Research article

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Manifestation of the spontaneous parity-time symmetry breaking phase transition in hot-electron photodetection based on a tri-layered metamaterial

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Abstract: We theoretically and numerically demonstrate that the spontaneous parity-time (PT) symmetry breaking phase transition can be realized respectively by using two independent tuning ways in a tri-layered metamaterial that consists of periodic array of metal-semiconductor Schottky junctions. The existence conditions of PT symmetry and its phase transition are obtained by using a theoretical model based on the coupled mode theory. A hot-electron photodetection based on the same tri-layered metamaterial is proposed, which can directly show the spontaneous PT symmetry breaking phase transition in photocurrent and possesses dynamical tunability and switchability. This work extends the concept of PT symmetry into the hot-electron photodetection, enriches the functionality of the metamaterial and the hot-electron device, and has varieties of potential and important applications in optoelectronics, photodetection, photovoltaics, and photocatalytics.

Keywords: parity-time symmetry; phase transition; hot electron; metamaterial; photodetection.

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1 Introduction

Non-Hermitian quantum mechanics, as an extended class of Hermitian quantum mechanics, has drawn a considerable attention in the past two decades, as it can possess real eigenvalues provided that its Hamiltonian is parity-time (PT)-symmetric, i.e. the Hamiltonian can commute with the PT operator [1–4]. Thanks to the similarity between the Schrödinger equation in quantum mechanics and the wave equation in optics, the concept of

PT-symmetry has been extended into the realm of optics [5–7]. A large number of exotic and remarkable optical phenomena and properties stemming from PT symmetry have been theoretically and experimentally demonstrated [8–14], for example, unidirectional invisibility and reflectionless [15–17], power oscillation [18, 19], loss-induced optical transparency [20], and nonreciprocal light propagation [21, 22]. More recently, some intriguing lasers utilizing PT symmetry have also been theoretically and experimentally realized [23–26]. Especially, this kind of PT-symmetric non-Hermitian system can experience the spontaneous PT-symmetry breaking phase transition when its degree of non-Hermiticity, which is usually indicated by an external parameter, exceeds some certain threshold, which is referred to as the exceptional point at which the eigenvalues and the corresponding eigenvectors coalesce [1–4]. An effective optical method for direct observation of this kind of spontaneous PT-symmetry breaking phase transition has been proposed [27]. It is highly desired to exploit PT symmetry in optoelectronics and to develop a simpler and more direct electronic way to detect the spontaneous PT-symmetry breaking phase transition.

Hot electron in plasmonic nanostructures has attracted growing interest in recent years because of its potential applications in photodetection, photovoltaics, photocatalytics, and so on. A variety of hot-electron devices have been exploited [28–32]. In particular, hot-electron photodetection, as one of the most promising applications, has achieved considerable interest in recent years [33–38]. It provides a new path to detect photons with energy less than the bandgap of semiconductor. Additionally, benefitting from advances in nanofabrication, metamaterials have provided a versatile platform for exploiting various peculiar physical properties and for engineering the permittivity and permeability of materials in both the real and complex planes [39–41]. Some hot-electron photodetection based on metamaterials have been theoretically and experimentally proposed and demonstrated [42, 43]. Therefore, it is very interesting to exploit the PT-symmetry breaking in hot-electron photodetection using metamaterials, and a dynamically

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tunable and switchable hot-electron photodetection is also highly desired.

In this paper, we propose a tri-layered metamaterial that is composed of periodic array of subwavelength metamolecules consisting of radiating and nonradiating metaatoms made of metal-semiconductor Schottky junctions. The spontaneous PT-symmetry breaking phase transition can be realized respectively by tuning the horizontal or vertical spacing distances between two metaatoms in our tri-layered metamaterial. The existence conditions of PT-symmetry and its phase transition in our tri-layered metamaterial are discussed by using a theoretical model based on the coupled mode theory. A hot-electron photodetection based on the same tri-layered metamaterial is theoretically and numerically demonstrated, which can exhibit the spontaneous PT-symmetry breaking phase transition in photocurrent and can be dynamically tuned and switched with light. This work extends the concept of PT symmetry into hot-electron photodetection, enriches the functionality of hot-electron devices and metamaterial, and has lots of potential and significant applications in optoelectronics, photodetection, photovoltaics, and photochemistry.

2 Theoretical model

We consider a tri-layered metamaterial that is normally illuminated by two coherent light beams from two opposite directions, i.e. the so-called two-port optical system. The tri-layered metamaterial is composed of square lattice of unit cell of radiating and nonradiating metaatoms, which have identical resonant frequencies and interact with each other through near-field coupling. The radiating metaatom can only be excited by two light beams, and there is no polarization conversion during the interaction. The electromagnetic response and the underlying physics of the aforementioned optical system can be analytically described and given by the following theoretical model, which is built by using the coupled mode theory [44–46]:

$$\mathbf{R} \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = \mathbf{C} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} \quad (1a)$$

$$\mathbf{C}^+ \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = \mathbf{D} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} - \mathbf{P} \begin{pmatrix} O_1 \\ O_2 \end{pmatrix} \quad (1b)$$

$$\mathbf{R} = \begin{pmatrix} \delta - i(\gamma_1 + \Gamma_1) & -\kappa \\ -\kappa & \delta - i\Gamma_2 \end{pmatrix} \quad (1c)$$

$$\mathbf{C} = \begin{pmatrix} \sqrt{\gamma_1} & \sqrt{\gamma_1} \\ 0 & 0 \end{pmatrix} \quad (1d)$$

$$\mathbf{D} = \begin{pmatrix} i & 0 \\ 0 & i \end{pmatrix} \quad (1e)$$

$$\mathbf{P} = \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix} \quad (1f)$$

in which $\delta = \omega - \omega_0$ denotes the frequency detuning. γ_1 and Γ_1 represent the scattering and dissipating loss rates of the radiating metaatom, respectively. Γ_2 indicates the dissipating loss rate of the nonradiating metaatom. κ is the near-field coupling between the radiating and nonradiating metaatoms. $A_{1(2)}$ is the amplitudes of resonant modes of the radiating and nonradiating metaatoms, respectively. $I_{1(2)}$ represents the amplitudes of input lights from two opposite directions, respectively. $O_{1(2)}$ denotes the amplitudes of output lights from two opposite directions, respectively. + indicates the conjugate transpose.

The above two-port optical system is a non-Hermitian optical system, as there exists loss in this optical system. Coherent perfect absorption (CPA) is one of the most intriguing optical effects in a non-Hermitian optical system, which originates from the interaction of loss and light interference [47]. The eigenequation of the above optical system possessing the intriguing CPA can be obtained by using the above theoretical model under the condition of $I_{1(2)} \neq 0$ and $O_{1(2)} = 0$:

$$\mathbf{H} \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = \omega \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} \quad (2a)$$

$$\mathbf{H} = \begin{pmatrix} \omega_0 - i(\gamma_1 - \Gamma_1) & \kappa \\ \kappa & \omega_0 + i\Gamma_2 \end{pmatrix} \quad (2b)$$

where $\mathbf{H}$ denotes the effective Hamiltonian of our non-Hermitian optical system possessing the intriguing CPA. From equations (2a) and (2b), two eigenvalues of our optical system can be obtained as $\omega_0 - \sqrt{4\kappa^2 - (\gamma_1 - \Gamma_1 + \Gamma_2)^2} / 2 - i(\gamma_1 - \Gamma_1 - \Gamma_2) / 2$ and $\omega_0 + \sqrt{4\kappa^2 - (\gamma_1 - \Gamma_1 + \Gamma_2)^2} / 2 - i(\gamma_1 - \Gamma_1 - \Gamma_2) / 2$. It can be seen that the identical resonant frequencies of the radiating and nonradiating metaatoms ω_0 are split into two different eigenfrequencies because of near-field coupling, and the hybrid metamolecule consisting of radiating and nonradiating metaatoms has more abundant optical properties than single radiating or nonradiating metaatom. Here we consider an interesting optical system that has $\gamma_1 - \Gamma_1$ being equal to Γ_2 . Two eigenvalues can then be reduced to $\omega_0 - \sqrt{\kappa^2 - \Gamma_2^2}$ and $\omega_0 + \sqrt{\kappa^2 - \Gamma_2^2}$. As a result, our optical system has three possible situations: (1) When

$\kappa^2 > \Gamma_2^2$, two eigenvalues are real numbers, which means CPA can simultaneously exist at two eigenfrequencies and our optical system has a PT-symmetric phase that can be found from the fact that non-Hermitian Hamiltonian has real eigenvalues. (2) When $\kappa^2 = \Gamma_2^2$, two eigenvalues coalesce to single real eigenvalue, which corresponds to an exceptional point in our optical system and means CPA can only be observed at this single eigenfrequency. (3) When $\kappa^2 < \Gamma_2^2$, two eigenvalues become complex numbers, which means CPA does not exist and our optical system possesses a PT-symmetry breaking phase. Therefore, our optical system can experience the PT-symmetry breaking phase transition by tuning the near-field coupling κ . This kind of phase transition can be manifested in evolutions of both CPA and eigenvalues of optical system.

The optical properties of our tri-layered metamaterial can also be understood by using the scattering matrix that directly gives the relation of input and output lights. For our aforementioned two-port optical system, its scattering matrix can be expressed as

$$\begin{pmatrix} O_1 \\ O_2 \end{pmatrix} = \mathbf{S} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} \quad (3a)$$

$$\mathbf{S} = \begin{pmatrix} r & t \\ t & r \end{pmatrix} \quad (3b)$$

Here we have assumed that our optical system has reciprocity and symmetry. From equations (3a) and (3b), two eigenvalues of our scattering matrix can be obtained as $r-t$ and $r+t$, which are corresponding to two eigenvectors of $(-1,1)$ and $(1,1)$, respectively. Two eigenvectors of $(-1,1)$ and $(1,1)$ represent the antisymmetric and symmetric incidences, respectively. The existence of CPA also corresponds to the eigenvalue of scattering matrix being equal

to zero. Therefore, for our optical system, CPA can only be observed for symmetric incidence because only the eigenvalue of $r+t$ can become zero. The analytical reflection and transmission coefficients in the scattering matrix can be obtained by using our aforementioned theoretical model

$$\mathbf{S} = \mathbf{P}^{-1}(\mathbf{D} - \mathbf{C}^* \mathbf{R}^{-1} \mathbf{C}) \quad (4)$$

For symmetric incidence, the coherent absorption (CA) coefficient can be calculated using the following formula:

$$a_c = 1 - |r+t|^2 \quad (5)$$

However, for single light beam incidence, the absorption coefficient can be calculated by using the following formula:

$$a = 1 - |r|^2 - |t|^2. \quad (6)$$

3 Spontaneous PT-symmetry breaking phase transition

To get the fascinating optical properties predicted previously, a tri-layered metamaterial is designed, which is composed of periodic array of unit cell of radiating and nonradiating metaatoms with a period of p , and the structure of which is illustrated in Figure 1A and B. The radiating metaatom is made up of a vertical metal-semiconductor Schottky junction with the width of w_b , height of h_b and thickness of t_b along the x , y , and z directions, respectively. The nonradiating metaatom consists of four

Figure 1: Schematic of our designed tri-layered metamaterial.

(A) Our tri-layered metamaterial is normally illuminated by two coherent light beams from two opposite directions. Red represents two coherent light beams. (B) Geometric structure of unit cell of our tri-layered metamaterial. Yellow and green represent metal and semiconductor, respectively.

horizontal metal-semiconductor Schottky junctions, each of which has the width of w_d , height of h_d , and thickness of t_d along the x , y , and z directions, respectively. For the nonradiating metaatom, the spacing distances between the geometric centers of metal parts of two Schottky junctions located in the same xy and xz planes are s_{d1} and s_{d2} along the y and z directions, respectively. The spacing distances between the geometric center of the metal part of the radiating metaatom and the symmetric center of the nonradiating metaatom are s_w , s_h , and s_t along the x , y , and z directions, respectively. For both radiating and nonradiating metaatoms, each Schottky junction has the same thickness of metal and semiconductor. Taking into consideration the asymmetry of thin-film single-barrier Schottky junction and/or hybridization between metaatoms, the tri-layered metamaterial consisting of thin-film single-barrier Schottky junctions is a better choice than the single- or two-layered metamaterials composed of the same Schottky junctions, which is beneficial to achieve the conditions of both CPA and PT symmetry. The material between the layered metal-semiconductor Schottky junctions can be any material that is transparent to infrared light and will not influence the final results, as we can tune the geometric parameters of metal-semiconductor

Schottky junctions to achieve the similar or same optical properties we need when the material is changed. We would like to mention that the material between the layered metal-semiconductor Schottky junctions should be symmetric with respect to the geometric center of the nonradiating metaatom, which is beneficial to achieve CPA. Without loss of generality, we choose the metal and semiconductor to be gold and silicon, respectively. The relative permittivity of gold is $\varepsilon_r = \varepsilon_\infty - \omega_p^2 / (\omega^2 + i\gamma_p\omega)$ with $\varepsilon_\infty = 9$, $\omega_p = 1.3697 \times 10^{16}$ Hz, and $\gamma_p = 1.0179 \times 10^{13}$ Hz [48]. The relative permittivity of silicon is 12.2972. The material between the layered metal-semiconductor Schottky junctions is vacuum. The numerical simulations are carried out by utilizing the finite-difference time-domain method.

We first consider the optical properties of single radiating or nonradiating metaatom. Figure 2 shows the change of absorption and reflection coefficients of radiating metaatom with frequency when $w_b = 20$ nm, $h_b = 172.56$ nm, and $t_b = 40$ nm. It can be seen that there is only one resonant mode at the frequency of 250.2 THz in the frequency range of interest. The scattering field of metaatom can be estimated by using $E_s \cong i\gamma E_i / (\omega - \omega_0 - i\gamma - i\Gamma)$, in which E_s and E_i are the scattering and incident fields, respectively, and which can be used to fit the above

Figure 2: The simulation and theoretical results of a single radiating metaatom which is depicted in the inset.

(A) Absorption coefficient, (B) absolute value of reflection coefficient, (C) real part of reflection coefficient, and (D) imaginary part of reflection coefficient as a function of frequency for normally incident light. Red circle and blue solid line represent the simulation and theoretical results, respectively.

numerical simulation results. The fitted scattering and dissipating loss rates of radiating metaatom are $\gamma_1 = 8.6$ THz and $\Gamma_1 = 4.29$ THz, respectively. The spectral of absorption and reflection coefficients of nonradiating metaatom with $w_d = 175.23$ nm, $h_d = 50$ nm, $t_d = 40$ nm, $s_{d1} = 70$ nm, and $s_{d2} = 270$ nm are depicted in Figure 3. Similar to the radiating metaatom, there is also only one resonant mode at the frequency of 250.2 THz in the same frequency range. The fitted dissipating loss rate of nonradiating metaatom is $\Gamma_2 = 4.31$ THz. Therefore, the radiating metaatom has the same resonant frequency as that of the nonradiating one.

Furthermore, the difference of scattering and dissipating loss rates of radiating metaatom $\gamma_1 - \Gamma_1$ is equal to the dissipating loss rate of nonradiating metaatom Γ_2 . These interesting optical properties of single radiating or nonradiating metaatom are the basis of our above theoretical predictions.

For the two-port optical system with two coherent input light beams from two opposite directions, CA may be generated under some conditions because of loss of our tri-layered metamaterial. Figure 4 shows the change of spectrum of CA of our tri-layered metamaterial with

Figure 3: The simulation and theoretical results of a single nonradiating metaatom which is depicted in the inset. (A) Absorption coefficient, (B) absolute value of reflection coefficient, (C) real part of reflection coefficient, and (D) imaginary part of reflection coefficient as a function of frequency for normally incident light. Red circle and blue solid line represent the simulation and theoretical results, respectively.

Figure 4: The change of spectrum of CA of our designed tri-layered metamaterial with the horizontal spacing distance s_w . (A) and (B) correspond to the simulation and theoretical results, respectively.

the horizontal spacing distance s_w when $s_h=0$ nm and $s_t=0$ nm. It can be found that there are two peaks of CPA at the frequencies of 247.58 and 252.82 THz, respectively, when $s_w=150$ nm, both of which correspond to two real eigenvalues of our optical system. With increasing s_w from 150 to 279 nm, two peaks of CPA gradually come closer to each other. This is because the value of $\sqrt{\kappa^2 - \Gamma_2^2}$ is gradually decreased. Our optical system has an ideal PT-symmetric phase. In particular, as $s_w=279.01$ nm, two peaks of CPA coalesce to a single peak of CPA at the frequency of 250.2 THz. This means that two real eigenvalues in our optical system coalesce to a single real eigenvalue because $\kappa=\Gamma_2$. This special case corresponds to the exceptional point in the two dimensional parameter space of the horizontal spacing distance s_w and incident frequency. With further increasing s_w , a single peak of CPA gradually disappears because there is no real eigenvalue in our optical system, which has a PT-symmetry breaking phase. The spectra of CA of our tri-layered metamaterial is also calculated by using our theoretical model with the fitted parameters, the results of which are illustrated in Figure 4B. The simulation results are in an excellent agreement with the theoretical ones. In the evolution process of the PT-symmetry breaking phase transition, the near-field coupling κ is changed from initial 16.91 THz at $s_w=150$ nm then to 4.31 THz at exceptional point and finally to -0.88 THz at $s_w=350$ nm. All these results are quantitatively consistent with our aforementioned theoretical analysis on the basis of our effective Hamiltonian. Therefore, our tri-layered metamaterial experiences the spontaneous PT-symmetry breaking phase transition by only changing the horizontal spacing distance s_w .

The change of spectrum of CA of our tri-layered metamaterial with the vertical spacing distance s_h when $s_w=180$ nm and $s_t=0$ nm are illustrated in Figure 5. When $s_h=0$ nm, the near-field coupling κ between radiating and

nonradiating metaatoms is 13.08 THz so that our optical system possesses two peaks of CPA at the frequencies of 248.2 and 252.18 THz, respectively, both of which correspond to two real eigenvalues of our optical system. Thus, our optical system is in the ideal PT-symmetric phase. Then the near-field coupling κ is decreased as s_h is increased from 0 to 97 nm, and these two peaks of CPA approach each other. This can be understood from the fact that the value of $\sqrt{\kappa^2 - \Gamma_2^2}$ is decreased. Specially, when $s_h=97.1$ nm, the corresponding near-field coupling κ is 4.31 THz, and there exists an exceptional point, at which two peaks of CPA coalesce to a single peak of CPA at the frequency of 250.2 THz, in the two-dimensional parameter space of the vertical spacing distance s_h and incident frequency due to $\kappa=\Gamma_2$. The near-field coupling κ finally becomes 2.67 THz, which gives rise to two complex eigenvalues, and a single peak of CPA is gradually vanished with the increase of s_h from 97.1 to 150 nm. Our optical system is now in the PT-symmetry breaking phase. All these results agree well with our above theoretical analysis on the basis of our effective Hamiltonian. The theoretical results obtained by using our theoretical model with the fitted parameters, which are depicted in Figure 5B, have a good agreement with the simulation ones. This demonstrates that our tri-layered metamaterial can also experience the spontaneous PT-symmetry breaking phase transition by only altering the vertical spacing distance s_h .

The phenomenon realized in our tri-layered metamaterial is not the electromagnetically induced transparency (EIT)-like phenomenon discussed in previous works [49–52]. The EIT-like phenomenon achieved in metamaterials consisting of the radiating and nonradiating metaatoms works in the strong coupling regime and requires that the loss of the nonradiating metaatom is much smaller than the loss of the radiating metaatom, i.e. $\Gamma_2 \ll \gamma_1 + \Gamma_1$. In contrast, the phenomenon achieved in our tri-layered

Figure 5: The change of spectrum of CA of our designed tri-layered metamaterial with the vertical spacing distance s_h . (A) and (B) correspond to the simulation and theoretical results, respectively.

metamaterial works in the intermediate coupling regime near the critical point and requires that the loss of the non-radiating metaatom has the comparable size with the loss of the radiating metaatom, i.e. $\Gamma_2 = \gamma_1 - \Gamma_1$, in order to realize both CPA and PT symmetry in effective Hamiltonian. Moreover, the EIT-like phenomenon in metamaterials coupling the radiating and nonradiating metaatoms corresponds to the high transmission. In contrast, the phenomenon in our tri-layered metamaterial corresponds to that the incoming lights from two ports are completely absorbed and there are no outgoing lights, which is embodied in the condition of the theoretical model, i.e. $I_{1(2)} \neq 0$ and $O_{1(2)} = 0$.

4 Manifestation of spontaneous PT-symmetry breaking phase transition in hot-electron photodetection

Because our tri-layered metamaterial is made up of the metal-semiconductor Schottky junctions, it has the potential to be used as a hot-electron photodetection as hot electron in metal may be generated and then be collected to form photocurrent when two coherent light beams are normally impinging onto our tri-layered metamaterial. The internal photoemission process of hot electron from metal to semiconductor in our Schottky junction may be divided into three steps: (1) free electron in metal is excited up to a higher energy state and then becomes hot electron because of the absorption of photon when photon is impinging onto our tri-layered metamaterial; (2) hot electron diffuses to the interface between metal and semiconductor; and (3) hot electron arriving at the metal-semiconductor interface

has a finite probability to be injected into the semiconductor across the Schottky barrier. The responsivity $R_{I,p}$ of hot-electron photodetection is the ratio of photocurrent I_{ph} to incident optical power P_{inc} , which quantitatively describes the internal photoemission process of hot electron and is usually used to characterize hot-electron photodetection [53]. Here we use the theoretical model of Schottky barrier photodetection in the reference [53] to calculate the responsivity $R_{I,p}$, which has an excellent agreement with experimental results. The Schottky barrier is made of gold and n-type silicon.

Figure 6 depicts the change of spectrum of responsivity of hot-electron photodetection based on our tri-layered metamaterial with the horizontal spacing distance s_w when $s_h = 0$ nm and $s_t = 0$ nm. When s_w is increased from 150 to 279 nm, there are two peaks of responsivity, but they gradually approach each other. It indicates that our optical system is in an ideal PT-symmetric phase. However, when s_w is increased to be 279.01 nm, two peaks of responsivity coalesce to a single peak of responsivity, which corresponds to an exceptional point. With s_w being further increased, a single peak of responsivity is gradually decreased, which means that our optical system is in a PT-symmetry breaking phase. The change of spectrum of responsivity of hot-electron photodetection based on our tri-layered metamaterial with the horizontal spacing distance s_w is also calculated by using our theoretical model with the fitted parameters and the theoretical model in reference [53]. The theoretical results have a good agreement with the simulation ones. Therefore, hot-electron photodetection based on our tri-layered metamaterial can reflect that our optical system undergoes the spontaneous PT-symmetry breaking phase transition.

The change of spectrum of responsivity of hot-electron photodetection based on our tri-layered metamaterial

Figure 6: The change of spectrum of responsivity of hot-electron photodetection based on our tri-layered metamaterial with the horizontal spacing distance s_w . (A) and (B) correspond to the simulation and theoretical results, respectively.

Figure 7: The change of spectrum of responsivity of hot-electron photodetection based on our tri-layered metamaterial with the vertical spacing distance s_h .

(A) and (B) correspond to the simulation and theoretical results, respectively.

Figure 8: The change of spectrum of responsivity of hot-electron photodetection based on our tri-layered metamaterial with the relative phase difference θ between two coherent light beams. All of these are simulation results.

with the vertical spacing distance s_h when $s_w = 180$ nm and $s_t = 0$ nm is shown in Figure 7. It can be seen that our optical system has two peaks of responsivity, which are gradually coming closer to each other when s_h is gradually increased from 0 to 97 nm. This means that our optical system is in an ideal PT-symmetric phase. At $s_h = 97.1$ nm, two peaks of responsivity coalesce to a single peak of responsivity. It indicates that our optical system has an exceptional point. A single peak of responsivity is decreased when s_h is further increased, which shows that our optical system is in a PT-symmetry breaking phase. The theoretical results calculated by utilizing our theoretical model with the fitted parameters and the theoretical model in reference [53] are also illustrated in Figure 7B, which agree well with the simulation ones. This demonstrates that the spontaneous PT-symmetry breaking phase transition in our optical

system can be manifested in hot-electron photodetection based on our tri-layered metamaterial.

It is very significant to explore a dynamically tunable and switchable hot-electron photodetection. Figure 8 illustrates the change of spectrum of responsivity of hot-electron photodetection based on our tri-layered metamaterial with the relative phase difference θ between two coherent light beams when $s_w = 150$ nm, $s_h = 0$ nm, and $s_t = 0$ nm. It can be found that there are two peaks of responsivity in the frequency range of interest, in which the one on the right is slightly higher than the other on the left. This can be understood from the fact that the quantum efficiency of emission of hot-electron absorbing photon of high frequency is higher than that of the hot-electron absorbing photon of low frequency. With the relative phase difference θ increased from 0 to π by a step of $\pi/8$, two peaks

Figure 9: The change of spectrum of responsivity of hot-electron photodetection based on our tri-layered metamaterial with the relative phase difference θ between two coherent light beams. All of these are theoretical results.

of responsivity are gradually decreased and are finally vanished. When relative phase difference θ is π , some small fluctuations in the spectrum of responsivity may originate from the numerical errors. This intriguing property originates from the active tunability of CPA with light in our tri-layered metamaterial and is highly desired in many applications. The change of spectrum of responsivity of hot-electron photodetection based on our tri-layered metamaterial with the relative phase difference θ is also calculated by using our theoretical model with the fitted parameters and the theoretical model in reference [53], the results of which are shown in Figure 9. The theoretical results are consistent with the simulation ones. Therefore, a dynamically tunable and switchable hot-electron photodetection can be realized in our tri-layered metamaterial only by altering the relative phase difference between two coherent incident light beams.

5 Conclusion

In conclusion, we have theoretically and numerically demonstrated that the spontaneous PT-symmetry breaking phase transition can be achieved respectively by tuning the horizontal or vertical spacing distance between two subwavelength metaatoms in a designed tri-layered metamaterial. This tri-layered metamaterial is composed of square lattice of radiating and nonradiating metaatoms, which are made up of metal-semiconductor Schottky junctions. A theoretical model is obtained by using the coupled mode theory, which gives the existence

conditions of PT symmetry and its phase transition in our tri-layered metamaterial. An intriguing hot-electron photodetection is theoretically and numerically demonstrated and proposed, in which the spontaneous PT-symmetry breaking phase transition can be directly manifested in the photocurrent and the dynamical tunability and switchability can be obtained with light. This work extends the concept of PT-symmetry into hot-electron photodetection, enriches the functionality of metamaterial and hot-electron devices, and has numerous significant applications in optoelectronics, photodetection, photovoltaics, and photochemistry.

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