Widely Wavelength-Tunable Parity-Time Symmetric Single-Longitudinal-Mode Fiber Ring Laser With a Single Physical Loop

Zheng Dai, Zhiqiang Fan, Peng Li, and Jianping Yao, *Fellow, IEEE, Fellow, OSA*

***Abstract*—A wavelength-tunable single-longitudinal-mode fiber ring laser based on parity-time (PT) symmetry for mode selection is proposed and experimentally demonstrated. The PT symmetry is implemented using a single physical fiber-optic loop, which functions equivalently to two mutually coupled optical loops with an identical geometry but balanced gain and loss. In the proposed system, a linearly polarized light wave is split into two, which are traveling in a Sagnac loop incorporating a polarization beam splitter (PBS) and two polarization controllers (PCs). By controlling the polarization states of the light waves injected into the PBS via tuning the PCs, the gain and loss of the two equivalent loops corresponding to the light waves traveling in the clockwise (CW) and counter-clockwise (CCW) directions are controlled. When the gain and loss are balanced and exceed the coupling coefficient, PT-symmetry breaking condition is met, and single-longitudinal-mode lasing is achieved. The proposed PT-symmetric fiber ring laser is experimentally demonstrated. Single-longitudinal-mode lasing with a tunable wavelength from 1530 to 1565 nm and a narrow linewidth as small as 390 Hz is achieved. The sidemode suppression ratio is 41.9 dB confirming the effectiveness of using PT symmetry for mode selection.**

***Index Terms*—Parity-time symmetry, fiber optics, Sagnac loop, ring lasers, single-longitudinal-mode lasers.**

I. Introduction

SINGLE-LONGITUDINAL-MODE fiber lasers have been widely studied and can find applications in lidar [1], optical communications [2], and holographic imaging [3], owing to the key advantages of high power, long coherent length, and narrow linewidth. According to the Schawlow-Townes formula [4], the linewidth of a light wave generated by a laser source can be narrowed by increasing the effective cavity length. A fiber ring laser usually has a long cavity length, thus the linewidth of a light wave generated by a fiber ring laser is narrow. However, a long length fiber ring laser has a large number of closely-spaced longitudinal modes in the cavity due to a small free spectral range (FSR), making mode selection extremely difficult. Numerous approaches have been reported for the past few decades to achieve stable single-longitudinal-mode lasing. For example, an un-pumped erbium-doped fiber (EDF) as a saturable absorber to form an ultra-narrowband optical filter can be incorporated in a fiber ring laser cavity. The optical pumping from the two ends of the un-pumped EDF will generate a standing wave, creating a self-induced weak Bragg grating corresponding to an ultra-narrowband filter, which is employed to perform mode selection [5], [6]. The key limitation of this approach is the poor stability of the operation since the spectral response of the self-induced Bragg grating is drifting due to mode hoping. The use of a fiber Bragg grating (FBG) with an ultra-narrow bandwidth, such as a phase-shifted FBG (PS-FBG), can improve the stability [7]. However, if the length of the fiber loop is very long, the bandwidth of a PS-FBG may still be wide and not be narrow enough to ensure single-mode lasing. A simple solution is to implement a fiber ring laser with dual or multiple loops having different lengths. Due to the Vernier effect, the effective FSR is significantly increased, making mode selection less challenging [8]. The limitations of a dual- or multiple-loop fiber ring laser are the complicity of the system and the limited wavelength tunability. Recently, a new concept, parity-time (PT) symmetry [9], [10], has been proposed and employed for mode selection. It is different from conventional mode selection schemes in which a physical narrow passband filter is used for mode selection; in a PT-symmetric system, the mode selection is done due to PT symmetry breaking. A few PT-symmetric laser sources implemented based on photonic integrated platforms have been reported [11]–[16]. In a PT-symmetric system, two mutually coupled optical loops with an identical geometry but balanced gain and loss are needed, which can be easier to implement on an integrated platform, but more difficult in a fiber optic system since a precise match of the two loops is hard. However, a photonic integrated laser source has a very short cavity length, making the linewidth of the generated light wide. To implement a laser source with an ultra-narrow linewidth, a long cavity length is needed. A fiber ring cavity can be made long and the loss can be compensated by an erbium-doped fiber amplifier (EDFA) [17], [18], thus it is a good candidate for light generation with a narrow linewidth, but mode selection is a challenging issue. PT symmetry would be an effective solution to meet the mode selection challenge in a long length fiber ring laser with stable single-longitudinal-mode lasing.

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In this paper, we propose and experimentally demonstrate a narrow-linewidth and wavelength-tunable single-mode fiber ring laser based on PT symmetry for mode selection. The PT symmetry is implemented using a single physical fiber-optic loop, which functions equivalently to two mutually coupled loops with an identical geometry but balanced gain and loss. The work here is an extension of our earlier work reported in [19], with more analysis and experimental results presented. It is different from a conventional PT-symmetric laser source in which two spatially separated optical loops with an identical geometry are employed. For a fiber ring laser with a long cavity length, it is extremely difficult to make the two mutually coupled loops precisely identical. In addition, environmental changes would also destroy the geometry match, making stable operation hard to achieve. It is highly desirable that such a two-loop configuration can be implemented using a single physical loop. In [20], we reported a PT-symmetric fiber ring laser in which the PT symmetry was achieved based on the reciprocity of a microdisk resonator in the ring cavity. The system was complicated, and the wavelength tunable range was limited due to a limited wavelength tuning range of a microdisk resonator. The approach proposed here has a much simpler configuration in which the PT symmetry is achieved based on a Sagnac loop incorporating a polarization beam splitter (PBS) and two polarization controllers (PCs). By controlling the polarization states of the linearly polarized light waves injected into the PBS via tuning the PCs, the gain and loss of the loops corresponding to the light waves traveling in the clockwise (CW) and counter-clockwise (CCW) directions can be precisely controlled. In addition, since the two light waves are traveling in the same physical Sagnac loop, the two equivalent loops are inherently identical in length. When the gain and loss are well balanced and exceed the coupling coefficient, PT symmetry is broken, single-mode lasing is thus achieved. The wavelength tunability is realized by tuning the center wavelength of a tunable optical bandpass filter (TOBF) incorporated in the ring cavity. Single-mode lasing with a widely tunable range from 1530 to 1565 nm and a narrow linewidth of 390 Hz is experimentally demonstrated.

II. Principle

The proposed PT-symmetric fiber ring laser is shown in Fig. 1(a). A Sagnac loop incorporating a PBS and two PCs is used to establish two mutually coupled ring loops. The mutual coupling between the two loops is achieved at a 3-dB optical coupler (OC1). The coupling k between two coupled loops in the PT-symmetric system is given by

$$k = Kz/l \tag{1}$$

where K is the coupling coefficient of OC1, z is the coupling length, and l is the ring cavity length. Since the two mutually coupled loops are implemented in a single physical loop, the length match between the two loops is much simplified. By controlling the polarization states of the light waves injected into the PBS along the CW and CCW directions, the gain and loss can be independently and precisely controlled. An EDFA in the ring cavity is used to provide a gain to compensate for the loss. A wavelength-tunable Fabry-Perot (F-P) filter used as a TOBF is incorporated in the fiber loop to achieve wavelength tuning. An optical spectrum analyzer (OSA) is used to monitor the optical spectrum of the generated light wave and a frequency-shifted self-heterodyne system shown in Fig. 1(b) is used to evaluate the singe-longitudinal-mode operation of the laser and to measure the linewidth.

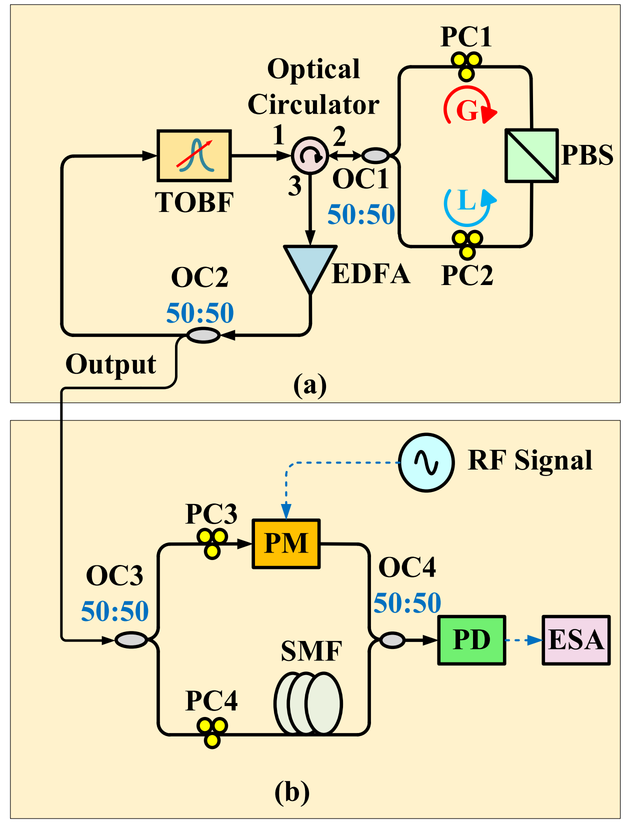

Fig. 1. (a) Schematic diagram of the proposed PT-symmetric fiber ring laser. (b) Frequency-shifted self-heterodyne interferometer for evaluating the performance of the proposed PT-symmetric fiber ring laser. OC: optical coupler; PC: polarization controller; PBS: polarization beam splitter; TOBF: tunable optical bandpass filter; EDFA: erbium-doped fiber amplifier; PM: phase modulator; RF Signal: radio frequency signal; SMF: single-mode fiber; PD: photodetector; ESA: electrical spectrum analyzer.

In a ring cavity, once the gain provided by the EDFA is greater than the loss, standing waves satisfying the phase condition given by $n_{eff} l = mc/\omega_m$ will be generated, where n_{eff} is the effective refractive index of the fiber in the ring cavity, m is an integer, ω_m is the mth order oscillating frequency, and c is the speed of light in vacuum. To enable single-longitudinal-mode lasing, an ultra-narrow passband optical filter should be used to select only a single longitudinal mode. However, for a fiber ring laser with a long cavity length, the mode spacing is very small, it is extremely difficult to perform effective mode selection.

The problem can be effectively solved by employing PT symmetry based on two mutually coupled loops having an identical geometry. It has been demonstrated that a single longitudinal mode can be selected if the gain and the loss of two coupled loops are matched and greater than the coupling coefficient [12].

In the proposed system, the two mutually coupled loops are implemented based on a single Sagnac loop, as shown in Fig. 1 (a).

The coupled differential equations that relate two modes in the two coupled loops are given by [21]

$$\frac{d}{dt}\begin{bmatrix} A_n \\ B_n \end{bmatrix} = \begin{bmatrix} -i\Omega_n + g_{A_n} & ik_n \\ ik_n & -i\Omega_n + g_{B_n} \end{bmatrix}\begin{bmatrix} A_n \\ B_n \end{bmatrix} \quad (2)$$

where A_n and B_n are the amplitudes of the nth longitudinal modes in the two coupled loops, Ω_n is the eigenfrequency of the nth mode without PT-symmetry, g_{A_n} and g_{B_n} represent the net gain and loss coefficients of the two coupled loops for the nth mode, and k_n is the coupling coefficient between the two loops for the nth mode.

By solving (1), we can calculate the eigenfrequencies of the PT-symmetric system, given by

$$\Omega_n{}^{(1,2)} = \Omega_n + i\left(\frac{g_{A_n} + g_{B_n}}{2}\right) \pm \sqrt{k_n{}^2 - \left(\frac{g_{A_n} - g_{B_n}}{2}\right)^2} \quad (3)$$

To satisfy the PT-symmetry condition, the net gain and loss should be controlled identical in magnitude, which means, $g_{A_n} = -g_{B_n} = g_n$. Thus, Eq. (2) can be re-written as

$$\Omega_n{}^{(1,2)} = \Omega_n \pm \sqrt{k_n{}^2 - g_n{}^2} \quad (4)$$

When the gain/loss of the two loops is equal to the coupling coefficient, i.e., $g_n = k_n$, the two eigenfrequencies coalesce, reaching the so-called exceptional point (EP). For a low-level gain/loss, i.e., $g_n < k_n$, the eigenfrequencies would split. However, once the gain/loss exceeds the coupling coefficient, i.e., $g_n > k_n$, a conjugate pair of modes with one experiencing amplification and the other decay are resulted while others remain neutral, illustrating the PT-symmetry condition is broken, as can be seen in Fig. 2, leading to single-longitudinal-mode lasing.

In the analysis, we call the mode with the highest gain the primary mode, or the *0*th longitudinal mode. In a conventional laser source, single-longitudinal-mode operation is realized by controlling the gain of the *0*th longitudinal mode to exceed the lasing threshold, while the gains of the other modes below the threshold, as shown in Fig. 3(a). The gain contrast between the primary mode and the second highest mode for a conventional laser source is given by

$$g_{\max} = g_0 - g_1 \quad (5)$$

where g_0 is the gain coefficient of the primary mode and g_1 is the gain coefficient of the next largest competing mode. Since the gain difference or the gain contract between the primary and the second highest mode, is small, it is hard to achieve stable single-longitudinal-mode lasing without mode hoping.

On the other hand, mode selection can be improved based on PT symmetry. As shown in Fig. 3(b), under the PT-symmetric setting, based on (3), we get the gain difference, which is given by

$$g_{\max\_PT} = \sqrt{g_0{}^2 - g_1{}^2} \quad (6)$$

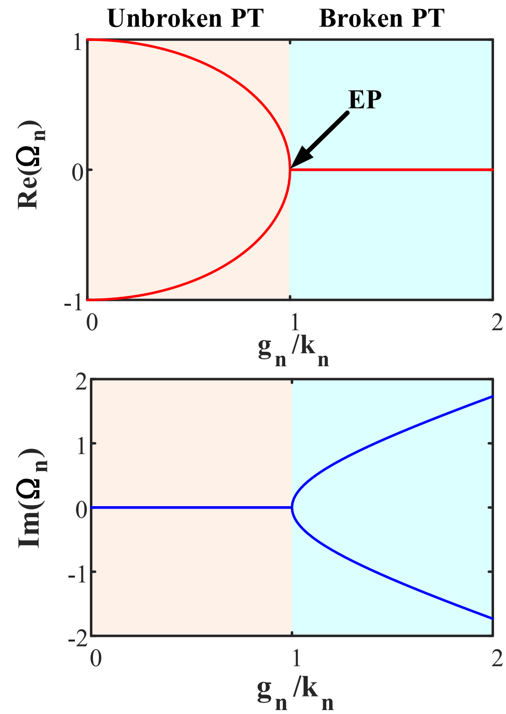

Fig. 2. The real and imaginary parts of the eigenfrequencies of the nth mode under the conditions of unbroken and broken PT-symmetry.

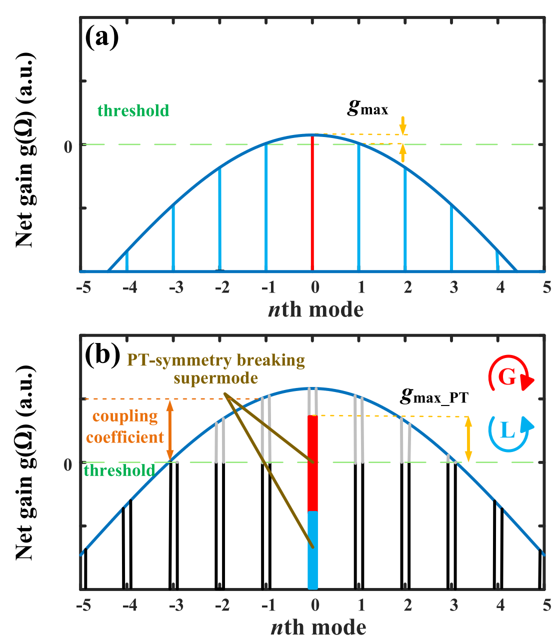

Fig. 3. Gain contrasts of (a) a conventional single-loop fiber ring laser, and (b) the proposed PT-symmetric fiber ring laser.

To quantify the improvement in mode selection, we calculate the gain enhancement, also called gain contrast ratio, which is defined as the ratio between the gain difference between a PT-symmetric laser source and a conventional laser source, given by

$$G = \frac{g_{\max\_PT}}{g_{\max}} = \sqrt{\frac{g_0/g_1 + 1}{g_0/g_1 - 1}} \quad (7)$$

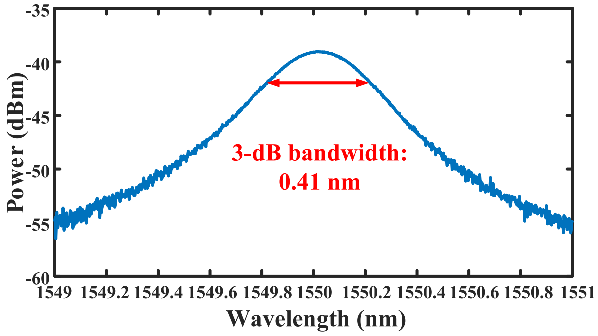

Fig. 4. The optical spectral response of the Fabry-Perot (F-P) filter at a center wavelength of 1550 nm.

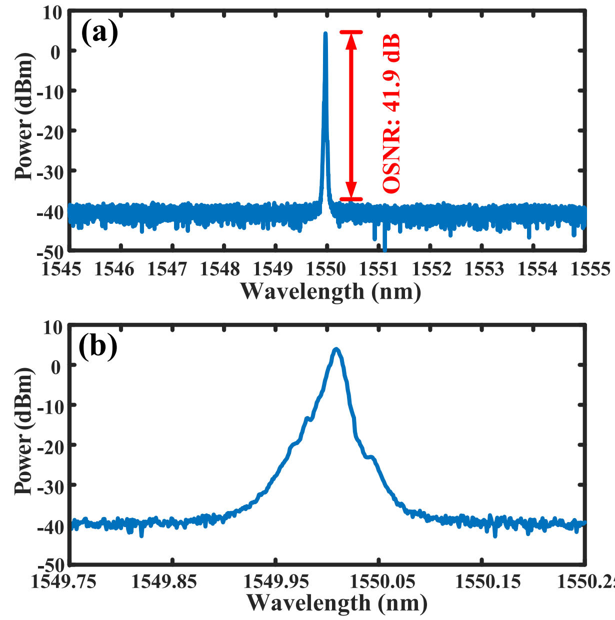

Fig. 5. Optical spectrum measured by an OSA. (a) The measured optical spectrum of the generated light wave at the center wavelength of 1550 nm and (b) its zoom-in view with a span of 0.5 nm.

Since $g_0 > g_1$, a significant enhancement in the gain difference is achieved, ensuring stable single-longitudinal-mode lasing of the primary mode.

III. Experimental Results and Discussion

The performance of the proposed PT-symmetric fiber ring laser is experimentally evaluated based on the setup shown in Fig. 1. In the experiment, the EDFA (NORTEL FA17UFAC-119C28) has a gain of 30 dB and a saturated output power of 16 dBm. The TOBF (OZ Optics) has a 3-dB bandwidth of 0.41 nm and a wavelength tuning range of 40 nm, from 1520 to 1570 nm. The spectral response of the TODB with its center wavelength tuned at 1550 nm is shown in Fig. 4. The loop length of the laser cavity is 80.08 m with an FSR of 2.55 MHz. Within the bandpass of the TOBF, there are more than 20000 longitudinal modes. Thus, single-longitudinal-mode lasing is not possible if PT symmetry is not implemented. The function of the TOBF is to perform coarse wavelength section to achieve wavelength tunability. The PCs are manual 3-paddle fiber polarization controllers, having a sandwiched structure with a half-wave plate located between two quarter-wave plates. To implement PT symmetry, the gain and loss of the two loops are precisely controlled by tuning the half-wave plates of PC1 and PC2 to make them precisely matched, the phase difference between two loops induced by OC1 and fiber bending is eliminated by tuning the quarter-wave plates. Since the coupling between two loops is achieved by using OC1 with a fixed coupling coefficient, the gain of the EDFA is controlled high enough to ensure that PT symmetry is broken. The generated light is sent to an OSA with a resolution of 0.01 nm (ANDO AQ6317B) to monitor its optical spectrum.

As shown in Fig. 5(a), a lasing wavelength at 1550 nm is generated. The optical signal to noise ratio (OSNR) of the generated light wave is measured to be 41.9 dB, also shown in Fig. 5(a). Fig. 5(b) gives a zoom-in view of the optical spectrum. Since the resolution of the OSA is low, we cannot determine if the laser is operating in single longitudinal mode or not, and we cannot measure the linewidth of the generated light wave using the OSA.

To make a high-resolution measurement, here we use the shifted self-heterodyne method [22] to measure the spectrum. The measurement setup is shown in Fig. 1(b). A 1 GHz microwave signal is applied to a phase modulator (PM) to shift the frequency in the upper arm by 1 GHz, to make the beat signal between the two signals from the two arms at a frequency away from DC (at 1 GHz), to enable a clearer observation of the beat signal. In the experiment, the 1 GHz microwave signal is generated by a microwave signal generator (Agilent E8254A) and applied to the PM (JDSU Model-10023874). A 10-km single-mode fiber is incorporated in the lower arm as a delay line. A photodetector (PD) (New Focus 10058B) with a 3-dB bandwidth of 20 GHz is employed to generate the beat signal, and an electrical spectrum analyzer (ESA) (Agilent E4448A) is used to observe the electrical spectrum.

Fig. 6(a) shows the electrical spectrum at the output of the PD. At this time, the gain and the loss are not tuned to be matched, PT symmetry is not realized, and single-mode lasing is not enabled. As can be seen from Fig. 6(a), a series of RF beat signals are generated, which indicates that the fiber ring laser is operating in multi-mode. The zoom-in view is shown in Fig. 6(b), from which we can see the FSR is 2.55 MHz. Then, we tune the gain and loss of the two loops by tuning PC1 and PC2 to make the gain and loss well matched, and to make the gain/loss greater than the coupling coefficient to make PT-symmetry broken. Single-longitudinal-mode lasing is thus achieved. As can be seen from Fig. 6(c), a single frequency at 1 GHz is observed, which confirms that the fiber ring laser is operating in single longitudinal mode. A zoom-in view is shown in Fig. 6(d), from which we can see that sidemodes are highly suppressed. As a comparison, the electrical spectrum of a conventional fiber ring laser with a single optical loop is also measured. To do so, we disconnect the Sagnac loop and connect the EDFA directly to the TOBF. Fig. 6(e) shows the spectrum at the output of the PD. As can be seen, multiple RF

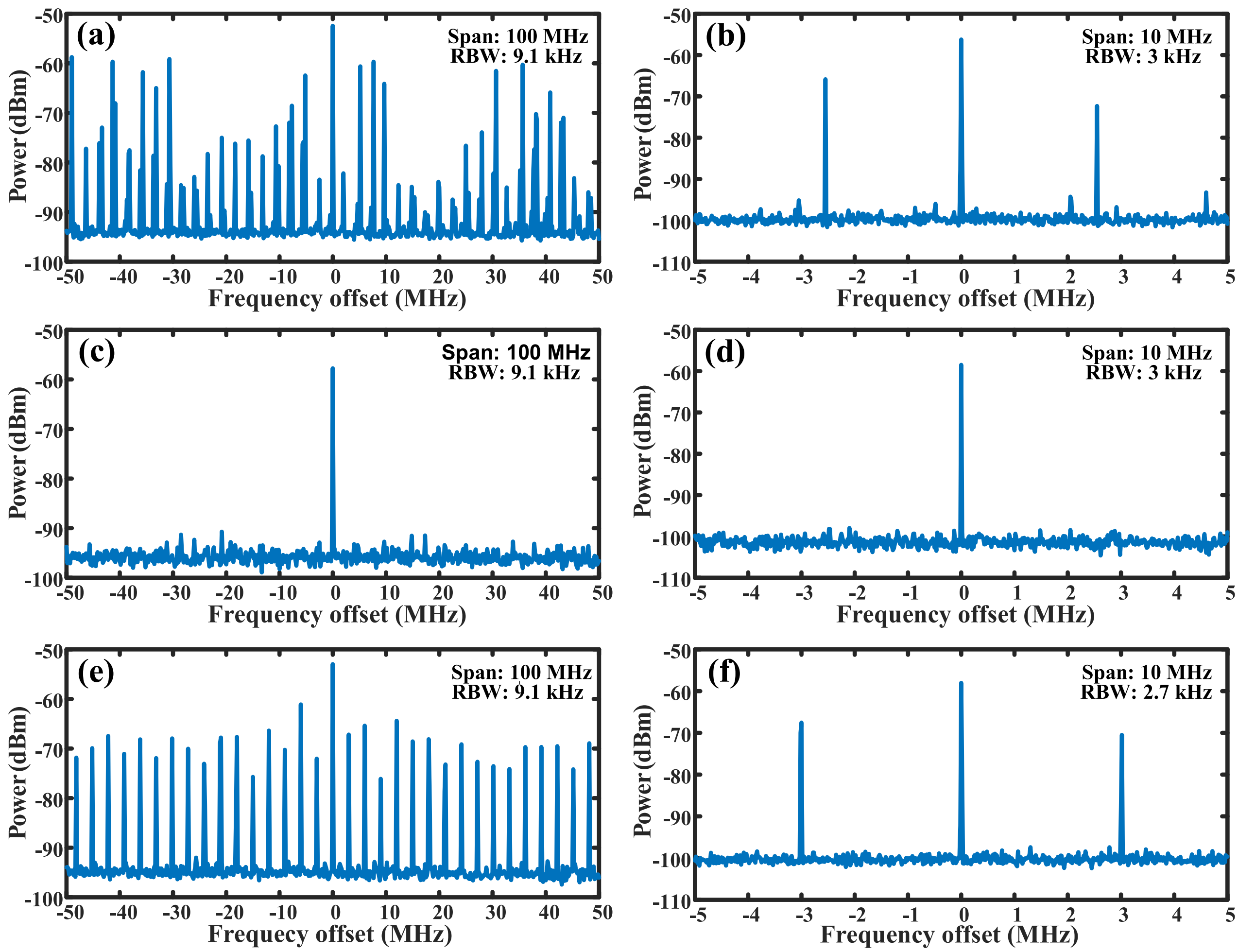

Fig. 6. The measured spectra of the RF beat signals at the output of the PD (a) without PT symmetry and (b) its zoom-in view, (c) with PT symmetry and (d) its zoom-in view. (e) The measured spectrum for a conventional single-loop fiber ring laser and (f) its zoom-in view.

beat signals are generated, which are resulted from the beating of the multiple modes in the laser cavity. Since the loop length of this conventional fiber ring laser is shorter than that of the PT-symmetric laser source (the Sagnac loop is disconnected), the FSR is 3 MHz, which is greater, as can be seen by comparing Fig. 6(b) and (f).

We then allow the PT-symmetric laser to operate in single mode and measure the linewidth of the generated light. The electrical spectrum at the output of the PD is shown in Fig. 7. The 20-dB linewidth is measured to be 7.8 kHz, corresponding to a 3-dB linewidth of 390 Hz. It worth noting that theoretically, several thousand kilometers of fiber is required to eliminate the coherence between the two light waves from the upper and lower arms to obtain an accurate linewidth measurement at a sub-kHz level. In the experiment, the length of the fiber is 10 km, which is able to partially destroy the coherence. However, it is not long enough to eliminate the interference effect, which will cause broadening of the self-heterodyne spectrum. In addition, the broadening of the self-heterodyne linewidth due to 1/f frequency noise is also inevitable [23]. Thus, the measured linewidth is smaller than the actual linewidth.

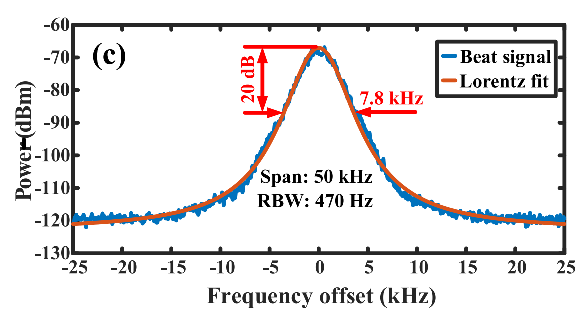

Fig. 7. The electrical spectrum at the output of the PD when the fiber ring laser is operating in the single-mode. The 20-dB linewidth is 7.8 kHz.

The tunability of the proposed PT-symmetric fiber ring laser is also evaluated. To do so, we manually tune the center wavelength of the TOBF from 1530 to 1565 nm. A light wave with a wide wavelength tunable range from 1530 to 1565 nm covering the entire C band is generated. The spectra of the light wave when the wavelength is tuned are shown in Fig. 8(a). Fig. 8(b) shows the spectra of the light wave that is continuously tuned

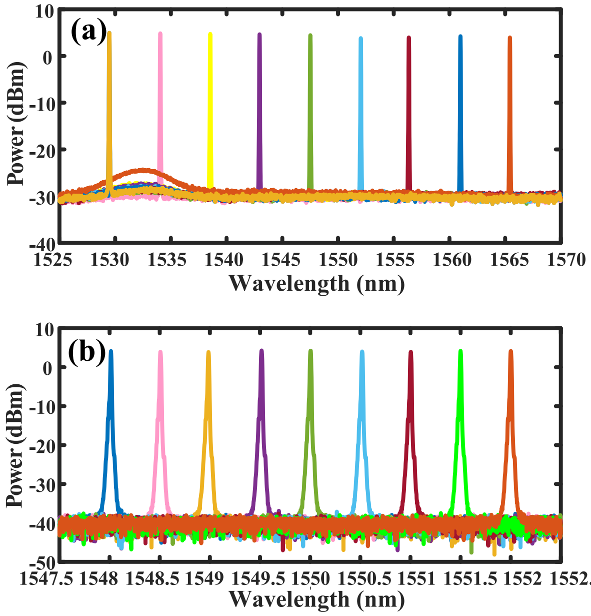

Fig. 8. The tuning of the wavelength of the fiber ring laser. (a) Measured wavelength-tunable range covering the entire C band and (b) continuous wavelength tuning by tuning the TOBF in a 4 nm range.

from 1548 to 1552 nm by continuously tuning the TOBF. The wavelength tunable range can be wider if the EDFA in the cavity can have a wider gain spectrum. The large tunability without using an ultra-narrowband wavelength tunable optical filter is one of the key advantages of employing PT symmetry, making the implementation greatly simplified and at a much lower cost.

IV. Conclusion

We have proposed and experimentally demonstrated a widely wavelength-tunable single-longitudinal-mode fiber ring laser with the mode selection based on PT-symmetry implemented using a single physical loop. Thanks to the PT symmetry, an increased gain contrast was achieved, making stable single-mode operation without using an ultra-narrow bandwidth optical filter possible. The key advantage of the proposed PT-symmetric fiber ring laser source is that the gain and loss loops were implemented in a single physical loop, which was a Sagnac loop incorporating a PBS, making the implementation greatly simplified and the stability greatly enhanced. The proposed PT-symmetric fiber ring laser was experimentally demonstrated. Single-longitudinal-mode lasing with a wide wavelength tunable range from 1530 to 1565 nm and a linewidth in a sub-kHz level was achieved experimentally.

References

[1] S. W. Henderson *et al.*, "Coherent laser radar at 2 μm using solid-state lasers," *IEEE Trans. Geosci. Remote Sens.*, vol. 31, no. 1, pp. 4–15, Jan. 1993.

[2] C. C. Lee and S. Chi, "Single-longitudinal-mode operation of a grating-based fiber-ring laser using self-injection feedback," *Opt. Lett.*, vol. 25, no. 24, pp. 1774–1776, Dec. 2000.

[3] F. Dubois, M. L. N. Requena, C. Minetti, O. Monnom, and E. Istasse, "Partial spatial coherence effects in digital holographic microscopy with a laser source," *Appl. Opt.*, vol. 43, no. 5, pp. 1331–1339, Feb. 2004.

[4] A. L. Schawlow and C. H. Townes, "Infrared and optical masers," *Phys. Rev.*, vol. 112, no. 6, pp. 1940–1949, Dec. 1958.

[5] 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, Apr. 1995.

[6] J. Liu, J. P. Yao, J. Yao, and T. H. Yeap, "Single-longitudinal-mode multiwavelength fiber ring laser," *IEEE Photon. Technol. Lett.*, vol. 16, no. 4, pp. 1020–1022, Apr. 2004.

[7] 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.

[8] C. Yeh, J. Chen, H. Chen, J. Chen, and C. W. Chow, "Stable and tunable single-longitudinal-mode erbium-doped fiber triple-ring laser with power-equalized output," *IEEE Photon. J.*, vol. 8, no. 2, Apr. 2016, Art. no. 1500906.

[9] C. M. Bender and S. Boettcher, "Real spectra in non-Hermitian hamiltonians having PT symmetry," *Phys. Rev. Lett.*, vol. 80, no. 24, pp. 5243–5246, Jun. 1998.

[10] R. El-Ganainy *et al.*, "Non-Hermitian physics and PT symmetry," *Nat. Phys.*, vol. 14, pp. 11–19, Jan. 2018.

[11] L. Feng, Z. Wong, R. Ma, Y. Wang, and X. Zhang, "Single-mode laser by parity-time symmetry breaking," *Science*, vol. 346, no. 6212, pp. 972–975, Nov. 2014.

[12] H. Hodaei, M. A. Miri, M. Heinrich, D. N. Christodoulides, and M. Khajavikhan, "Parity-time–symmetric microring lasers," *Science*, vol. 346, no. 6212, pp. 975–978, Nov. 2014.

[13] W. Liu *et al.*, "An integrated parity-time symmetric wavelength-tunable single-mode microring laser," *Nat. Commun.*, vol. 8, no. 15389, pp. 1–6, May 2017.

[14] B. Peng *et al.*, "Chiral modes and directional lasing at exceptional points," *Proc. Nat. Acad. Sci.*, vol. 113, no. 25, pp. 6845–6850, Jun. 2016.

[15] J. Ren *et al.*, "Unidirectional light emission in PT-symmetric microring lasers," *Opt. Express*, vol. 26, no. 21, pp. 27153–27160, Oct. 2018.

[16] W. E. Hayengae *et al.*, "Direct generation of tunable orbital angular momentum beams in microring lasers with broadband exceptional points," *ACS Photon.*, vol. 6, no. 8, pp. 1895–1901, Aug. 2019.

[17] Z. You *et al.*, "Single-longitudinal-mode Er:GGG microchip laser operating at 2.7 μm," *Opt. Lett.*, vol. 40, no. 16, pp. 3846–3849, Aug. 2015.

[18] J. H. Huang, Y. J. Chen, Y. F. Lin, X. H. Gong, Z. D. Luo, and Y. D. Huang, "940 mW 1564 nm multi-longitudinal-mode and 440 mW 1537 nm single-longitudinal-mode continuous-wave Er:Yb:$Lu_2Si_2O_7$ microchip lasers," *Opt. Lett.*, vol. 43, no. 8, pp. 1643–1646, Apr. 2018.

[19] Z. Dai, Z. Fan, and J. Yao, "Wavelength-tunable PT-symmetric single-longitudinal-mode fiber laser with a single physical loop," in *Proc. Opt. Fiber Commun. Conf. Exhib.*, San Diego, CA, USA, 2020, Paper Th2A.22.

[20] Z. Fan, Z. Dai, Q. Qiu, and J. Yao, "Parity-time symmetry in a single-loop photonic system," *J. Lightw. Technol.*, vol. 38, no. 15, pp. 3866–3873, Aug. 2020.

[21] K. G. Makris, R. El-Ganainy, D. N. Christodoulides, and Z. H. Musslimani, "Beam dynamics in PT symmetric optical lattices," *Phys. Rev. Lett.*, vol. 100, Mar. 2008, Art. no. 103904.

[22] T. Okoshi, K. Kikuchi, and A. Nakayama, "Novel method for high resolution measurement of laser output spectrum," *Electron. Lett.*, vol. 16, no. 16, pp. 630–631, Jul. 1980.

[23] 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.

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