRef]
19. Yeh, C.H.; Tsai, N.; Zhuang, Y.H.; Chow, C.W.; Chen, J.H. Stabilized and tunable single-longitudinal-mode erbium fiber laser employing ytterbium-doped fiber based interference filter. *Opt. Laser Technol.* **2017**, *88*, 180–183. [CrossRef]
20. Lin, W.; Zhou, S.; Shao, L.Y.; Vai, M.I.; Shum, P.P.; Zhao, F.; Liu, S.; Hu, J.; Liu, Y. In-fiber Mach-Zehnder interferometer based on Er doped up-taper and peanut-shaped fiber structure in fiber ring laser. *IEEE Access* **2021**, *9*, 128126–128132. [CrossRef]
21. Wang, Z.; Shang, J.; Li, S.; Mu, K.; Qiao, Y.; Yu, S. All-polarization maintaining single-longitudinal-mode fiber laser with ultra-high OSNR, sub-KHz linewidth and extremely high stability. *Opt. Laser Technol.* **2021**, *141*, 107135. [CrossRef]
22. Lai, Y.T.; Chen, L.C.; Yeh, C.H.; Chow, C.W.; Liaw, S.K. Vernier effect based fiber laser with switchable and stable single-mode output behavior. *Opt. Quantum Electron.* **2022**, *54*, 378. [CrossRef]
23. Yeh, C.H.; Ko, H.S.; Liu, L.H.; Liaw, S.K.; Chow, C.W. A stable and wavelength-selectable quad-ring based erbium laser with 2-kHz linewidth output. *Opt. Laser Technol.* **2022**, *149*, 107819. [CrossRef]