A proposal for on-chip isolator based on nonreciprocity of parity-time symmetric directional coupler

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***Abstract*—Non-Hermitian system has attracted extensive attention, which possesses real eigenvalues if the Hamiltonian satisfies the parity-time (PT) symmetry. In this paper, we adopt the concept of PT symmetry to the widely used directional coupler and theoretically analyze its amplitude and phase characteristics. Finally, we propose an on-chip isolator based on the nonreciprocal characteristic of passive PT symmetric directional coupler. Our proposal can avoid the introduction of the gain on chip or magneto-optical materials.**

Keywords—parity-time symmetry, exceptional point, PT symmetric directional coupler, nonreciprocity

I. Introduction

The characteristics of a system can be described by its Hamiltonian. For a realistic system, it often exchanges energy with the outside world. Such a system is called a non-Hermitian system. The Hamiltonian of a non-Hermitian system is a non-Hermitian matrix ($H \neq H^{\dagger}$). In most cases, the eigenvalues corresponding to above matrix are no longer real numbers. Until 1998, Bender and Boettcher demonstrated that when the Hamiltonian of a non-Hermitian system satisfies parity-time (PT) symmetry ([*PT,H*]=*PTH-HPT*=0), the system has real eigenvalues [1]. The emergence of PT symmetry theory paves a new way for studying non-Hermitian systems. The concept of PT symmetry originates from quantum field theory. Due to the similarity between the paraxial wave equation and the Schrödinger equation, this concept has been widely used in optics [2].

To study the concept of PT symmetry, we need to control the relationship between coupling strength and gain or loss. Accordingly, the state of the system can be classified as PT symmetric state, PT symmetry broken state and exceptional point (EP) [3]. Many functional devices can be realized by making full use of the characteristics of these different states, such as fast-response photonic microheaters [4], single-mode lasers [5-8], optoelectronic oscillators [9-13], unidirectional transmission devices [14-17], sensors with high sensitivity [16,18-20], chiral mode converters [21-24], and so on. On the other hand, nonreciprocal optical devices such as isolators or circulators are widely used in photonic systems. Conventionally, the methods of generating nonreciprocity include magneto-optical materials [25,26], nonlinearity [27] or time-dependent materials [28]. These methods require either the introduction of magneto-optical materials or strong input signal. Recently, many new schemes have been proposed to overcome the shortcomings of magneto-optical materials. The concept of PT symmetry is an option since the asymmetric distribution of loss in the waveguide will lead to the difference of output ports when light is injected to different input ports. However, isolators based on the nonreciprocity of passive PT symmetric directional coupler have not been proposed.

In this paper, we will show that by utilizing the asymmetric distribution of loss when the device operates in PT symmetric state, the proposed PT symmetric directional coupler exhibits a characteristic of nonreciprocity, which will avoid the use of magneto-optical materials. The electric field distribution of the device reveals the origin of nonreciprocity. Simulation results show that the isolation ratio and insertion loss of our proposed device are 20 dB and 0.5 dB, respectively, which is acceptable for practical applications.

II. Amplitude and Phase Characteristics of PT Symmetric Directional Coupler

In this section, we will adopt the theory of PT symmetry to the directional coupler and obtain the input-output relationship of the directional coupler. Then we analyze the amplitude and phase characteristics of the output ports.

Fig. 1(a) shows the schematic diagram of PT symmetric directional coupler with balanced gain and loss. Suppose that the amount of gain and loss is $g/2$ (g represents the gain loss contrast), the Hamiltonian of the directional coupler is

$$H = \begin{pmatrix} ig/2 & -\kappa \\ -\kappa & -ig/2 \end{pmatrix} \tag{1}$$

Next, we solve the eigenequation $H\psi = E\psi$. Operator E represents $i\dfrac{d}{dz}$. Eigenstate ψ is $(a,b)^T$, where a and b are electric field strength in waveguide a and b , respectively.

We suppose that the coupler operates in PT symmetric state, that is, $\kappa > g/2$. By solving the above eigenequation, the relationship between input and output ports can be expressed as:

$$\begin{pmatrix} a \\ b \end{pmatrix} = \frac{1}{\cos\theta}\begin{pmatrix} \cos(Z\cos\theta-\theta) & i\sin(Z\cos\theta) \\ i\sin(Z\cos\theta) & \cos(Z\cos\theta+\theta) \end{pmatrix}\begin{pmatrix} a_0 \\ b_0 \end{pmatrix} \quad (2)$$

where $\theta = \arcsin\frac{g}{2\kappa}$, $Z=\kappa z$ [30], a_0 and b_0 are the electric field strength of input signal in waveguide a and b, respectively. For the case that the coupler operates in PT symmetry broken state, the analysis method is similar.

According to (2), we can obtain the expressions of amplitude and phase of two output ports.

$$Amp(a) = \frac{1}{\cos\theta}\sqrt{\cos^2(Z\cos\theta-\theta)a_0^2 + \sin^2(Z\cos\theta)b_0^2} \quad (3)$$

$$Amp(b) = \frac{1}{\cos\theta}\sqrt{\sin^2(Z\cos\theta)a_0^2 + \cos^2(Z\cos\theta+\theta)b_0^2} \quad (4)$$

$$phase(a) = \arctan\frac{\sin(Z\cos\theta)b_0}{\cos(Z\cos\theta-\theta)a_0} \quad (5)$$

$$phase(b) = \arctan\frac{\sin(Z\cos\theta)a_0}{\cos(Z\cos\theta+\theta)b_0} \quad (6)$$

We consider the case that the signal is applied in only one of the two input ports, i.e, $a_0=1$, $b_0=0$, as well as the signal is applied in both of the two input ports with the same amplitude and phase, i.e, $a_0=b_0=1$. The relationship between the amplitude, phase and propagation distance for different $g/(2\kappa)$ is shown in Fig. 2 and Fig. 3, respectively. From the black curves in Figs. 2 and 3, we can observe that when $g/(2\kappa)=0$, the device operates as a conventional directional coupler. When fixing the parameters of the device, the output is always the same. With the increase of the gain and loss in the waveguide, the coupling characteristics between the two waveguides will change. We can see from Figs. 2(a) and 3(a) that with the increase of gain and loss, the coupling period becomes longer. As for the phase characteristic, for single input, the phase of output port does not change with gain and loss except for a mutation of π (see Fig. 2(b)), and the phase difference between ports a and b is always $\pm\pi/2$. However, for two inputs, the phase of two output ports is no longer the same (see Fig. 3(b)) and the phase difference varies with gain and loss.

We have discussed the directional coupler with balanced gain and loss. However, it is challenging to introduce gain to

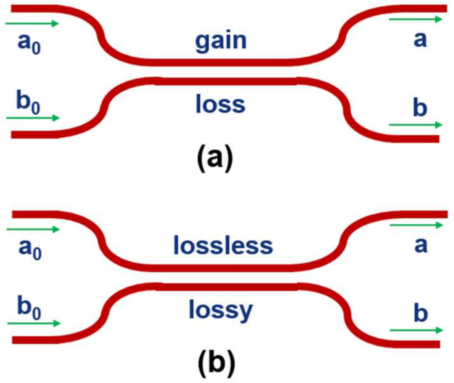

Fig. 1. Schematic diagram of PT symmetric directional coupler with balanced gain and loss (a), with loss only (b).

silicon based on-chip photonic devices due to the indirect bandgap. A possible way to avoid introducing gain is to construct a passive system. For example, we can construct such a directional coupler that one of the waveguides has loss while the other has neither gain nor loss. Next, we will analyze the passive PT symmetric directional coupler, as shown in Fig. 2(b). As a matter of fact, the expressions of the phase characteristic are the same as equations (5) and (6), while the expressions of amplitude characteristic are almost the same as equations (3) and (4), except that there is an attenuation coefficient $e^{-Z\sin\theta}$.

From (3)-(6), we can observe that the amplitude and phase characteristics of two output ports are the functions of the loss in the lossy waveguide when other parameters are fixed. Therefore, the amplitude and phase of two output ports can be changed by changing loss, which can be used as a modulator or a switch. We simulate the passive PT symmetric directional coupler using Lumerical FDTD Solutions. The schematic diagram of the device is shown in Fig. 4(a). The length and width of the two waveguides are 49 μm and 0.6 μm, respectively. The gap between the two waveguides is 150 nm. The method of introducing loss is to deposit gold antennas on top of the waveguide. The width of the metal is the same as that of the waveguide and the thickness is 300 nm. The amount of the introduced loss can be measured by the duty cycle of the gold antennas, which can be expressed as the percentage of the length of metal in length of the waveguide. If the amount of loss is less (greater) than 641.14 cm^{-1}, the device operates in PT symmetric (PT symmetry broken) state. The simulation result of the relationship between the transmission of two output ports and the amount of loss is shown in Fig. 4(b). When the duty cycle of the metal is between 0 and 0.2, the PT symmetric directional coupler acts as a switch.

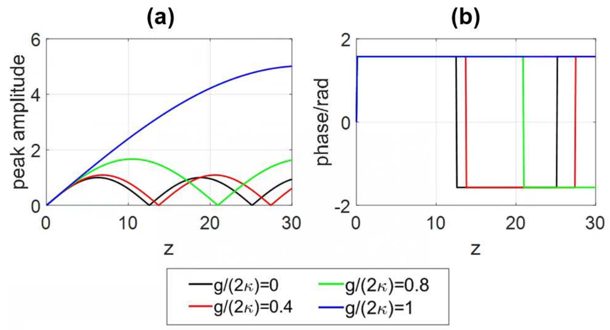

Fig. 2. The relationship between the amplitude (a), phase (b) and propagation distance of output port b when $g/(2\kappa)$ =0 (black), 0.4 (red), 0.8 (green) and 1 (blue) for single input ($\kappa=0.25$).

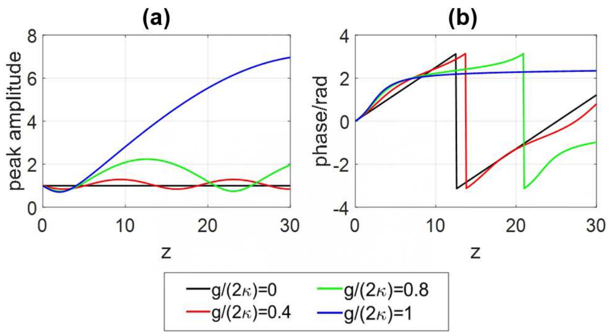

Fig. 3. The relationship between the amplitude (a), phase (b) and propagation distance of output port b when $g/(2\kappa)$ =0 (black), 0.4 (red), 0.8 (green) and 1 (blue) for 2 inputs with the same amplitude and phase ($\kappa=0.25$).

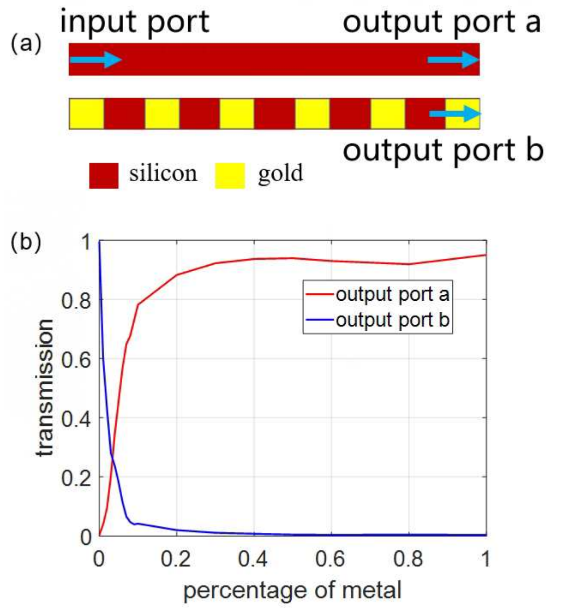

Fig. 4. (a) Schematic diagram of the passive PT symmetric directional coupler with deposited metal. (b) Simulation result of the relationship between the transmission of output ports and the percentage of metal.

III. The nonreciprocal characteristic of PT symmetric directional coupler

In this section, we will focus on the nonreciprocity property of the passive PT symmetric directional coupler based on the amplitude and phase characteristics derived above. The main challenge of passive PT symmetric directional coupler is to solve the problem of large loss. Therefore, in order to avoid introducing too much loss, the device should operate in PT symmetric state.

Since the loss is added to only one of the waveguides, which breaks the symmetry of the distribution of gain and loss, the output is different between the light is injected from lossless waveguide and from lossy waveguide. We can find a special position where the light input from the lossless waveguide is totally coupled into the lossy waveguide. On the other hand, the light input from the lossy waveguide, however, will not be totally coupled into the lossless waveguide (see the green dot curve in Fig. 5), which is the origin of the nonreciprocal characteristic in PT symmetric state.

To take advantage of this characteristic, we add a Y-branch to combine the two output ports, as shown in Fig. 6. In previous section, we have already derived the relationship between input and output ports of PT symmetric directional coupler. Next, we will continue to derive the isolator based on the nonreciprocal characteristic. Suppose light inputs from lossless waveguide only, for forward transmission, the intensity of output port is

$$I_F = \frac{e^{-2Z\sin\theta}}{\cos^2\theta}[\cos^2(Z\cos\theta-\theta)+\sin^2(Z\cos\theta)] \quad (7)$$

For backward transmission, suppose that the power split ratio of the Y-branch is $r_1 : r_2$, the intensity at the output port is

$$I_B = \frac{e^{-2Z\sin\theta}}{\cos^2\theta}\cdot\frac{\cos^2(Z\cos\theta-\theta)r_1+\sin^2(Z\cos\theta)r_2}{r_1+r_2} \quad (8)$$

The isolation ratio is defined as decibels of the ratio of the intensity of forward and backward transmission.

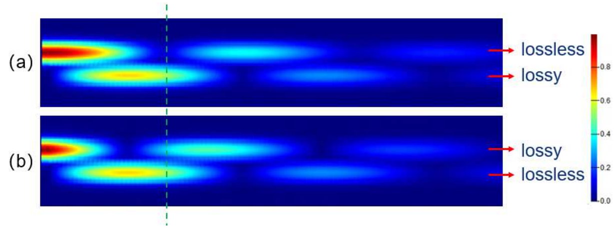

Fig. 5. The electric field distribution when light inputs from lossless waveguide (a) and lossy waveguide (b).

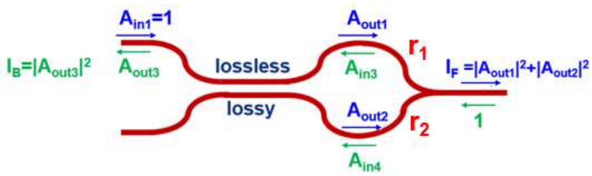

Fig. 6. Schematic diagram of the nonreciprocal characteristic of PT symmetric directional coupler.

$$R(dB) = 10\lg\frac{\cos^2(Z\cos\theta-\theta)+\sin^2(Z\cos\theta)}{\cos^2(Z\cos\theta-\theta)r_1+\sin^2(Z\cos\theta)r_2}(r_1+r_2) \quad (9)$$

We can see from (9) that isolation ratio is the function of the loss in lossy waveguide, coupling strength, length of the coupler and power split ratio of Y-branch. In addition, the isolation ratio has a maximum, which can be expressed as

$$R_{\max}(dB) = 10\lg\frac{r_1+r_2}{\min(r_1,r_2)} \quad (10)$$

According to (10), we can conclude that the maximum value of isolation ratio depends on the power split ratio of Y-branch. When the loss, length, coupling strength of the PT symmetric directional coupler satisfy a certain condition ($Z\cos\theta-\theta=\pi/2$), R can reach its maximum.

Suppose that the power split ratio $r_1 : r_2 = 1:10$, then $R_{\max} = 10.4$ dB. In order to satisfy the commercial demand that isolation ratio > 20 dB, two couplers need to be cascaded. Each coupler contributes an isolation ratio of ~ 10 dB and an insertion loss of ~ 0.25 dB. Therefore, our proposal of using the concept of PT symmetry to achieve an on-chip isolator can avoid the use of magneto-optical materials, thus reducing the footprint and making it easier for large-scale integration. In addition, nonreciprocity can be realized for any intensity of light, which is impossible to achieve by using nonlinear effects. Table 1 compares our proposal with other reported isolators based on different mechanisms.

IV. Conclusion and outlook

In conclusion, we derived the amplitude and phase characteristics of PT symmetric directional coupler and proposed an on-chip isolator based on the nonreciprocity of passive PT symmetric directional coupler. From the derivation and simulation result, we can see that our proposed device has advantages of CMOS compatibility, avoidance of gain, and showing nonreciprocity for light of any intensity.

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TABLE I. COMPAROSON OF OUR PROPOSAL WITH PREVIOUS WORK

Refs.	Structure	Mechanism	Footprint	IR[a]/ dB	IL[b]/dB
25	MZI	direct bonding of Ce:YIG and waveguide	4.0 mm	21	8
26	MZI	electric controlling	0.941 mm	29	9~11
27	cascaded Si Fano-Lorentzian resonator	$\chi(3)$ nonlinearity	37.5 μm per ring	20	1.3
28	AlN piezoelectric modulators	spatio-temporal modulation of Si_3N_4	118 μm	10	0.1
31	MZI	interband Brillouin scattering	2.39 cm	38	<1
32	a unidirectional mode converter	nonlinear anti-adiabatic encirclement near EP	1 mm	10	<1
Our proposal	passive PT symmetric directional coupler	nonreciprocity of PT symmetry	~100 μm	20	0.5

[a]IR: isolation ratio; [b]IL: insertion loss

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