Frequency-tunable parity-time-symmetric optoelectronic oscillator using a polarization-dependent Sagnac loop

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Abstract: A frequency-tunable parity-time-symmetric optoelectronic oscillator with a single physical loop is proposed. Frequency-tunable single-mode oscillation from 2 to 12 GHz and a phase noise of -108 dBc/Hz at an offset frequency of 10 kHz is achieved.

1. Introduction

High-frequency microwave signals with low phase noise are highly needed for applications such as in modern radar and communications systems [1]. Microwave generation based on photonic techniques has been studied in the past few decades, and numerous techniques have been proposed [2,3]. One effective solution to generate a high frequency and low phase noise microwave signal is to use an optoelectronic oscillator (OEO) [4]. An OEO has an optical and electrical hybrid loop in which the Q factor of the loop can be increased by using a long optical fiber. One major difficulty in implementing an OEO with a long loop is the mode selection, since an OEO with a long loop has multiple closely spaced modes, making mode selection difficult [5].

Recently, a new concept was introduced to the field of microwave photonics [6-8], in which mode selection based on Parity-Time (PT) symmetry was proposed. PT-symmetry is a concept originated from quantum mechanics, which has recently been employed in optics for optical mode selection [6-9]. To implement PT-symmetry in an OEO, we need to have two mutually coupled loops with identical geometry, but one has a gain and the other has a loss, identical in magnitude. Once the gain and loss are matched and the gain/loss coefficient of one mode is exceeding the coupling coefficient, the PT symmetry is broken, and the mode will start to oscillate while all others remain neutral. By exploiting this mechanism, single-mode oscillation can be realized. However, the implementation of an OEO with two physically separated loops is challenging since the lengths must be controlled identically and the interference between the two loops will make the stability poor.

In this paper, we propose and experimentally demonstrate a tunable PT-symmetric OEO with a single physical loop. Instead of using two physically separated loops, we use a Sagnac loop incorporating a polarization beam splitter (PBS) to form two equivalent loops. The gain and loss of the two loops are precisely controlled by tuning the polarization states of light waves injected into the PBS. By controlling the gain and loss to make the OEO satisfy the PT-symmetric breaking condition, a single-frequency microwave signal is generated. The frequency tunability of the OEO is achieved by tuning the central frequency of a microwave photonic filter (MPF) implemented based on phase modulation and phase-modulation to intensity-modulation (PM-IM) conversion by using a phase modulator (PM) and a phase-shifted fiber Bragg grating (PS-FBG) [10]. The proposed PT-symmetric OEO is experimentally demonstrated. Single-mode oscillation with a frequency-tunable range of 10 GHz and a phase noise of -108 dBc/Hz at an offset frequency of 10 kHz is achieved.

2. Principle

Fig. 1(a) shows the proposed PT-symmetric OEO. A light wave from a tunable laser source (TLS) is sent to a PM via a polarization controller (PC1). A RF modulated optical signal generated at the PM is sent through a long fiber to a Sagnac loop consisting of a PBS and two PCs (PC2 and PC3), transmitting in the loop along the CW and CCW directions, to form two equivalent loops with one having a gain and the other a loss. The gain and loss of the two loops are controlled by tuning PC2 and PC3. According to the coupled-mode equation, the eigenfrequencies are given [5]

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

where ω_n represent the eigenfrequency of the n-th oscillating mode without PT symmetry, g_n is the gain or loss coefficient of a loop for the n-th mode, and κ_n is the coupling coefficient between the two loops. Once the gain/loss coefficient exceeds the coupling coefficient ($\kappa_n < g_n$), a conjugate pair of modes with one experiencing amplification and the other attenuation are resulted, while other modes remain neutral. The PT symmetry condition is broken, and single-mode oscillation is implemented.

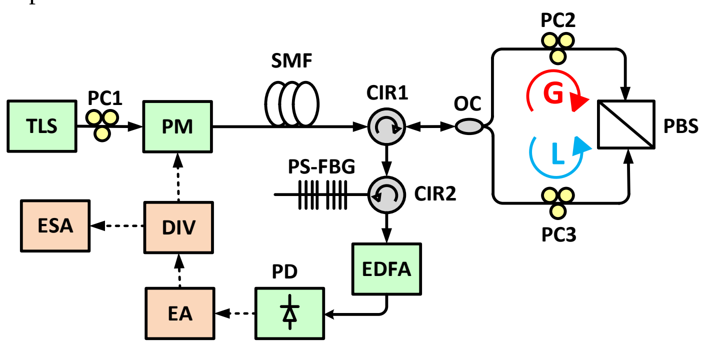

Fig. 1. Schematic diagram of the proposed PT-symmetric OEO. TLS: tunable laser source; PC: polarization controller; PM: phase modulator; SMF: single mode fiber; CIR: optical circulator; OC: optical coupler; PBS: polarization beam splitter; PS-FBG: phase-shifted fiber Bragg grating; EDFA: erbium-doped fiber amplifier; PD: photodetector; EA: electrical amplifier; DIV: electrical divider; ESA: electrical spectrum analyzer.

Note that single-mode operation can still be realized in a regular single-loop OEO if the net gain of the primary mode, say the 0-th mode, is controlled to exceed one while the net gains of other modes are less than one. However, this required that an optical filter with an ultra-narrow bandwidth is incorporated in the fiber loop to select the oscillating mode and reject other modes, which is hard to implement. This stringent requirement can be alleviated if PT-symmetry is employed, in which the gain contract ratio is increased. Here the gain contrast ratio is defined as the ratio between the gain of the primary mode and the gain of the secondary mode. Assume g_0 is the gain coefficient of the primary mode and g_1 is the gain coefficient of the secondary competing mode, the gain contrast ratio enhancement factor G with PT symmetry and without PT symmetry is given by [5]

$$G = \frac{\Delta g_{PT}}{\Delta g} = \sqrt{\frac{g_0/g_1+1}{g_0/g_1-1}} \tag{2}$$

where Δg_{PT} and Δg are the gain contrast ratios with and without PT symmetry, respectively. As can be seen, with PT symmetry a significant increase in the gain contrast is resulted, which will make it easier to select the primary mode to ensure stable single-mode oscillating.

3. Experimental results

A proof-of-concept experiment is carried out based on the setup shown in Fig. 1. A light wave generated by the TLS (Yokogawa AQ2201) is sent to the PM (JDSU), which has a 3-dB bandwidth of 20 GHz. A phase-modulated optical signal generated at the PM is sent via a length of 550 m single-mode fiber to the Sagnac loop to implement two equivalent loops with one having a gain and the other a loss. The light from the Sagnac loop is sent to a PS-FBG, where PM-IM conversion is performed, to form a MPF. After amplification by an erbium-doped fiber amplifier (EDFA) (FiberPrime Inc. EDFA-C-14-S-FA), the optical signal is applied to a photodetector (PD) (Optilab LR-12-A-M, 12 GHz bandwidth). The detected microwave signal is amplified by two cascaded electrical amplifiers (EAs) and applied to the PM, to close the OEO loop. The generated microwave signal is monitored by an electrical spectrum analyzer (Agilent E4448A) and its phase noise is measured by a signal analyzer (Agilent E5052B).

Fig. 2(a)-(d) shows the measured electrical spectra of the generated microwave signals. Multi-mode oscillation is found in Fig. 2(a), where the PT symmetry condition is not met. By tuning PC1 and PC2, the gain and loss of the two feedback loops are controlled to satisfy the PT symmetry condition, and a single-mode oscillation is achieved, with the spectra shown in Fig. 2(b)-(d) with different spans and resolution bandwidths (RBWs). From Fig. 2(c) and (d), we can see that the side modes are significantly suppressed, with a sidemode suppression ratio (SMSR) more than 45 dB.

The frequency tuning of the OEO is done by tuning the central frequency of the MPF, which is accomplished by tuning the wavelength of the TLS. Fig. 2(e) shows the measured transmission spectrums of the MPF by a vector network analyzer (VNA, Agilent E8364A). The 3-dB bandwidth is measured to be 200 MHz. Fig. 2(f) shows the frequency tunability of the PT-symmetric OEO. A frequency tuning range from 2 to 12 GHz is achieved. Note that the tuning range can be expanded by using devices (PM, PD, and EAs) with broader bandwidths.

The phase noise measurements at two different frequencies of 5.5 and 8.8 GHz are performed, with the results shown in Fig. 3. As can be seen, the phase noise levels are -108 at a frequency offset of 10 kHz, and -120 dBc/Hz at a frequency offset of 100 kHz. The length of the single-mode fiber in the OEO is 550 m, which can be increased to further reduce the phase noise.

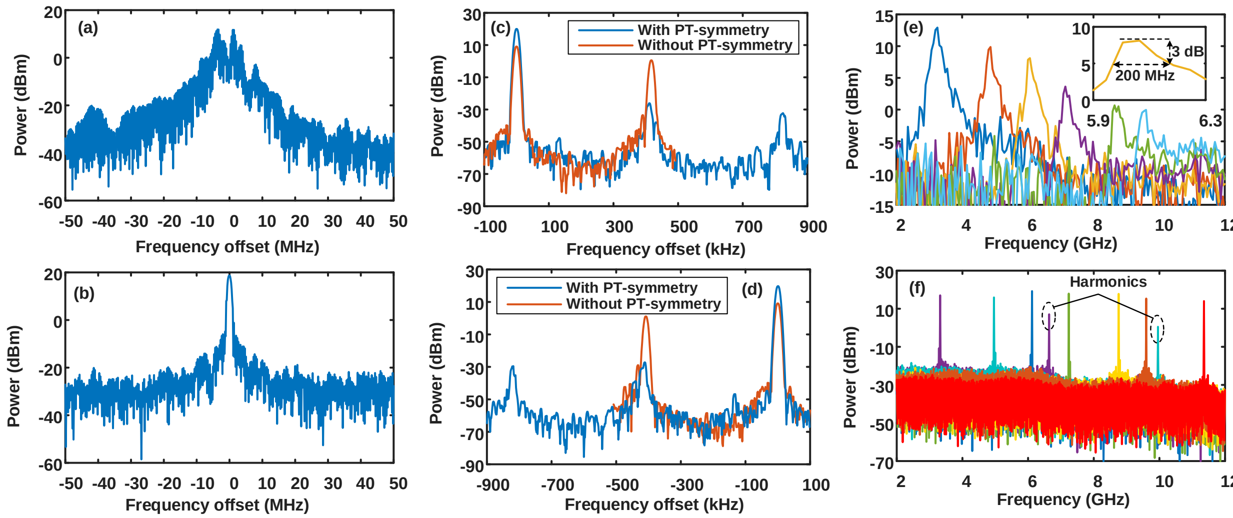

Fig. 2. (a) Multimode oscillation measured with a span of 100 MHz and a RBW of 910 kHz; (b) Single-mode oscillation measured with a span of 100 MHz and a RBW of 910 kHz; (c) Single-mode oscillation measured with a span of 1 MHz and a RBW of 9.1 kHz; (d) Single-mode oscillation measured with a span of 1 MHz and a RBW of 9.1 kHz. (e) Measured transmission spectra of the MPF. (f) Frequency tunability of the proposed PT-symmetric OEO with a tuning range from 2 to 12 GHz.

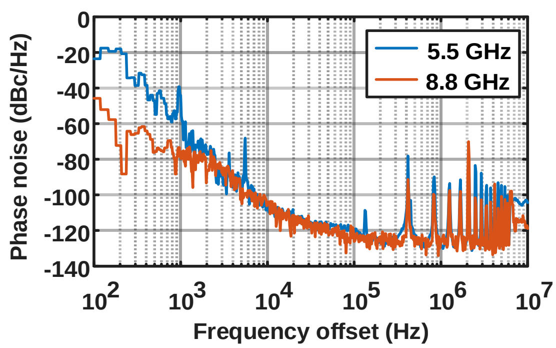

Fig. 3. Phase noise measurements at frequencies of 5.5 and 8.8 GHz. The phase noise levels are -108 dBc/Hz at a frequency offset of 10 kHz and -120 dBc/Hz at a frequency offset of 100 kHz.

4. Conclusion

We have proposed and experimentally demonstrated a tunable PT-symmetric OEO with a single physical Sagnac loop. Since a single physical loop was employed, the implementation was greatly simplified. Frequency-tunable single-mode oscillation with a frequency tunable range from 2 to 12 GHz with an SMSR greater than 45 dB was achieved. The phase noise was -108 dBc/Hz at an offset frequency of 10 kHz.

References

[1] D. K. Barton, Radar System Analysis and Modeling. Boston, MA, USA: Artech House, (2005).
[2] T. M. Fortier, et al., "Generation of ultrastable microwaves via optical frequency division," Nat. Photonics **5**, 425-429 (2011).
[3] E. P. Campa, et al., "Ultra-low phase-noise microwave generation using a diode-pumped solid-state laser based frequency comb and a polarization-maintaining pulse interleaver," Opt. Express **43**, 32441-32451 (2015).
[4] X. S. Yao, and L. Maleki, "Optoelectronic Oscillator for Photonic Systems," IEEE J. Quantum Electron. **32**, 1141-1149 (1996)
[5] J. P. Yao, "Photonic generation of frequency-tunable microwave signal based on an optoelectronic oscillator," IMS 2013, Seattle, WA, USA.
[6] J. J. Zhang, and J. P. Yao, "Parity-time–symmetric optoelectronic oscillator," Sci. Adv. **4**, eaar6782 (2018).
[7] H. T. Tang, et al., "Widely tunable optoelectronic oscillator based on selective parity-time-symmetry breaking," Optica **6**, 944-950 (2019).
[8]. Z. Fan, et al, "Widely tunable parity-time-symmetric optoelectronic oscillator based on a silicon microdisk resonator" in International Topical Meeting on Microwave Photonics, Ottawa, 2019, pp.119-122.
[9] H. Hodaei, et al., "Parity-time-symmetric microring lasers," Science **436**, 975-978 (2014).
[10] F. Zeng and J. P. Yao, "Generation and distribution of UWB pulse signals by use of optical phase modulation and PM-IM conversions," Proc. of SPIE, **6343**, 63432H (2006). Photonics North 2006.