Hybrid Frequency-Tunable Parity-Time Symmetric Optoelectronic Oscillator

Zhiqiang Fan, Weifeng Zhang, *Member, IEEE*, Qi Qiu, and Jianping Yao, *Fellow, IEEE, Fellow, OSA*

***Abstract*—An optoelectronic oscillator (OEO) is a microwave photonic system consisting of an amplified optoelectronic feedback loop to generate a microwave signal. To reduce the phase noise, the feedback loop must be long to ensure a high Q factor, which is usually implemented by incorporating a long optical fiber in the loop. The key limitation of using a long fiber is that a large number of closely spaced longitudinal modes exist in the feedback loop, which makes single-frequency oscillation difficult to achieve. In this article, we propose to incorporate a photonic integrated microdisk resonator (MDR) in an OEO to implement parity-time (PT) symmetry as well as frequency tuning. By employing the reciprocity of light propagation in the MDR, two mutually coupled optoelectronic loops having an identical geometry with one having a gain coefficient and the other a loss coefficient, identical in magnitude, to form a PT-symmetric OEO that support single-frequency oscillation, are implemented. The tuning of the frequency is realized by thermally tuning the MDR. Experimental results show a microwave signal with a frequency that is tunable from 2 to 12 GHz is realized. The phase noise of the generated microwave signal at a frequency of 11.5 GHz is −117.3 dBc/Hz at a 10-kHz frequency offset. The use of a photonic integrated microdisk resonator makes the entire PT symmetric system have high potential for full photonic integration.**

***Index Terms*—Optoelectronic oscillator, photonic signal generation, parity-time symmetry, silicon photonics.**

I. Introduction

MICROWAVE signals having an ultra-low phase noise is of fundamental importance for high-performance operation of systems such as communications systems, radar, and modern instruments [1], [2]. A microwave signal generated based on electronics has relatively high phase noise, especially at high frequencies due to a relatively small Q factor [3], [4]. To reduce the phase noise, a solution is to generate a microwave signal in the optical domain. For instance, by beating two optical comb lines from an optical comb generator, a microwave signal with an ultra-low phase noise can be generated [5]–[7]. Based on photonics, a microwave signal with a wide frequency tunable range can also be generated. For example, a microwave signal with a frequency tunable range from 0.5 to 110 GHz was generated based on optical sideband injection locking [8]. In addition to the generation of a microwave signal using an optical comb generator, a microwave signal with a low phase noise can also be generated by an optoelectronic oscillator (OEO). An OEO is a microwave photonic system consisting of a hybrid optical and electronic feedback loop [9]. By using a long fiber in the loop, a microwave signal with a low phase noise can be generated. For example, by using a fiber with a length of 16 km in the feedback loop, a microwave signal with an ultra-low phase noise of −163 dBc/Hz at an offset frequency of 6 kHz was generated [10], [11]. One important feature of an OEO for microwave generation is that the phase noise performance is not affected by the frequency tuning. This feature provides the possibility of generating a highly frequency-tunable microwave signal with a constant phase noise over the entire frequency tunable range.

However, the key limitation of using a long fiber in an OEO is that a large number of closely spaced longitudinal modes exist in the loop, making single-frequency oscillation difficult to implement [9], [12]. The use of an optical or microwave filter with an ultra-narrow bandwidth may make an OEO operate in a single frequency, but the implementation is extremely difficult, especially for tunable microwave generation [13]–[17]. To ease the requirement for narrow bandwidth, an OEO with dual or multiple loops was proposed and demonstrated [18]–[20]. Thanks to the Vernier effect, single-mode oscillation is implemented while maintaining a low phase noise. However, an OEO with dual or multiple loops has very limited tunability because the loop lengths of the two or multiple loops should be re-adjusted if the oscillation frequency is tuned, to make the resonance frequency of the OEO loop match the OEO oscillation frequency. Recently, parity-time (PT) symmetry, an effective solution for mode selection [21]–[23], was employed in an OEO to achieve single-mode oscillation [24], [25]. In a PT-symmetric OEO, two mutually coupled optoelectronic loops having an identical geometry with one having a gain coefficient and the other an equal amount of loss coefficient, were formed to achieve single-frequency oscillation. Stable oscillation with very low phase noise was realized. The limitation of the technique reported in [24], [25]

Manuscript received October 14, 2019; revised December 14, 2019; accepted December 23, 2019. Date of publication December 27, 2019; date of current version April 15, 2020. This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC). Z. Fan was supported by a scholarship from China Scholarship Council. *(Corresponding author: Jianping Yao.)*

Z. Fan is with Microwave Photonics Research Laboratory, School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON K1N 6N5, Canada, and also with the School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China.

W. Zhang and J. Yao are with the Microwave Photonics Research Laboratory, School of Electrical Engineering and Computer Science, University of Ottawa, ON K1N 6N5, Canada (e-mail: jpyao@eecs.uottawa.ca).

Q. Qiu is with the School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China (e-mail: qqiu@uestc.edu.cn).

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JLT.2019.2962508

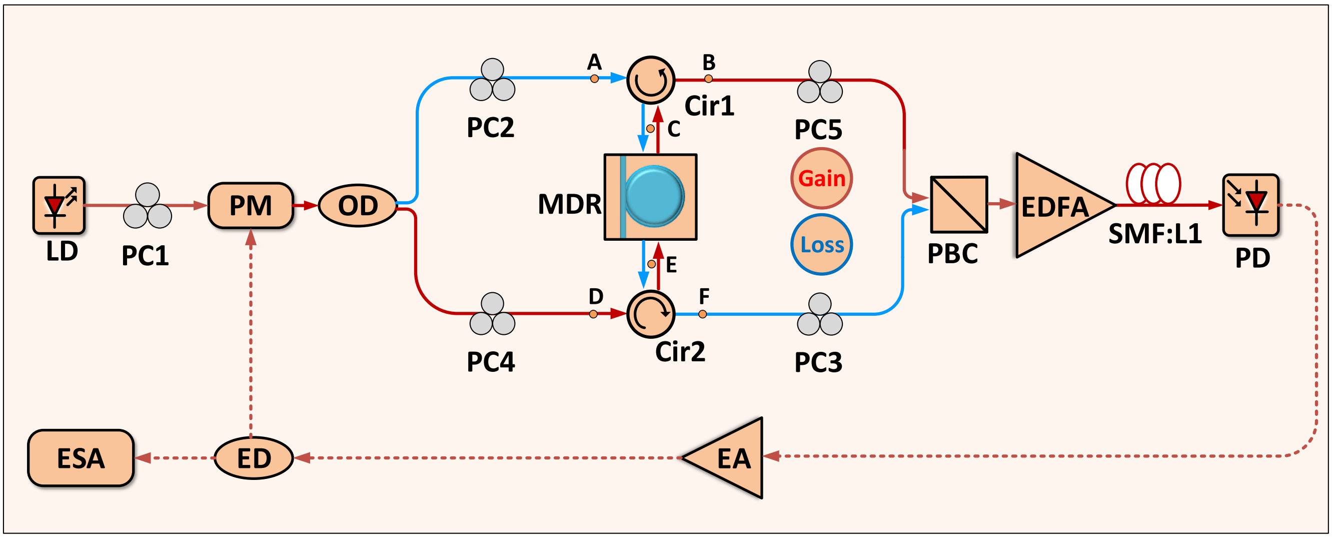

Fig. 1. The schematic diagram of the proposed highly tunable PT-symmetric OEO based on an integrated microdisk resonator. LD: laser diode; PM: phase modulator; OD: optical divider; PC: polarization controller; Cir: circulator; MDR: microdisk resonator; PBC: polarization beam combiner; SMF: single mode fiber; EDFA: erbium-doped fiber amplifier; PD: photoelectric detector; EA: electrical amplifier; ED: electrical divider; ESA: electrical spectrum analyzer.

is that the frequency of the generated microwave signal is fixed with no frequency tunability.

To implement a frequency-tunable PT-symmetric OEO, one solution is to have a frequency-tunable microwave photonic bandpass filter (MPBF) in the OEO. Recently, we proposed and experimentally demonstrated a frequency-tunable PT-symmetric OEO, incorporating an MPBF implemented based on phase modulation to intensity modulation (PM-IM) conversion using a phase modulator (PM) and an integrated microdisk resonator (MDR) [26]. The frequency tunability was realized by thermally tuning the MDR, to change the center frequency of the MPBF. The work reported in this article is an extension of the work in [26]. Specifically, in this paper an in-depth study of the frequency-tunable PT-symmetric OEO including a detailed theoretical analysis and more experimental results is performed.

The key to achieve single-frequency oscillation is to employ PT symmetry, which is realized by using two mutually coupled optoelectronic loops that are formed by a shared use of the MDR. The two loops have an identical geometry due to the reciprocity of light propagation in the MDR. By controlling the polarization states of the light waves injected into the MDR from the two ends, the gain and loss coefficients of the two loops can be controlled. When the PT symmetry for a specific oscillation mode is broken, a stable single-mode oscillation at that specific frequency is realized. Again, the frequency tunability is realized by tuning the center frequency of the MPBF through thermal tuning of the MDR. The proposed frequency-tunable PT-symmetric OEO is analyzed theoretically and evaluated experimentally. Single-mode oscillation with a frequency tunable range from 2 to 12 GHz is experimentally demonstrated. The phase noise of the generated microwave signal at 11.5 GHz is measured to be -117.3 dBc/Hz at a 10-kHz frequency offset, which can be further reduced if the length of the OEO loop is further increased.

II. Principle

Fig. 1 shows the schematic diagram of the proposed highly tunable PT-symmetric OEO based on an integrated MDR. As can be seen, a laser diode (LD) is used to generate a light wave that is coupled into a PM via a polarization controller (PC1). Note that PC1 is used to minimize the polarization-dependent loss. The modulated signal at the output of the PM is divided into two branches by an optical divider (OD). In the upper branch, the signal is launched into an MDR via a second PC (PC2) and a circulator (Cir1), transmitted through an MDR, and connected to a polarization beam combiner (PBC) via a second circulator (Cir2) and a third PC (PC3). In the lower branch, the signal is launched into the other end of the MDR via a fourth PC (PC4) and Cir2, transmitted through the MDR, and connected to the PBC via Cir1 and a fifth PC (PC5). Note that PC3 and PC5 are employed to make the polarization directions of the optical signals at the inputs of the PBC orthogonal to eliminate the interferences between the two optical signals. The two signals are combined at the PBC. After being amplified by an erbium-doped fiber amplifier (EDFA), the signals are sent to a single-mode fiber (SMF) and detected at a PD. The microwave signal at the output of the PD is amplified by an electrical amplifier (EA) and fed back to the PM. An electrical divider is used to tap part of the generated microwave signal for performance evaluation, including the spectrum analysis through an electrical spectrum analyzer (ESA) and the phase noise analysis through a signal analyzer (SA). The OEO has two identical and mutually coupled feedback loops which are implemented due to the reciprocity of light propagation in the MDR. Since only the transverse electronic (TE) mode can be excited in the bus waveguide in the MDR, the gain and loss of the two loops can be controlled by adjusting the polarization states of the light waves by tuning PC2 and PC4. It should be noted that the joint operation of the LD, the PM, the MDR, and the PD

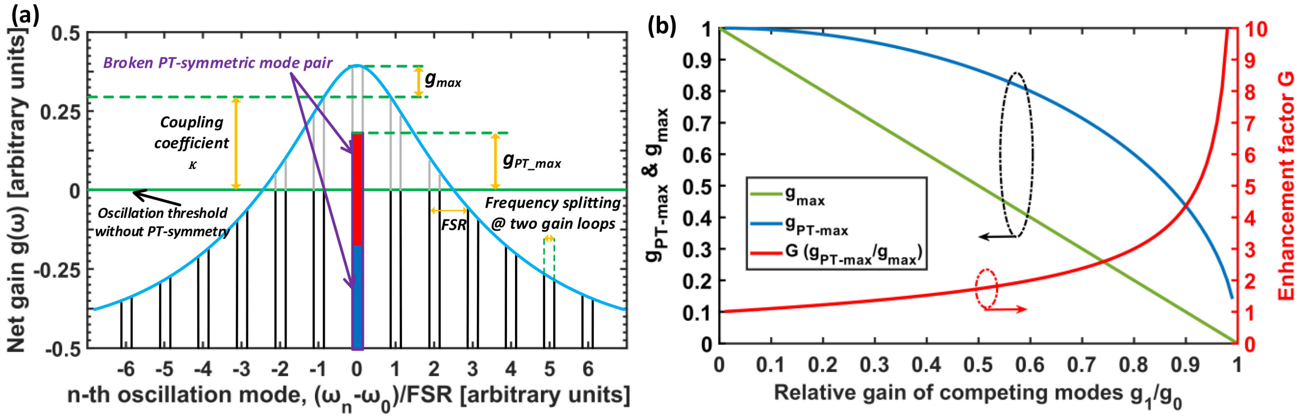

Fig. 2. Principle of mode suppression in the PT-symmetric OEO. (a) The selective oscillation mode under broken PT-symmetry. (b) Gain difference enhancement with PT-symmetry.

corresponds to a microwave photonic bandpass filter (MPBF) with its center frequency equal to the wavelength difference between the optical carrier and the notch of the MDR [27].

In the proposed PT-symmetric OEO, two mutually coupled feedback loops having an identical geometry are implemented due to the reciprocity of light propagation in the MDR, thus PT-symmetry is realized. Mathematically, the *n*th-eigenfrequencies are given by [22]

$$\omega_n^{(1,2)} = \omega_n + i\frac{g_{a_n}+g_{b_n}}{2} \pm \sqrt{\kappa_n^2 - \left(\frac{g_{a_n}-g_{b_n}}{2}\right)^2} \tag{1}$$

where ω_n is the *n*th-eigenfrequency of the two loops, g_{an} and g_{bn} denote the gain coefficients of the two loops for the *n*th modes, κ_n indicates the coupling coefficient between the two loops for the *n*th mode.

By adjusting the gain and the loss of the two loops to make $g_{an} = -g_{bn} = g_n$, PT symmetry condition is satisfied, and the *n*th-eigenfrequencies given in Eq. (1) can be rewritten as

$$\omega_n^{(1,2)} = \omega_n \pm \sqrt{\kappa_n^2 - g_n^2} \tag{2}$$

It can be seen from Eq. (2) that there is a transition point when the gain or loss coefficient of the two loops equals to the coupling coefficient ($g_n = \kappa_n$). When the gain or loss coefficient is smaller than the coupling coefficient ($g_n < \kappa_n$), any pair of the oscillation modes in the proposed PT-symmetric OEO undergoes bounded neutral oscillations, which indicates the PT-symmetry is unbroken. In contrast, the gain or loss coefficient exceeds the coupling coefficient ($g_n > \kappa_n$), the proposed PT-symmetric OEO has a conjugate pair of oscillating and decaying modes, which indicates the PT-symmetry is broken. Clearly, when only the PT-symmetry of the mode with the largest gain, we assume it is the *0*th mode, is broken ($g_0 > \kappa_0$), and the PT-symmetry of all the other modes is unbroken ($g_n < \kappa_n, n \neq 0$), the broken PT-symmetric *0*th mode is selected to oscillate in the proposed OEO, and all the other unbroken modes are suppressed (see Fig. 2(a)). It should be noted that the single-mode oscillation can also be realized by selecting only one mode with the largest gain coefficient to be amplified, where the amplification does not exceed the gain contrast $g_{max} = g_0 - g_1$ (see Fig. 2(a)). Here, g_0 is the gain coefficient of the oscillation mode with the largest gain, g_1 is the gain coefficient of the mode with the next largest gain. Obviously, this condition put forward a strict requirement for the bandwidth of the bandpass filter.

In comparison, under the PT-symmetric condition, where the coupling coefficient can be regarded as a virtual loss, the gain contrast g_{PT_max} (see Fig. 2(a)) between the modes with the largest gain and the next largest gain can be deduced from Eq. (1), given by

$$g_{\mathrm{PT\_max}} = \sqrt{g_0^2 - g_1^2} = G \cdot g_{\max} \tag{3}$$

$$G = \frac{g_{PT\_\max}}{g_{\max}} = \sqrt{\frac{g_0/g_1+1}{g_0/g_1-1}} \tag{4}$$

where *G* is the enhancement factor for the gain contrast. Fig. 2(b) shows the gain contrast enhancement under the PT-symmetric condition. Obviously, the gain contrast g_{PT_max} of the PT-symmetric OEO is significantly increased compared with the gain contrast g_{max} of a single-loop OEO. A sharp increase is found for the enhancement factor *G* when the gain of the oscillation mode with the largest gain g_0 is close to the gain of the mode with the next largest gain g_1. An extreme enhancement in the gain contrast in the PT-symmetric OEO provides an effective solution for mode selection to ensure a very stable single-mode oscillation.

In the proposed PT-symmetric OEO, the joint operation of the LD, the PM, the MDR, and the PD corresponds to an MPBF. In the MPBF, the spectral response of the notch of the MDR is translated to the spectral response of the microwave bandpass filter by using one wavelength through phase-modulation to intensity-modulation (PM-IM) conversion. Its center frequency equals the wavelength difference between the optical carrier and the notch of the MDR. By thermally tuning the MDR, the center frequency of the MPBF is changed. Consequently, the oscillation frequency of the proposed PT-symmetric OEO is tuned by thermally tuning the MDR.

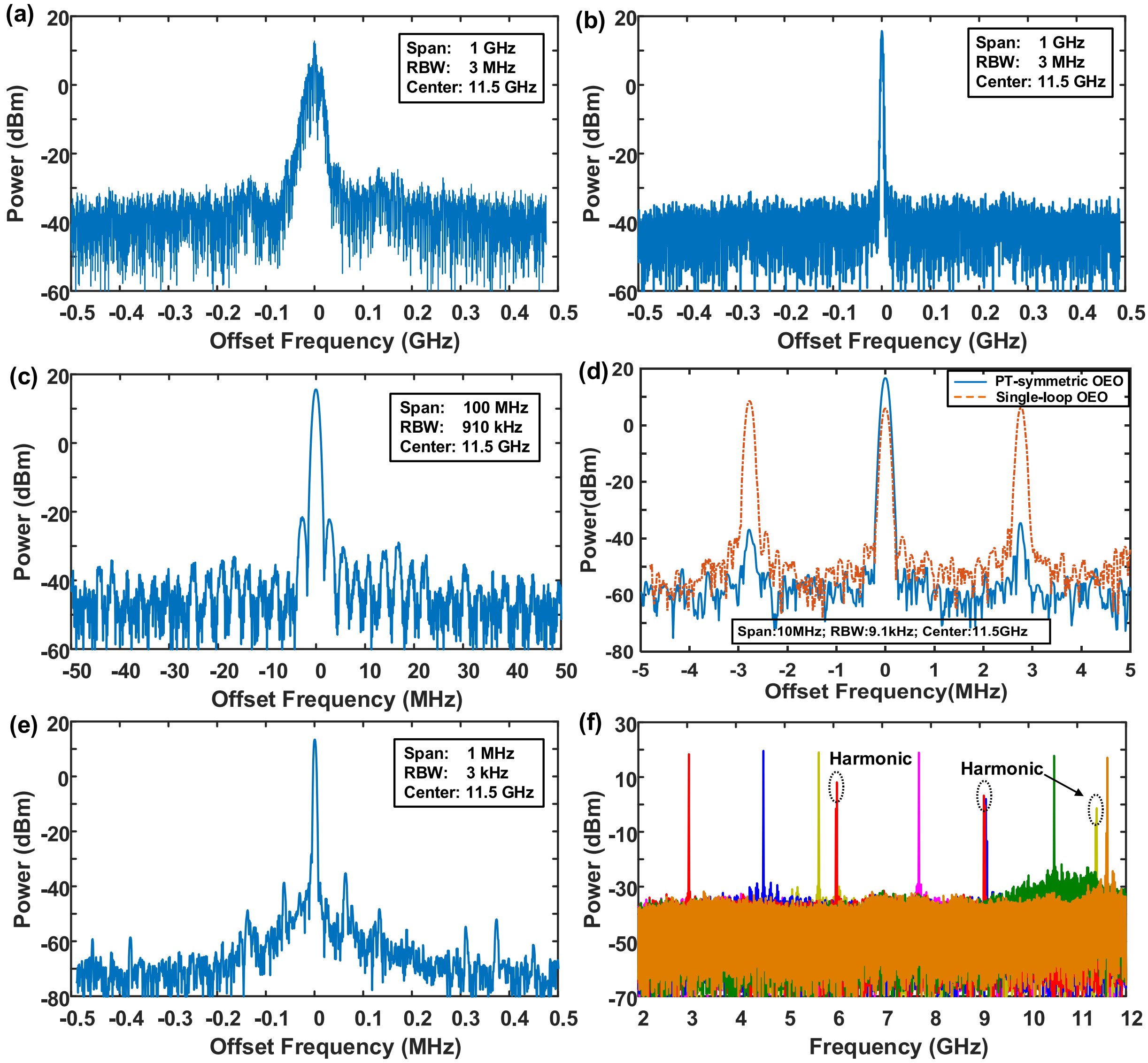

Fig. 3. The electrical spectra of the microwave signals generated by the PT-symmetric OEO with a loop length of 74.39 m. The spectra are measured at a central frequency at 11.5 GHz. (a) Multi-mode oscillation measured with a span of 1 GHz and a resolution bandwidth (RBW) of 3 MHz; (b) single-mode oscillation measured with a span of 1 GHz and an RBW of 3 MHz; (c) single-mode oscillation measured with a span of 100 MHz and an RBW of 910 kHz; (d) single-mode oscillation and multi-mode oscillation measured with a span of 10 MHz and an RBW of 9.1 kHz. (e) single-mode oscillation measured with a span of 1 MHz and an RBW of 3 kHz. (f) Frequency tunability of the proposed PT-symmetric OEO with tuning range from 2 GHz to 12 GHz.

III. Experiment

A proof-of-concept experiment is carried out based on the setup in Fig. 1. The optical carrier with an optical power of 8 dBm from the LD (Anritsu MG9638A) has a wavelength of 1557 nm, which differs from the wavelength of the notch of the MDR by 11.5 GHz. The phase modulator (JDSU 10023874) has a 3-dB bandwidth of 20 GHz. The PD (Optilab LR-12-A-M) and EA (MultiLink modulator driver MTC5515-751) have a 3-dB bandwidth of 12 GHz. The MDR is implemented based on silicon with a diameter of 3.7 μm and has a 3-dB bandwidth of around 20 pm. The fiber in the loop is an SMF of around 70 m. The 3-dB bandwidth of the MPBF is measured to be around 2.7 GHz, which contains around a thousand modes. The spectra of the generated microwave signals are measured by an electrical spectrum analyzer (Agilent E4448A). The phase noise of the generated microwave signals is measured by a signal analyzer (Agilent E5052B). The signal analyzer works with a down-converter (Agilent E5053A) to extend the frequency measurement range from 7 to 26.5 GHz. Fig. 3(a) shows the measured electrical spectra of the OEO without PT symmetry and a multi-mode oscillation is found. A narrowband bandpass filter with a 3-dB bandwidth of less than 3 MHz will be needed to realize a single-mode oscillation in this condition.

By tuning PC2 and PC4 to match the gain and loss coefficients of the two feedback loops, single-mode oscillation is implemented. The solid lines in Fig. 3(b) to (e) shows the measured spectra of the single-mode oscillation with different spans and RBWs. As a comparison with the multi-mode oscillation in Fig. 3(a), a purer spectrum with the same span of 1 GHz is

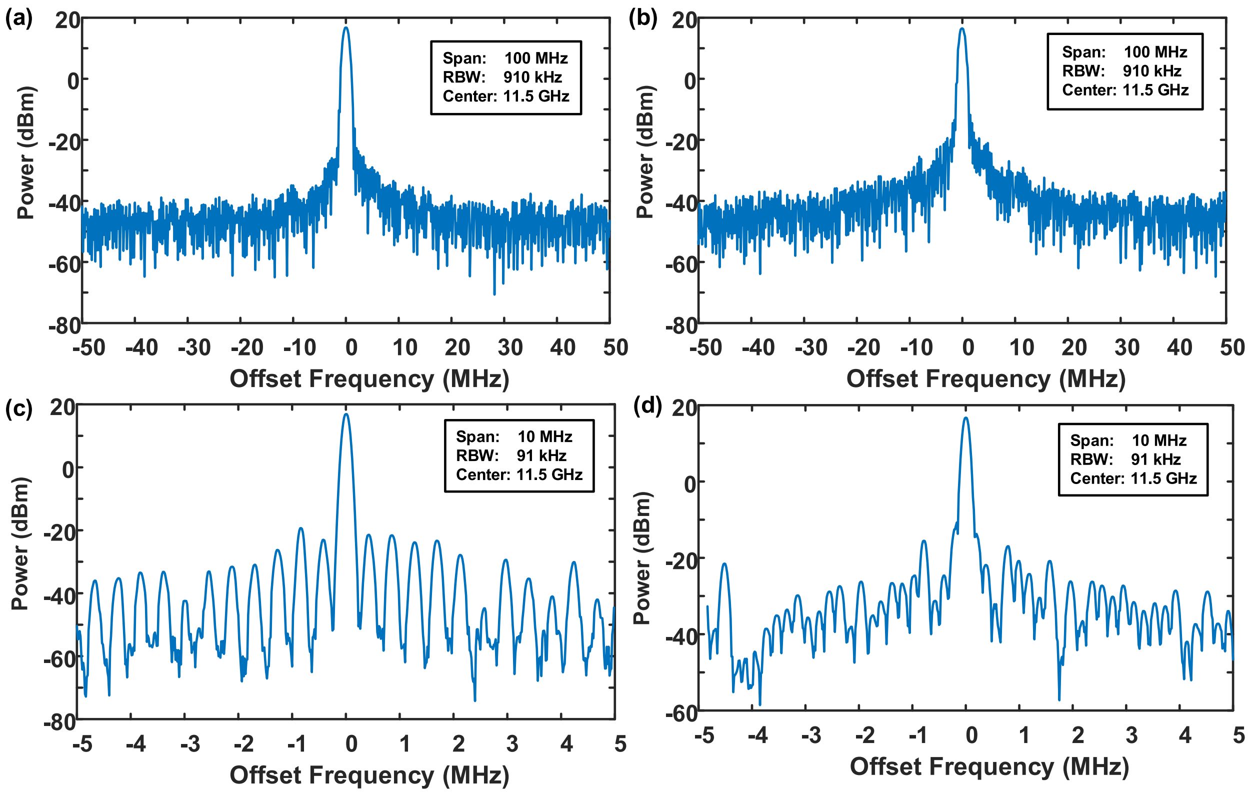

Fig. 4. The electrical spectra of the microwave signals generated by the PT-symmetric OEO with a loop length and a RBW of (a) 500 m and 910 kHz, (b) 1 km and 910 kHz, (c) 500 m and 91 kHz, and (d) 1 km and 91 kHz. The spectra are measured at a central frequency at 11.5 GHz.

measured in Fig. 3(b) when the OEO is in single-mode oscillation. Fig. 3(c) shows the measured spectrum with a span of 100 MHz, clearly, a single-mode oscillation is observed in the proposed PT-symmetric OEO. Fig. 3(d) shows the spectrum with a 10-MHz span. Note that the solid and the dotted lines represent the measured spectra of the OEO with PT symmetry and operating in a single loop, respectively. Obviously, the side mode suppression ratio (SMSR) of the OEO with PT symmetry is significantly increased as compared with the OEO in a single loop. An enhancement of more than 50 dB is found. In addition, the output power of the OEO with PT symmetry is increased by more than 10 dB to 16.66 dBm. The great enhancement in the SMSR and output power indicates that the PT-symmetric OEO provides an effective solution for mode selection. Further reducing the frequency span to 1 MHz, the spectrum of the generated microwave signal is shown in Fig. 3(e). It shows an extremely narrow bandwidth of the generated microwave signal.

By thermally tuning the MDR, the center frequency of the PM-IM conversion based MPBF is tuned. Meanwhile, the oscillation frequency of the proposed PT-symmetric OEO is measured in Fig. 3(f). Clearly, a tuning range from 2 to 12 GHz is achieved. It should be noted that the maximum oscillation frequency of 12 GHz is limited by the 3-dB bandwidth of the devices used in the OEO (PM, PD, and EA), which can be increased by using devices with a wider bandwidth. Besides, the high-order harmonics are found due to the nonlinearity in the feedback loop.

Theoretically, the phase noise of the OEO will be decreased by using a longer fiber [9], [12]. By increasing the loop length of the OEO with PT symmetry to around 500m and 1 km, the spectra of the generated signals at an oscillation frequency of 11.5 GHz is measured in Fig. 4. The spectra with a span of 100 MHz in Fig. 4(a) and (b), where the loop lengths are around 500 m and 1 km, respectively, show that the OEO oscillates at single frequency. Fig. 4(c) and (d) show the zoom-in view of the spectra with a 10-MHz span when the loop lengths are around 500 m and 1 km, respectively. The suppression of the side modes in both the OEOs with longer loop lengths is not as good as it in the OEO with a loop length of around 70 m. That is because the longer loop length causes the smaller mode spacing between the main oscillation mode and the next strongest mode, thus a smaller gain contrast between the two modes. This makes the manually selective breaking the PT symmetry in the OEO more difficult. A solution is to use an electrical feedback electrical loop to detect the change of the loop insertion loss and finely tune the PC for selective breaking the PT symmetry in the OEO.

Fig. 5 shows the phase noise of the generated microwave signals, which is measured by a microwave signal analyzer. When the loop length is around 70 m, the phase noise of the generated microwave signals at different oscillation frequencies of 11.5 GHz and 4.5 GHz are measured and shown in Fig. 5(a). The phase noise of the signals are measured to be -78, -102, -122, and -140 dBc/Hz at an offset frequency of 1, 10, 100, and 1000 kHz, respectively. As can be seen the phase noise measurements between the two signals match quite well, confirming that the phase noise of an oscillation signal is not altered when its frequency is tuned, which is consistent with

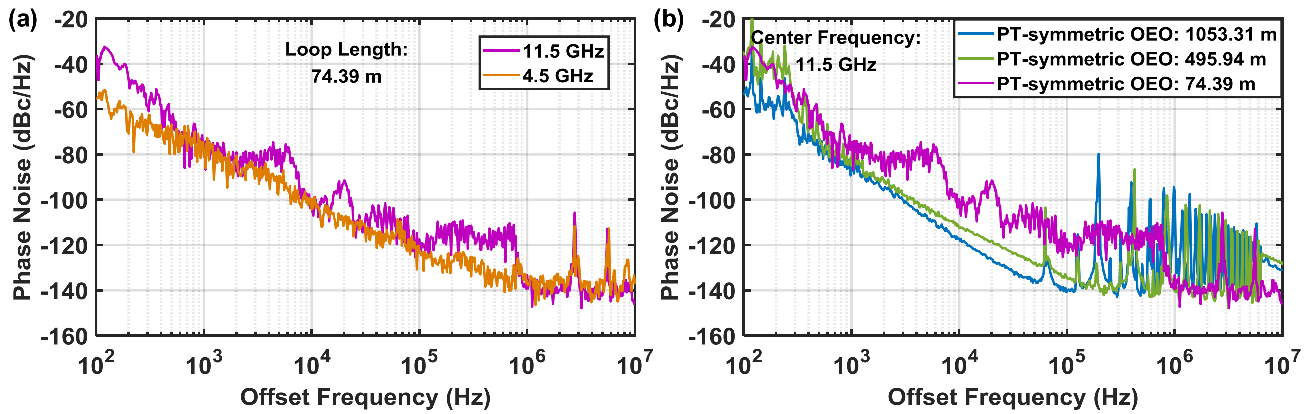

Fig. 5. The measured phase noise of the proposed PT-symmetric OEO. (a) The OEO has a same loop length of 74.39 m and different oscillation frequencies of 11.5 GHz and 4.5 GHz. (b) The OEO has a same oscillation frequency of 11.5 GHz and different loop lengths of 74.39 m, 495.94 m, and 1053.31 m.

the theoretical analysis in [9], [12]. It should be noted, however, there are fluctuations in the measured phase noise spectrum for the 11.5-GHz signal, which are caused due to the environmental disturbance. A solution to eliminate the fluctuations is to package the system to make it isolated from the environment. Fig. 5(b) shows the phase noise measurements of the 11.5-GHz signal generated by the PT-symmetric OEO with different loop lengths of around 70 m, 500 m, and 1 km. As can be seen the phase noise levels at an offset frequency of 10 kHz are −102, −112, and −117.3 dBc/Hz for the OEO with a different loop length of around 70 m, 500 m, and 1 km, respectively. Clearly, a longer loop length enables a lower phase noise, which agrees well with the theoretical analysis in [9], [12].

Multiple peaks are observed in the phase noise measurements in Fig. 5(a) and (b), which are induced by the side modes of the OEO with different loop lengths. As can be seen for the loop lengths of around 70 m, 500 m, and 1 km, the highest peaks for each loop length are measured to be around −105, −86.5, and −79.7 dBc/Hz, respectively. Clearly, a shorter loop length enables a higher side mode suppression, which is consistent with the analysis for the measured spectra in Figs. 3 and 4.

IV. Conclusion

In summary, a highly tunable PT-symmetric OEO based on an integrated MDR was proposed and experimentally demonstrated. A stable single-mode oscillation was implemented in the proposed PT-symmetric OEO thanks to the extremely high enhancement in the gain contrast when the PT symmetry was realized based on the reciprocity of light propagation in an MDR. Two mutually coupled loops having an identical geometry due to the reciprocity of light propagation in the MDR were constructed. The PT-symmetry was realized by controlling the gain and loss of the two loops are identical. The tunability of the proposed OEO was realized by using the frequency tunable MPBF, which consists of an LD, a PM, an MDR, and a PD. By thermally tuning the MDR, the center frequency of the MPBF was tuned and thus the oscillation frequency of the proposed PT-symmetric OEO was tuned. The operation of the PT-symmetric OEO was experimentally evaluated when the OEO has different loop lengths of around 70 m, 500 m, and 1 km. Single-mode oscillation was achieved for all the three loop lengths. For the longest loop length of around 1 km, the phase noise was as low as −117.3 dBc/Hz at an offset frequency of 10 kHz and the phase noise density induced by the side modes of the OEO was suppressed below −79.7 dBc/Hz. In addition, a frequency tuning range from 2 to 12 GHz was implemented by thermally tuning the MDR, which can be extended by using devices (PM, PD, and EA) with a wider bandwidth. The demonstration opens new avenues for highly tunable ultra-low phase noise signal generation.

References

[1] J. Capmany and D. Novak, "Microwave photonics combines two worlds," *Nat. Photon.*, vol. 1, no. 6, pp. 319–330, Jun. 2007.
[2] J. Yao, "Microwave photonics," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 314–335, Feb. 2009.
[3] J. G. Hartnett, C. R. Locke, E. N. Ivanov, M. E. Tobar, and P. L. Stanwix, "Cryogenic sapphire oscillator with exceptionally high long-term frequency stability," *Appl. Phys. Lett.*, vol. 89, no. 20, p. 203513, Nov. 2006.
[4] T. M. Fortier *et al.*, "Sub-femtosecond absolute timing jitter with a 10 GHz hybrid photonic-microwave oscillator," *Appl. Phys. Lett.*, vol. 100, no. 23, p. 231111, Jun. 2012.
[5] X. Xie *et al.*, "Photonic microwave signals with zeptosecond-level absolute timing noise," *Nat. Photon.*, vol. 11, no. 1, pp. 44–47, Jan. 2017.
[6] T. M. Fortier *et al.*, "Generation of ultrastable microwaves via optical frequency division," *Nat. Photon.*, vol. 5, no. 7, pp. 425–429, Jul. 2011.
[7] J. Li, X. Yi, H. Lee, S. A. Diddams, and K. J. Vahala, "Electro-optical frequency division and stable microwave synthesis," *Science*, vol. 345, no. 6194, pp. 309–313, Jul. 2014.
[8] G. J. Schneider, J. A. Murakowski, C. A. Schuetz, S. Shi, and D. W. Prather, "Radiofrequency signal-generation system with over seven octaves of continuous tuning," *Nat. Photon.*, vol. 7, no. 2, pp. 118–122, Jan. 2013.
[9] X. S. Yao and L. Maleki, "Optoelectronic microwave oscillator," *J. Opt. Soc. Am. B*, vol. 13, no. 8, pp. 1725–1735, Aug. 1996.
[10] D. Eliyahu, D. Seidel, and L. Maleki, "Phase noise of a high performance OEO and an ultra low noise floor cross-correlation microwave photonic homodyne system," in *Proc. IEEE Int. Frequency Control Symp.*, Honolulu, USA, May 2008, pp. 811–814.
[11] L. Maleki, "Sources: The optoelectronic oscillator," *Nat. Photon.*, vol. 5, no. 12, pp. 728–730, Dec. 2011.
[12] X. S. Yao and L. Maleki, "Optoelectronic oscillator for photonic systems," *IEEE J. Quantum Electron.*, vol. 32, no. 7, pp. 1141–1149, Jul. 1996.
[13] D. Eliyahu and L. Maleki, "Tunable, ultra-low phase noise YIG based optoelectronic oscillator," in *Proc. IEEE MTT-S Int. Microw. Symp. Digest*, Philadelphia, USA, Jun. 2003, pp. 2185–2187.
[14] D. Strekalov, D. Aveline, N. Yu, R. Thompson, A. B. Matsko, and L. Maleki, "Stabilizing an optoelectronic microwave oscillator with photonic filters," *J. Lightw. Technol.*, vol. 21, no. 12, pp. 3052–3061, Dec. 2003.

[15] I. Ozdur, D. Mandridis, N. Hoghooghi, and P. J. Delfyett, "Low noise optically tunable opto-electronic oscillator with Fabry–Perot etalon," *J. Lightw. Technol.*, vol. 28, no. 21, pp. 3100–3106, Nov. 2010.

[16] W. Zhang and J. Yao, "Silicon photonic integrated optoelectronic oscillator for frequency-tunable microwave generation," *J. Lightw. Technol.*, vol. 36, no. 19, pp. 4655–4663, Oct. 2018.

[17] H. Tang, Y. Yu, Z. Wang, L. Xu, and X. Zhang, "Wideband tunable optoelectronic oscillator based on a microwave photonic filter with an ultra-narrow passband," *Opt. Lett.*, vol. 43, no. 10, pp. 2328–2331, May 2018.

[18] X. S. Yao and L. Maleki, "Multiloop optoelectronic oscillator," *IEEE J. Quantum Electron.*, vol. 36, no. 1, pp. 79–84, Jan. 2000.

[19] Z. Fan, Q. Qiu, J. Su, T. Zhang, and Y. Lin, "Phase noise measurement of an optoelectronic oscillator based on the photonic-delay line cross-correlation method," *Opt. Lett.*, vol. 44, no. 8, pp. 1992–1995, Apr. 2019.

[20] E. Shumakher and G. Eisenstein, "A novel multiloop optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 20, no. 22, pp. 1881–1883, Nov. 2008.

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

[22] 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.

[23] J. Schindler, A. Li, M. C. Zheng, F. M. Ellis, and T. Kottos, "Experimental study of active LRC circuits with PT symmetries," *Phys. Rev. A*, vol. 84, no. 4, p. 040101, Oct. 2011.

[24] Y. Liu, T. Hao, W. Li, J. Capmany, N. Zhu, and M. Li, "Observation of parity-time symmetry in microwave photonics," *Light: Sci. Appl.*, vol. 7, no. 1, p. 38, Jul. 2018.

[25] J. Zhang and J. Yao, "Parity-time–symmetric optoelectronic oscillator," *Sci. Adv.*, vol. 4, no. 6, p. eaar6782, Jun. 2018.

[26] Z. Fan, W. Zhang, Q. Qiu, and J. Yao, "Widely tunable parity-time-symmetric optoelectronic oscillator based on a silicon microdisk resonator," in *Proc. Int. Topical Meeting Microw. Photon. (MWP)*, Ottawa, Canada, Oct. 2019, pp. 1–4.

[27] W. Zhang and J. Yao, "On-chip silicon photonic integrated frequency-tunable bandpass microwave photonic filter," *Opt. Lett.*, vol. 43, no. 15, pp. 3622–3625, Aug. 2018.

Zhiqiang Fan received the B.Eng. degree in electronic science and technology (optoelectronic engineering and optical communication) from the University of Electronic Science and Technology of China (UESTC), Chengdu, China in 2015. He is currently working toward the Ph.D. degree with the School of Optoelectronic Science and Engineering at UESTC and is working as a joint Ph.D. student with the Microwave Photonics Research Laboratory, School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON, Canada.

His current research interests include photonic generation of microwave waveforms and integrated microwave photonics.

Weifeng Zhang (S'12–M'18) received the B.Eng. degree in electronic science and technology from Xi'an Jiaotong University, Xi'an, China in 2008, the M.A.Sc. degree in electrical engineering from Politecnico di Torino, Torino, Italy, in 2011 and the Ph.D. degree in electrical engineering from the University of Ottawa, Ottawa, ON, Canada in 2017. He is currently a Postdoctoral Fellow with Microwave Photonics Research Laboratory, School of Electrical Engineering and Computer Science, University of Ottawa.

His current research interests include silicon photonics and its applications in microwave photonics.

Qi Qiu received the B.S. degree in laser technology from the Huazhong University of Science and Technology, Wuhan, China and the Ph.D. degree in optical engineering with the University of Electronic Science and Technology of China (UESTC), Chengdu, China in 1985 and 2007, respectively. He is currently a Professor with UESTC. He has authored or coauthored more than 100 international journals and conferences.

His current research interests include optical communication, microwave photonics, and optical fiber sensor.

Jianping Yao (M'99–SM'01–F'12) received the Ph.D. degree in electrical engineering from the Université de Toulon et du Var, Toulon, France, in 1997. He is a Distinguished University Professor and University Research Chair with the School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON, Canada. From 1998 to 2001, he was with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, as an Assistant Professor. In 2001, he joined the School of Electrical Engineering and Computer Science, University of Ottawa as an Assistant Professor, where he was promoted to an Associate Professor in 2003, and a Full Professor in 2006. He was appointed the University Research Chair in Microwave Photonics in 2007. In 2016, he was conferred the title of Distinguished University Professor at the University of Ottawa. From 2007 to 2010 and from 2013 to 2016, he was the Director of the Ottawa-Carleton Institute for Electrical and Computer Engineering.

He has authored or coauthored more than 620 research papers including more than 360 papers in peer-reviewed journals and more than 260 papers in conference proceedings. He is the Editor-in-Chief of IEEE PHOTONICS TECHNOLOGY LETTERS, a Topical Editor of *Optics Letters*, an Associate Editor of Science Bulletin, a Steering Committee Member of the IEEE JOURNAL OF LIGHTWAVE TECHNOLOGY, and an Advisory Editorial Board Member of *Optics Communications*. He was a Guest Editor of a Focus Issue on Microwave Photonics in Optics Express in 2013, a Lead-Editor of a Feature Issue on Microwave Photonics in Photonics Research in 2014, and a Guest Editor of a Special Issue on Microwave Photonics in the IEEE JOURNAL OF LIGHTWAVE TECHNOLOGY in 2018. He is currently the Chair of the IEEE PHOTONICS Ottawa Chapter and is the Technical Committee Chair of IEEE MTT-3 Microwave Photonics. He was a Member of the European Research Council Consolidator Grant Panel in 2016, the Qualitative Evaluation Panel in 2017, and a Member of the National Science Foundation Career Awards Panel in 2016. He was also a Chair of a number of international conferences, symposia, and workshops, including the Vice Technical Program Committee (TPC) Chair of the 2007 IEEE Topical Meeting on Microwave Photonics, TPC Co-Chair of the 2009 and 2010 Asia-Pacific Microwave Photonics Conference, TPC Chair of the High-Speed and Broadband Wireless Technologies Subcommittee of the IEEE Radio Wireless Symposium 2009-2012, TPC Chair of the Microwave Photonics Subcommittee of the IEEE Photonics Society Annual Meeting 2009, TPC Chair of the 2010 IEEE Topical Meeting on Microwave Photonics, General Co-Chair of the 2011 IEEE Topical Meeting on Microwave Photonics, TPC Co-Chair of the 2014 IEEE Topical Meetings on Microwave Photonics, and General Co-Chair of the 2015 and 2017 IEEE Topical Meeting on Microwave Photonics. He was also a Committee Member for a number of international conferences, such as IPC, OFC, BGPP, and MWP. He is the recipient of the 2005 International Creative Research Award of the University of Ottawa, the 2007 George S. Glinski Award for Excellence in Research, a Natural Sciences and Engineering Research Council of Canada Discovery Accelerator Supplements Award in 2008, an inaugural OSA Outstanding Reviewer Award in 2012, and the Award for Excellence in Research 2017–2018 at the University of Ottawa. He was one of the top ten reviewers of IEEE/OSA Journal of Lightwave Technology (2015–2016). He was an IEEE MTT-S Distinguished Microwave Lecturer for 2013–2015. He is a registered Professional Engineer of Ontario. He is a Fellow of the Optical Society of America, the Canadian Academy of Engineering, and the Royal Society of Canada.