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Stable Single-Longitudinal-Mode Fiber Laser With Ultra-Narrow Linewidth Based on Convex-Shaped Fiber Ring and Sagnac Loop

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ABSTRACT In this investigation, a convex-shaped fiber ring (CSFR)-based single-longitudinal-mode (SLM) erbium-doped fiber laser (EDFL) is proposed and experimentally verified. The CSFR, composed of only two optical couplers and forming a double-ring architecture, is employed to serve as a high quality mode filter to eliminate the dense longitudinal modes of the EDFL. The unpumped erbium-doped fiber in the Sagnac loop is utilized to produce the ultra-narrowband auto-tracking filter effect as a saturable absorber to guarantee the SLM out. The experimental results show that the linewidth of the proposed EDFL is 840 Hz with a high optical signal to noise ratio of 63 dB. In addition, the stability of the EDFL with the maximum output power fluctuation of 0.01 dB and the maximum central wavelength variation of 0.01 nm, in both the short-term and the long-term observations. Hence, we obtained a SLM EDFL with extremely high stability, ultra-narrow linewidth and high optical signal to noise ratio (OSNR).

INDEX TERMS Single longitudinal mode (SLM), erbium-doped fiber laser (EDFL), saturable absorber.

I. INTRODUCTION

Single-longitudinal-mode (SLM) erbium-doped fiber lasers (EDFLs) have attracted a great amount of attention for their favorable applications in the optical fiber communication, the optical fiber sensor, the microwave photonics and the high-resolution spectroscope [1]–[4]. The configurations reported to achieve SLM operation of EDFL mainly include linear and ring cavities [5], [6]. The erbium-doped fiber (EDF) ring laser configuration not only can avoid the spatial gain hole-burning induced by the sanding-wave effect presented in linear cavity fiber lasers but also have the advantages of the high output power, the narrow linewidth and the all-fiber format [7], [8]. However, an EDF ring fiber laser with stable SLM behavior is difficult to achieve mainly due to the long lasing cavity and the unstable multi-longitudinal-mode (MLM) oscillation caused by the homogenous broadening of the EDF. To obtain a stable SLM EDF ring fiber laser with superior performance, many approaches have been applied in the laser cavity, such as using the expensive ultra-narrow passband optical filter [9], employing the complicated optical injection method [10], applying the Mach-Zehnder interferometer (MZI) structure [11], utilizing unpumped EDF-based saturable absorber (SA) [12], applying Rayleigh backscattering in tapered fiber [13], employing phase-shifted FBG filter [8], using FBG Fabry-Pérot filter [14] and designing the compound-ring structure [15]–[17].

Exploiting the compound cavity structure to realize the SLM operation with narrow linewidth can save the cost of using expensive devices like the ultra-narrow passband

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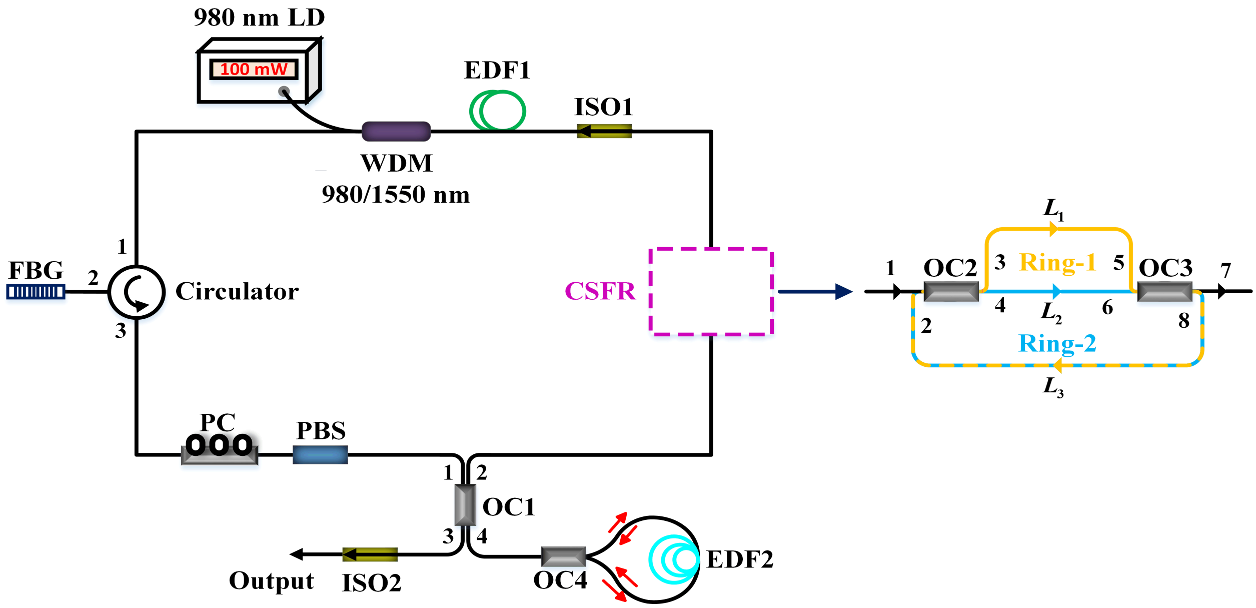

FIGURE 1. **The schematic setup of the SLM EDF ring laser.**

optical filter and reduce the complexity of the fiber laser by avoiding complicated structures such as the optical injection method. A compound cavity is composed of an active main ring cavity and one or more passive subring cavities. The passive subring cavities can be obtained from a single optical coupler fiber ring (SCFR) or a dual-coupler fiber ring (DCFR) which is composed of an optical coupler (OC) or two OCs with identical coupling ratios. Feng *et al*. demonstrated a widely tunable SLM EDFL by cascading an SCFR and a DCFR together [15]; unfortunately the measured linewidth of the EDFL is approximately 10 KHz. Tang *et al*. implemented an EDFL by nesting a DCFR inside an SCFR [18]; however, the output performance of the fiber laser is unsatisfied due to the increasing cavity loss induced by the use of three OCs. So it is significant to design a more effective passive subring cavity with fewer OCs to serve as the high-quality mode filter.

In this research, a convex-shaped fiber ring (CSFR)-based SLM EDFL with very high stability and excellent output performance is experimentally demonstrated. Composed of only two OCs with identical coupling ratios, the CSFR is equivalent to cascading two DCFRs of different lengths, which is used as an effective mode filter. The two OCs in the CSFR form a double-ring architecture and we can obtain a very wide free spectral range (FSR) thanks to the Vernier effect [19] in the EDFL to suppress the dense MLM effectively. In addition, there are no rigid restrictions on the lengths and the coupling ratios of the CSFR since the unpumped EDF in the Sagnac loop functions as an ultra-narrowband auto-tracking filter to guarantee and to stabilize the SLM operation, which makes it relative easy to fabricate. To the best of authors' knowledge, this is the first report for using such CSFR and Sagnac loop together to achieve ultra-narrow linewidth SLM EDFL. With the application of the CSFR and the Sagnac loop, the proposed EDFL exhibits remarkable performance of extremely high stability, ultra-narrow linewidth of 840 Hz and high OSNR of 63 dB.

II. EXPERIMENT AND RESULTS

The configuration of the SLM EDF ring laser is illustrated in Fig. 1. The main cavity of the proposed fiber laser consists of a CSFR composed of two 2 × 2 OCs (OC2 and OC3) and a Sagnac loop comprised by a 1 × 2 OC (OC4) and a 6-m-long unpumped EDF2 (Nufern EDFC980-HP), apart from a 2-m-long commercial EDF1 (Liekki Er30-4/125), a 980-nm laser diode (LD), a 980/1550-nm wavelength division multiplexer (WDM), a circulator, a fiber Bragg grating (FBG), two optical isolators (ISO1 and ISO2), a polarization controller (PC), a polarization beam splitter (PBS) and a 2 × 2 OC (OC1). The coupling ratio of each of the OCs mentioned above is 50:50, whose insertion loss is about 0.3 dB. The 3-dB bandwidth, peak reflectivity and central wavelength of the FBG are approximately 0.18 nm, 96% and 1550.189 nm. Besides, the insertion loss of each of the isolators, the PBS and the circulator is less than 0.5 dB. The 2-m-long commercial EDF1 is used as the gain medium pumped by a 980-nm LD through the WDM. ISO1 and the circulator are employed in the main cavity to ensure the unidirectional operation of the EDFL, which is to avoid the MLM oscillation caused by spatial hole burning. In addition, ISO1 itself can also suppress the undesired counter-propagating amplified spontaneous emission noise caused by the gain medium. The FBG functions as the reflector and the coarse mode filter. The PBS, combined with a PC which adjusts the polarization state of the light in the cavity, is exploited not only to work as a mode filter by inducing polarization dependent loss to suppress the mode competition

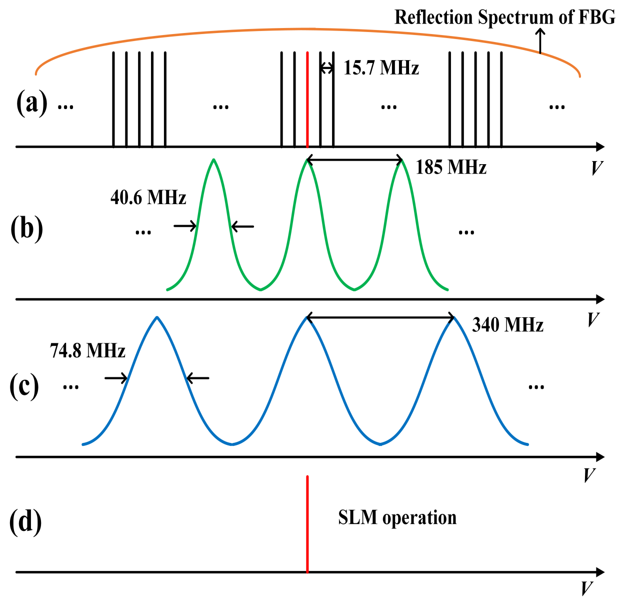

FIGURE 2. **The schematic of the SLM operation in the fiber laser. (a) Dense longitudinal modes of the main ring cavity and the reflection spectrum of the FBG; (b) The FSR and the 3-dB pass-band bandwidth of the Ring-1; (c) The FSR and the 3-dB pass-band bandwidth of the Ring-2; (d) The selected SLM.**

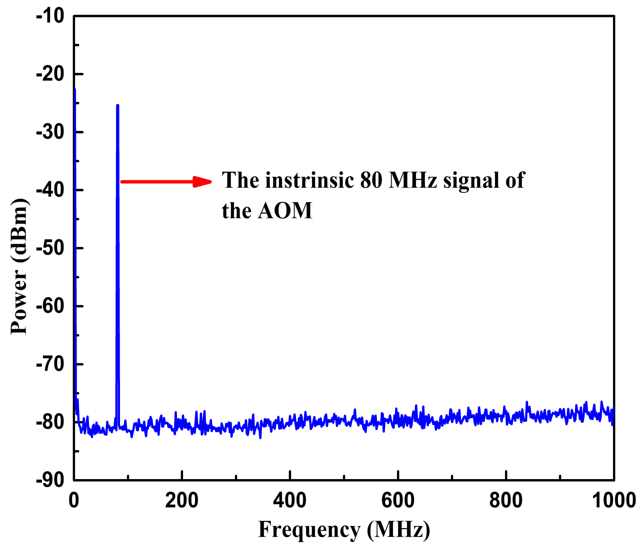

FIGURE 3. **The measured frequency spectrum for the EDFL at 500-MHz center, 1-GHz span and 300-kHz resolution.**

but also to divide the light beam into two orthogonal linearly polarized light beams.

It should be noted that a CSFR is formed in the EDFL in Fig. 1. The CSFR consisting of only two OCs (OC2 and OC3) is inserted between ISO1 and the second port of OC1. With the connection of the third port of OC2 to the fifth port of OC3 and that of the fourth port of OC2 to the sixth port of OC3, the two OCs in the CSFR form a double-ring architecture (Ring-1 and Ring-2) and we can obtain a wide FSR in the magnitude of GHz thanks to the Vernier effect. Thus, the CSFR can be used as an effective mode filter to suppress the dense MLM. A Sagnac loop is employed at the fourth port of the OC1 and the unpumped EDF2 of the loop can be used as the SA to guarantee the SLM operation when the output light from the fourth port of OC1 passes through the OC4 and is divided into two parts traveling in two opposite directions. The output of the EDFL is extracted by the third port of the OC1, and the ISO2 is used to suppress undesired reflection. The main ring cavity is measured to be about 13 m, corresponding to the longitudinal mode spacing of 15.7 MHz (see Fig. 2(a)).

A large amount of longitudinal modes can be decreased effectively because of the utilization of the CSFR, which is used in the EDFL to serve as the mode filter and to facilitate the SLM out. Ring-1 (see the yellow line in Fig. 1) and Ring-2 (see the blue line in Fig. 1) of the CSFR have their corresponding FSR_1 and FSR_2. Here, the FSR is represented by $FSR=c/nL$ [14], where c is the light velocity in a vacuum, n is the effective index of the fiber, and L is the length of the cavity. $L_{Ring-1} = L_1 + L_3 = 1.1$ m and $L_{Ring-2} = L_2 + L_3 = 0.6$ m are the lengths of Ring-1 and Ring-2 of the CSFR, corresponding to the FSR of 185 MHz and 340 MHz. In fact, the CSFR is equivalent to cascading two DCFRs with the length of 1.1 mand 0.6 m; the calculated 3-dB pass-band bandwidth of Ring-1 and that of Ring-2 are approximately 40.6 MHz and 74.8 MHz (see Fig. 2(b) and Fig. 2(c)). Then the effective FSR of the CSFR is 12.58 GHz by calculating the least common multiple of FSR1 and FSR2 through the Vernier effect. Therefore, the CSFR can suppress the dense spaced longitudinal modes and make it easier for SLM selection.

In the Sagnac loop, the unpumped EDF2 serves as the SA to guarantee the SLM operation. The output light from the fourth port of the OC1 is divided into two parts traveling in two opposite directions after passing through the OC4, and a standing wave is formed in the SA when two counter lights interfere with each other, as shown in Fig. 1. The self-written dynamic Bragg grating (DBG) can be established in the EDF2 by the standing-wave saturation effect [8], [12]. As the FWHM of the DBG is very small and the center frequency of DBG tracks the lasing mode [20], the unpumped EDF2 can serve as the ultra-narrowband auto-tracking filter. Accordingly, the dense MLM oscillation of EDFL could be suppressed and the SLM operation of the EDFL is guaranteed, as shown in Fig. 2(d).

It should be noted that all measurements are carried out at room temperature and there is no violent vibration. In this experiment, we observe not only the long-term (40-min) stability of the EDFL with the interval of 1 min, as is being reported commonly, but also the short-term (200-sec) stability of it with the interval of as short as 5 sec to strictly prove the extremely high stability of the proposed EDFL. The OSNR, the stability and the linewidth of the proposed EDFL are measured after the EDFL is in SLM operation.

First, the SLM operation of the fiber laser is verified through the delayed self-heterodyne measurement system

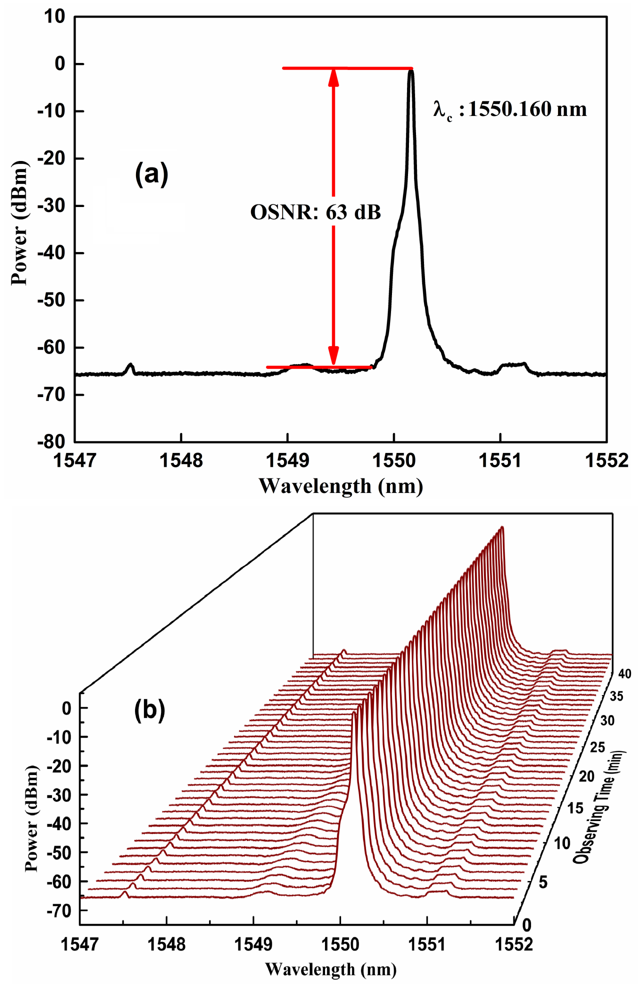

FIGURE 4. The optical spectrum measurements. (a) The optical spectrum of the fiber laser at the pump power of 100 mW; (b) The laser output spectra of 40 times repeated scans at 1 min interval.

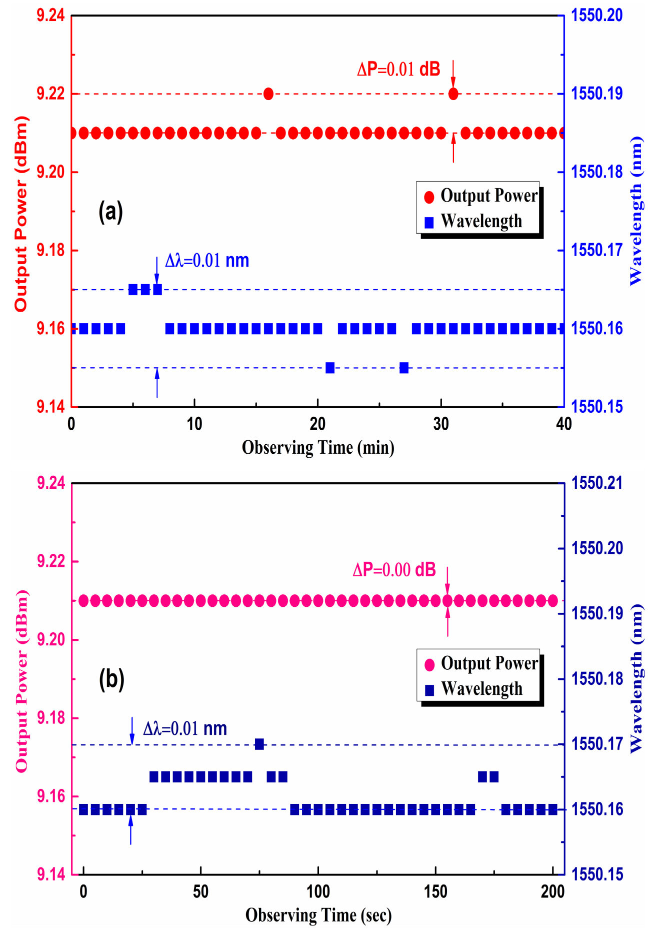

FIGURE 5. The stability performances of the output power and the lasing wavelength at the pump power of 100 mW in (a) a 1-min interval over 40 min and (b) a 5-secs interval over 200 sec.

composed of a 1-GHz photodiode (PD), an electrical spectrum analyzer and a Mazh-zehnder interferometer (MZI) configuration with a 47-km-long single mode fiber delay line and an 80-MHz acousto-optic modulator (AOM) in two arms respectively. When the pump power is 100 mW, the RF beating signal is given in Fig. 3. It demonstrates that one and only one strong signal exists at 80 MHz and there is no any other beating signal being observed, indicating the EDFL is in SLM operation. Subsequently, the SLM operation has been monitored in 3 hours without mode hopping, so it is safe to deduce that the proposed EDFL can successfully suppress the multimode operation and obtain a stable SLM operation.

Then, the excellent mode selecting performance of the proposed EDFL is demonstrated by the value of the OSNR. It is as high as 63 dB, which is obtained from the output wavelength of the fiber laser measured by an optical spectrum analyzer (Advantest Q8384) with the resolution of 0.01 nm when the pump power is 100 mW, as shown in Fig. 4(a). The lasing wavelength λ_c is 1550.160 nm which is slightly different from the center reflecting wavelength of the FBG due to the slight changes of the ambient temperature and the small vibration induced by human motion. Moreover, a very stable operation without any significant fluctuation in the optical output power and lasing wavelength can also be obtained from the laser output spectra of 40 times repeated scans at 1-min interval, which is monitored and measured by the optical spectrum analyzer, as shown in Fig. 4(b).

Besides, the stability of the output power and the lasing wavelength of the proposed EDFL can be further investigated by a power meter (JW3208) with the resolution of 0.01 dB and an optical spectrum analyzer (Advantest Q8384) with the resolution of 0.01 nm when the pump power is 100 mW. The long-term stability of the output power fluctuation and the central wavelength variation are 0.01 dB and 0.01 nm respectively in a 1-min interval over 40 min, as illustrated in Fig. 5(a), indicating the proposed laser possesses outstanding long-term stability. It should be noticed that the data of the wavelength in both Fig. 4(b) and Fig. 5(a) are identical. We also investigate the short-term stability of the output power and the central wavelength of EDFL to reflect the output stability of the proposed EDFL. The output power remains unchanged and the maximum variation of the central wavelength is 0.01 nm in a 5-sec interval over 200 sec, as shown

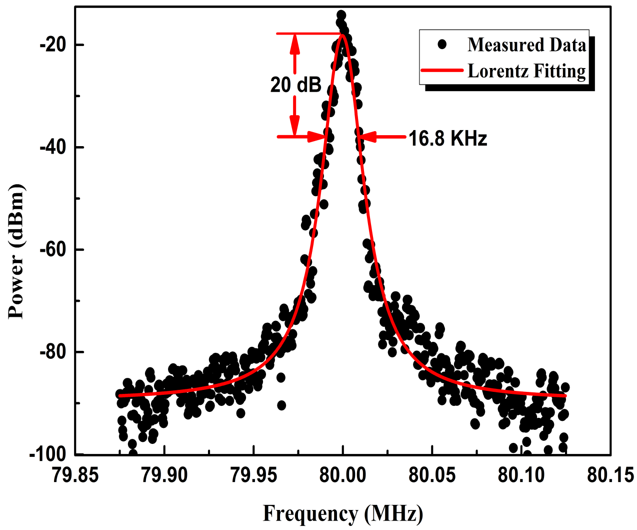

FIGURE 6. The measured output spectra of laser linewidth.

in Fig. 5(b), presenting superior short-term stability of the EDFL. Both the long-term and short-term stability results of the EDFL show that the proposed laser possesses extremely high stability.

Finally, the linewidth of the EDFL is also measured by the delayed self-heterodyne measurement system [21]. The RF beating signal, which is at 80-MHz center, 250-kHz span and 1-kHz resolution, is shown in Fig. 6. Theoretically, the linewidth of the EDFL should be measured using a delay line over 1000 Km to achieve complete incoherent mixing of MZI's two arms, which is impossible to achieve due to the limited laser output power and 1/f frequency noise. The linewidth of the EDFL can be obtained by fitting the measured data to a Lorentz curve to reduce the measurement error in the case of the limited length of the single mode fiber delay line. In addition, it is more accurate to calculate the linewidth of the fiber laser using the 20-dB bandwidth since the 3-dB bandwidth is too small to introduce calculation error. The 20-dB bandwidth achieved from the Lorentzian fit curve is 16.8 kHz, meaning that the real laser linewidth of the proposed EDFL is as narrow as 840 Hz since the laser linewidth is about 1/20 ($1/2\sqrt{99}$) of the 20-dB bandwidth of the Lorentzian fit curve [22], [23].

III. CONCLUSION

In this study, we have proposed a CSFR and a Sagnac loop in an SLM EDFL. The CSFR is embedded in the EDFL to serve as a high quality mode filter to suppress the dense MLM. The unpumped EDF of the Sagnac loop can produce the ultra-narrowband auto-tracking filter effect to stabilize and to guarantee the SLM operation. The experiment results suggest that the linewidth is as narrow as 840 Hz and the OSNR is as high as 63 dB of the EDFL. Furthermore, the proposed EDFL possesses excellent stability: The output power fluctuation and central wavelength variation is less than 0.01 dB and 0.01 nm, in both the short-term and the long-term observations. In conclusion, the proposed CSFR-and-Sagnac-loop-based SLM EDFL is characterized by ultra-narrow linewidth, high OSNR and extremely high stability.

REFERENCES

[1] S. Diaz, D. Leandro, and M. Lopez-Amo, "Stable multiwavelength erbium fiber ring laser with optical feedback for remote sensing," *J. Lightw. Technol.*, vol. 33, no. 12, pp. 2439–2444, Jun. 15, 2015.
[2] C.-H. Yeh, M. C. Lin, B. C. Cheng, and S. Chi, "Long-distance strain-induced-grating-based fiber sensors with erbium-based amplifiers," *Proc. SPIE*, vol. 46, no. 6, Jun. 2007, Art. no. 064401.
[3] X. Chen, Z. Deng, and J. Yao, "Photonic generation of microwave signal using a dual-wavelength single-longitudinal-mode fiber ring laser," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 2, pp. 804–809, Feb. 2006.
[4] C.-S. Kim, F. N. Farokhrooz, and J. U. Kang, "Electro-optic wavelength-tunable fiber ring laser based on cascaded composite Sagnac loop filters," *Opt. Lett.*, vol. 29, no. 14, pp. 1677–1679, 2004.
[5] X. He, X. Fang, C. Liao, D. N. Wang, and J. Sun, "A tunable and switchable single- longitudinal-mode dual-wavelength fiber laser with a simple linear cavity," *Opt. Express*, vol. 17, no. 24, pp. 21773–21781, 2009.
[6] X. Chen, J. Yao, F. Zeng, and Z. Deng, "Single-longitudinal-mode fiber ring laser employing an equivalent phase-shifted fiber Bragg grating," *IEEE Photon. Technol. Lett.*, vol. 17, no. 7, pp. 1390–1392, Jul. 2005.
[7] B. Lin, S. C. Tjin, H. Zhang, D. Tang, S. Liang, J. Hao, and B. Dong, "Dual-wavelength single-longitudinal-mode erbium-doped fiber laser based on inverse-Gaussian apodized fiber Bragg grating and its application in microwave generation," *Opt. Fiber Technol.*, vol. 17, no. 2, pp. 120–123, Mar. 2011.
[8] M. Horowitz, R. Daisy, B. Fischer, and J. L. Zyskind, "Linewidth-narrowing mechanism in lasers by nonlinear wave mixing," *Opt. Lett.*, vol. 19, no. 18, pp. 1406–1408, 1994.
[9] H. Zou, S. Lou, G. Yin, and W. Su, "Switchable Dual-Wavelength PM-EDF Ring Laser Based on a Novel Filter," *IEEE Photon. Technol. Lett.*, vol. 25, no. 11, pp. 1003–1006, Jun. 2013.
[10] C.-H. Yeh, T.-J. Huang, Z.-Q. Yang, C.-W. Chow, and J.-H. Chen, "Stable single-longitudinal-mode erbium fiber ring laser utilizing self-injection and saturable absorber," *IEEE Photon. J.*, vol. 9, no. 6, Dec. 2017, Art. no. 7106206.
[11] M. I. MdAli, S. A. Ibrahim, M. H. Abu Bakar, A. S. M. Noor, S. B. Ahmad Anas, A. K. Zamzuri, and M. A. Mahdi, "Tapered-EDF-based mach–zehnder interferometer for dual-wavelength fiber laser," *IEEE Photon. J.*, vol. 6, no. 5, Oct. 2014, Art. no. 5501209.
[12] S. H. Lee, H. G. Yun, M.-H. Lee, S. H. Choi, and K. H. Kim, "Single-longitudinal-mode fiber ring lasers with a saturation-level-controlled saturable absorber," *Opt. Commun.*, vol. 308, pp. 15–19, Nov. 2013.
[13] J. Gu, Y. Yang, M. Liu, J. Zhang, X. Wang, Y. Yuan, and Y. Yao, "A switchable and stable single-longitudinal-mode, dual-wavelength erbium-doped fiber laser assisted by Rayleigh backscattering in tapered fiber," *J. Appl. Phys.*, vol. 118, no. 10, Sep. 2015, Art. no. 103107.
[14] X. X. Yang, L. Zhan, Q. S. Shen, and Y. X. Xia, "High-power single-longitudinal-mode fiber laser with a ring Fabry–Pérot resonator and a saturable absorber," *IEEE Photon. Technol. Lett.*, vol. 20, no. 11, pp. 879–881, Jun. 1, 2008.
[15] S. Feng, Q. Mao, Y. Tian, Y. Ma, W. Li, and L. Wei, "Widely tunable single longitudinal mode fiber laser with cascaded fiber-ring secondary cavity," *IEEE Photon. Technol. Lett.*, vol. 25, no. 4, pp. 323–326, 2013.
[16] C.-H. Yeh, J.-Y. Chen, H.-Z. Chen, and C.-W. Chow, "Selectable dual-wavelength erbium-doped fiber laser with stable single-longitudinal-mode utilizing eye-type compound-ring configuration," *Opt. Laser Technol.*, vol. 82, pp. 72–75, Aug. 2016.
[17] Z. Wang, J. Shang, L. Tang, K. Mu, S. Yu, and Y. Qiao "Study of dual-coupler fiber ring and satuarable absorber based stable single-longitudinal-mode fiber ring," *Proc. SPIE*, vol. 58, no. 6, Jun. 2019, Art. no. 066113.
[18] L. Tang, J. Shang, Z. Wang, K. Mu, S. Yu, and Y. Qiao, "Gourd-shaped sub-ring resonator-based single longitudinal mode erbium-doped fiber laser," *Proc. SPIE*, vol. 58, no. 6, 2019, Art. no. 066110.
[19] J. F. Lemieux, A. Bellemare, C. Latrasse, and M. Tetu, "Step-tunable (100 GHz) hybrid laser based on Vernier effect between Fabry–Perot cavity and sampled fibre Bragg grating," *Electron. Lett.*, vol. 35, no. 11, pp. 904–906, May 1999.
[20] Y. Cheng, J. T. Kringlebotn, W. H. Loh, R. I. Laming, and D. N. Payne, "Stable single-frequency traveling-wave fiber loop laser with integral saturable-absorber-based tracking narrow-band filter," *Opt. Lett.*, vol. 20, no. 8, pp. 875–877, 1995.

[21] L. B. Mercer, "1/f frequency noise effects on self-heterodyne linewidth measurements," *J. Lightw. Technol.*, vol. 9, no. 4, pp. 485–493, Apr. 1991.

[22] Y. Zhao, J. Chang, Q. Wang, J. Ni, Z. Song, H. Qi, C. Wang, P. Wang, L. Gao, Z. Sun, G. Lv, T. Liu, and G. Peng, "Research on a novel composite structure Er^{3+}-doped DBR fiber laser with a p-phase shifted FBG," *Opt. Express*, vol. 21, no. 19, pp. 22515–22522, 2013.

[23] X. He, S. Xu, C. Li, C. Yang, Q. Yang, S. Mo, D. Chen, and Z. Yang, "1.95 μm kHz-linewidth single-frequency fiber laser using self-developed heavily Tm^{3+}-doped germanate glass fiber," *Opt. Express*, vol. 21, no. 19, pp. 20800–20805, 2013.

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