Frequency-Tunable Parity-Time-Symmetric Optoelectronic Oscillator Using a Polarization-Dependent Sagnac Loop

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

***Abstract*—A widely frequency-tunable parity-time (PT) symmetric optoelectronic oscillator (OEO) implemented based on a single polarization-dependent Sagnac loop is proposed and experimentally demonstrated. Two mutually coupled feedback loops having an identical geometry with balanced gain and loss are implemented to achieve PT-symmetry, which is essential for single-mode selection without using an ultra-narrow passband microwave filter. In the implementation, a Sagnac loop consisting of a polarization beam splitter (PBS) and two polarization controllers (PCs) is employed which functions equivalently as two mutually coupled feedback loops, with the gain, loss and coupling coefficient being independently controllable. Since only a single physical loop is used, the implementation is greatly simplified and the stability is highly improved. The operation of the proposed OEO is experimentally verified. Stable single-mode oscillation with a wide frequency tunable range from 2 to 12 GHz is achieved. The phase noise is −128 dBc/Hz at an offset frequency of 10 kHz.**

***Index Terms*—Frequency tunability, optoelectronic oscillator, parity-time symmetry, sagnac loop.**

I. INTRODUCTION

HIGH quality microwave signals are widely used in modern radar, electronic measurement and communications systems [1]–[4]. A microwave signal can be generated electronically by an electronic oscillator. To reduce the phase noise, a high-quality (high Q) factor microwave filter is needed, such as a quartz filter. However, an electronic oscillator based on a quartz filter can generate a microwave signal with a relatively low frequency, or frequency multiplication must be used to increase the frequency, but at the cost of a reduced phase noise [5]. On the other hand, a microwave signal at a high frequency with a low phase noise can be generated in the optical/electrical domain using an optoelectronic oscillator (OEO). Thanks to the low loss of state-of-the-art optical fiber, an OEO can have a long loop length, making the cavity have a high Q factor. In addition, modern modulators and photodetectors (PDs), which are usually used in OEOs to perform electrical-to-optical and optical-to-electrical conversions, can operate at high frequencies, thus high frequency and low phase noise microwave generation is possible [6], [7]. One challenge of implementing an OEO with a long loop length is that multiple modes with small mode separation exist in the OEO cavity, making the selection of single mode to achieve single-frequency oscillation difficult [8]. The use of an ultra-narrow passband microwave filter to perform mode section may solve the problem, but an ultra-narrow passband microwave filter has very limited frequency tunability, which makes the generation of a frequency-tunable and low phase noise microwave signal difficult [9].

Instead of using an ultra-narrow passband microwave filter that has a limited frequency tunable range, one may use a microwave photonic (MWP) bandpass filter (MPBF) which can be designed to have a large frequency tunable range [10]–[14]. For example, a frequency-tunable MPBF can be implemented using a phase modulator (PM) and an optical notch filter such as a phase-shifted fiber Bragg grating (PS-FBG), a microdisk resonator (MDR), or an optical filter based on the stimulated Brillouin scattering (SBS) effect in high nonlinear fiber. Thanks to the phase-modulation to intensity-modulation (PM-IM) conversion, the optical notch is translated to a passband of a microwave filter. The tunability is achieved by tuning either the wavelength of the optical carrier or the center wavelength of the notch. The major difficulty of the approach is that an optical notch filter with an ultra-narrow bandwidth is needed, which makes the implementation costly. To ease the requirement for an optical filter with an ultra-narrow notch, one may implement an OEO with dual or multiple optoelectronic loops, to increase the effective free spectral range (FSR) due to the Vernier effect [15], [16]. The key limitation of the approach is that the frequency tunability is limited or the lengths of the loops must be adjustable when the frequency is being tuned, making the implementation very complicated. Optical injection locking is another way to implement an MPBF in an OEO to enable single-mode and frequency-tunable oscillation [17]. The system is simple, but the stability is poor due to mode hopping in an injection-locked laser source (usually a Fabry-Pérot laser source). In addition, the frequency tuning is not continuous since the modes in the injection-locked laser source are discrete.

Recently, a new concept, parity-time (PT) symmetry, has been introduced to the field of microwave photonics, in which mode selection without using an ultra-narrow bandpass filter

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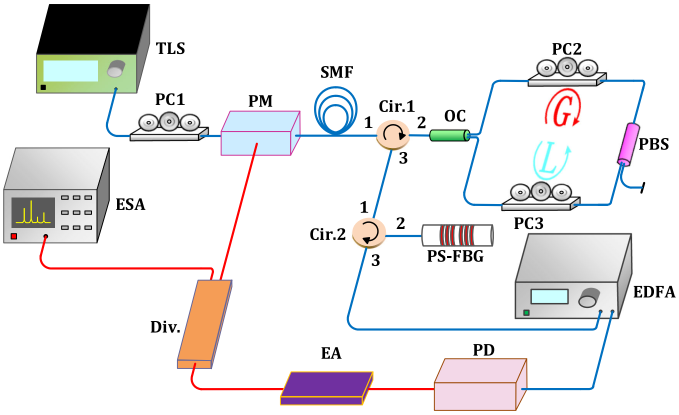

Fig. 1. Schematic diagram of the proposed PT-symmetric OEO. TLS: tunable laser source; PC: polarization controller; PM: phase modulator; SMF: single-mode fiber; Cir.: circulator; OC: optical coupler; PBS: polarization beam splitter; PS-FBG: phase-shifted fiber Bragg grating; EDFA: erbium-doped fiber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

was demonstrated [18]–[22]. To implement PT-symmetry in an OEO, two mutually coupled feedback loops with an identical geometry, but balanced gain and loss coefficients are needed. When the gain/loss coefficient for a specific mode exceeds the coupling coefficient, PT symmetry is broken, the specific mode will start to oscillate and the other modes will remain neutral. The oscillation frequency can be tuned by tuning the center frequency of an optical filter in the OEO loop. Note that the optical filter does not need to have an ultra-narrow passband since the mode selection is realized due to the PT symmetry. The major difficulty in implementing a PT-symmetric OEO is that two mutually coupled loops with exactly an identical geometry are needed, making the implementation difficult. In addition, two mutually coupled, but physically separated loops will make the stability poor.

Recently, we have proposed and demonstrated a PT-symmetric OEO implemented using a single polarization-dependent Sagnac loop. Since a single physical loop was employed, the implementation was simplified and the stability was improved [22]. The work reported in this paper is an extension of the work reported in [22], in which a more detailed theoretical analysis is provided. In addition, more experimental results including phase noise measurements for the proposed OEO using a much longer loop length are provided.

The key innovation of the work is that instead of using two physically separated loops, a single polarization-dependent Sagnac loop is employed. By incorporating a polarization beam splitter (PBS) in the Sagnac loop, two equivalent optical loops with an identical geometry is realized. The gain and loss coefficients of the two equivalent loops are precisely controlled by tuning the polarization states of light waves injected into the PBS. By controlling the gain, loss and coupling coefficients to make the OEO satisfy the PT symmetry broken condition, single-frequency oscillation is enabled and a single-frequency microwave signal is generated. To tune the oscillation frequency, a PS-FBG is incorporated in the OEO loop. The joint of operation of a PM, the PS-FBG and a PD is equivalent to an MPBF with its center frequency tunable by tuning the wavelength of the optical carrier. The proposed PT-symmetric OEO is experimentally demonstrated. Single-mode oscillation with a frequency-tunable range from 2 to 12 GHz and a phase noise of −128 dBc/Hz at an offset frequency of 10 kHz is achieved.

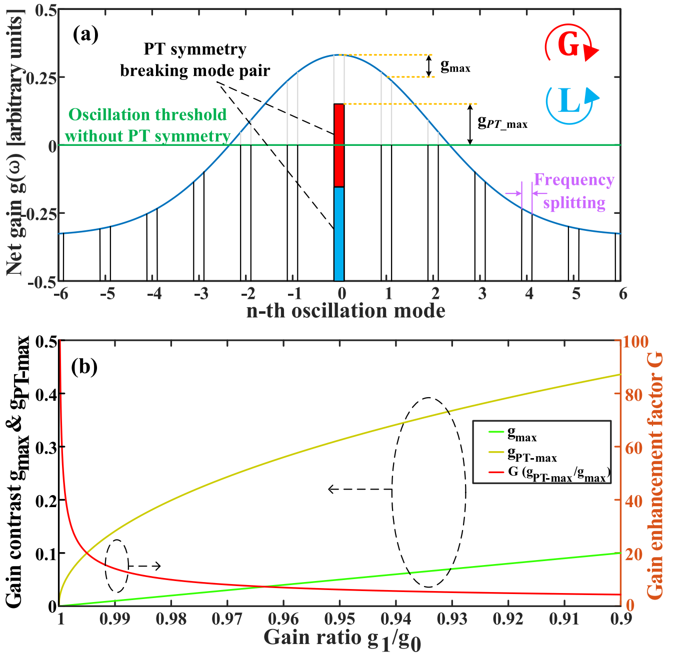

Fig. 2. Mode selection due to PT symmetry in a PT-symmetric OEO. (a) The mechanism of mode selection under PT symmetry broken condition. (b) The gain contrast enhancement when using PT-symmetric breaking.

II. OPERATION PRINCIPLE

Fig. 1 shows the schematic diagram of the proposed tunable PT-symmetric OEO. A continuous-wave (CW) light wave coming from a tunable laser source (TLS) is sent to a PM via a polarization controller (PC1). PC1 is used to make the polarization direction of the light wave into the PM be aligned with the principal axis of the PM, to minimize the polarization-dependent loss. A phase-modulated optical signal is generated and it is then transmitted through a long single-mode fiber (SMF) and launched into a Sagnac loop, in which a PBS and two PCs (PC2 and PC3) are incorporated. The incident light is split into two and is traveling along clockwise (CW) and counter-clockwise (CCW) directions to form two mutually coupled loops with one having a gain and the other a loss. The gain and the loss can be precisely controlled by tuning PC2 and PC3. The two light waves are combined at an optical coupler and then sent to a PS-FBG. After being amplified by an erbium-doped fiber amplifier (EDFA), the light waves are applied to a PD where a microwave signal is generated. Note that the PS-FBG is used to form an MPBF, based on PM-IM conversion to perform coarse frequency selection. The generated microwave signal is amplified by an electrical amplifier (EA) and sent to an electrical power divider, with one portion of the signal sent to the PM, to close the OEO loop, and the other portion of the microwave signal to an electrical spectrum analyzer, to analyze the performance.

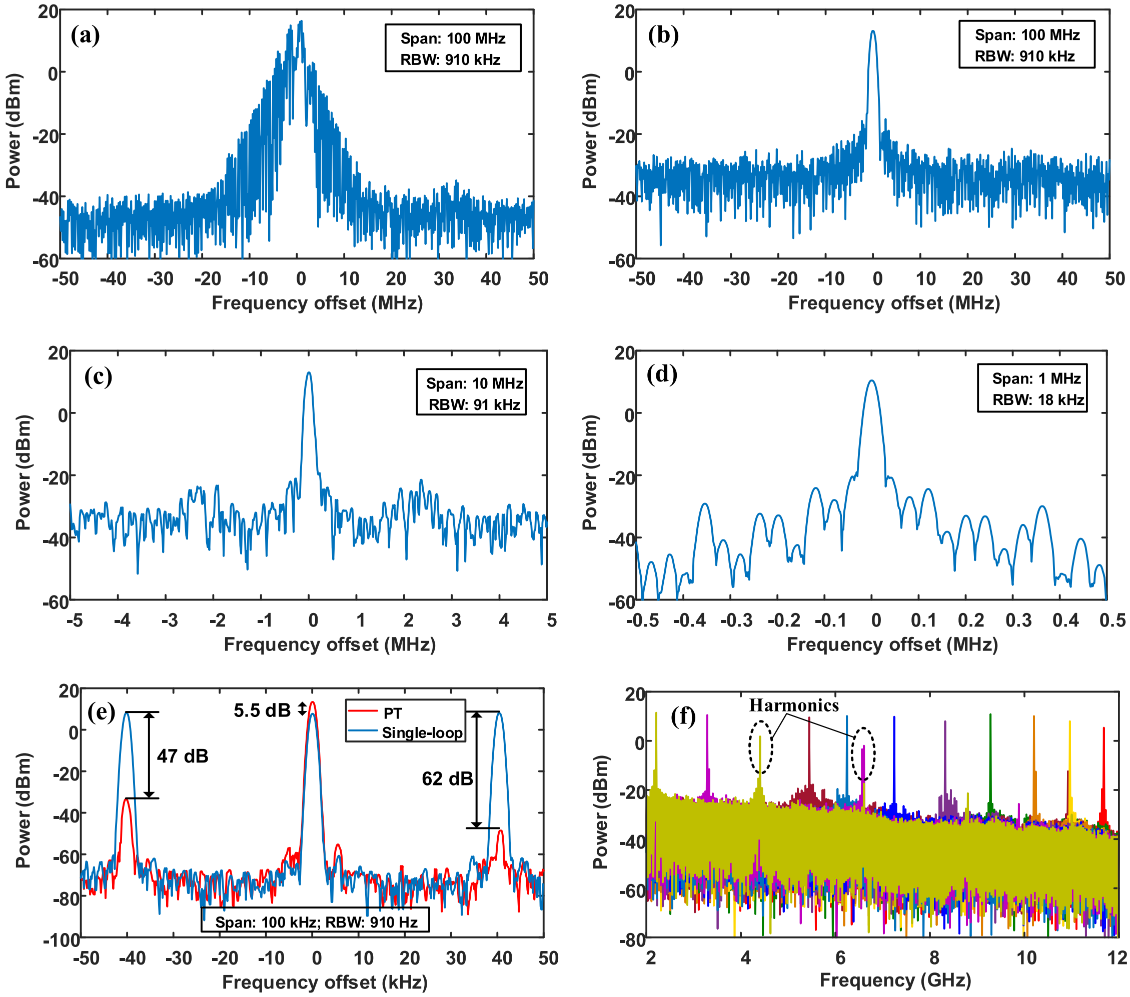

Fig. 3. The electrical spectra of the microwave signals generated by the PT-symmetric OEO with a loop length of 5 km. The spectra are measured at a central frequency of 6 GHz by an electrical spectrum analyzer. (a) Multi-mode oscillation measured with a span of 100 MHz and a resolution bandwidth (RBW) of 910 kHz; (b) Single-mode oscillation measured with a span of 100 MHz and an RBW of 910 kHz; (c) Single-mode oscillation measured with a span of 10 MHz and an RBW of 91 kHz; (d) Single-mode oscillation measured with a span of 1 MHz and an RBW of 18 kHz. (e) Single-mode oscillation measured with a span of 100 kHz and an RBW of 910 Hz. (f) Frequency tunability of the proposed PT-symmetric OEO with a tuning range from 2 to 12 GHz.

By solving the coupled mode equations, the eigenfrequencies of a PT-symmetric system can be expressed as [20]

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

where ω_n is the eigenfrequency of the *n-th* 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 *n-th* modes, and k_n is the coupling coefficient between the two loops.

Under the PT-symmetry condition, the gain coefficient of one loop is equal to the loss coefficient of the other loop in magnitude, that is, $g_{a_n} = -g_{b_n} = g_n$. Then, Eq. (1) can be rewritten as

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

When $g_n < \kappa_n$, the system is operating in the PT-symmetry unbroken regime, which will lead to frequency splitting of a mode. When $g_n > \kappa_n$, the PT-symmetry broken condition is satisfied for a conjugate pair of modes with one experiencing a gain and the other an attenuation, while other modes remain neutral, as seen in Fig. 2(a).

Note that single-mode oscillation can also be realized in a regular single-loop OEO if the gain of the primary mode g_0, say the 0-*th*, exceeds the oscillation threshold while that of other modes is beneath the threshold. The maximum gain contrast under this condition is given by

$$g_{\max} = g_0 - g_1 \quad (3)$$

where g_1 is the gain of the mode with the next largest gain. In general, the difference between g_0 and g_1 is quite small, making the single-mode oscillation unstable.

By contrast, in the PT-symmetric setting, the coupling coefficient κ can be regarded as a virtual loss. In this case, the maximum gain differential is

$$g_{PT\_\max} = \sqrt{g_0{}^2 - g_1{}^2} \quad (4)$$

To quantify the relationship between under PT-symmetric condition and without PT- symmetry, a gain contrast ratio enhancement factor G is given, which is expressed by

$$G = \frac{g_{PT\_\max}}{g_{\max}} = \sqrt{\frac{g_0/g_1 + 1}{g_0/g_1 - 1}} \tag{5}$$

As can be seen from Fig. 2(b), a significant increase in the gain contrast is demonstrated, which will make it more effective in the selection of the primary mode to ensure stable single-mode oscillating.

III. Experimental Setup and Results

An experiment is performed based on the setup shown in Fig. 1. A light wave generated by the TLS (Yokogawa AQ2201) is coupled into the PM (JDSU), which has a 3-dB bandwidth of 20 GHz. The EDFA (FiberPrime Inc. EDFA-C-14-S-FA) has a 30-dB maximum gain and a 16-dBm saturated output power. The PD (Optilab LR-12-A-M) has a 3-dB bandwidth of 12 GHz with a photo responsibility of 0.85 A/W at 1550 nm. Two cascaded EAs (MultiLink modulator driver MTC5515-751) are used to provide a sufficiently large gain. The generated microwave signal is monitored by the electrical spectrum analyzer (Agilent E4448A) and its phase noise is measured by a signal analyzer (Agilent E5052B).

Fig. 3(a)–(f) illustrates the measured electrical spectra of the generated microwave signals. When the PT-symmetry condition is not met, multi-mode oscillation is observed, as shown in Fig. 3(a). By tuning PC2 and PC3, the gain and loss can be precisely controlled to make the two loops have an identical magnitude to satisfy the PT symmetry condition. Once the gain/loss exceeds the coupling coefficient, PT-symmetry breaking is satisfied, single-mode oscillation is achieved. As can be seen, a microwave signal at 6 GHz is generated, with the spectrum shown in Fig. 3(b)–(d) with different spans and resolution bandwidths (RBWs). The side modes are significantly suppressed. A sidemode suppression ratio (SMSR) of 47 dB is observed in Fig. 3(d). Fig. 3(f) shows the frequency tunability of the PT-symmetric OEO. A frequency tuning range from 2 to 12 GHz is achieved.

As pointed out in Section II, the coarse frequency selection is done by the MPBF which is implemented using a PS-FBG, to translate the notch of the PS-FBG to the passband of the MPBF. The frequency tuning is realized by tuning the center frequency of the MPBF, which is done by tuning the wavelength of the TLS in the experiment. The frequency response of the MPBF is measured by a vector network analyzer (VNA, Agilent E8364A), shown in Fig. 4(a) and (b). As can be seen from Fig. 4(b), the 3-dB bandwidth of the MPBF is measured to be 260 MHz, which means more than 6000 oscillation modes exist in the passband, illustrating the primary mode is selected due to the PT symmetry breaking condition.

In the experiment, a maximum frequency tunable range of 10 GHz is realized. The frequency tunable range is limited by the bandwidths of the devices used in the PT-symmetric OEO (PM, PD, and EAs). By using the devices with broader bandwidths, a much wider frequency tunable range can be achieved. The phase noise performance is also evaluated. In the experiment, the phase noise is measured using a microwave signal analyzer (Agilent E5052B), which works with a frequency down-converter (Agilent E5053A). The results are shown in Fig. 5. As can be seen, the phase noise level is −128 dBc/Hz at a frequency offset of 10 kHz. Multiple peaks starting from 40 kHz are observed, which are resulted due to the FSR of the OEO loop. The length of the OEO loop is 5 km, the FSR is 40 kHz. To further reduce the phase noise, a solution is to use a longer OEO loop. Since single mode oscillation is enabled by the PT symmetry, no other mode selection mechanism is needed, making implementation greatly simplified.

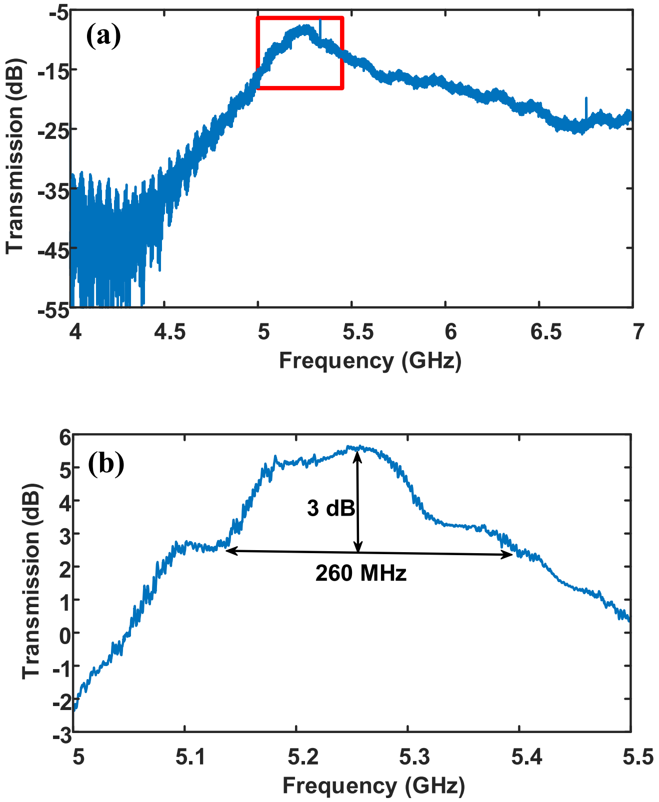

Fig. 4. (a) Measured transmission spectra of the MPBF and (b) Its zoom in version.

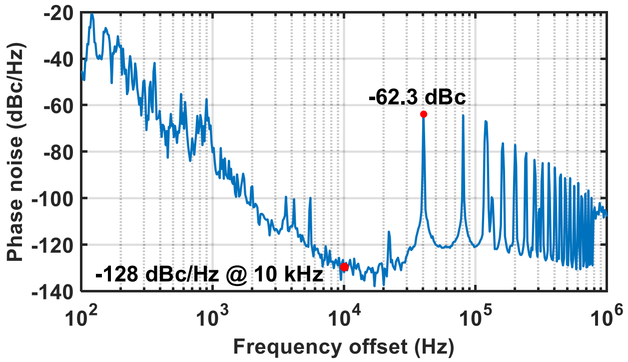

Fig. 5. Phase noise measurement at the frequency of 6 GHz. The phase noise level is −128 dBc/Hz at a frequency offset of 10 kHz.

IV. CONCLUSION

We have proposed and experimentally demonstrated a widely frequency tunable PT-symmetric OEO with a single physical Sagnac loop. By using this structure, the mismatch in length between the two mutually coupled loops, which is the main concern for the implementation of a PT-symmetric system, is no longer a problem since the two mutually coupled loops have intrinsically an identical length. By independently controlling the gain and loss to be balanced and to make the gain/loss coefficient greater than the coupling coefficient, PT-symmetry breaking was achieved, making single-mode oscillation without using an ultra-narrow passband filter. The frequency tunability was done by tuning the center frequency of the MPBF via tuning the wavelength of the TLS. The proposed PT-symmetric OEO was experimentally demonstrated. The results showed that a frequency-tunable microwave signal with a frequency tunable range from 2 to 12 GHz was generated. The phase noise was measured to be -128 dBc/Hz at an offset frequency of 10 kHz and the SMSR was 47 dB. The phase-noise performance can be further improved if a longer loop length of the OEO is employed without changing the configuration of the entire system. We may note that multiple peaks in the phase noise measurement in Fig. 5 at frequencies higher than 10 kHz are observed, which are produced by the side modes in the generated signal. Although a single mode oscillation is achieved due to PT-symmetry, side modes are not completely suppressed, which produce the peaks shown in the phase noise measurement in Fig. 5.

It is worth noting that the frequency tunable range is limited by the bandwidths of the active devices used including the PD, the PM and the EA. A higher frequency microwave signal can be generated when the bandwidths of the devices are wider.

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