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Phase-coupled optical diode based on $\mathcal{PT}$ symmetric system

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ABSTRACT

Here we investigate a phase-coupled parity-time symmetric plasmonic system, and theoretically achieved the all optical on-chip plasmonic diode using the coupled mode theory. The proposed symmetrical system consists of one loss cavity and one gain cavity each coupled with the waveguide, and we find that the controllable amplification of the input field can be achieved by changing the power coupling fraction between the resonators and the waveguide. Moreover, this loss–gain symmetric system could work as a frequency comb filter, and the operation on the device could be controlled by tuning the coupling strength between the two plasmonic cavities by tuning the coupling distance between the cavities and the waveguide.

1. Introduction

Optical diode is a time-reversal asymmetric device which denotes a nonlinear circuit that allows the flux of optical current in one direction only. During the past decades, optical diode is considered to have dramatically potential applications in optical communication and information processing. Recently, the achievement of nanoscale all-optical diode is becoming an important issue for the requirement of the integrated optical computing and optical interconnection systems [1–5]. And during the past decades, a large amount of progress has been theoretically and experimentally investigated in different systems, such as the standard bulk Faraday rotators [6,7], nonlinear photonic crystal microcavities [8–11], diodes operating in an optically controllable way [12,13], plasmonic chiral asymmetric transmission metamaterials [14–21], and parity-time ($\mathcal{PT}$) symmetric systems [22–25].

Recently, the $\mathcal{PT}$ symmetric systems have attracted much attention since the first progress of the work by Bender [26]. This symmetry has drawn much attention for its novel non-Hermitian characteristic with real eigenvalues, which expands the quantum mechanics to complex domain [27]. Later, a large amount of theoretical results have been given [28–32]. And various physical systems have been studied experimentally to illustrate the issue of $\mathcal{PT}$ symmetry [33–40]. Especially in 2014, $\mathcal{PT}$ symmetric system is experimentally demonstrated by using optical microtoroid resonators [37]. The system consists of one loss resonator coupled and one optical gain resonator through the waveguide, there coupling phase is decided by the distance between the two coupling point of the waveguide. We may find that the output power is asymmetrical when we excited this system in different directions. And we must emphasize that different from the optical isolator, this system is not nonreciprocal. The asymmetric transmission mainly comes from the difference in interferometric phase and strength of the cavities and waveguide.

Surface plasmons polaritons (SPPs) describe the electrons' oscillation which generates the electromagnetic waves trapped on metal–dielectric interfaces and propagates in the metals [41,42]. Such plasmonic device exhibits perfect properties in the realization of integrated circuit due to the capability to overcome the diffraction limit of light which could work in the sub-wavelength nanoscale if we can overcome the ohmic loss of the metallic material. Recently, there are various researches on SPPs devices, for example, an experimental observation of the asymmetric transmission for linearly polarized light in a 3D low-symmetry metamaterials (MMs) is presented [17], and the on-chip plasmonic diode is proposed based on the grating of plasmonic slot waveguides [21].

Hereby considering the behavior of the $\mathcal{PT}$ symmetric system, we designed a plasmonic system by using the loss cavity and gain cavity which are phase-coupled with one waveguide. Previously, the coupling phase of the two plasmonic cavities is always set as a constant. However, a phase-coupled plasmonic system [43] shows that the phase-coupled induced transparency could be achieved by using the coupling phase. In this work, we propose a general

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on-chip plasmonic system consisting of $\mathcal{PT}$ symmetric phase-coupled plasmonic nanoresonators. The output intensity of one side can be larger than the other side of the waveguide without considering the direction of excitation, which shows the behaviors as a plasmonic diode.

2. Model and method

Fig. 1 shows the nanoscale plasmonic system with two plasmonic cavities that are set on top of a dielectric-loaded plasmonic waveguide with a separation s. The two cavities structure marked with A and B can be served as plasmonic cavities, which act as resonators for SPPs and allow for the effective coupling to the SPPs waveguide. Here we assume that the waveguide metallic surface is adjacent to quantum coherence medium composed of three-level quantum emitters [44], thus the decay of the waveguide is balanced which makes it a lossless waveguide. To realize the $\mathcal{PT}$ symmetric system, the right cavity is overcompensated by the three-level quantum emitters [44], which provides the optical gain of plasmonic field while the left cavity remains a lossy cavity.

The basic concept of $\mathcal{PT}$ symmetry could be described as the joint action of the parity operation $\mathcal{P}$ and time operation $\mathcal{T}$. Here the action of the parity $\mathcal{P}$ and time $\mathcal{T}$ operators could be expressed as: $\hat{p} \to -\hat{p}$, $\hat{x} \to -\hat{x}$ and $\hat{p} \to -\hat{p}$, $\hat{x} \to \hat{x}$, $i \to -i$, respectively. In the proposed structure, the $\mathcal{P}$-transform reflects the structure to a left-gain and right-lossy system. However, the $\mathcal{T}$-transform will change the properties of gain and loss again. So we can conclude that when the gain in the right cavity is equal to the loss in the left cavity, and consider that the coupling phase is time independent but space symmetry, this system is $\mathcal{PT}$ symmetric. In order to provide a detailed analysis to illustrate the properties of the $\mathcal{PT}$ symmetric plasmonic system, we introduce a theoretical model of the system based on coupled mode theory. The Hamiltonian of the system could be described as $H = \hbar\omega_1 a_1^\dagger a_1 + \hbar\omega_2 a_2^\dagger a_2 + i\hbar|\kappa|^2(a_1^\dagger a_2 + a_2^\dagger a_1)e^{-i\phi}$, where a_1 and a_2 represent the amplitude of the field in the two resonators, respectively, $|\kappa|^2$ denotes the coupling strength between the two resonators through phase coupling and ϕ is the phase difference induced by the waveguide between the two resonators. Consider the structure of this system, the coupling equation can be written directly as using coupled mode theory as [45],

$$\frac{da_1}{dt} = i(\delta_1 - i\gamma_1)a_1(t) - |\kappa|^2 e^{-i\phi} a_2(t) - i\kappa s_i, \tag{1a}$$

$$\frac{da_2}{dt} = i(\delta_2 - i\gamma_2)a_2(t) - |\kappa|^2 e^{-i\phi} a_1(t) + i\kappa s_i e^{-i\phi}, \tag{1b}$$

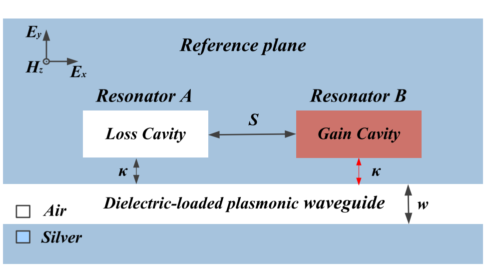

Fig. 1. Structure of the phase-coupled $\mathcal{PT}$-symmetric cavity system. Here the forward direction and backward direction are denoted as the left to right direction and the right to left direction, respectively. The resonant frequency of the left resonator A (with mode a_1) is ω_1, and decay rate is γ_l. The right resonator is filled with the gain medium which could be pumped by a resonant laser. Its frequency is denoted as ω_2, and gain rate is γ_2. The coupling rate from the waveguide to the resonator is κ.

where a_1 (a_2) represents the amplitude of the SPPs field in the left (right) cavity, and s_i denotes the amplitude input field. $\delta_{1,2} = \omega - \omega_{1,2}$ symbolizes the detuning between the input field and the cavity resonance frequency. $2\gamma_1$ and $2\gamma_2$ correspond to the energy-decay rate and gain rate of the uncoupled cavities, respectively. And κ represents the fraction of power coupling rate into the waveguide. For a transport field model with frequency ω, the effective index n_{eff} using the Drude model could be described as $\epsilon_{eff} = \epsilon_\infty - \omega_p^2/(\omega^2 - i\omega\Gamma)$, and the phase accumulated in propagating between the cavities is $\phi = \omega n_{eff} s/c$. Here c denotes the speed of light and s represents the distance between the cavities. Here $|\kappa|^2$ means that the coupling between cavity A and B through the waveguide, and ϕ means the relative phase between A and B. Consider the steady state of this system. Then we can get

$$\begin{Bmatrix} a_1 \\ a_2 \end{Bmatrix} = \begin{Bmatrix} \delta_1 - i\gamma_1 & i|\kappa|^2 e^{-i\phi} \\ i|\kappa|^2 e^{-i\phi} & \delta_2 + i\gamma_2 \end{Bmatrix}^{-1} \begin{Bmatrix} \kappa s_i \\ -\kappa s_i e^{-i\phi} \end{Bmatrix}. \tag{2}$$

By solving Eq. (2) using the steady state solution, we can get the plasmonic cavity field a_1 and a_2 as

$$a_1 = \frac{s_i\kappa((\gamma_2 - i\delta_2)e^{2i\phi} + \kappa^2)}{(\delta_1 - i\gamma_1)(\gamma_2 - i\delta_2)e^{2i\phi} - i\kappa^4}, \tag{3a}$$

$$a_2 = \frac{s_i\kappa(\kappa^2 - \gamma_1 - i\delta_1)e^{i\phi}}{(\gamma_1 + i\delta_1)(i\gamma_2 + \delta_2)e^{2i\phi} + i\kappa^4}. \tag{3b}$$

Based on the input–output relation, the transmitted field and transmission coefficient T could be written as

$$s_t = e^{-i\phi}(s_i + i\kappa a_1) - i\kappa a_2, \tag{4a}$$

$$T = \frac{s_t}{s_i}. \tag{4b}$$

By employing T_1 and T_2 to describe the transmission in the forward and backward directions, the two transmission coefficients could be expressed as

$$T_1 = \left| \frac{e^{i\phi}\left(e^{2i\phi}\left(\gamma_2 - i\delta_2\right)\left(\gamma_1 + i\delta_1 - \kappa^2\right)\right)}{e^{2i\phi}\left(\gamma_1 + i\delta_1\right)\left(\gamma_2 - i\delta_2\right) + \kappa^2} - \frac{e^{i\phi}\left(\kappa^4 + \kappa^2\left(\gamma_1 + i\delta_1 - 2\kappa^2\right)\right)}{e^{2i\phi}\left(\gamma_1 + i\delta_1\right)\left(\gamma_2 - i\delta_2\right) + \kappa^2} \right|, \tag{5a}$$

$$T_2 = \left| \frac{e^{i\phi}\left(e^{2i\phi}\left(\gamma_1 + i\delta_1\right)\left(\gamma_2 - i\delta_2 - \kappa^2\right)\right)}{e^{2i\phi}\left(\gamma_1 + i\delta_1\right)\left(\gamma_2 - i\delta_2\right) + \kappa^2} + \frac{e^{i\phi}\left(\kappa^4 - \kappa^2\left(\gamma_2 - i\delta_2 - 2\kappa^2\right)\right)}{e^{2i\phi}\left(\gamma_1 + i\delta_1\right)\left(\gamma_2 - i\delta_2\right) + \kappa^2} \right|. \tag{5b}$$

3. The transmission of the plasmonic field under the tuning of coupled-phase

In order to maintain the consistency of the gain and loss of the cavities, we denote the system is totally $\mathcal{PT}$-symmetric which means the loss and gain value of the right cavity as $\gamma_1 = \gamma_2 = \gamma$, and we set the two cavities with the same resonance frequency as $\omega_1 = \omega_2$. Furthermore, we analytically solved the transmission field