Research article

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Phase-coupled simultaneous coherent perfect absorption and controllable hot-electron photodetection in Schottky junction metamaterial

<https://doi.org/10.1515/nanoph-2019-0407>

Received October 7, 2019; revised November 19, 2019; accepted December 4, 2019

Abstract: We report a new type of coherent perfect absorption that is determined by the phase coupling between metaatoms and is referred to as the phase-coupled simultaneous coherent perfect absorption (PC-SCPA) for antisymmetric and symmetric incidences and especially the PC-SCPA for antisymmetric and symmetric incidences can be simultaneously achieved in the same bi-layered Schottky junction metamaterial possessing the phase coupling. Our proposed mechanism exploits the phase coupling between metaatoms, which is in contrast with the existing mechanism which depends on the near-field coupling. The theory of PC-SCPA is provided using coupled mode theory with the phase coupling. The operating wavelengths of PC-SCPA are insensitive to the variations of the spacing distances between metaatoms in the lateral and vertical directions. An infrared PC-SCPA-based hot-electron photodetection with dynamically switchable operating wavelengths and dynamically tunable bandwidth is theoretically and numerically verified in the same bi-layered Schottky junction metamaterial. The peak of spectrum of responsivity for antisymmetric and symmetric incidences can be switched to the same wavelength only by altering the phase coupling. Our study may build the bridge among the new type of PC-SCPA, metamaterial, and hot electron and may find potential and significant applications in hot-electron photodetection.

Keywords: metamaterial; phase-coupled simultaneous coherent perfect absorption; controllable hot-electron photodetection.

1 Introduction

Metamaterial, which is a kind of artificial microstructured material, has gained great interest in nanoscience and has provided us with an unprecedented way to manipulate the light and more degrees of freedom to control the properties of materials at will [1–9]. Different from natural materials that exist in nature, the properties of metamaterials are dominated by their microstructures. A lot of fascinating optical effects and phenomena have been demonstrated in various metamaterials, such as negative index of refraction [10, 11], cloaking [12, 13], optical black hole [14, 15], and superresolution imaging [16, 17]. However, bulk metamaterial usually has a large loss, which restricts its application, especially in optical regime. In order to reduce the loss of metamaterial while retaining sufficient tunability, bi-layered metamaterial has been proposed, which has more advantages, for example, less loss and easier fabrication. Many interesting applications utilizing bi-layered metamaterials have been achieved [18–21]. Meanwhile, active optical device is highly desired. Coherent perfect absorption (CPA), as one of the schemes to achieve the control with light, has been realized in a variety of metamaterials [22–31]. However, so far CPA is hardly studied in optical or acoustic systems that have the phase coupling.

Hot electron, which is the energetic electron absorbing photon in metal, has become a hot research topic in the past decade due to its unique significance in infrared photodetection. In contrast to the common photodetection based on electron transition across the bandgap of semiconductor, hot-electron photodetection depends on electron jumping across the Schottky barrier formed at the metal–semiconductor interface and can operate in infrared regime where an infrared photon usually has energy below the bandgap. Strong electromagnetic resonance can greatly enhance the absorption of photons by electrons and benefit hot-electron photodetection [32]. A great number of hot-electron photodetections and devices have been realized in various plasmonic

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nanostructures and metamaterials, which efficiently convert photon into electron [33–44]. Hot-electron photodetection can be tuned in graphene-silicon Schottky junctions where the junction bias can modulate the Schottky junction [45–47]. However, so far the operating wavelength and bandwidth of hot-electron photodetection based on plasmonic metamaterial cannot be dynamically switched and tuned with light.

In this paper, a new type of PC-SCPA for antisymmetric and symmetric incidences is proposed. Especially, the PC-SCPA for antisymmetric and symmetric incidences can be simultaneously achieved in the same bi-layered Schottky junction metamaterial possessing the phase coupling. Our proposed mechanism exploits the phase coupling in contrast to the near-field coupling. The detailed theory of PC-SCPA is given based on coupled mode theory with the phase coupling. The evolutions of operating wavelengths of PC-SCPA with the spacing distances between metaatoms are investigated in detail, the behaviors of which exhibit the interesting insensitivity to the variations of the lateral and vertical spacing distances. Furthermore, an infrared PC-SCPA-based hot-electron photodetection is theoretically and numerically verified in the same bi-layered Schottky junction metamaterial. Its operating wavelengths can be dynamically switched, and its operating bandwidth can be dynamically tuned. The peak of spectrum of responsivity for antisymmetric and symmetric incidences can be switched to the same wavelength only by altering the phase coupling. Our study may join the new type of PC-SCPA, metamaterial, and hot electron and may find various important applications in hot-electron photodetection.

2 Theory of phase-coupled simultaneous coherent perfect absorption

Let us consider an optical system that consists of two bright metaatoms respectively located on two different planes separated by certain spacing distance d along the direction of light propagation. Two counterpropagating coherent light beams are normally incident on this optical system from two sides. We assume that both bright metaatoms are the same and can be simultaneously excited by two coherent light beams, and no polarization conversion occurs between input and output. Therefore, this optical system has the phase coupling

between bright metaatoms, which makes it completely different from the previously studied optical or acoustic systems which consist of either a bright and a dark metaatoms that are all located on the same single plane or a single bright metaatom that is located on a single plane along the direction of light or sound propagations [25–28]. Before implementing this optical system possessing the phase coupling, we first give the theory of this optical system possessing the phase coupling from a microscopic point of view. A microscopic theoretical model embodying the phase coupling is built using coupled mode theory with the phase coupling [48, 49], which analytically characterizes the dynamics of our optical system possessing the phase coupling and can directly show how each factor works and how much it contributes.

$$\begin{pmatrix} \omega - \omega_0 - i(\gamma + \Gamma) & -\kappa - i\gamma \exp(-i\varphi) \\ -\kappa - i\gamma \exp(-i\varphi) & \omega - \omega_0 - i(\gamma + \Gamma) \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = \begin{pmatrix} \sqrt{\gamma} & \sqrt{\gamma} \exp(-i\varphi) \\ \sqrt{\gamma} \exp(-i\varphi) & \sqrt{\gamma} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} \quad (1a)$$

$$\begin{pmatrix} \sqrt{\gamma} & \sqrt{\gamma} \exp(-i\varphi) \\ \sqrt{\gamma} \exp(-i\varphi) & \sqrt{\gamma} \end{pmatrix}^+ \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = \begin{pmatrix} i & 0 \\ 0 & i \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} - \begin{pmatrix} 0 & i \exp(i\varphi) \\ i \exp(i\varphi) & 0 \end{pmatrix} \begin{pmatrix} O_1 \\ O_2 \end{pmatrix} \quad (1b)$$

where $+$ denotes the conjugate transpose. $A_{1(2)}$ represents the amplitudes of resonant modes of two bright metaatoms, respectively. $I_{1(2)}$ and $O_{1(2)}$ indicate the amplitudes of input and output lights from two sides, respectively. ω_0 , γ , and Γ are the resonant angular frequency, scattering and dissipating loss rates of the bright metaatom, respectively. κ and $\varphi = kd$ represent the near-field and phase couplings between two bright metaatoms, respectively. Two bright metaatoms interact with each other through the phase and near-field couplings. The phase coupling φ comes from the propagating fields emitted by the bright metaatoms, and the near-field coupling κ comes from the evanescent fields of the bright metaatoms. In the following, we will demonstrate in our proposed optical system the phase coupling dominates the interaction between two bright metaatoms.

Absorption plays an important role in various optical systems. It has been a long-term desire to dynamically manipulate the absorption of light in an optical system. CPA provides a route to achieve this goal and has been investigated in various optical or acoustic systems that do not possess the phase coupling [25–28]. Therefore, it

is very interesting to study whether or not the CPA can be achieved in our optical system possessing the phase coupling. Following from the above microscopic theoretical model with the phase coupling and $O_{1(2)} = 0$ and $I_{1(2)} \neq 0$, the effective Hamiltonian of our optical system possessing the phase coupling can be analytically derived as

$$\begin{pmatrix} \omega_0 - i(\gamma - \Gamma) & \kappa - i\gamma \exp(i\varphi) \\ \kappa - i\gamma \exp(i\varphi) & \omega_0 - i(\gamma - \Gamma) \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = \omega \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} \quad (2)$$

As CPA can only arise at real eigenfrequencies, we will explore the conditions under which the eigenfrequencies of the above effective Hamiltonian are real. To simplify the analytical derivation, the bright metaatom is assumed to have equal scattering and dissipating loss rates, i.e. $\gamma = \Gamma$. Thus, two eigenfrequencies of our optical system can be analytically derived as $\omega_0 + \kappa - i\gamma \exp(i\varphi)$ and $\omega_0 - \kappa + i\gamma \exp(i\varphi)$, which correspond to two eigenvectors (1, 1) and (-1, 1), respectively. These two eigenfrequencies show that the CPA in our optical system is controlled by the phase coupling φ between bright metaatoms and can only arise at some discrete phase couplings, i.e. $\varphi = n\pi/2$, $n = 1, 3, \dots$. This feature is completely different from the existing common CPA that does not depend on the phase coupling [25–28]. Especially, when the phase coupling φ is equal to $n\pi/2$, $n = 1, 3, \dots$, two above eigenfrequencies become real at the same time. This feature means that the CPA for antisymmetric and symmetric incidences can be simultaneously achieved in the same optical system possessing the phase coupling and is also completely different from the existing common CPA that cannot simultaneously arise for antisymmetric and symmetric incidences in the same optical or acoustic systems [25–28]. The real eigenfrequencies of our optical system can be physically understood from that the incident lights interact with our optical system through the scattering loss rate γ , which provide energy into our optical system and thus can be thought of as an effective gain. When the conditions of $\gamma = \Gamma$ and $\varphi = n\pi/2$, $n = 1, 3, \dots$ are satisfied, the effective gain provided by the incident lights fully compensates for the dissipating loss of our optical system. The CPA for antisymmetric and symmetric incidences in our optical system is determined by the phase coupling between bright metaatoms and thus is referred to as PC-SCPA for antisymmetric and symmetric incidences, which cannot be predicted by and is in contrast with the existing common CPA that does not involve the phase coupling at all [25–28]. Symmetric and antisymmetric incidences correspond to two eigenvectors (1, 1) and (-1,

1), respectively. The analytical expressions for reflection and transmission coefficients of our optical system possessing the phase coupling can be derived from

$$\begin{pmatrix} 0 & i\exp(i\varphi) \\ i\exp(i\varphi) & 0 \end{pmatrix} \begin{pmatrix} r_{11} & t_{12} \\ t_{21} & r_{22} \end{pmatrix} = \begin{pmatrix} i & 0 \\ 0 & i \end{pmatrix} - \begin{pmatrix} \sqrt{\gamma} & \sqrt{\gamma} \exp(-i\varphi) \\ \sqrt{\gamma} \exp(-i\varphi) & \sqrt{\gamma} \end{pmatrix}^+ \times \begin{pmatrix} \omega - \omega_0 - i(\gamma + \Gamma) & -\kappa - i\gamma \exp(-i\varphi) \\ -\kappa - i\gamma \exp(-i\varphi) & \omega - \omega_0 - i(\gamma + \Gamma) \end{pmatrix}^{-1} \times \begin{pmatrix} \sqrt{\gamma} & \sqrt{\gamma} \exp(-i\varphi) \\ \sqrt{\gamma} \exp(-i\varphi) & \sqrt{\gamma} \end{pmatrix} \quad (3)$$

in which $r_{11(22)}$ represents the reflection coefficient from port 1(2) to port 1(2), and $t_{12(21)}$ denotes the transmission coefficient from port 2(1) to port 1(2). The analytical expressions that can be obtained from our microscopic theoretical model with the phase coupling are very useful and efficient tools for analyzing and designing the experiments of our optical system.

3 Realization and discussion of phase-coupled simultaneous coherent perfect absorption

The schematic illustration of our designed optical system possessing the phase coupling and its structure parameters are sketched in Figure 1, which consists of a square lattice of two identical bright metal-semiconductor Schottky junctions separated by certain spacing distance along the direction of light propagation. The lattice constant of the square lattice is 326 nm. The nanostrip is a type of plasmonic nanoantenna, which can provide the strong electric dipolar resonance and has more tunable degrees of freedom to achieve the balanced scattering and dissipating loss rates. The numerical simulations are performed with the finite-difference time-domain method. Periodic boundary conditions are used for the x and y directions. The input light is emitted from the input port with the electric field along the y direction, and the output light with the same polarization is calculated at the output port. All of the parameters of the materials come from the experimental data. The semiconductor and metal are taken to be silicon and gold, respectively, which are widely used in the nanofabrication of artificial microstructured materials. The relative permittivity of silicon

Figure 1: Schematic illustration of the designed optical system possessing the phase coupling.

(A) Two counterpropagating coherent light beams are normally incident on the optical system from two sides. The purple part denotes two counterpropagating coherent light beams. (B) The structure of its unit cell. The green and yellow parts respectively indicate semiconductor and metal.

is 12.2972. The relative permittivity of gold is described by a Drude model $\epsilon_r = \epsilon_\infty - \omega_p^2 / (\omega^2 + i\gamma_p\omega)$ with $\epsilon_\infty = 9$, $\omega_p = 1.3673 \times 10^{16}$ Hz, and $\gamma_p = 1.0027 \times 10^{14}$ Hz [50]. The metal-semiconductor Schottky junctions are in a dielectric matrix which is transparent in our interested frequency range and is assumed to be the vacuum. Because of the center symmetry and reciprocity of our optical system, the reflection and transmission coefficients become $r_{11} = r_{22} = r$ and $t_{12} = t_{21} = t$, respectively.

Figure 2 illustrates the spectral of reflection and absorption coefficients of a single bright metaatom when $h_a = 171$ nm, $w_a = 20$ nm, and $t_a = 20$ nm. A single resonant mode exists at the frequency of 248.24 THz, at which the absolute values of reflection and absorption coefficients $|r|$ and $|a|$ reach 0.5. This is a macroscopical fingerprint of a balanced bright metaatom, which is microscopically determined by the condition of the scattering and dissipating loss rates being equal to each other. Therefore, our microscopic theoretical model with the phase coupling is more essential and more superior than the prediction from macroscopic reflection and transmission properties, as it can directly reveal the deeply underlying physics and the various deterministic factors behind the macroscopical optical phenomena. Additionally, the simulated result is fitted using our microscopic theoretical model with the phase coupling, which gives $\gamma = 43.5$ THz and $\Gamma = 43.5$ THz. This further quantitatively demonstrates that our designed bright metaatom has identical scattering and dissipating loss rates, which is one of conditions required by the above theory of our optical system possessing the phase coupling. Figure 3 shows the distributions of electric and magnetic fields on the y - z plane at the resonant frequency of 248.24 THz. It can be seen that the resonance at the frequency of 248.24 THz is an electric dipolar resonance of localized surface plasmon. The metal-semiconductor

Schottky junction can be regarded as the plasmonic nanoantenna, which has an electric dipolar resonance shown in both reflection and absorption spectrums. The enhanced fields around/in the metaatom can benefit both absorption of photons and generation of hot electron.

The evolution process of spectrum of phase-coupled coherent absorption (PC-CA) of our designed optical system possessing the phase coupling for antisymmetric incidence when the phase coupling φ increases from $\pi/2$ to $3\pi/2$ by a step of $\pi/4$ is shown in Figure 4. For antisymmetric incidence, the PC-CA coefficient can be obtained from the above reflection and transmission coefficients as $a_{as} = 1 - |r - t|^2$. The PC-SCPA only arises when φ is equal to $\pi/2$ and $3\pi/2$. This is because the eigenfrequency of our optical system corresponding to the eigenvector $(-1, 1)$ becomes real when φ takes these two values of $\pi/2$ and $3\pi/2$. With increasing φ from $\pi/2$ to $3\pi/2$, the peak of PC-CA experiences a blue-shift, and the operating frequency of PC-SCPA is switched from 241.2 THz to 255.28 THz. The same evolution process of spectrum of PC-CA of our optical system possessing the phase coupling is analytically calculated using our microscopic theoretical model with the phase coupling. The theoretical results, which are illustrated in Figure 4, are in excellent agreement with those of the simulation.

For symmetric incidence, the PC-CA coefficient can be obtained as $a_s = 1 - |r + t|^2$. Figure 5 depicts the evolution process of spectrum of PC-CA of our optical system possessing the phase coupling with the φ being increased from $\pi/2$ to $3\pi/2$ by a step of $\pi/4$. Similar to the antisymmetric incidence case, the PC-SCPA also only arises when φ is equal to $\pi/2$ and $3\pi/2$. This is also because the eigenfrequency of our optical system corresponding to the eigenvector $(1, 1)$ becomes real when φ takes these two values of $\pi/2$ and $3\pi/2$. In contrast to the antisymmetric incidence case, the peak of PC-SCPA experiences a

Figure 2: The change of reflection and absorption coefficients of a single bright metaatom with incident frequency. (A) Absolute value, (B) real and (C) imaginary parts of reflection coefficient, and (D) absorption coefficient. Blue line and red circle respectively denote theoretical and simulation results.

Figure 3: Distributions of the electric and magnetic fields on the y - z plane at the frequency of 248.24 THz for normally incident y polarized light. (A) and (B) show the distributions of the electric and magnetic fields, respectively. The black solid line outlines the metaatom.

red-shift and switches from 255.5 THz to 241.42 THz as φ increases from $\pi/2$ to $3\pi/2$. Specially, the PC-SCPA completely vanishes when φ is equal to π . This is because two symmetric coherent light beams completely cancel each other at the positions of two bright metaatoms because of destructive interference when φ is equal to π .

The corresponding theoretical results analytically calculated using our microscopic theoretical model with the phase coupling are shown in Figure 5, which agree well with those of the simulation. Therefore, the PC-SCPA for antisymmetric and symmetric incidences can be simultaneously achieved in our designed optical system

Figure 4: The spectrum of PC-CA of the designed optical system possessing the phase coupling as a function of the phase coupling φ for antisymmetric incidence.

The left and right columns respectively show simulation and theoretical results.

Figure 5: The spectrum of PC-CA of the designed optical system possessing the phase coupling as a function of the phase coupling φ for symmetric incidence.

The left and right columns respectively show simulation and theoretical results.

possessing the phase coupling. The operating frequencies of PC-SCPA for antisymmetric and symmetric incidences can be switched to the same frequency only by varying the phase coupling φ by a step of π in our optical system possessing the phase coupling. In contrast to the optical or acoustic systems that do not have the phase coupling, which are usually composed of single-layered metamaterial [25–28], the generation of PC-SCPA in our optical system possessing the phase coupling, which consists of bi-layered metamaterial, is determined by the phase coupling φ between bright metaatoms. These above fascinating optical properties can be physically understood from that when two identical metaatoms are placed together, two new eigenmodes will be generated due to the interactions between plasmonic resonances of two metaatoms, which correspond to two different eigenfrequencies $\omega_0 - \kappa - \gamma$ and $\omega_0 + \kappa + \gamma$, respectively. These two new eigenmodes can be selectively excited using antisymmetric or symmetric incidences, which can be used to dynamically switch the operating wavelengths of hot-electron photodetection and to dynamically tune the operating bandwidth of hot-electron photodetection.

The spectrum of PC-SCPA for antisymmetric and symmetric incidences in our optical system possessing the phase coupling as a function of the lateral spacing distance w when $h=0$ nm and $\varphi=\pi/2$ is illustrated in Figure 6. Only a single peak of PC-SCPA exists in our interested frequency range for both antisymmetric and symmetric incidences. When w is increased from 0 to 150 nm, for antisymmetric incidence, the peak of PC-SCPA is almost never shifted, and the operating frequency of PC-SCPA remains around 241.2 THz. Similarly, for symmetric incidence, the peak of PC-SCPA is also almost never shifted, and the operating frequency of PC-SCPA is kept around 255.5 THz. These simulation results have been confirmed by theoretical calculations using our microscopic theoretical model with the phase coupling, which are depicted in Figure 6B and D. Both simulation and theoretical results are very consistent with each other. This can be understood from that two eigenfrequencies of our optical system respectively become $\omega_0 - \kappa - \gamma$ and $\omega_0 + \kappa + \gamma$ for antisymmetric and symmetric incidences under the condition of the above given geometric parameters. For our designed optical system possessing the phase coupling,

Figure 6: The spectrum of PC-SCPA of the designed optical system possessing the phase coupling as a function of the lateral spacing distance w for antisymmetric and symmetric incidences, respectively. (A) and (C) are simulation results for antisymmetric and symmetric incidences, respectively. (B) and (D) are theoretical results for antisymmetric and symmetric incidences, respectively.

the magnitudes of both resonant angular frequency ω_0 and scattering loss rate γ are much larger than that of near-field coupling κ . Therefore, two eigenfrequencies are dominated by both resonant angular frequency ω_0 and scattering loss rate γ , both of which are constants in our optical system. The near-field coupling κ varies from 0.94 THz to 0.77 THz as w increases from 0 to 150 nm.

Figure 7 shows the spectrum of PC-SCPA for antisymmetric and symmetric incidences in our optical system possessing the phase coupling as a function of the vertical spacing distance h when $w=0$ nm and $\varphi=\pi/2$. For both antisymmetric and symmetric incidences, only a single peak of PC-SCPA occurs in our interested frequency range, which corresponds to one of the eigenmodes of our optical system. The peak of PC-SCPA is almost never shifted and remains around 241.2(255.5) THz for antisymmetric and symmetric incidences, respectively, when h increases from 0 to 150 nm. The corresponding theoretical results utilizing our microscopic theoretical model with the phase coupling are shown in Figure 7B and D, which are very consistent with those of the simulation. This can be also understood from that two eigenfrequencies

of our optical system become $\omega_0 - \kappa - \gamma$ and $\omega_0 + \kappa + \gamma$ for antisymmetric and symmetric incidences, respectively. The magnitude of near-field coupling κ is much smaller than the magnitudes of both resonant angular frequency ω_0 and scattering loss rate γ , both of which are constants and dominate two eigenfrequencies in our designed optical system possessing the phase coupling. The near-field coupling κ is altered from 0.94 THz to -0.94 THz as h is raised from 0 to 150 nm, which is in contrast with the case of changing the lateral spacing distance w . This might be understood from that the near-field coupling κ between metaatoms might be proportional to the interaction between the fields from metaatoms. The interacting fields undergo a change in sign as h is raised from 0 to 150 nm because the signs of the fields will change along the height of metaatom due to the electric dipolar resonance of metaatom. However, for the above case of changing the lateral spacing distance w , the interacting fields will not undergo a change in sign as w increases from 0 to 150 nm.

As can be seen from the above results, the peaks of PC-SCPA for antisymmetric and symmetric incidences in

Figure 7: The spectrum of PC-SCPA of the designed optical system possessing the phase coupling as a function of the vertical spacing distance h for antisymmetric and symmetric incidences, respectively. (A) and (C) are simulation results for antisymmetric and symmetric incidences, respectively. (B) and (D) are theoretical results for antisymmetric and symmetric incidences, respectively.

our optical system possessing the phase coupling exhibit the interesting insensitivity when w and h are tuned, respectively. This feature cannot be predicted by and is in contrast with the existing common CPA that does not involve the phase coupling at all [25–28], relaxes the alignment between metaatoms on two different planes, and benefits the experimental realization of our designed optical system. Additionally, these above interesting results also demonstrate that two eigenmodes of our optical system possessing the phase coupling can be selectively excited using antisymmetric or symmetric incidences. This feature cannot be achieved by the optical or acoustic systems that do not have the phase coupling [25–28]. These two eigenmodes are not magnetic resonances as they can only be excited by the electric field of input light and their eigenfrequencies will not be changed when increasing the lateral and vertical spacing distances between metaatoms in the same unit cell. Our proposed optical system can be experimentally fabricated using a variety of advanced nanofabrication processes and technologies. For example, the silicon part of metaatom may be achieved by using plasma-enhanced chemical vapor deposition followed by electron beam lithography and reactive ion etching. The metal part of metaatom may be obtained using electron beam lithography followed by electron beam evaporation and lift-off process.

4 Application of phase-coupled simultaneous coherent perfect absorption

These above unique features of PC-SCPA in our optical system possessing the phase coupling can find significant application in hot-electron photodetection. The structure of hot-electron photodetection based on the PC-SCPA is depicted in Figure 8. The metaatoms made of gold and n-silicon are placed in a dielectric matrix which is non-conductive and can be made of any transparent dielectric in our interested frequency range, for example, silicon dioxide, and so on. The ultrathin transparent conductive plane only contacts gold or n-silicon, which is Ohmic contact, is used to collect hot electron which is injected from gold into n-silicon and may be made of transparent conductive oxide (e.g. ITO), transparent carbon nanotube, n-silicon, and so on [51]. In the optical simulation, the dielectric is assumed to be the vacuum and the very small effect of the ultrathin

Figure 8: Schematic illustration of hot-electron photodetection based on the PC-SCPA in our optical system possessing the phase coupling.

(A) The structure of hot-electron photodetection. (B) The right view of hot-electron photodetection. (C) The top view of hot-electron photodetection.

transparent conductive plane is neglected as both the dielectric and the ultrathin transparent conductive plane are transparent in our interested frequency range, the thickness of the ultrathin transparent conductive plane is much smaller than the wavelength of incident light, and the ultrathin transparent conductive plane has a very small effect on the optical properties of the metaatoms in our interested frequency range. These assumptions will not affect the correctness of all of the results. The same results can be achieved when the dielectric is changed and the very small effect of the ultrathin transparent conductive plane is taken into account as the PC-SCPA can be achieved by tuning the geometric parameters of the metaatoms and unit cell when the dielectric is changed and the very small effect of the ultrathin transparent conductive plane is taken into account. The hot electrons in gold, which jump across the Schottky barrier formed at the interface between gold and n-silicon and enter the n-silicon, are collected by the ultrathin transparent conductive plane which is Ohmic contact with gold or n-silicon. The responsivity R of hot-electron photodetection is calculated using the theoretical model of Schottky barrier photodetection proposed in Ref. [52] as follows:

$$R = \frac{qA\eta}{h\nu} \quad (4a)$$

$$\eta = \frac{1}{h\nu} \int_{\Phi_B}^{h\nu} P(E) dE \quad (4b)$$

$$P(E) = P_0 + (1 - P_0)P_1 + \dots + P_n \prod_{m=0}^{n-1} (1 - P_m) \quad (4c)$$

where q represents the elemental charge, A is the absorption, η denotes the internal quantum efficiency, h indicates the Planck's constant, ν is the frequency of light, Φ_B denotes the Schottky barrier energy, $P(E)$ represents the total emission probability of hot electron with the initial excess energy E , $P_m = 1/2(1 - \sqrt{\Phi_B/E_m})$ indicates the emission probability of hot electron with the excess energy $E_m = E \exp(-2mt/L)$, t is the thickness of metal, L denotes the mean free path of hot electron in the metal, and $n = (L/2t) \ln(E/\Phi_B)$ represents the total number of round trips. The Schottky barrier energy Φ_B between gold and n-silicon is taken to be 0.8 eV, and the mean free path L of hot electron in gold is 74 nm. Figure 9 shows the internal quantum efficiency of hot-electron photodetection based on the PC-SCPA as a function of incident frequency. It can be found that the internal quantum efficiency η is greater than zero only when the energy of incident photon is greater than the Schottky barrier energy Φ_B .

Figure 10 illustrates the spectral of responsivity of hot-electron photodetection based on the PC-SCPA in our optical system possessing the phase coupling for antisymmetric and symmetric incidences when the lateral and vertical spacing distances w and h are 0 nm but the phase coupling φ is equal to $\pi/2$ and $3\pi/2$, respectively. For antisymmetric incidence, when the phase coupling φ is $\pi/2$, a single peak of responsivity exists at the frequency of 244.28 THz. This peak of responsivity is switched to 256.82 THz when the phase coupling φ is altered to $3\pi/2$. For symmetric incidence, the only

Figure 9: The internal quantum efficiency of hot-electron photodetection based on the PC-SCPA in our optical system possessing the phase coupling as a function of incident frequency.

single peak of responsivity is switched from 257.48 THz to 244.28 THz while the phase coupling φ is changed from $\pi/2$ to $3\pi/2$. These peaks of responsivity originate from the combined effect of the peaks of PC-SCPA and internal quantum efficiency in our optical system possessing the phase coupling. The spectral of responsivity are also calculated using our microscopic theoretical model with the phase coupling and the theoretical model of Schottky barrier photodetection [52], the results of which are shown in Figure 10. The theoretical results have an excellent agreement with those of the simulation. Therefore, a hot-electron photodetection for both antisymmetric and symmetric incidences can be realized in our optical system possessing the phase coupling, and its peak of responsivity for both antisymmetric and symmetric incidences can be switched to the same frequency by only changing the phase coupling φ from $\pi/2$ to $3\pi/2$.

These above intriguing features that the PC-SCPA can be simultaneously achieved for antisymmetric and symmetric incidences in the same optical system with the phase coupling can enrich the functionality of hot-electron photodetection by dynamically tuning relative phase difference between two counterpropagating coherent light beams. The spectrum of responsivity of hot-electron photodetection based on the PC-SCPA in our optical system possessing the phase coupling as a function of relative phase difference between two coherent incident light beams when the lateral and vertical spacing distances w and h and the phase coupling φ are respectively equal to 100 nm, 0 nm, and $\pi/2$ is depicted in Figure 11. When the relative phase difference θ is equal to 0, a single peak of responsivity arises at the frequency of 257.48 THz. With increasing relative phase difference θ from 0 to π , the peak of responsivity at the frequency of 257.48 THz gradually decreases and finally disappears, but the other peak of responsivity at the frequency of 244.28 THz gradually increases and finally arises when the relative phase difference θ is altered to π . Specially, when the relative phase difference θ is altered from 0 to $5\pi/8$, the bandwidth of full width at half maximum of the spectrum of responsivity is dynamically tuned from 26.84 THz to 39.6 THz, which is needed in some applications, due to the simultaneous excitation of two eigenmodes in our optical system. The same evolution process of the spectrum of responsivity of our PC-SCPA-based hot-electron photodetection is obtained in the theoretical results calculated using our microscopic theoretical model with the phase coupling and the theoretical model of Schottky barrier photodetection [52], illustrated in Figure 11. Both theoretical and simulation results have a great agreement with each other.

Figure 10: The responsivity of hot-electron photodetection based on the PC-SCPA in our optical system possessing the phase coupling as a function of incident frequency when the phase coupling φ is equal to $\pi/2$ and $3\pi/2$, respectively.

(A) and (B) are results for antisymmetric and symmetric incidences, respectively, when the phase coupling φ is equal to $\pi/2$. (C) and (D) are results for antisymmetric and symmetric incidences, respectively, when the phase coupling φ is equal to $3\pi/2$. Simulation and theoretical results are respectively shown on top and at the bottom.

Figure 11: The spectrum of responsivity of hot-electron photodetection based on the PC-SCPA in our optical system possessing the phase coupling as a function of relative phase difference between two counterpropagating coherent light beams. Simulation and theoretical results are shown in the upper and lower panels, respectively.

Therefore, an infrared PC-SCPA-based hot-electron photodetection that has dynamically switchable operating wavelengths and dynamically tunable operating bandwidth can be achieved in our optical system possessing the phase coupling.

Based on the above discussions, the PC-SCPA-based hot-electron photodetection in our optical system possessing the phase coupling might be used to retrieve the relative phase difference between two coherent incident light beams, as there is a one-to-one correspondence between the spectrum of responsivity and relative phase difference in our PC-SCPA-based hot-electron photodetection, which can be observed in Figure 11. First, a spectrum of responsivity is obtained by our PC-SCPA-based hot-electron photodetection in our optical system possessing the phase coupling. Second, this obtained spectrum of responsivity is reproduced by our microscopic theoretical model with the phase coupling and the theoretical model of Schottky barrier photodetection [52] utilizing the relative phase difference as the only tuned variable.

Both the dynamically switchable operating wavelengths and the dynamically tunable operating bandwidth achieved in the hot-electron photodetection based on the PC-SCPA in plasmonic metamaterial cannot be obtained by the hot-electron photodetection based on the existing common CPA in plasmonic metamaterial [25–28], which can only achieve the amplitude tunability of responsivity from the finite value to zero and by the hot-electron photodetection based on the single-port perfect absorption in plasmonic metamaterial [53], which can hardly achieve the dynamical tunability.

5 Conclusion

To summarize, we have presented a new type of PC-SCPA for antisymmetric and symmetric incidences and especially the PC-SCPA for antisymmetric and symmetric incidences can be simultaneously achieved in the same bi-layered Schottky junction metamaterial that has the phase coupling. Our proposed mechanism exploits the phase coupling between metaatoms, which is very different from the existing mechanism which depends on the near-field coupling. The theory of PC-SCPA in our optical system possessing the phase coupling is provided by using the coupled mode theory with the phase coupling. The operating wavelengths of PC-SCPA for antisymmetric and symmetric incidences are insensitive to the variations of the lateral or vertical spacing distances. An infrared PC-SCPA-based hot-electron photodetection that has dynamically switchable operating wavelengths and dynamically tunable bandwidth has been theoretically and numerically achieved in the same bi-layered Schottky junction metamaterial. The peak of spectrum of responsivity for antisymmetric and symmetric incidences can be switched to the same wavelength only by altering the phase coupling. Our study may bridge the new type of PC-SCPA, metamaterial, and hot electron and may enable various potential applications in hot-electron photodetection.

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