Dynamically Tunable Plasmon-induced Transparency in Parallel Black Phosphorus Nanoribbons

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Research Article

Keywords: Plasmon-induced transparency, Black phosphorus, Radiating two-oscillator model, Finite Difference Time Domain method

Posted Date: November 10th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1018540/v1>

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Version of Record: A version of this preprint was published at Plasmonics on March 7th, 2022. See the published version at <https://doi.org/10.1007/s11468-022-01608-9>.

Dynamically tunable plasmon-induced transparency in parallel black phosphorus nanoribbons

Baojing Hu^{1,2}, Ming Huang², Sumei Hong¹, and Jingjing Yang²

Abstract

In this paper, we investigate the dynamically tunable plasmon-induced transparency (PIT) effects in parallel black phosphorus nanoribbons (BPNRs). The results show that the BPNRs having different lengths can be regarded as bright modes. Single-band, double-band, triple-band, and multi-band PIT effects based on the bright-bright mode coupling between parallel BPNRs are achieved. The physical mechanism of the single-band model can be explained theoretically by the radiating two-oscillator (RTO) model. Due to the heavier effective mass in the zigzag (ZZ) direction of the BP, the frequencies of the transparent peaks are shifted to lower frequencies when the placement directions of BPNRs are changed from the X-direction to the Y-direction. Furthermore, the resonant frequencies of the transparent windows in each model can be tuned by changing the relaxation rates of the BPNRs. The frequencies of the transparent windows are blue-shifted as the relaxation rates are increased. Finally, The corresponding sensors based on single-band PIT effect show high sensitivities of 7.35 THz/RIU. Our study has potential applications for improving the design of multiple-band filters, sensors and on-off switcher .

Keywords Plasmon-induced transparency. Black phosphorus. Radiating two-oscillator model. Finite Difference Time Domain method

Introduction

Plasmon-induced transparency (PIT), an electromagnetically-induced transparency (EIT)-like optical effect in metamaterials, is caused by the coupling between the bright mode and dark mode or the bright mode and bright mode [1]. This plasma phenomenon significantly changes the optical responses of the system and causes the appearance of a transparent window in the transmission spectrum. In recent years, PIT has been widely applied in the fields of optical filtering [2], sensing [3], slow light, and light conversion [4–6]. However, in practical applications, an active modulation of the transparent windows is necessary to control the optical responses dynamically and potentially expand the range of applications [7]. Because of the difficulties of active modulation in transparent windows, traditional metallic materials have been replaced by novel two-dimensional (2D) crystal metamaterials.

In recent years, black phosphorus (BP) has attracted extensive attentions as an alternative 2D material due to its excellent optical and electrical performances. Unlike graphene, the atoms in the BP

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material have a wrinkled hexagonal honeycomb structure, as shown in Fig. 1(a) [8–9]. Therefore, BP possesses larger conductivity in the armchair (AC) direction than in the zigzag (ZZ) direction, resulting in an anisotropic plasmonic response in the AC and ZZ directions [10–11]. Furthermore, the band gap of BP is related to the thickness of the material. The band gaps of bulk BP and monolayer BP are approximately 0.3 eV and 2.0 eV, respectively [12–13]. Because of the unique physical features of BP, the researches on tunable PIT effects by using BP have become a new research highlight [14–16]. For example, in 2021, Wu *et al.* realized a tunable single-band PIT effect based on the destructive interference between the bright and dark modes by using monolayer BP metamaterial. [17] Han *et al.* achieved a single-band PIT effect with large tunability and high Q-factor by using graphene and BP hybrid system [18]. Moreover, Chen *et al.* also designed a single-band PIT model in a monolayer BP metasurface based on near-field coupling between two bright modes [19]. However, to the best of our knowledge, utilizing parallel black phosphorus nanoribbons (BPNRs) to achieve tunable PIT effects has not been reported in the literature.

In this study, we achieved single-band, double-band, triple-band, and multi-band PIT effects based on bright-bright mode coupling by using parallel BPNRs with different lengths. The single-band PIT effect can be explained theoretically by the radiating two-oscillator (RTO) model. The resonant frequencies at the transmission peaks in all PIT models can be dynamically tuned by changing the relaxation rates of the BP. Due to the anisotropy of BP, the frequencies of the transparent peaks and transmission valleys are shifted to lower frequencies when the placement directions of the BPNRs are changed. Finally, the sensing performances and the relationships between transmission spectra and polarization angle θ of the incident light in single-band model are investigated.

Theoretical methods and single-band PIT model

The PIT effect based on bright-bright mode coupling can be explained theoretically by the radiating two-oscillator (RTO) model [20–21].

$$\ddot{p}_1(t) + \gamma_1 \dot{p}_1(t) + \omega_1^2 p_1(t) - \Omega^2 \exp(j\phi) p_2(t) = f_1(t) \quad (1)$$

$$\ddot{p}_2(t) + \gamma_2 \dot{p}_2(t) + \omega_2^2 p_2(t) - \Omega^2 \exp(j\phi) p_1(t) = f_2(t) \quad (2)$$

The first bright mode resonator is described by $p_1(t)$. Its resonant frequency is ω_1 , and its damping factor is γ_1 . The second bright mode resonator is described as $p_2(t)$. Its resonant frequency and damping factor are ω_2 and γ_2 , respectively. $\Omega^2 \exp(j\phi)$ is the complex coupling coefficient, and ϕ is the phase shift between the two bright mode resonators.

By assuming $p_1(t) = P_1 \exp(-j\omega t)$, $p_2(t) = P_2 \exp(-j\omega t)$, and $f_1(t) = f_2(t) = f \exp(-j\omega t)$, equations (1) and (2) in the frequency domain can be solved:

$$P_1 = \frac{\Omega^2 + (\omega_2^2 - \omega^2 - j\omega\gamma_2)}{(\omega_1^2 - \omega^2 - j\omega\gamma_1)(\omega_2^2 - \omega^2 - j\omega\gamma_2) - \Omega^4} f \quad (3)$$

$$P_2 = \frac{\Omega^2 + (\omega_1^2 - \omega^2 - j\omega\gamma_1)}{(\omega_1^2 - \omega^2 - j\omega\gamma_1)(\omega_2^2 - \omega^2 - j\omega\gamma_2) - \Omega^4} f \quad (4)$$

Under the approximation of a thin structure, the physical relationship between the electric current density J and the surface conductivity σ_e can be expressed as:

$$J = -jn_s\omega(P_1 + P_2) = \sigma_e E_s \quad (5)$$

where n_s and E_s denote the average electron density and spatially averaged electric field, respectively. If $f \propto E_s$, the surface conductivity σ_e can be solved by:

$$\sigma_e = -jn_s\omega \frac{2\Omega^2 + (\omega_2^2 - \omega^2 - j\omega\gamma_2) + (\omega_1^2 - \omega^2 - j\omega\gamma_1)}{(\omega_1^2 - \omega^2 - j\omega\gamma_1)(\omega_2^2 - \omega^2 - j\omega\gamma_2) - \Omega^4} \quad (6)$$

Once the surface conductivity is determined, the transmission coefficient of the metamaterial is:

$$T = \frac{2}{2 + Z_0\sigma_e} \quad (7)$$

where Z_0 is the wave impedance of the external wave. Finally, the transmissivity of the metamaterial can be determined by fitting the corresponding $|T|^2$.

The permittivity of a 2D BP layer can be characterized as a diagonal tensor [22]:

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix} \quad (8)$$

where ε_{xx} , ε_{yy} , and ε_{zz} denote the dispersion elements in the X-, Y-, and Z-directions, which can be expressed as

$$\varepsilon_{ii} = \varepsilon_r + \frac{j\sigma_{ii}}{\varepsilon_0\omega d} \quad (i = x, y, z) \quad (9)$$

where ε_r is the relative permittivity, which is 5.76 for the monolayer BP. ε_0 is free space permittivity. d represents the thickness of the BP layer. ω is the frequency of incident light. σ_{ii} is the surface conductivity, and $\sigma_{zz} \cong 0$. Based on the classical Drude model, the conductivity σ_{ii} of BP can be expressed as [9]:

$$\sigma_{ii} = \frac{jD_{ii}}{\pi(\omega + j\eta/\eta)} \quad (i = x, y) \quad (10)$$

where η is the reduced Planck constant, and η denotes the electron doping, which is 10 meV [23].

D_{ii} is the Drude weight, which is defined as:

$$D_{ii} = \frac{\pi e^2 n_s}{m_{ii}} \quad (11)$$

where e is the electron charge. n_s represents the relaxation rate. m_{ii} is the carrier effective mass in the X- and Y-directions, respectively, and can be described as:

$$m_{xx} = \frac{\eta^2}{2\gamma^2 / \Delta + \eta_c}, m_{yy} = \frac{\eta^2}{v_c} \quad (12)$$

For the monolayer BP with a scale length $a = 0.223 \text{ nm}$, the parameter values in equation (12) are $\gamma = 4a / \pi eVm$, $\eta_c = \eta^2 / (0.4m_0)$ and $v_c = \eta^2 / (0.7m_0)$; the band gap $\Delta = 2 \text{ eV}$, and for a standard electron rest mass, $m_0 = 9.10938 \times 10^{-31} \text{ kg}$ [24,25].

Fig. 1 (a) Different crystal structures of monolayer BP in the AC (x) and ZZ (y) directions. The real parts (b) and imaginary parts (c) of permittivity of BP in the X-direction. The real parts (d) and imaginary parts (e) of permittivity of BP in the Y-direction. The relaxation rates are changed from $0.2 \times 10^{14} \text{ cm}^{-2}$ to $1.4 \times 10^{14} \text{ cm}^{-2}$

Figure 1 (a) displays the staggered atomic structure of the monolayer BP. The X-axis and Y-axis represent the AC and ZZ crystal directions following the routine treatment.

Figure 1 (b-e) shows the real and the imaginary parts of the permittivity of BP with different relaxation rates. When the relaxation rates increase from $0.2 \times 10^{14} \text{ cm}^{-2}$ to $1.4 \times 10^{14} \text{ cm}^{-2}$,

$\text{Re}(\varepsilon_{xx})$ and $\text{Re}(\varepsilon_{yy})$ are negative, whereas $\text{Im}(\varepsilon_{xx})$ and $\text{Im}(\varepsilon_{yy})$ are positive. $\text{Re}(\varepsilon_{xx})$ is smaller than $\text{Re}(\varepsilon_{yy})$, and $\text{Im}(\varepsilon_{xx})$ is larger than $\text{Im}(\varepsilon_{yy})$. Most importantly, as the relaxation rates of BP increase, $\text{Re}(\varepsilon_{xx})$ and $\text{Re}(\varepsilon_{yy})$ decrease, and $\text{Im}(\varepsilon_{xx})$ and $\text{Im}(\varepsilon_{yy})$ increase. Therefore, the responses of the proposed PIT models in this study can be controlled by adjusting the relaxation rates of the BP.

The three-dimensional space schematics of single-band model are shown in Figs. 2(a) and (b). The dielectric layer is assumed to be a non-dispersive dielectric with a refractive index of 1.6 [14]. In Fig. 2(a), the parallel BPNRs are placed along the X direction. In Fig. 2(b), the placement direction of parallel BPNRs are changed to the Y direction. The two-dimensional perspective side views and plane schematics of Figs. 2(a) and (b) are shown in Figs. 2(c) and (d) respectively. In Fig. 2(a), the AC direction of BP is along X-axis. In the Fig. 2(b), the ZZ direction is along X-axis, indicating that the AC direction of BP is along Y-axis.

The period of a transverse in the structure is $P = 500 \text{ nm}$. It consists of four BPNRs in one transverse period. The geometric parameters of a pair of BPNRs in the first layer are the same as $W_1 = 200 \text{ nm}$. The geometric parameters of a pair of BPNRs in the second layer are $W_2 = 120 \text{ nm}$. The left and right intervals of twin BPNRs in both layers are $d_1 = 60 \text{ nm}$. The distance between twin BPNRs in two layers is $d_2 = 1 \mu\text{m}$. In the simulation, the thickness of BP is set to 1 nm .

The numerical calculations are performed by using the finite-difference time-domain (FDTD) method. The two-unit cells have periodic boundary conditions in the X- and Y-directions and perfectly matched layer (PML) absorbing boundary conditions in the Z-direction. The surface plasmon resonances are excited by incident transverse magnetic (TM) waves in the model.

Fig. 2 The three-dimensional space schematics of single-band model. (a) The BPNRs are placed along X direction. (b) The BPNRs are placed along Y direction. (c) The two-dimensional perspective side view and plane schematic of Fig. 2(a). (d) The two-dimensional perspective side view and plane schematic of Fig. 2(b)

Results and Discussions

Figure 3 shows the transmission spectra of the single-band PIT model. The relaxation rates of twin BPNRs in both layers are $n_s = 1.0 \times 10^{14} \text{ cm}^{-2}$. Fig. 3(a) shows the transmission spectrum of Fig. 2(a), and Fig. 3(b) shows the transmission spectrum of Fig. 2(b). As a reference, the transmission spectra of BPNRs in the two layers under the same E-field polarization are also given.

As shown in Figs. 3(a) and (b), regardless of the placement directions of BPNRs are in X-axis or Y-axis direction, all the single-band models in Figs. 2(a) and (b) present a distinct absorption peak. Meanwhile, all the BPNRs in first and second layers exhibit typical Lorentz line-shaped resonances; thus, the BPNRs can be regarded as bright modes that are excited by the incident light. Moreover, it is observed that the transmission dips of the PIT spectra are close to the initial resonant modes of the BPNRs. Therefore, based on the bright-bright mode coupling between the BPNRs in first and second layers, the model produces a single-band PIT effect that can be explained theoretically by the RTO model depicted in Fig. 5.

Furthermore, because of the instinct anisotropic structure of 2D BP, the permittivity along the AC and ZZ directions is different. Hence, the optical responses of the BP are also different in the AC and ZZ directions. As shown in Fig. 3(a), when the placement directions of the BPNRs are in the X-axis direction, a transmission peak occurs at 28.0905 THz, with two dips at 22.2111 THz and 33.5176 THz. However, as shown in Fig. 3(b), when the placement directions of the BPNRs are in the Y-axis direction, the peak (18.5930 THz) and the transmission valleys (14.0704 THz and 21.3065 THz) are

shifted to lower frequencies due to the heavier effective mass in the ZZ directions [15]. In the following content, we mainly discuss the results of single-band model in Fig. 2(a).

Fig. 3 The transmission spectra of first BPNRs layer, second BPNRs layer and single-band PIT model. (a) the placement directions of the two BPNRs layer are in the X-axis. (b) the placement directions of the two BPNRs layer are in the Y-axis

In order to investigate the electromagnetic mechanism of the single-band PIT model in Fig. 2(a), Fig. 4 shows the distributions of electric field intensity at the frequencies of dip I, dip II, and peak in Fig. 3(a).

As shown in Figs. 4(a) and (b), at dip I, only the BPNRs in the first layer is excited by the incident wave and produces a dipole, whereas BPNRs in the second layer is only weakly excited. In contrast, at dip II, only the BPNRs in the second layer is excited strongly by the incident light and produces a dipole, whereas BPNRs in the first layer is weakly excited. At the peak, the BPNRs in both layers are excited simultaneously to produce two dipoles. Therefore, a single-band PIT effect is produced by the bright-bright mode coupling between the BPNRs in first and second layers.

Fig. 4 The distributions of electric field intensity at frequencies of (a) dip I, (b) dip II and (c) peak when the placement directions of the BPNRs in both layers are in the X-axis

For the purpose of analyzing the tunability of the single-band PIT model in Fig. 2(a), Fig. 5 depicts the transmission spectra of the single-band PIT model at different relaxation rates and the results fitted by the RTO model.

As described above, the PIT effect based on the bright-bright mode coupling can be explained theoretically by the RTO model. As shown in Fig. 5, the numerical results calculated by the FDTD method at different relaxation rates are consistent with the theoretical results fitted by the RTO model, confirming that the single-band PIT effect is produced by bright-bright mode coupling between the twin BPNRs in first and second layers.

Furthermore, according to the perturbation theory [26–27], $\Delta\omega$ will be greater than 0 if $\Delta\varepsilon$ is less than 0, indicating that the dips and peak frequencies will be increased as the relaxation rates rise. As a result, when the relaxation rates of the BPNRs are changed from $0.8 \times 10^{14} \text{ cm}^{-2}$ to $1.4 \times 10^{14} \text{ cm}^{-2}$, the frequencies of dip I increase from 19.9 THz to 26.3 THz. The frequencies of dip II increase from 30.1 THz to 39.4 THz. Meanwhile, as the frequencies of dip I and dip II increase, the frequencies of the transparent peak also increase from 25.6 THz to 33.1 THz.

Therefore, the proposed single-band PIT model can be dynamically tuned by changing the relaxation rates of the twin BPNRs in first and second layers without changing the structure.

Fig. 5 The transmission spectra of the single-band PIT model at different relaxation rates and the results fitted by the RTO model. The relaxation rates of BPNRs are changed from $0.8 \times 10^{14} \text{ cm}^{-2}$ to $1.4 \times 10^{14} \text{ cm}^{-2}$

To evaluate the application potentials of the single-band PIT model as a refractive index sensor.

Fig. 6 shows the sensing performances of the model for different refractive indices of the surrounding medium. The relaxation rates of BPNRs in both layers are $n_s = 1.0 \times 10^{14} \text{ cm}^{-2}$.

As shown in Fig. 6(a), as the refractive index increases from 1.0 to 1.8, the dip I and peak exhibit a significant red-shift. The relationships between the refractive index and the frequencies of the dip I and peak are approximately linear (Fig. 6b).

The performance of a sensor usually can be evaluated by the sensitivity ($S = \Delta\lambda / \Delta n$). The sensitivity of dip I is 7.35 (THz/RIU), which is higher than the sensors in papers[28-32]. The sensitivity of dip II is only 0.29 (THz/RIU) because the BPNRs in second layer are in the dielectric layer, and the medium surrounding them is almost unchanged as the refractive indices of the surrounding medium increase.

Fig. 6 Sensing performances of single-band PIT model. (a) calculated transmission spectra, (b) The relationships between the refractive index and the frequencies of the dip I, dip II and peak

Finally, the relationships between transmission spectra and polarization angle θ of the incident light in single-band model are investigated. The polarization angle of the incident light shown in Fig. 7(a) is assumed to be the angle between the incident electric field direction and the X-axis direction.

As shown in Fig. 7(b), when the θ is changed from 0° to 90° , the resonant frequencies at transmission dips and peak remain basically unchanged, but the transmittance values at transmission dips increase, and the PIT effect is gradually weakened. As shown in Fig. 7(a), when the $\theta < 40^\circ$, the PIT effect is evident, and when the $\theta > 60^\circ$, the PIT effect is disappeared.

Fig. 7 The relationships between transmission spectra and polarization angle θ of the incident light. The polarization angle θ is defined by the illustration

Design and result of a tunable double-band PIT model

The plane schematics of tunable double-band PIT model are shown in Figs. 8(a) and (b). The dielectric layer is also assumed to be a non-dispersive dielectric with a refractive index of 1.6. In Fig. 8(a), the parallel BPNRs are placed along the X direction. In Fig. 8(b), the parallel BPNRs are placed along the Y direction. The two units can be obtained by adding a pair of BPNRs with different lengths based on the single-band PIT model shown in Fig. 2.

The period of a transverse in the structure is also $P = 500 \text{ nm}$. It is composed of six BPNRs in a period. The geometric parameters of a pair of BPNRs in the first layer are $w_1 = 200 \text{ nm}$. The lengths of two pairs of BPNRs in the second and third layers are $w_2 = 160 \text{ nm}$, and $w_3 = 120 \text{ nm}$ respectively. The left and right intervals of twin BPNRs in both layers are $d_1 = 60 \text{ nm}$. The distance between twin BPNRs in each layer is $d_2 = 1 \mu\text{m}$. The thickness of BP is also set to 1 nm . The incident light configuration is the same as in the single-band PIT model.

Fig. 8 The plane schematics of the proposed double-band PIT model. (a) The placement directions of the BPNRs are in the X-axis. (b) The placement directions of the BPNRs are in the Y-axis. The incident light configuration is the same as in the single-band PIT model

Figure 9 shows the transmission spectra of the double-band PIT model. The relaxation rates of twin BPNRs in both layers are also $n_s = 1.0 \times 10^{14} \text{ cm}^{-2}$. Fig. 9(a) shows transmission spectrum of Fig. 8(a), and the transmission spectrum of Fig. 8(b) is shown in Fig. 9(b). As a reference, the transmission spectra of the BPNRs in three layers under same E-field polarization are also shown.

In Figs. 9(a) and (b), two distinct transmission peaks are observed. Similar to the results in Fig. 3, all BPNRs produce Lorentz line-shaped resonances; therefore, all of them can also be regarded as bright modes. The transmission dips in the PIT spectra are also close to the initial resonant modes of the BPNRs. Thus, similar to the single-band PIT effect, the double-band PIT effect is achieved by the bright-bright mode coupling between the BPNRs in the first, second and third layers. Meanwhile, because of the heavier effective mass in the ZZ directions, the transmission peaks and valleys have also shifted to lower frequencies when the placement directions of BPNRs are changed. In the next, we mainly discuss the results of the double-band model shown in Fig. 8(a).

Fig. 9 The transmission spectra of the BPNRs in three layers and the double-band PIT model. (a) the placement directions of the BPNRs are in the X-axis. (b) the placement directions of the BPNRs are in the Y-axis

Figure 10 shows the distributions of electric field intensity at the frequencies of the three transmission dips and two transparent peaks in Fig. 9(a).

As shown in Figs. 10(a-c), since the dips I--III are close to the initial resonant modes of BPNRs in the first, second, and third layers respectively, Therefore, at dip I, the electric field has high values at the edge and end of the BPNRs in the first layer, exhibiting a typical electric dipole mode. At dip II, only the BPNRs in the second layer is excited by the incident wave to produce a dipole. At dip III, the electric field has high values around the BPNRs in the third layer, producing a dipole mode. Furthermore, at peak A, the BPNRs in the first and second layers are excited simultaneously to produce

two dipoles, and at peak B, the BPNRs in the second and third layers are excited simultaneously to produce two dipoles. Therefore, similar to the single-band PIT effect, the double-band PIT effect is produced by the bright-bright mode coupling between the BPNRs in the first, second and third layers.

Fig. 10 The distributions of electric field intensity at frequencies of (a) dip I, (b) dip II, (c) dip III, (d) peak A, and (e) peak B in Fig. 8(a)

Figure 11 shows the transmission spectra of the proposed double-band PIT model for different relaxation rates. As the relaxation rates of the BPNRs are increased, the frequencies of the three dips and two peaks in Fig. 9(a) are also blue-shifted.

When the relaxation rates of the BPNRs are changed from $0.8 \times 10^{14} \text{ cm}^2$ to $1.4 \times 10^{14} \text{ cm}^2$, the frequencies of dip I increase from 19.9497 THz to 26.5075 THz. The frequencies of dip II increase from 24.9246 THz to 32.6131 THz, and the frequencies of dip I increase from 29.8995 THz to 39.6231 THz.

Furthermore, as the relaxation rates of the BPNRs are increased, the frequencies of peak A increase from 22.6633 THz to 29.6734 THz, and the frequencies of peak B increase from 27.864 THz to 36.4573 THz.

Fig. 11 The transmission spectra of the proposed double-band PIT model for different relaxation rates. The relaxation rates of the BPNRs in three layers are changed from $0.8 \times 10^{14} \text{ cm}^{-2}$ to $1.4 \times 10^{14} \text{ cm}^{-2}$

Tunable multi-band PIT effects

The triple-band and four-band PIT effects can be achieved by continuing to add the layers of twin BPNRs having different lengths based on the double-band model.

Figure 12 shows The transmission spectra of the triple-band PIT model. The relaxation rates of BPNRs are still $1.0 \times 10^{14} \text{ cm}^{-2}$. The lengths of twin BPNRs in each layer are shown in Fig. 12(b). The placement directions of BPNRs in Fig. 12(a) are along X-axis direction and the placement directions of BPNRs in Fig. 12(b) are along Y-axis.

Figure 13 shows the variation laws of transmission spectra of triple-band PIT model when the n_s increases from $0.8 \times 10^{-14} \text{ cm}^{-2}$ to $1.4 \times 10^{-14} \text{ cm}^{-2}$. The BPNRs are placed along X-axis direction.

Figure 14 shows the transmission spectra of the four-band PIT model. In Fig. 14(a), the BPNRs are placed along X- direction. In Fig. 14(b), the BPNRs are placed along Y- direction.

Obviously, The physical mechanism and variation laws of transmission spectra in triple-band and four-band models are same as the single-band and double-band models.

Fig. 12 The transmission spectra of the proposed triple-band PIT model. **(a)** The placement directions of BPNRs are along X-axis direction. **(b)** The placement directions of BPNRs are along Y-axis direction. The relaxation rates of BPNRs are $1.0 \times 10^{14} \text{ cm}^{-2}$. The lengths of BPNRs in each layer are shown in Fig. 12(b)

Fig. 13 The variation laws of transmission spectra of triple-band PIT model when the n_s increases from $0.8 \times 10^{14} \text{ cm}^{-2}$ to $1.4 \times 10^{14} \text{ cm}^{-2}$

Fig.14 Transmission spectra of the four-band PIT model. (a) The BPNRs are placed along X direction. (b) The BPNRs are placed along Y direction. The relaxation rates of BPNRs are $1.0 \times 10^{14} \text{ cm}^2$. The lengths of BPNRs in each layer are shown in Fig. 14(b)

Conclusions

In summary, dynamically tunable single-band, double-band and multi-band PIT effects in parallel BPNRs are proposed due to the bright-bright mode coupling between BPNRs with different lengths. The physical mechanism of single-band can be explained by RTO model. Secondly, the dynamically tunable behavior is realized by changing the relaxation rates of the BPNPs. As the relaxation rates are increased, the resonant frequencies of the transmission peaks in each model are blue-shifted. The phenomena can be explained by the perturbation theory. Thirdly, because of the heavier effective mass in the ZZ direction, the frequencies of the transmission peaks and valleys are shifted to lower frequencies when the placement directions of BPNRs are changed from the X-direction to the Y-direction. Fourthly, as the refractive index increases from 1.0 to 1.8, the frequencies of the transmission peaks and valley in the single-band PIT model exhibit a significant red-shift, and the sensitivity can reach as high as 7.35 THz/RIU. Finally, the relationships between transmission spectra and polarization angle θ of the incident light in single-band model are investigated. When the $\theta < 40^\circ$, the PIT effect is evident, and when the $\theta > 60^\circ$, the PIT effect is disappeared. The results

of this study have potential applications for improving the designs of multiple-band filters sensors and on-off switcher.

Acknowledgements The authors would like to thank the reviewers for their thoughtful comments.

Author Contributions All authors contributed to the design and implementation of the research, analysis of the results, and the manuscript's preparation.

Data Availability All data generated or used during the study appear in the submitted article.

Declarations

Ethics Approval The authors assure that this material is the authors' own original work, which has not been previously published elsewhere. The paper is not currently being considered for publication elsewhere.

The paper reflects the authors' own research and analysis in a truthful and complete manner. The paper properly credits the meaningful contributions of co-authors and co-researchers. The results are appropriately placed in the context of existing research. All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

Consent to Participate All authors agreed to participate in this research.

Consent for Publication Permission from all the authors has been taken to publish this manuscript.

Competing Interests The authors declare no competing interests.

Funding This work was supported in part by National Natural Science Foundation of China (NSFC) (61461052, 11564044, 61863035).

Code Availability Not applicable.

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