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Propagation of Surface Plasmon Polaritons in A Ring Resonator with PT-symmetry

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Abstract: We proposed a PT-symmetric metal-insulator-metal waveguide system, in which two waveguides coupled to a ring resonator, one arm of ring resonator was filled with gain medium, the other arm with loss medium. The transmission character of the system was studied. The results showed that, through balancing of gain and loss medium, PT-symmetry induced transparency can be clearly seen, which indicated the transmission peak have an opposite phases.

Key words: metal-insulator-metal waveguide; PT-symmetry; PT-symmetry induced transparency
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表面等离激元在具有PT对称性的环谐振器中的传输

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摘要: 提出了具有PT对称性的金属-绝缘体-金属波导系统,由两个波导耦合一个环谐振器组成,环谐振器的上臂填充增益介质而下臂填充损耗介质。对表面等离激元在该系统的传输特性进行了研究,结果表明:通过平衡增益介质和损耗介质,PT对称性诱导的透明峰可以被清楚地看到,并且该透明峰具有反相位的特点。

关　键　词: 金属-绝缘体-金属波导; PT对称性; PT对称性诱导透明

1　Introduction

In 1998, Bender and Boettcher theoretically predicted that a non-Hermitian Hamiltonian could also have real eigenvalue in energy spectrum, provided that it had PT-symmetry[1]. The necessary condition (not sufficient) for a Hamiltonians having PT-symmetry is $V(\hat{x}) = V^{*}(-\hat{x})$, in optics, this condition requires that the real part of refractive index is even function of position and the imaginary part of refractive index is odd function of position[2]. The implications of PT-symmetry exhibit several intriguing phenomenon, such as power oscillations[3], absorption enhanced transmission[4], optical Bloch oscillations[5], laser-absorber modes[6], spectral singularities[7], nonreciprocity of light propagation[8] and so on[9].

Surface plasmon polaritons (SPPs) are coherent

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electron oscillations that exist at the interface between metal and dielectric. It propagates along the interface of metal, where the real part of the dielectric function changes sign across the interface of metal and dielectric[10]. Since SPPs was first predicted in 1957 by R. H. Ritchie[11], following years, SPPs was widely investigated in theory and applications, such as extraordinary optical transmission through subwavelength hole arrays[12], airy beam generation[13] and so on[14]. Therefore, it is valuable for us to study the field which containing the SPPs and PT-symmetry. In this paper, we proposed a two dimension metal-insulator-metal waveguide system which having PT-symmetry. By investigating the transmission properties of the waveguide system, PT-symmetry induced transparency can be clearly seen.

2 Theory

2.1 Metal-insulator-metal Waveguide

It is well known that the dispersion equation of SPPs in metal-insulator-metal structure can be expressed as:

$$\frac{\varepsilon_0 k_1}{\varepsilon_m k_2} = \frac{1 - e^{kd}}{1 + e^{kd}}, \qquad (1)$$

Where $k_1 = (\beta^2 - \varepsilon_m k_0^2)^{\frac{1}{2}}$, $k_2 = (\beta^2 - \varepsilon_0 k_0^2)^{\frac{1}{2}}$ and $k_0 = \frac{2\pi}{\lambda}$, β are the propagation constants of SPPs, d is the width of insulator, ε_0 and ε_m are dielectric functions of insulator and metal. Based on metal-insulator-metal (MIM) structure, such as all-angle negative refraction[15] and Mach-Zehnder interferometers[16-17] have been theoretical demonstrated.

2.2 Model Description

The system in this paper is composed of two waveguides, one is filled with gain medium, the other is filled with loss medium. As illustrated in Fig. 1, the shades areas denotes gain and loss medium, the white denotes the insulator filled in waveguide and the dark denotes the metal. SPPs propagate along two channel in the ring resonator, one is along clockwise, the other along counter clockwise, then they interference with each other. The geometric parameters are taken as following, the width $a = 1.8 \times 10^{-6}$ m and the height $b = 8 \times 10^{-7}$ m of the system, the width $d = 4.0 \times 10^{-8}$ m, the gap $g = 1.0 \times 10^{-8}$ m, the width of gain/loss medium is $c = 1.0 \times 10^{-7}$ m, the parameters of ring resonator are $f = 2.2 \times 10^{-7}$ m, $e = 3.9 \times 10^{-7}$ m. Port 1 is the source port and port 2 is receiving port.

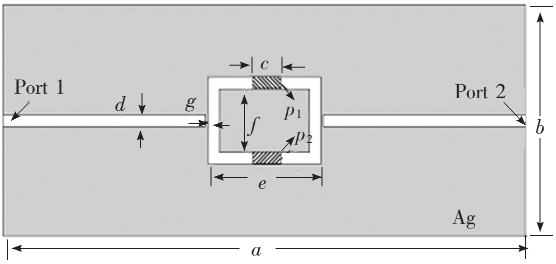

Fig. 1 Schematic of our metal-insulator-metal waveguide system. One arm of ring resonator is filled with gain medium, the other arm is filled with loss medium.

3 Results and Discussion

We use commercial finite-element solver (COMSOL Mutiphysics 3.5a) to calculate the transmission spectra of our waveguide system. In calculation, the metal is silver, with permittivity defined by a Drude model, $\varepsilon(\omega) = 1 - \omega_p^2/\omega^2$, where $\omega_p = 1.367\,3 \times 10^{16}$ rad/s. In order to simplify, we assume that the metal is lossless. The waveguide are filled with the medium of $\varepsilon_1 = 2.25$. The permittivity of loss and gain medium set as $\varepsilon_i = 2.25 + \mathrm{i}\alpha_1$ and $\varepsilon_g = 2.25 - \mathrm{i}\alpha_2$, respectively. For the reason of preserving PT-symmetry, the imaginary part of gain and loss medium takes the same value ($\alpha_1 = \alpha_2 = \alpha$). Two ports detect the incident wave amplitude B_1 and transmitted wave amplitude B_2, so the transmittance can be defined as $T = B_2/B_1$. Firstly, we calculate the transmission without considering the gain and loss ($\alpha = 0$), present as solid line in Fig. 2. We can see there are three transmission peaks ($f_1 = 3.31 \times 10^{14}$ Hz, $f_2 = 4.13 \times 10^{14}$ Hz and $f_3 = 4.9 \times 10^{14}$ Hz) in the frequency range of 3×10^{14} Hz to 5×10^{14} Hz. The transmission peak satisfied the equation of $m\lambda = n_{\text{eff}} L$, where L is the perimeter of ring resonator, here $L = 1.22 \times 10^{-6}$ m, $n_{\text{eff}} = \beta/k_0$ is the effective refraction index of the MIM structure. Then the transmission peak frequency f_1, f_2 and f_3 correspond to $m_1 = 3$, $m_2 = 4$ and $m_3 = 5$, respectively. We consider the gain and loss medium in calculations.

The transmission spectra of the system with $\alpha = 0.3$ and $\alpha = 0.5$ are plotted in Fig. 2. In addition to the transmission peak $f_1 \sim f_3$, there is a new transmission peak near the frequency of $f_0 = 4.35 \times 10^{14}$ Hz, and the line shape becomes asymmetric. The transmittance of frequency f_0 increased with α. We noted that PT-symmetry is critical for the physical origin of this transparency tip. In other words, through balancing gain and loss medium, two channels interference with each other and produce new transmission tip.

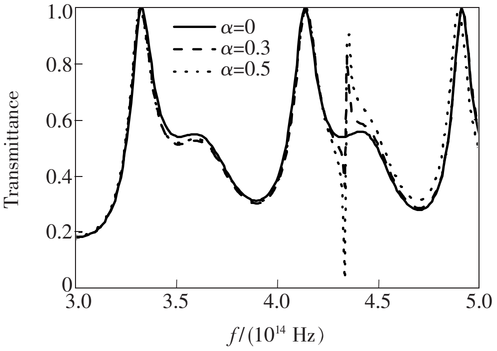

Fig. 2　Transmission spectra with different values of α, which denotes the imaginary part of gain/loss medium.

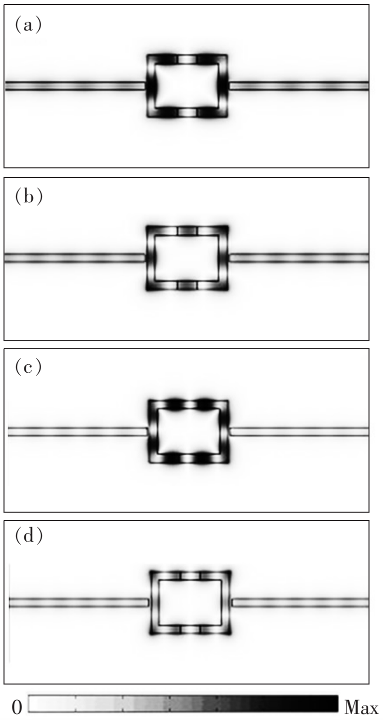

Fig. 3　$|H_z|$ field distribution of different frequency with the parameter $\alpha = 0.5$. (a) ~ (d) correspond to the frequency of 3.32×10^{14}, 4.14×10^{14}, 4.35×10^{14}, 4.89×10^{14} Hz, respectively.

In Fig. 3, we plot the field distribution ($|H_z|$) of transmission peak with the parameters of $\alpha = 0.5$. Fig. 3(a) ~ (d) correspond to the frequency of $f_1 = 3.31 \times 10^{14}$ Hz, $f_2 = 4.13 \times 10^{14}$ Hz, $f_0 = 4.35 \times 10^{14}$ Hz and $f_3 = 4.9 \times 10^{14}$ Hz, respectively. There are 3, 4, 4 and 5 modes in the rings of Fig. 3(a) ~ (d), respectively. In Fig. 3(c), the field in the ring is very strong while the field in waveguide is weak which different from Fig. 3(a), (b) and (d).

As illustrated in Fig. 1, p_1 and p_2 are two points located in the center position of the gain and loss medium boundary. In Fig. 4, we plot the absolute value of z component of magnetic field which p_1 and p_2 detected with the parameter of $\alpha = 0.5$. As seen from the figure, $|H_{z1}|$ and $|H_{z2}|$ almost coincide, the field of frequency $f_0 = 4.35 \times 10^{14}$ Hz is stronger than the other two frequencies and the most of electromagnetic energy localizes in the ring resonator. In Fig. 4, the phase of H_{z1}/H_{z2} is shown (circle), which denotes the phase difference of two channels. In this case, the imaginary part of gain and loss medium make the phase difference. We can see that the transmission peak with frequency of f_2 and f_3 are in phase, while the frequency of f_0 is out phase and shows a sharp normal dispersion. Two characteristics discussed above are unique in the PT-symmetry induced transparency.

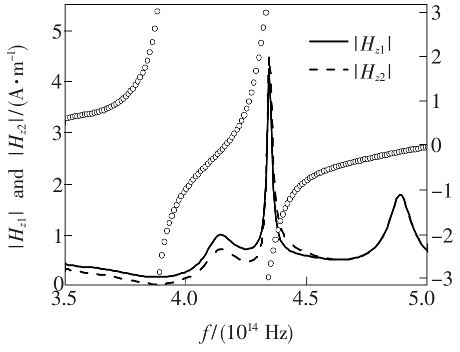

Fig. 4　The absolute value of H_z field which p_1 and p_2 detected with the parameter of $\alpha = 0.5$. The circle represent the phase of (H_{z1}/H_{z2}).

4 Conclusion

In conclusion, we demonstrated the SPPs propagates in a PT-symmetric metal-insulator-metal waveguide system which is composed of two waveguide coupled to a ring resonator . PT-symmetry induced transparency is shown, which the transmission peak exists with opposite phases and can localize most of the field in ring resonator. This study has a potential application in nanoscale optics and photonic integration.

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