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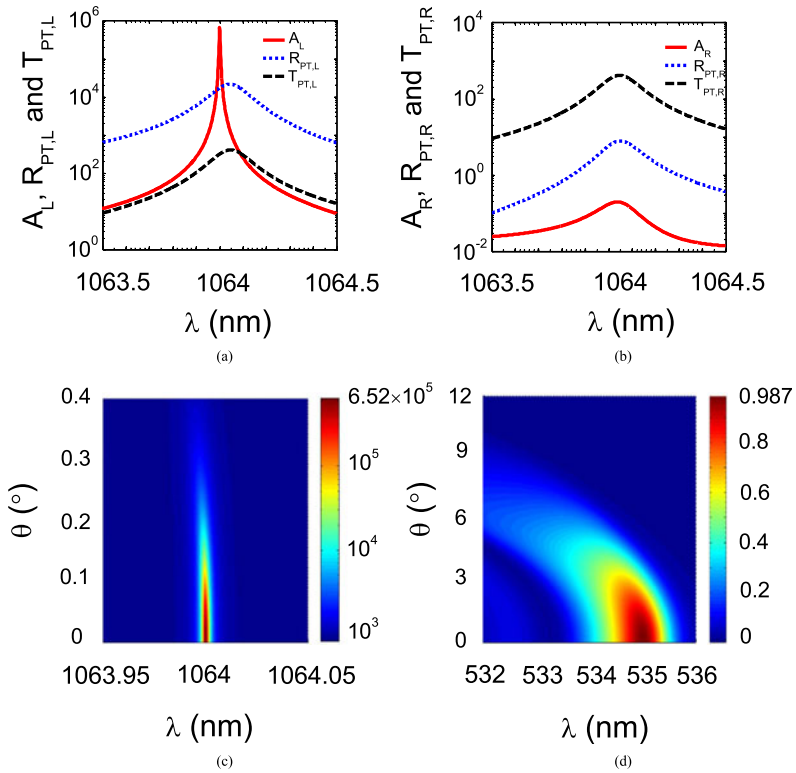

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Ultrastrong Graphene Absorption Induced by One-Dimensional Parity-Time Symmetric Photonic Crystal

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Abstract: A novel microcavity structure based on 1-D parity-time (PT) symmetric photonic crystal (PC) is presented to get the embedded monolayer graphene absorption enhanced significantly, which paves a path to achieve ultrastrong, controllable, and anisotropic graphene absorption for incident eigenfrequency wave from near infrared to visible. When oscillation of absorption is at the center of the PT broken phase, because of exact matching usage of gain and loss modulation, and singular strong coupling effects that are induced by the PT symmetric PC behind graphene layer, ultrastrong and nonreciprocal graphene absorption can be obtained, and the maximum could reach the order of 10^5. This approach offers a way to improve the responsivities of graphene-based optodetectors and even to the design of direction sensitive graphene optical communication components.

Index Terms: Parity time symmetry, absorption, photonic crystal.

1. Introduction

With its wide variety of excellent optical and electrical properties, graphene has been one of the most important research topics over the decade since its experimental realization [1]. This atomic thickness 2-D semiconductor monolayer offers high transmittance and low absorptance for light waves in the range from near infrared to visible [2], which means that it could be used to form flexible displays, transistors, mode-locked ultrafast lasers and other graphene-based optoelectronic devices [3]–[6]. However, graphene's weak absorption can seriously limit its application areas and performance, and thus, numerous models have been proposed in an attempt to increase the interaction between light and graphene; among the proposed models, cavity-like structures based on graphene-photonic crystals (PCs) were widely studied [7]–[9]. Graphene layer in the structure can be considered as a defect, and enhanced photon localization, which was attributed to strong

Bragg oscillation, has emerged in this monolayer, the enhanced localization may allow higher or even complete graphene absorption to be obtained [10]–[12].

From quantum mechanics, one knows that Hamiltonian should be hermitian because the eigenvalues of Hamiltonian ought to be real numbers; otherwise, they can not be detective. However, in 1998 Bender and Boettcher found that even if Hamiltonians are non-hermitian after an operation of parity and time symmetric inversion transformation, all the eigenvalues could be still real numbers when the potential functions are below the thresholds, while imaginary eigenvalues will appear only if the potential functions exceed the thresholds [13]. Therefore the symmetry of a Hamiltonian experienced a parity and time symmetric inversion transformation is usually described as parity-time symmetry (PT symmetry), and the potential function corresponds to the Hamiltonian should be complex conjugated. PT symmetry has attracted much attention in mechanics, optics, material science and acoustics, etc. In 2007, El-Ganainy introduced this concept into optics through making the refractive index and nonlinear Schrodinger equation in optics correspond to the potential function and Hamiltonian equation in quantum mechanics [14]. From then on PT symmetric system has been studied extensively, and many intriguing physical phenomena have been observed using this judiciously designed system [15]–[18], including Bloch oscillation of energy [15], coherent perfect absorbers in laser cavities [16], and non-Hermitian optical transmission [17], [18]. Additionally, 1-D PT symmetric PCs have also been discussed in depth; in this structure with balanced gain and loss, the complex refractive indices of the layers along light propagation direction meet the optical PT symmetric condition $n(z) = n^*(-z)$ [19]. A plane wave in this 1-D double-port system has only two eigenvectors, and where two patterns coincidence, a PT threshold point then exists; this point is known as an exceptional point (EP). Due to abrupt phase change near EPs, photons that traverse through PT symmetric systems will experience both gain and loss, and anisotropic amplified and attenuated resonances could be generated [16], [20]–[22]. In acoustics, one can make the bulk modulus and mass density being complex conjugate to form a PT acoustic structure [23], [24]. Recently, the one-way invisible 2-D PT symmetric acoustic ground cloak was designed and the perfect sensing in 1-D acoustic PT symmetric lattice was also studied [23], [24].

In this paper, we present a 1-D graphene-PT symmetric PC microcavity that can significantly enhance the absorption of embedded monolayer graphene. In a PT symmetric PC, electromagnetic waves will produce significant gain and loss resonant coupling effects, and then the intensities of reflective and transmissive light of the PT symmetric PC will be greatly increased. Consequently, the enhanced electromagnetic waves can increase the absorption of graphene enormously. We obtain ultrastrong graphene absorption, particularly when the resonance of the absorption occurs at the center of PT broken phase. Absorptance is a complex function of the materials, and is dependent on the imaginary modulation strength, the thickness of layers and the number of PT symmetric unit cells, along with the wavelength, direction and angle of incidence of the light. For example, when we set 1064 nm as an eigenwavelength, the maximum absorptance can reach the order of 10^5. Interestingly, absorption also exhibits a directional response for light incident from the opposite direction. Our approach can be used to obtain remarkably improved responsivities in graphene based components such as ultrafast optical detectors and sensors, and is likely to have broad application prospects in the design of orientation sensitive optical devices, such as graphene based unidirectional communication components.

2. Model and Theory

Before studying the model shown in Fig. 1, we first consider the PT symmetric lattices that are composed of N periodic BCD unit-cells, denoted by $(BCD)^N$, which are embedded in a homogeneous SiO_2 background [25], and all layers are nonmagnetic. For our designed structure, the PT symmetric lattice can be realized experimentally by two ways. In order to make the refractive indices of the two basic layers be complex conjugate, one method is doping gain and loss materials and the other is modulating the density of materials [18], [26]. In this paper, we make use of the former and set the three kinds of layers B, C, and D as the gain-doped SiO_2, MgF_2 and loss-doped SiO_2 [25], respectively, and the refractive indices of both B and D are complex conjugated [19], where λ

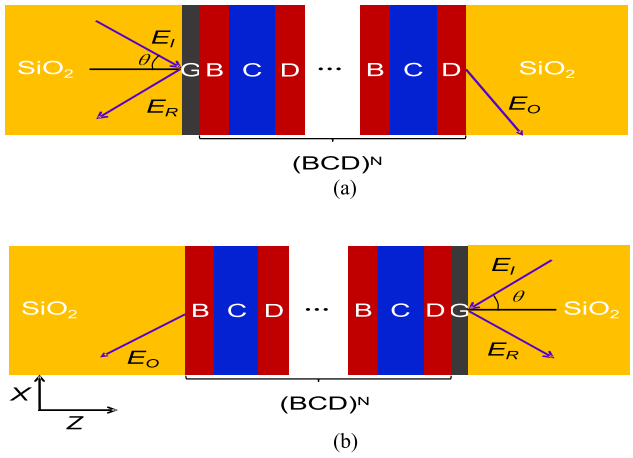

Fig. 1. Schematic of graphene layer prepared at the front of a PT symmetric PC, G is graphene, and $(BCD)^N$ is the PT symmetric PC. (a) and (b) Waves propagate from the left side and the right side, respectively.

is the wavelength of the incident light. Using the transfer matrix method (TMM) [27], [28], we can obtain the transfer matrix of a PT symmetric PC containing *3N* layers in the form

$$M_{\mathrm{PT}} = \prod_{j=1}^{3N} \begin{bmatrix} \cos(k_j n_j d_j) & -\imath \sin(k_j n_j d_j)/\eta_j \\ -\imath \eta_j \sin(k_j n_j d_j) & \cos(k_j n_j d_j) \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{1}$$

where $k_j = (2\pi/\lambda)\cos\theta_j$ and represents the wave vector in the *j*-th layer. θ_j is the angle of incidence, n_j is the refractive index, d_j is the thickness, and η_j is the admittance of the *j*-th layer; $\eta_j = n_j \cos\theta_j$, and η_0 is the admittance of the background media. The reflection and transmission coefficients are given as:

$$r_{\mathrm{PT}} = \frac{(M_{11} + M_{12}\eta_0)\eta_0 - (M_{21} + M_{22}\eta_0)}{(M_{11} + M_{12}\eta_0)\eta_0 + (M_{21} + M_{22}\eta_0)}$$
$$t_{\mathrm{PT}} = \frac{2\eta_0}{(M_{11} + M_{12}\eta_0)\eta_0 + (M_{21} + M_{22}\eta_0)}. \tag{2}$$

Then, the reflectance $R_{\mathrm{PT}} = |r_{\mathrm{PT}}|^2$ and transmittance $T_{\mathrm{PT}} = |t_{\mathrm{PT}}|^2$ can be obtained, respectively.

3. Numerical Results and Discussions

We set the thicknesses of layers B, C, and D to be 109.4 nm, 154 nm, and 109.4 nm, respectively, when the double characteristic wavelengths are fixed at 1064 nm and 535 nm. Assuming that a perturbation parameter ρ is introduced to describe the gain-loss modulation strengths of layers B and D, then the dielectric constants of B, C, and D can be written as $\varepsilon_B(\lambda, \rho) = \varepsilon_{\mathrm{SiO_2}}(\lambda) - \imath\rho$, $\varepsilon_C(\lambda) = \varepsilon_{\mathrm{MgF_2}}(\lambda)$ and $\varepsilon_D(\lambda, \rho) = \varepsilon_{\mathrm{SiO_2}}(\lambda) + \imath\rho$.

As shown in Fig. 2, based on an estimate of the semi-trace of the transfer matrix, we can generate the bandgaps of the PT symmetric PC in terms of their dependence on λ and ρ near 1064 nm and 535 nm. The Bloch wave vector will change into complex from real as ρ increases up to a threshold, denoted by ρ_{PT}, and the gaps of periodic multilayers become narrower before finally disappearing. This EP marks the point at which two eigenstates of original continuous spectrum merge into one state, and the system will then experience a phase transition with zero bandwidth of resonance

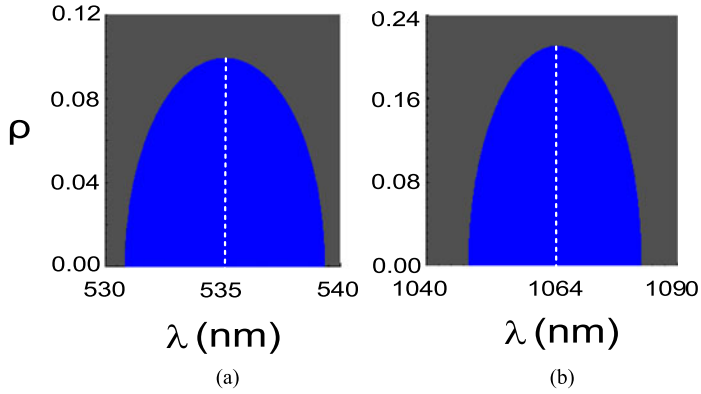

Fig. 2. Bandgaps of PT symmetric PC vary with wavelength and the modulation strength of gain-loss (ρ) of layers B and D. Dark gray region and blue region are the bands and the gaps, respectively.

[20], [21]. From Fig. 2, we can see that $\rho_{PT,1} = 0.1981(\rho_{PT,2} = 0.1053)$ for $\lambda_{PT,1} = 1064$ nm ($\lambda_{PT,2} = 535$ nm). Therefore, the dielectric constants of B and D involve only wavelength or frequency in Lorentz formula can be obtained as [18]

$$\varepsilon'(\lambda) = \varepsilon_{SiO_2}(\lambda) + \sum_m C'_m / \left(\omega_m^2 - \omega^2(\lambda) - \imath\gamma\omega(\lambda)\right)$$

$$C'_m = \frac{\rho_{PT,m}\gamma\lambda_{PT,m}}{2\pi} \quad (m = 1, 2) \tag{3}$$

where $\omega = 2\pi/\lambda$ is angular frequency of the incident wave, ω_m is center frequency and the relaxation parameter γ is 10^{14}. For layer B, $C'_m < 0$, and for layer D, $C'_m > 0$. For example, when two light beams enter separately at wavelengths of 1064 nm and 535 nm, the refractive indices of layers B, C and D are $1.4650 - 0.0676\imath$, 1.3732 and $1.4650 + 0.0676\imath$ for the former wavelength, whereas $1.4746 - 0.0356\imath$, 1.3789 and $1.4746 + 0.0356\imath$ for the latter wavelength. The phases are changed by π and 2π for 1064 nm and 535 nm waves respectively, when they traverse one unit-cell length.

The scattering matrix (S matrix) is often used to emphasize the scattering processes of PT symmetric and broken behaviors in a PT system. We set the system is at PT symmetric phase when the two eigenvalues of the S matrix are unimodular, but different from most scattering processes, the PT structure violates traditional conservation law; we also set the system is at PT broken phase when the magnitudes of the S matrix eigenvalues are reciprocal, one is greater than 1 and the other is less than 1 [30]. When the system is exactly at the center of PT broken phase, magnitude difference between the two eigenvalues is maximum.. Additionally, the S matrix of a 1-D PT symmetric PC can be expressed as $S_{PT} = [r_{PT,L}\ t_{PT};\ t_{PT}\ r_{PT,R}]$ [16], [29], [30], in which $r_{PT,L(R)}$ denotes the reflection coefficient for left (right) incidence. The two eigenvalues α_{PT} and β_{PT} are [30]

$$\alpha_{PT}, \beta_{PT} = \frac{r_{PT,L} + r_{PT,R} \pm \imath\sqrt{(2\imath t_{PT})^2 - (r_{PT,L} - r_{PT,R})^2}}{2} \quad (|\alpha_{PT}\beta_{PT}| = 1). \tag{4}$$

As the existence of different time delays for photons traversing in the gain regions and the loss regions, the system has unequal reflection coefficients and identical transmission coefficients for incidences in opposite directions, and the traditional photon flux conservation $R_{PT} + T_{PT} = 1$ is invalidated. Simultaneously, a generalized pseudounitary conservation relation has been developed [30]:

$$\sqrt{R_{PT,L}R_{PT,R}} = |T_{PT} - 1| \tag{5}$$

where $R_{PT,L(R)} = |r_{PT,L(R)}|^2$, and $T_{PT} = |t_{PT}|^2$. Obviously, this system is either bidirectionally or unidirectionally reflectionless, with complete transparency when $R_{PT,L}R_{PT,R} \to 0$. In contrast, the system

may also undergo amplified bidirectional or unidirectional reflection with magnified transmission, and thus the entire PT symmetric structure could be regarded as a unique amplifier. Based on the conservation relation and Eq. (5), a criterion that involves only transmittance and reflectance for estimation of the degree to which a PT scattering system is broken can be deduced as $\Delta = \frac{R_{PT,L} + R_{PT,R}}{2} - T_{PT}$ [30]. If $\Delta < 1$, then $|\alpha_{PT}| = |\beta_{PT}| = 1$, and the system is in a PT symmetric phase. However, if $\Delta > 1$, and $|\alpha_{PT}| = 1/|\beta_{PT}| \neq 1$, the system is in a PT broken phase, where $\Delta = 1$ is the PT phase transition boundary. Traditionally, the errors produced by the TMM method cannot be ignored when the number of layers is greater than 1000. To ensure that these types of errors are in the negligible range, we calculate and compare the totals of propagation matrix elements in three cases ($3N =$ 267, 531 and 1593) with double precision and single precision, respectively. Our results show that the errors may be enlarged for increasing numbers of layers, but the errors of T, R and the matrix elements are all of the order of less than 10^{-15}, i.e., they are still negligible.

Dielectric constant of graphene can be generated using $\varepsilon_G(\lambda) = 1 + \imath \frac{\sigma_G(\lambda)}{d_G \varepsilon_0 \omega(\lambda)}$, where the thickness of graphene monolayer d_G is 0.34 nm, and the conductivity $\sigma_G(\lambda) = \sigma_{inter}(\lambda) + \sigma_{intra}(\lambda)$, where σ_{inter} and σ_{intra} are the interband and intraband conductivities of graphene, respectively; when $\hbar\omega \gg k_B T$ and $|\mu_C| \gg k_B T$, their expressions can be deduced to be [31]

$$\sigma_{inter}(\lambda) = \imath \frac{e^2}{4\pi\hbar} \ln \frac{2|\mu_c| - \hbar(\omega(\lambda) + \imath/\tau)}{2|\mu_c| + \hbar(\omega(\lambda) + \imath/\tau)},$$
$$\sigma_{intra}(\lambda) = \imath \frac{e^2 k_B T}{\pi\hbar^2(\omega(\lambda) + \imath/\tau)} \left[\frac{\mu_c}{k_B T} + 2\ln\left(e^{-\frac{\mu_c}{k_B T}} + 1 \right) \right] \tag{6}$$

where $\mu_C = 0.5$ eV is chemical potential energy, $\tau = 0.5$ ps represents the relaxation time of graphene sheet, and $T = 300$ K is tempreture.

As shown in Fig. 1, graphene can be regarded as a perturbation defect to the original periodic structure when it is placed at the front of the PT symmetric PC. Because of the exact matching usage of gain and loss modulation, and the strong coupling effects, interactions between light and graphene could be enhanced enormously. Total transfer matrix of the structure shown in Fig. 1 can be deduced to be $M_0 = M_G M_{PT}$, where M_G is the propagation matrix of graphene layer. First, one can use Poynting vectors to calculate the absorption in graphene layer as [9]

$$A = \frac{(S_0^+ - S_0^-) - (S_{PT}^+ - S_{PT}^-)}{S_0^+} \tag{7}$$

where S_0^+ and S_0^- represent the total incident and reflected Poynting vectors of the entire structure, respectively, and S_{PT}^+ and S_{PT}^- represent the incident and reflected Poynting vectors of the PT symmetric PC, respectively. This equation can be transformed as

$$A = 1 - \frac{S_0^-}{S_0^+} - \frac{S_{PT}^+}{S_0^+}\left(1 - \frac{S_{PT}^-}{S_{PT}^+}\right). \tag{8}$$

If the total reflection coefficient and transmission coefficient of the entire structure are r_0 and t_0, while the reflection coefficient and transmission coefficient of the PT symmetric PC are r_{PT} and t_{PT}, and the transmitted Poynting vector of the entire structure is S_{sub}^+ respectively, according to previous definitions, one can generate that

$$|r_0|^2 = \frac{S_0^-}{S_0^+}, \quad |t_0|^2 = \frac{S_{sub}^+}{S_0^+}, \quad |r_{PT}|^2 = \frac{S_{PT}^-}{S_{PT}^+} \text{ and } |t_{PT}|^2 = \frac{S_{sub}^+}{S_{PT}^+}. \tag{9}$$

Then the absorptance expression for the graphene layer involves only reflection and transmission coefficients can be deduced as

$$A_{L(R)} = 1 - |r_{0,L(R)}|^2 - \frac{|t_0|^2}{|t_{PT}|^2}\left(1 - |r_{PT,L(R)}|^2\right). \tag{10}$$

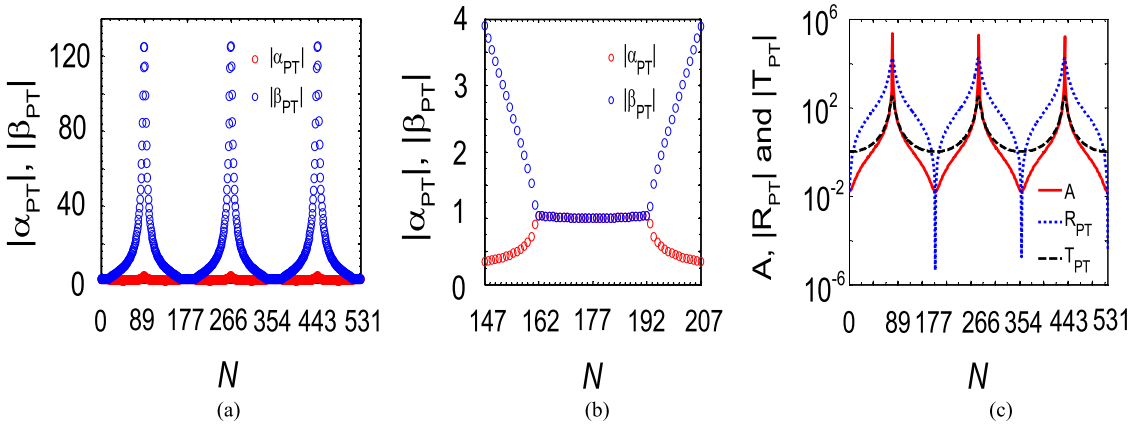

Fig. 3. (a) Modulus of eigenvalues $|\alpha_{PT}|$ and $|\beta_{PT}|$ vary with number of periods N increasing from 0 to 531. (b) Partial enlarged view of (a) when N increases from 147 to 207. (c) Absorptance of graphene (A, red line), reflectance (R_{PT}, blue dotted line), and transmittance (T_{PT}, black short line) of PT symmetric PC vs N and waves propagate from the left side.

In the following, the effects of number of periods of the PT symmetric PC N on the modulus of eigenvalues and graphene absorptance A are evaluated, and the results are as shown in Fig. 3, where the normally incident 1064 nm light is from left side. As shown in Fig. 3(a), both $|\alpha_{PT}|$ and $|\beta_{PT}|$ exhibit periodicity as N increases, and the new period is $P = 177$. If $N = N_0 + JP$ ($N_0 = 89$, and J is a natural number), then the resonance of the PT symmetric PC is generated, while the antiresonance will be generated when $N = JP$. From the viewpoint shown in Fig. 3(b), when $|N - JP| \leq 15$, the PC is in PT symmetric phase; if $|N - JP| = 15$ ($N > 0$), then the PC enters/leaves the PT symmetric phase; finally, if $N = JP$, then the PC is at the exact PT symmetric phase center, and the system will experience a minimum oscillation. In contrast, when $N = N_0 + JP$, the PT symmetric PC is at the center of PT broken phase exactly, $|\alpha_{PT}|$ and $|\beta_{PT}|$ experience inversion mutations, and the system will experience the strongest possible oscillation. As a result, the maximum A could be up to the order of 10^5 when $N = N_0 + JP$, and A shows approximate periodicity with increasing N.

Taking the wavelengths of 1064 nm and 535 nm wavelengths as examples, we simulate that how the direction and angle of incidence can affect graphene absorption in this structure, where $N = 89$. First, graphene absorptance is investigated in the scenario where normally incident light at a wavelength close to 1064 nm enters from the left and the right separately, and reflection and transmission of the PT symmetric PC are also calculated (see Fig. 4(a) and (b)). We then illustrate effect of the angle of incidence on A when 1064 nm and 535 nm waves enter obliquely from the left and the right, respectively (see Fig. 4(c) and (d)). From Fig. 4(a) and (b), one can obtain that at the wavelength of 1064 nm, the reflectance and absorptance from the left and the right are non-exchangeable. Numerical results for wave incidence from the left are $R_L = 2.1213 \times 10^4$, $T_L = 405.9902$ and $A_L = 6.5207 \times 10^5$. The corresponding results for wave incidence from the right are $R_R = 7.7319$, $T_R = 405.9902$ and $A_R = 0.1982$. Because of the exact matching usage of gain and loss modulation, and singular strong coupling effects that are induced by PT symmetric PC behind graphene layer at the center of PT broken phase, maximum graphene absorbance can reach the order of 10^5. This extraordinary but directionally nonreciprocal graphene absorption may have wide-ranging prospects for application to the design of special functional all optical devices. Additionally, the system will deviate from the center of PT broken phase as the angle increases, and thus the absorptance would undergo a drastic attenuation.

Substantially, the absorptance of graphene in our designed structure can reach the order of 105, the main reason is that the system is exactly set at the center of PT broken phase. From Fig. 3 one knows that the parameter configuration in this work satisfies that the system is at the center of PT broken phase exactly for incident wave from the left at 1064 nm wavelength, and only when

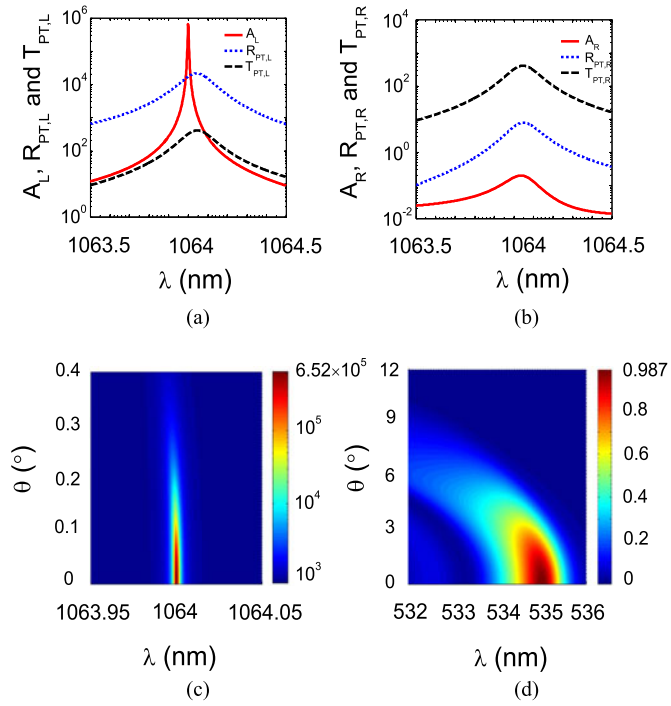

Fig. 4. (a) and (b) Absorptance of graphene (A, red line), reflectance (R_{PT}, blue dotted line), and transmittance (T_{PT}, black short line) of the PT symmetric PC, dependence of the direction (left/right) of incident light at the wavelength near $\lambda_{PT,1} = 1064$ nm, and where $N = 89$. (c) and (d) Absorptance of graphene A vs the angle of incident light θ at the wavelength near $\lambda_{PT,1} = 1064$ nm and $\lambda_{PT,2} = 535$ nm when the incident waves are from the left side and the right side, respectively.

the system is at this phase, incident wave of the PT symmetric PC at 1064 nm from the left can experience strongest gain and loss resonant coupling effect, then the intensities of reflective and transmissive light will be increased greatly, and the enhanced electromagnetic waves will improve the absorption of graphene enormously (see Fig. 4(a) and (c)). If the system is a bit deviated from this phase, gain and loss coupling effect will be decreased rapidly and resonance can no longer be caused, the singularities of the system will not be such apparent. The absorptance also shows noreciprocity, is because when the incident light is from the other side, the system is no longer at the center of PT broken phase, and it will not lead strong absorption of graphene (see Fig. 4(b) and (d)). Additionally, it is known that absorption is mainly dependent on the imaginary modulation strength, consequently, when the imaginary part of refractive index of material changes slightly, the absorption will vary enormously. However, the perfect match of gain and loss, namely the system is just at the center of broken phase accurately and can produce the strongest gain and loss resonant coupling effect, is hard to fabricate in practice, and therefore, the theoretical absorptance being much larger than 1 may not be easy to realize.

Graphene absorption at telecommunication wavelengths has been explored extensively in recent years because of its obvious importance [11], [12]. Liu *et al.* reported experimental demonstrations of the critically coupled total absorption from monolayer graphene at the 1550 nm near-infrared wavelength range [11]. Piper *et al.* demonstrated total absorption in graphene at telecommunication wavelengths using critical coupling with the guided resonances of a photonic crystal slab [12]. We have also investigated graphene absorption in the common communication frequency band in this work. If some of the parameters are changed such that $d_B = d_D = 164.8$ nm, $d_C = 211.8$ nm, $\mu_C = 0.15$ eV, $\tau = 0.15$ ps and $N = 18$, while the other variables remain unchanged, the refractive indices achieve $n_B = 1.4656 - 0.1009\,\imath$, $n_C = 1.3705$, $n_D = 1.4656 + 0.1009\,\imath$, respectively. As shown in Fig. 4, the maximum absorptance reaches 2.5580 when the incident wave enters from left, while

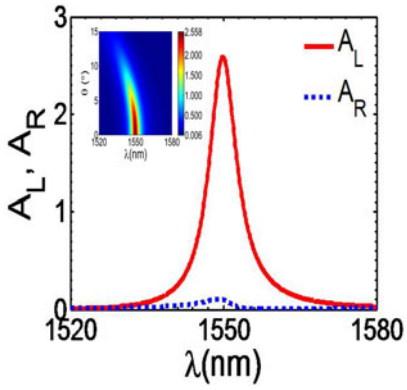

Fig. 5. Graphene absorption *A* at the telecommunication band when incident light from the left side (red line) and the right side (blue dotted line). The insert shows *A* dependence of the angle and the wavelength of incident light.

it becomes 0.1064 when the light is incident from the right (see Fig. 5), and the absorption angle could reach 10° (see insert). This directional communication behavior may provide a path towards the design of new graphene-based optical communication components.

4. Conclusion

In conclusion, using the TMM, we generated ultrastrong and nonreciprocal graphene absorption based on a novel PT symmetric PC microcavity. Due to the exact matching usage of gain and loss modulation, and singular strong coupling effects induced by PT symmetric lattices behind graphene at the center of PT broken phase, the maximum graphene absorptance can reach the order of 10^5. Additionally, the absorptance can be modulated by varying the materials used, the gain-loss modulation strength, the layer thicknesses, the number of unit cells used, and the wavelength, direction, and angle of incidence. This work thus offers a way to achieve controllable, extraordinary and ultrastrong graphene absorption. This interesting structure may contribute to enhancement of the responsivities of graphene photodetectors and sensors, and it represents a new path for the design of direction sensitive graphene communications devices.

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