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Vernier effect based fiber laser with switchable and stable single-mode output behavior

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Abstract
In this study, we study a simple quadruple-ring in the erbium-doped fiber (EDF) based laser to obtain the single-longitudinal-mode (SLM) action according to the Vernier operation. The output bandwidth of the presented fiber laser is reached in the wavelengths of 1524.0 to 1574.0 nm applying a C-band gain-medium. Moreover, the corresponding laser linewidth, optical signal to noise ratio (OSNR), output stability and power are also executed and discussed.

Keywords Erbium-doped fiber (EDF) · Fiber laser · Quad-ring · Single-longitudinal-mode (SLM)

1 Introduction

Due to the effective behaviors of high optical signal to noise ratio (OSNR), broad tunability, narrow wavelength linewidth and single-longitudinal-mode (SLM) in the erbium-doped fiber (EDF) based laser (Wang et al. 2019), it also can bring many useful applications of optical sensor, optical communication, bio-photonic, spectroscopy and RF-photonic (Dai et al. 2021; Yeh et al. 2020; Wang et al. 2014; Wang 2020). Nevertheless, the homogeneous broadening and mode-hopping effects of the EDF (Huang et al. 2021), a longer fiber cavity of EDF laser would lead to the occurrence of multiple multi-longitudinal-mode (MLM) noises. If the MLM effect wants to be removed in the EDF based laser, several techniques have been demonstrated, such as exploiting the saturable absorber (SA) based filter, ultranarrow optical filter, multiple-fiber-ring scheme, Mach-Zehnder interferometer (MZI) structure, and Rayleigh backscattering (RB) influence (Feng et al. 2013; Yan et al. 2015; He et al. 2015; Zhu et al. 2016; Md Ali et al. 2014; Gu et al. 2015). Besides, to achieve the continuous-wave (CW) tunability in the EDF laser, the Fabry-Perot tunable

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filter (FP-TF), optical tunable bandpass filter (TBF) and variable fiber Bragg grating (FBG) have been applied inside the fiber cavity (Yeh et al. 2019; He et al. 2018; Liaw et al. 2014).

In the demonstration, we investigate experimentally a quadruple-ring based EDF laser architecture to obtain CW output and stabilized SLM action. Here, the quadruple-ring configuration can generate a mode-filter effect to suppress the oscillated MLM spikes for SLM achievement based on the Vernier operation (Xie et al. 2019). The Vernier effect applied to fiber interferometers was also a method to improve the sensitivity and resolution of fiber sensors (Zhang et al. 2014; Liao et al. 2017). The observed side-mode suppression ratio (SMSR) of the EDF laser can be larger than 60.3 dB. Moreover, the presented laser can reach a tuning bandwidth of 1524.0 to 1574.0 nm together with the output powers of −13.6 to −8.1 dBm, OSNRs of 60.4 to 64.9 dB and laser linewidths of 2 to 3 kHz, respectively. In the measurement, the related stabilities of power and wavelength outputs are within 1.4 dB and 0.053 nm over the entire wavelength bandwidth, respectively, after an observation period of 40 min. Consequently, the demonstrated quadruple-ring EDF laser can not only operate at the SLM output, but also diminish the linewidth to kHz level.

2 Experiment and results

An experimental setup of the exhibited EDF laser configuration is schemed in Fig. 1. The commercial erbium-doped fiber amplifier (EDFA) with a C-band scale of 1528 to 1562 nm is exploited to regard as a gain-medium in the laser cavity. To perform the wavelength selection, an optical tunable bandpass filter (TBF) in the tuning of 1520 to 1610 nm, having the insertion loss of < 6 dB and 3 dB bandwidth of nearly 0.4 nm, is located inside the ring cavity for tuning continuously, as seen in Fig. 1. Besides, a polarization controller (PC) is applied to adopt the light polarization status for achieving the maximum output power and maintaining the stabilized output. As plotted in Fig. 1, in order to construct a scheme of four fiber rings in the EDF laser, two 1·4 optical couplers (CPR_1) with same coupling ratio are used. Hence, two CPR_1 can cause three sub-rings ($Ring_1$, $Ring_2$ and $Ring_3$) and a main-ring ($Ring_4$) to result in the quadruple-ring architecture. In the measurement, an optical

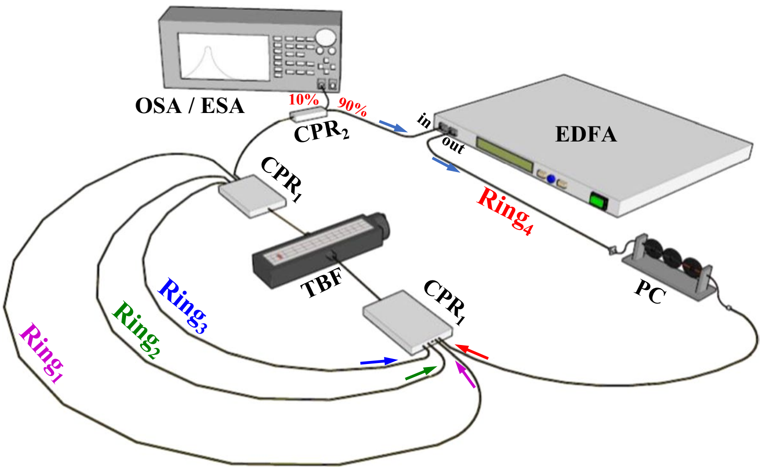


Fig. 1 Experimental setup of presented EDF quadruple-ring laser system

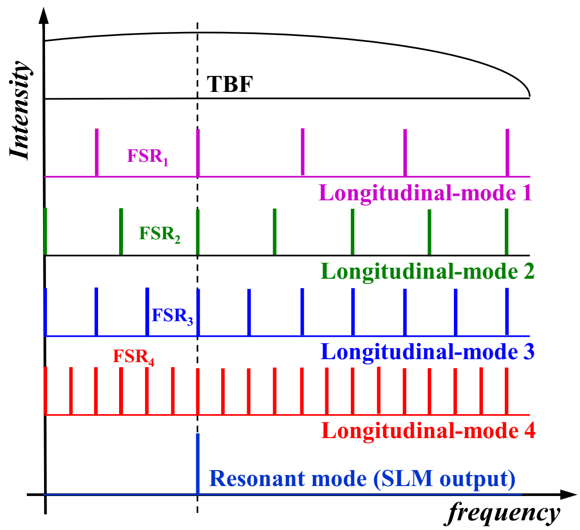
power and an optical spectrum analyzer (OSA) are requested to monitor and record the output of the 1·2 and 10:90 optical coupler (CPR_2).

Then, the proposed four rings will lead to the corresponding free spectrum ranges (FSRs), due to the different fiber lengths. Thus, the corresponding FSR_1 to FSR_4 of $Ring_1$ to $Ring_4$ can be also shown by an expression of $FSR = c/(n \cdot L)$, where the L, n and c are the fiber length, average index of fiber and the light speed in the vacuum, respectively. Here, the least common multiple can be produced by the four FSRs based on the well-known Vernier effect to cause a broad and effective FSR range for SLM generation, when the output spectrum of TBF is matched simultaneously (Xie et al. 2019). Therefore, the designed compound-ring can produce the mode-filter effect for dense side-mode suppression. In the experiment, the fiber lengths of $Ring_1$ to $Ring_4$ are 8, 9, 10 and 26 m, respectively. So, the corresponding four FSRs of 25.54, 22.71, 20.44 and 7.86 MHz can be obtained, respectively. The main ring ($Ring_4$) would cause a matching longitudinal-mode spacing of 7.86 MHz initially. According to the Vernier effect (Xie et al. 2019), the effective FSR of 11.86 GHz can be achieved based on the three sub-ring structure for MLM suppression. In the demonstration, to create a wider effective FSR, the length of the three fiber rings should be as short as possible and not the same length. Hence, the designed sub-ring of 8, 9, 10 m are selected in the fiber laser, respectively.

As mentioned above, the 3-dB bandwidth of TBF is around 50 GHz ($\Delta\lambda = 0.4$ nm). The attained effective FSR is much less than that of TBF. Thus, the compound-ring based mode-filter produced by two CPRs can reduce the number of longitudinal modes and suppress the dense MLM oscillation in the EDF laser effectively. The schematic diagram of each FSR and mode-selection in the presented quad-ring laser system is illustrated in Fig. 2.

Next, adjusting the output spectrum of TBF in the EDF laser can verify the widest adjustable range. Figure 3a–d present the selected four output wavelengths of 1524.0, 1542.0, 1560.0 and 1574.0 nm over the obtainable tuning scope, respectively. Here, the original amplified spontaneous emission (ASE) noise of EDFA can be suppressed fully by the proposed quadruple-ring design. And the four output spectra also exhibit the

Fig. 2 Schematic diagrams of each FSR and the mode-selection



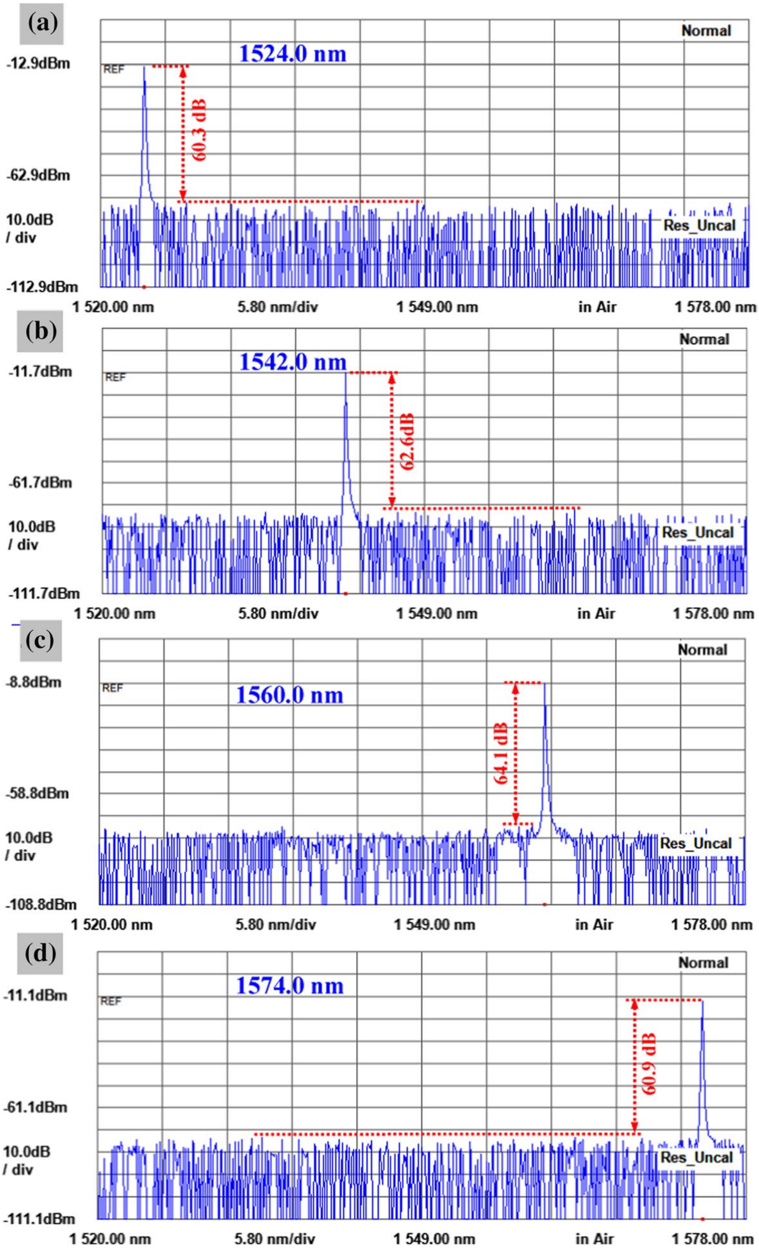


Fig. 3 Measured output spectrum of proposed laser at the wavelengths of **a** 1524.0, **b** 1542.0, **c** 1560.0 and **d** 1574.0 nm, respectively

good side-mode suppression ratio (SMSR) performance. The SMSR is a relation of power between central peak longitudinal mode with the close higher order mode. Hence, the whole measured SMSRs of lasing wavelengths are higher than 60.3 dB, as seen in Fig. 3a–d.

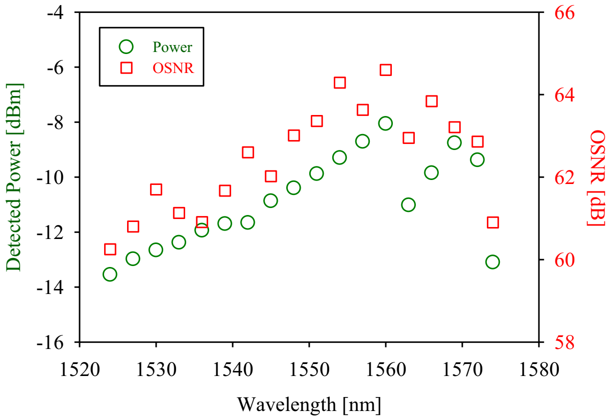


Fig. 4 Detected output powers and OSNRs in the tuning range of 1524.0 to1574.0 nm

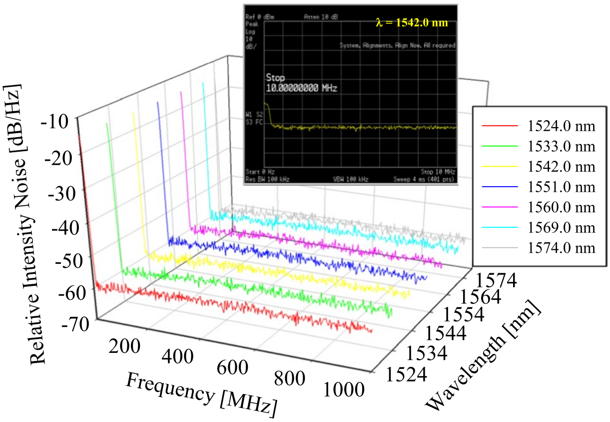


Fig. 5 Measured electrical spectra in the range of 1524.0 to 1574.0 nm for SLM exhibition. Inset is the observed spectrum of 1542.0 nm within 10 MHz bandwidtn

The output powers and optical signal to noise ratios (OSNRs) of the demonstrated EDF laser are plotted in green circle and red square of Fig. 4, respectively, in the wavelength scale of 1524.0 to 1574.0 nm. Here, the OSNR is defined as the ratio of the power of a signal to the power of background noise. The detected powers and OSNRs of output wavelengths are between − 13.6 and − 8.1 dBm and 60.4 and 64.9 dB, respectively, over the obtainable bandwidth. The observed greatest power and OSNR of −8.1 dBm and 64.9 dB is at the wavelength of 1560.0 nm. Moreover, the obtained power and OSNR curves will drop gradually on both sides of tuning range owing to the available C-band erbium gain, as exhibited in Fig. 4. Hence, the designed quadruple-ring laser can not only reach a tuning range of 50 nm, but also can result in the better SMSR and OSNR implementations.

To confirm SLM operation based on the presented quadruple-ring fiber laser, a delayed self-homodyne structure is setup for measurement (Xie et al. 2019). The structure is constructed by the Mach-Zehnder interferometer (MZI). Thus, two separate output wavelengths from the MZI can be beat by a photodiode (PD). Here, seven wavelengths of 1524.0, 1533.0, 1542.0, 1551.0, 1560.0, 1569.0 and 1574.0 nm are exploited, respectively. Figure 5 display the detected electrical spectra of the selected wavelengths by a 3 GHz electrical spectrum analyzer (ESA) over the frequency scope of 0 to 1000 MHz. We observe that all the obtained spectra are without any dense spike oscillations, as seen in Fig. 5. Thus, the quadruple-ring induced mode-filter effect can achieve the SLM output. In addition, the measured RF bandwidth also narrows to 10 MHz while the 1542.0 nm wavelength is used for observation, as exhibited in the inset of Fig. 5. Here, the obtained electrical spectrum is also maintained at the SLM operation.

Then, an output linewidth of the designed EDF laser can be verified by a self-heterodyne detection. First, we utilize the output wavelength of 1542.0 nm for linewidth surveillance. To generate a beat signal for observing linewidth, the RF signal of 210 MHz is applied in the experiment. The measured output electrical spectrum of 1542.0 nm wavelength in a frequency range of 209.99 to 210.01 MHz with a resolution of 1 kHz is shown in the pink circle of Fig. 6a. However, the real linewidth of 1542.0 nm wavelength can use the Lorentzian curve for obtaining. Hence, the 3 dB Lorentzian linewidth of 2 kHz can be found, as presented in the blue dash line of Fig. 6a. Next, we employ the same selected wavelengths as above for the implementation of Lorentzian linewidth. As indicated in Fig. 6b, the achieved Lorentzian linewidth is between 2 and 3 kHz over the obtainable tunability scope of 1524.0 to 1574.0 nm. This means that the presented quadruple-ring configuration not only suppresses the dense longitudinal-mode noise, but also achieve the narrow linewidth of 2 to 3 kHz.

As we know, the stabilization of every output wavelength is an important issue for switchable SLM EDF laser. Similarly, we apply the 1542.0 nm wavelength for monitoring the output stability first. Figure 7a presents the output fluctuations of power and wavelength within a 40-minute observation period at 1542.0 nm wavelength. The largest output variations of detected power and wavelength are within 0.4 dB and 0.04 nm. Then, to realize the complete output stability in the whole tuning bandwidth, we apply the same seven wavelengths as above during 40 min detection. As presented in Fig. 7b, the observed output variances of power and wavelength are between 0.1 and 1.4 dB and 0.032 and 0.054 nm, respectively, in the whole tuning range of 1524.0 to 1574.0 nm. Here, the maximum oscillations of power and wavelength of 1.4 dB and 0.054 nm is detected at the wavelength of 1574.0 nm, as seen in Fig. 7b.

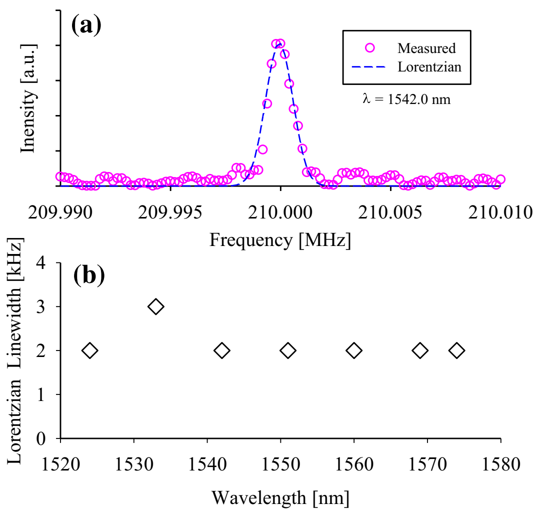


Fig. 6 **a** The measured frequency spectrum and Lorentzian fitting at 1542.0 nm wavelength. **b** Attained Lorentzian linewidth in the tuning span of 1524.0 to 1574.0 nm

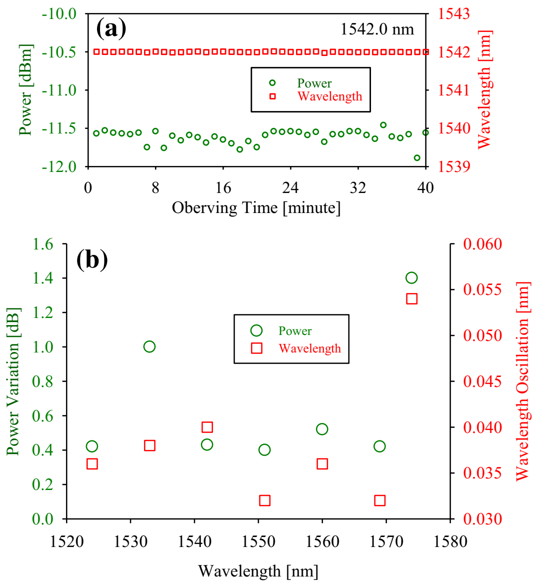


Fig. 7 **a** Detected output power and wavelength variations of 1542.0 nm wavelength through 40 min observation. **b** Exhibited output power and wavelength differences over a bandwidth from 1524.0 to 1574.0 nm

3 Conclusions

To realize a wavelength-switchable and stable SLM output of EDF laser, a quadruple-ring configuration was presented. Based on the Vernier operation of the presented four rings, the unstable longitudinal-mode spikes could be suppressed completely to achieve the SLM action. In the measurement, an available bandwidth of 50 nm was obtained in the tuning span of 1524.0 to 1574.0 nm. Here, the quadruple-ring scheme was also applied to filter the ASE background noise of EDFA and reach the SMSR of >60.3 dB in the EDF laser over the full tuning scale. The output power and OSNR of the fiber laser were measured in the spans of -13.6 to -8.1 dBm and 60.4 to 64.9 dB, respectively. Furthermore, the 3 dB Lorentzian linewidth of 2 to 3 kHz was attained in the obtainable bandwidth. And the observed power variation and wavelength oscillation of the EDF laser were between 0.1 and 1.4 dB and 0.032 and 0.054 nm, respectively. As a result, the demonstrated quadruple-ring EDF laser not only resulted in SLM action, but also reduced the linewidth to kHz level.

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References

Dai, Z., Fan, Z., Li, P., Yao, J.: Widely wavelength-tunable parity-time symmetric single-longitudinal-mode fiber ring laser with a single physical loop. J. Lightw Technol. **39**(7), 2151–2157 (2021)

Feng, S., Mao, Q., Tian, Y., Ma, Y., Li, W., Wei, L.: Widely tunable single longitudinal mode fiber laser with cascaded fiber-ring secondary cavity. IEEE Photon. Technol. Lett. **25**(4), 323–326 (2013)

Gu, J., Yang, Y., Liu, M., Zhang, J., Wang, X., Yuan, Y., Yao, Y.: A switchable and stable single-longitudinal-mode, dual-wavelength erbium-doped fiber laser assisted by Rayleigh backscattering in tapered fiber. J. Appl. Phys. **118**(10), 103107 (2015)
He, W., Zhu, L.: Switchable dual-wavelength single-longitudinal-mode erbium-doped fiber laser based on a thin-core fiber comb filter and saturable absorber. Microw. Opt. Technol. Lett. **57**(2), 287–292 (2015)
He, W., Zhu, L., Dong, M., Lou, X., Luo, F.: Wavelength-switchable and stable-ring-cavity, erbium-doped fiber laser based on Mach-Zehnder interferometer and tunable filter. Laser Phys. **28**(4), 045104 (2018)
Huang, L., Yang, C., Tan, T., Lin, W., Zhang, Z., Zhou, K., Zhao, Q., Teng, X., Xu, S., Yang, Z.: Sub-kHz-linewidth wavelength-tunable single-frequency ring-cavity fiber laser for C- and L-band operation. J. Lightw Technol. **39**(14), 4794–4799 (2021)
Liao, H., Lu, P., Fu, X., Jiang, X., Ni, W., Liu, D., Zhang, J.: Sensitivity amplification of fiber-optic in-line Mach–Zehnder Interferometer sensors with modified Vernier-effect. Opt. Express **25**(22), 26898–26909 (2017)
Liaw, S.-K., Shin, C.-S., Wu, W.-F.: Tunable fiber laser using fiber Bragg gratings integrated carbon fiber composite with large tuning range. Opt. Laser Technol. **64**, 302–307 (2014)
Md Ali, M.I., Ibrahim, S.A., Abu Bakar, M.H., Noor, A.S.M., Ahmad Anas, S.B., Zamzuri, A.K., Mahd, M.A.: Tapered-EDF-based Mach-Zehnder interferometer for dual-wavelength fiber laser. IEEE Photon. J. **6**(5), 5501209 (2014)
Wang, L., Dong, X., Shum, P.P., Huang, C., Su, H.: Erbium-doped fiber laser with distributed Rayleigh output mirror. Laser Phys. **24**(11), 115101 (2014)
Wang, Z., Shang, J., Tang, L., Mu, K., Yu, S., Qiao, Y.: Study of dual-coupler fiber ring and saturable absorber-based stable single-longitudinal-mode fiber laser. Opt. Eng. **58**(6), 066113 (2019)
Wang, Z., Shang, J., Mu, K., Qiao, Y., Yu, S.: L-band Erbium-doped fiber laser with coupling-ratio controlled wavelength tunability. Proc. of CLEO, (2020), paper STh3P.1
Xie, Y.-R., Luo, C.-M., Yeh, C.-H.: Use of C-band erbium gain-medium and compound-fiber-ring design for single-longitudinal-mode fiber laser with 84-nm achievable tunability. Opt. Fiber Technol. **52**, 101974 (2019)
Yan, F., Peng, W., Liu, S., Feng, T., Dong, Z., Chang, G.-K.: Dual-wavelength single-longitudinal-mode Tm-doped fiber laser using PM-CMFBG. IEEE Photon. Technol. Lett. **27**(9), 951–954 (2015)
Yeh, C.-H., Lin, W.-P., Chang, Y.-J., Xie, Y.-R., Luo, C.-M., Chow, C.-W.: A selectable single-mode erbium laser with power-flattened output employing dual-Sagnac-ring. IEEE Access. **7**, 92938–92942 (2019)
Yeh, C.-H., Luo, C.-M., Xie, Y.-R., Chow, C.-W.: Single-mode erbium laser with CW tunability by exploiting saturable absorber and self-injected loop. Opt. Commun. **459**, 124968 (2020)
Zhang, P., Tang, M., Gao, F., Zhu, B., Fu, S., Ouyang, J., Shum, P.P., Li, D.: Cascaded fiber-optic Fabry-Perot interferometers with Vernier effect for highly sensitive measurement of axial strain and magnetic field. Opt. Express **22**(16), 19581–19588 (2014)
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 **24**(2), 1324–1330 (2016)