Optoelectronic oscillator based on SBS-assisted parity-time symmetry

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Abstract: A parity-time symmetric optoelectronic oscillator is constructed based on stimulated Brillouin scattering. A stable microwave signal at 9.66 GHz is generated with a phase noise of −103.9 dBc/Hz at an offset frequency of 10 kHz. © 2022 The Author(s)

1. Introduction

The microwave signal with high spectral purity is of great importance for many applications, such as radars, wireless communications, and electronic warfare systems [1]. The optoelectronic oscillator (OEO) has been proven to be a simple and effective approach to generating microwave signals with ultra-low phase noise [2,3]. In OEO, a low-loss long fiber is used in the cavity to guarantee the ultra-low phase noise. However, the long fiber also induces numerous longitudinal modes with a small mode spacing, which significantly challenges the single-mode selecting in OEO. Consequently, a microwave bandpass filter with ultra-narrow bandwidth is required to enable single-mode oscillation [4,5].

Recently, a novel mode selection mechanism called parity-time (PT) symmetry has been proposed and demonstrated in microwave photonics [6–8]. To ensure the PT symmetry to be successfully established in the OEO cavity, the geometry of the two mutually coupled optoelectronic feedback loops must be identical, but one experiences gain while the other experiences an equal amount of loss. By precisely manipulating the gain, loss and coupling coefficients of the two mutually coupled feedback loops, the desired mode is under PT symmetry breaking while the other modes are under PT symmetry. Therefore, a stable single mode oscillation can be obtained. Nevertheless, the PT-symmetric OEO with two physically separated loops makes the complex structure, high cost, and more susceptible to environmental perturbations. To overcome these difficulties, the PT-symmetric OEO based on single-loop is rather attractive [8].

In this paper, we propose and experimentally demonstrate a PT-symmetric OEO based on stimulated Brillouin scattering (SBS) in a single physical loop. In the OEO, the probe light and the pump light are at the same wavelength. The PT-symmetry is implemented by using SBS in high nonlinear fiber (HNLF), in which the gain loop and the loss loop are constructed by the SBS gain and the SBS loss, respectively. By controlling the length of HNLF, pump power, and the polarization states (SOPs) of the probe light and the pump light, the gain and loss can be accurately controlled. When the gain/loss is larger than the coupling coefficient, the PT-symmetry is broken and a stable single mode oscillation is achieved. In the experiment, a stable microwave signal at 9.66 GHz is generated with a signal-sideband phase noise of −103.9 dBc/Hz at an offset frequency of 10 kHz, and the side-mode suppression ratio (SMSR) is 47.8 dB.

2. Principle

The schematic diagram of the proposed the SBS-assisted PT-symmetric OEO is depicted in Fig. 1. At first, the continuous wave (CW) light emitted from a tunable laser source (TLS) is separated into two parts. The CW light in the upper path and the CW light in the lower path are used as the pump light and the probe light, respectively. Then the probe light is launched into a phase modulator (PM) via a polarization controller (PC_1). The SBS process occurs in the HNLF, in which the ±1st order sidebands of the phase-modulated signal are located in the SBS loss spectrum and SBS gain spectrum, respectively. At port 3 of the circulator, the optical signal is fed into a single-mode fiber (SMF) and then detected by the photodetector (PD). The recovered microwave signal is amplified by two cascaded electrical amplifiers (EAs) and fed back to the PM to form a closed loop. In the proposed PT-symmetric OEO, the gain loop is established by amplifying the −1st order sideband, and the loss loop is established by attenuating the +1st order sideband. Since the SBS gain and the SBS loss depend on the pump power and the SOPs of the probe light and pump light, the attenuator in the upper path is used to adjust the pump power, and the PC_2 and PC_3 are used to adjust the SOPs of the probe light and pump light, respectively.

Under PT symmetry, the gain coefficient g_n and the loss coefficient α_n are equal in magnitude, i.e., $g_n = -\alpha_n$. The eigenfrequencies of the nth oscillation mode in the OEO loop can be expressed as:

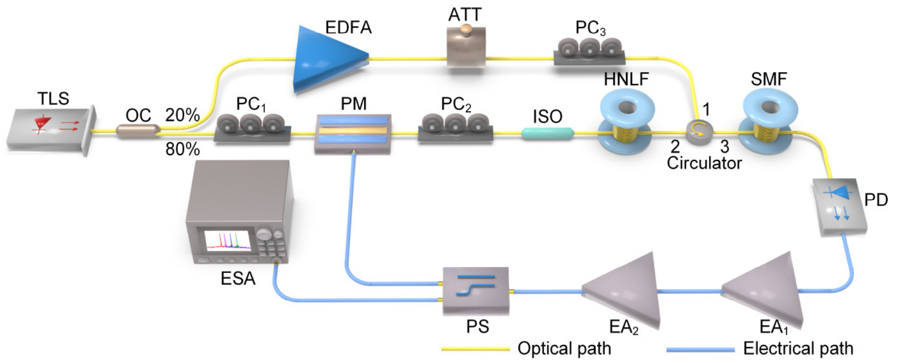

Fig. 1. Schematic diagram of the proposed OEO based on SBS-assisted PT symmetry. TLS: tunable laser source; OC: optical coupler; PC: polarization controller; PM: phase modulator; ISO: isolator; EDFA: erbium-doped fiber amplifier; ATT: attenuator; HNLF: high nonlinear fiber; SMF: single-mode fiber; PD: photodetector; EA: electrical amplifier; PS: power splitter; ESA: electrical spectrum analyzer.

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

where ω_n is the angular frequency of the nth oscillation mode, κ_n is the coupling coefficient between the gain and loss loops. When the gain coefficient is larger than the coupling coefficient ($g_n > \kappa_n$), PT symmetry is broken and a conjugate pair of amplifying and decaying eigenmodes are generated. Hence, the amplifying mode achieves stable oscillation. Additionally, compared with the traditional single-loop OEO, the PT-symmetric OEO provides a larger gain difference and enhances mode selection [7, 8]. The gain enhancement factor can be expressed as

$$F = \frac{\Delta g_{PT}}{\Delta g} = \frac{\sqrt{g_0^2 - g_1^2}}{g_0 - g_1} = \sqrt{\frac{g_0 + g_1}{g_0 - g_1}}\ , \tag{2}$$

where Δg_{PT} and Δg are the gain differences between the dominant oscillation mode and the secondary mode in a PT-symmetric OEO and a traditional single-loop OEO, and g_0 and g_1 are the gain coefficients of the dominant oscillation mode (n = 0) and the secondary mode (n = 1), respectively.

3. Experimental results

A proof-of-concept experimental setup based on the schematic diagram shown in Fig. 1 is performed. In the experiment, the TLS (NKT Basik E15) has a linewidth of 100 Hz. The coupling ratio of the optical coupler (OC) is 80:20. An erbium-doped fiber amplifier (EDFA, Accelink EDFA-BA-16-FC/APC-2−3) and an attenuator are used to adjust the pump power. In the lower path, the probe light is injected into the PM (iXblue, MPZ-LN-40) with a full width at half maximum (FWHM) bandwidth of 33 GHz. A 300-m HNLF is used as the SBS medium and a 500-m SMF is used to increase the time delay in the OEO loop. A high-speed PD (SHF AG Berlin) with a bandwidth of 40 GHz is used to convert optical signals to microwave signals. Two cascaded EAs (SHF S824A and SHF S804B) are used to provide a sufficiently large electrical gain. The generated microwave signal is monitored by the electrical spectrum analyzer (ESA, Keysight N9030A).

The amplitude frequency response of the SBS-based microwave photonic filter (MPF) is measured by a vector network analyzer (VNA, Anritsu MS4647B). The FWHM bandwidth of the SBS-based MPF is 21 MHz, which is too large to facilitate single-mode selection. Subsequently, the OEO loop is closed and multimode oscillations would occur when the PT symmetry is not met, as depicted in Fig. 2(a). The inset in Fig. 2(a) shows the zoomed-in view of the multimode oscillation with a span of 1 MHz and a resolution bandwidth (RBW) of 9.1 kHz. Adjusting PC2 and PC3 to precisely manipulated the gain and loss, the PT-symmetry breaking can be satisfied and single-mode oscillation can be achieved. Figures 2(b)–2(d) shows the electrical spectra of stable single-mode oscillation with different spans and RBWs. It can be observed that the sidemodes are suppressed effectively and the SMSR is 47.89 dB in Fig. 2(c). The electrical spectra of multimode oscillation and single-mode oscillation are compared when the span is 600 kHz and the RBW is 5.6 kHz, as shown in Fig. 2(d). The dominant oscillation mode obtains a gain of about 0.5 dB, while the side modes are suppressed by 41.7 and 41.8 dB, respectively. Furthermore, the phase noise of the generated microwave signal is also measured, as illustrated in Fig. 3. The corresponding phase noise at 10 kHz frequency offset is −103.9 dBc/Hz, and the side mode noise is below −84 dBc/Hz. It can be noticed that there exists a parasitic noise peak at 44 kHz frequency offset, which is caused by the EAs in the loop.

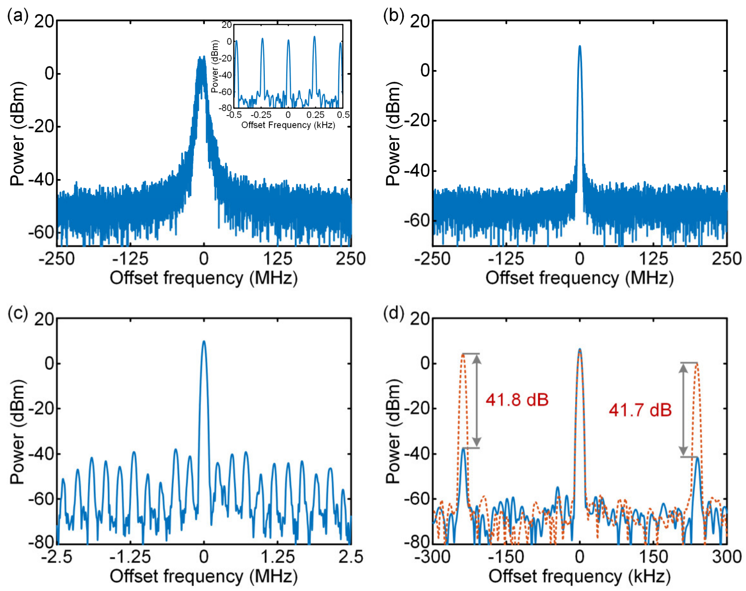

Fig. 2. The measured electrical spectra of the generated microwave signal with a center frequency of 9.66 GHz. The electrical spectra of multimode oscillation (a) and single-mode oscillation (b) with a span of 500 MHz and an RBW of 3 MHz. (c) Single-mode oscillation spectrum with a span of 5 MHz and an RBW of 47 kHz. (d) The electrical spectra of single-mode oscillation (blue solid curve) and multimode oscillation (red dashed curve) with a span of 600 kHz and an RBW of 5.6 kHz.

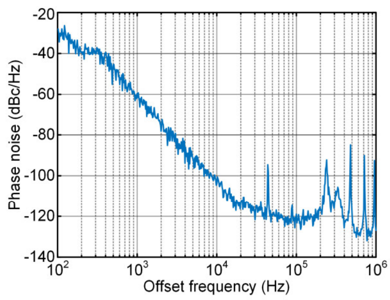

Fig. 3. The measured phase noise of the generated microwave signal.

4. Conclusion

We have proposed and experimentally demonstrated an SBS-assisted PT-symmetric OEO in a single physical loop. Two mutually coupled loops are constructed in a single-loop OEO utilizing SBS gain and SBS loss. The SBS-based MPF combining with PT symmetry affords stable single-mode oscillation. A microwave signal at 9.66 GHz is generated with an SMSR of 47.8 dB, and the phase noise reaches −103.9 dBc/Hz at the 10 kHz offset frequency.

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