Plasmonic biosensor based on excellently absorbable adjustable plasmon-induced transparency in black phosphorus and graphene metamaterials

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Abstract
Both black phosphorus (BP) and graphene metamaterials support surface plasmon resonance that is very sensitive to the local change of dielectric properties in the system. We design a novel BP ribbons and graphene sheet hybrid structures based on tunable mid-infrared plasmon-induced transparency. The destructive interference of two excited state modes in the structure leads to a pronounced induced transparent window, and the excellent absorption of the two channels is obtained. The transmission characteristics of the hybrid structures are theoretical calculation, and the results are in good agreement with the numerical simulation curve. The dynamic adjustment function can be realized by adjusting the carrier density of BP and the Fermi level of graphene, and the excellent absorption performance not affected within the adjustment range. Moreover, we found that the optical phase is rapid flips at the plasmon resonance position. Therefore, a sensing medium layer is added on top of the structure to implement a high-sensitivity plasmonic biosensor. This work may provide potential applications to plasmonic devices based on two-dimensional metamaterial.

1. Introduction

Surface plasmon resonance (SPR) is caused by the matching of the evanescent wavevector and material surface plasmon wavevector [1]. SPR has the unique optical properties of concentrating electromagnetic wave energy in the sub-wavelength range, provides opportunities for much interesting practical application research such as optical absorbers [2], plasmonic enhancement [3], optical modulators [4], switching [5], and sensing technology [6]. In particular, the application of SPR in the plasmon-induced transparency (PIT) has attracted extensive research and attention by scholars. PIT phenomenon is an optical response produced by the interaction of coherent light with matter, similar to the classical electromagnetic induction transparency (EIT) [7–9]. The PIT phenomenon provides a new possibility for implementing dual-channel absorbers [10]. Recent studies have shown that the phase information contained in the SPR-excited plasmonic can be used to implement and even replace traditional plasmonic sensing schemes [11, 12]. In fact, the phase-detection technology has dramatically reduced the detection limits of classic surface plasmon resonance sensors based on thin metal films [13, 14]. The high sensitivity of the plasmonic sensor is mainly due to the rapid phase flips at the resonance wavelength position [15]. However, excellent and highly sensitive plasmonic biosensors based on black phosphorus (BP) and graphene metamaterials are lacking to date.

In recent years, two-dimensional (2D) materials have been widely concerned because of their excellent performance in optoelectronics [16]. The intensity of interaction between light and 2D materials is relatively weak, but the excitation of surface plasmons in graphene and BP metamaterials greatly overcomes
the difficulty [17, 18]. Graphene has high electron mobility [19], thermal conductivity [20], mechanical strength [21], and unique zero-gap band structure [22]. Graphene has super-strong bandwidth absorption potential, and the absorption efficiency of graphene is 2.3% per layer from visible light to the terahertz band [23, 24]. This is very suitable for broadband photodetectors, but the disadvantage is that the light absorption efficiency is weak, leading to low absorption performance [25]. Several methods to improve the responsivity of graphene photodetectors have been studied, but they are still limited by the absorption wavelength range and intensity [26]. The interesting phenomenon produced by the hybrid structure of the two materials provides a new concept for developing nano-scale photonic devices. BP is an allotrope of phosphorus element, which is relatively stable thermodynamically at room temperature. The surface plasmons of BP can provide excellent electric-field localization and light confinement ability [27]. BP is a semiconductor material with a direct bandgap. The bandgap of monolayer BP is \( \sim 2.0 \) eV [28, 29]. Due to the interlayer interaction, the direct bandgap decreases with the increase of the number of BP layers, and the bandgap of multilayer BP is \( \sim 0.3 \) eV [30]. The adsorption energy of BP is stronger than graphene, so it is more suitable for the active binding of biomolecules [31]. Therefore, the hybridization of the modes of the BP plasmons and the graphene plasmons can further open up the new application potential of 2D materials for photonics and electronics in the infrared band. At room temperature, hydrogen is colorless, odorless, and highly flammable and explosive [32]. Traditional platinum wire-based hydrogen sensors have improved sensitivity at higher temperatures, and there are great hidden dangers in safety [32]. Our work is completely based on optical detection and has more significant advantages in sensitivity and security. Certain bacteria can also produce hydrogen, and hydrogen biosensors may have medical applications in the food industry [33, 34].

In this work, we propose an easy-to-implement, dynamically adjustable PIT hybrid structure consisting of an upper periodic BP ribbon and a lower graphene sheet. We use finite difference time domain (FDTD) numerical simulation and coupled mode theory (CMT) theoretical calculation to obtain consistent transmission spectrum results. The results of the absorption spectrum analysis show that the decrease in the distance between the BP ribbons and the graphene sheet caused an increase in the intensity of the destructive interference between the two radiation modes, and the PIT transparent window is deeper and wider. The absorption spectrum shift of the system is affected by the dielectric properties of BP and graphene. It is worth affirming that the absorption performance of the dual-channel produced by the PIT phenomenon has remained extremely high within the scope of the discussion. Utilizing the phase flips of the plasmon resonance wavelength position, we have added a sensing dielectric layer on top of the proposed structure to achieve a highly sensitive plasma biosensor. The proposed simple structure is conducive to experimental realization and can greatly promote the design of plasmon devices.

2. Structural design and theoretical analysis

A novel multifunctional SPR structure is proposed to realize excellent absorption and biochemical sensing, as sketched in figure 1(a). The incident transverse magnetic (TM) wave reacts with the coupling layer of the system to produce a plasmon resonance response in the mid-infrared band. The continuous ribbon and sheet 2D metamaterial structure has inherent advantages in manufacturing [35]. Two kinds of 2D materials in the structure are BP ribbons and a complete graphene sheet. Graphene is a metamaterial in which a carbon atom is composed of sp² hybrid orbital and a hexagonal honeycomb crystal lattice [36]. The in-plane effective mass of graphene is equal. BP is a metamaterial composed of phosphorus atomic sp³ hybrid orbitals that form a puckered hexagonal ring [37]. The puckered lattice results in-plane effective mass of BP are unequal, which exhibits a high degree of anisotropy [38]. Ball-and-stick models of monolayer BP and graphene, as shown in figure 1(b), where the x- and y-axes of the structure are defined as parallel to the BP armchair (AC) and zigzag (ZZ) directions.

The geometrical parameters and material representations of the structural cross-section in one cycle are shown in figure 1(c). The width of the monolayer BP ribbon placed centrally on the top of the structure is \( w_1 = 110 \) nm. A complete continuous monolayer graphene sheet is placed under the BP, and the graphene width is consistent with the structural period \( P = w_2 = 250 \) nm. A layer of dielectric separates BP and graphene with a thickness of \( d_1 = 100 \) nm. The distance from graphene to the gold mirror layer at the bottom of the structure is \( d_2 = 1.2 \) \( \mu \)m. The thickness of the gold mirror is set to 50 nm. The gold mirror is capable of reflecting almost all of the light so that it can form a similar Fabry Perot resonant cavity with the plasmon resonant coupling layer. The refractive index of the region above the BP ribbons is 1.0. The two dielectric layers indicated by red is assumed to be non-dispersive and has a fixed refractive index of 1.7. The spectral response of the structure is simulated by the FDTD numerical simulation. In the simulations, the mesh in the effective area is uniformly set to 1 nm. The boundary conditions in the x–y plane and the
vertical direction are set as the periodic boundary conditions and the perfect matching layer (PML), respectively. The simulated thicknesses of the dual 2D metamaterials are set at 1 nm.

The generation of the PIT phenomenon can be explained in principle by the $\Lambda$-type three-level for the PIT phenomenon. The $\Lambda$-type three-level consists of a ground state $|g\rangle$, a first excited state $|e_1\rangle$, and a second excited state $|e_2\rangle$ is shown in figure 2(a). When the frequency of the incident light (as detection-light) satisfies the transition frequency $\omega_{e_1g}$ from $|g\rangle$ to $|e_1\rangle$, the incident light is absorbed by the system to produce a prominent absorption peak. At this time, another light source (as pump-light), which satisfies the $|e_1\rangle$ to $|e_2\rangle$ transition frequency $\omega_{e_2g}$, causes the energy level to transition downward. The two groups of energy level transition at the same time produce mutual influence and cause the phenomenon of destructive interference. This phenomenon makes the absorption of the incident light source significantly reduced, and the transparent window appears in the absorption spectrum.

In this work, the proposed system has only one incident light source. The incident light interacts with the system like the detection-light mentioned before and is absorbed. Surface plasmons are produced on BP ribbons during the interaction of light and matter. The surface plasma on the BP ribbons excites the plasma on the graphene sheet to produce the plasmonic resonance. This is considered to be the process of pump-light excitation energy level transitions. The destructive interference of plasmon resonance and incident light causes the PIT phenomenon. We use CMT to further analysis the dynamic transmission laws and general mechanisms of PIT phenomena generated by structural systems [8]. In the CMT model, two resonant cavities B and D take the place of two excited state modes, as shown in figure 2(b). The 'in' and 'out' in the mode are incident and exit radiation waves, respectively. The simulated thicknesses of the dual 2D metamaterials are set at 1 nm.

Figure 1. (a) The schematic diagram of the proposed hybrid nanostructure consists of BP ribbons periodically distributed along the $x$-axis direction and a complete graphene sheet. (b) Ball-and-stick models of monolayer BP and graphene. The BP armchair (AC) and zigzag (ZZ) directions extend along the $x$- and $y$-axes of the structure, respectively. (c) A cross-section of a single cycle of the structure in figure 1(a) with those parameters: $w_1 = 110$ nm, $w_2 = 250$ nm, $P = 250$ nm, $d_1 = 100$ nm, $d_2 = 1.2$ m.

Figure 2. (a) Schematic diagram of the $\Lambda$-type three-level for the PIT phenomenon. (b) Schematic diagram of a CMT model for the proposed structure.

\[
\begin{pmatrix}
\gamma_B & -i\mu_{BD} \\
-i\mu_{DB} & \gamma_D
\end{pmatrix}
\begin{pmatrix}
|a_B\rangle \\
|a_D\rangle
\end{pmatrix} = 
\begin{pmatrix}
-\tau_{eB}^{-1/2} & 0 \\
0 & -\tau_{eD}^{-1/2}
\end{pmatrix}
\begin{pmatrix}
|B^\text{in}_+\rangle \\
|D^\text{in}_+\rangle
\end{pmatrix}
\]

where the $\mu_{BD}$ and $\mu_{DB}$ are the coupling coefficients between resonant cavities B and D modes. $\gamma_{BD(D)} = (i\omega - i\omega_{BD(D)} - 1/\tau_{BD(D)} - 1/\tau_{BD(D)})$, $\omega$ is the angular frequency of the incident wave, $\omega_{BD(D)}$ is the resonance angular frequency of the two modes, $1/\tau_{BD(D)} = \gamma_{BD(D)} = \omega_{BD(D)}/(2Q_{BD(D)})$ represents the attenuation rate due to internal losses, $Q_{BD(D)}$ is quality factor associated with the intrinsic loss, $1/\tau_{eB(D)} = \gamma_{eB(D)} = \omega_{eB(D)}/(2Q_{eB(D)})$ represents the attenuation rate caused by the escape of energy from modes to outer space, $Q_{eB(D)}$ is quality factor associated with the loss of diffusion into outer space. The total quality factor $Q_{BD(D)}$.\]
of the modes and mentioned above of two quality factor has the following relationship:

$$\frac{1}{Q_{\text{B(D)}}} = \frac{1}{Q_{\text{B(D)}}} + \frac{1}{Q_{\text{B(D)}}}$$  \hspace{1cm} (2)

where the $Q_{\text{B(D)}} = \lambda/\Delta \lambda$, $\lambda$ is the resonant wavelength, $\Delta \lambda$ is full width at half maximum. According to the definition of the effective refractive index $n_{\text{eff}} = \beta/k_0$, the quality factor $Q_{\text{in}} = \text{Re}(n_{\text{eff}})/|\text{Im}(n_{\text{eff}})|$ can be obtained \(^{[40]}\), $\beta = i(\varepsilon_1 + \varepsilon_2)\varepsilon_0\omega/|\sigma_{\text{BPX}} + \sigma_{\text{G}}|$ is the transverse magnetic mode \(^{[41, 42]}\), $\varepsilon_1 = 1$ and $\varepsilon_2 = 2.89$ are the dielectric constants of the medium and dielectrics, respectively. $\varepsilon_0$ and $k_0$ are vacuum dielectric constant and wave vector.

The conductivity $\sigma_{\text{BPX}}$ of monolayer BP is given as \(^{[43, 44]}\):

$$\sigma_{\text{BPX}}(\omega) = \frac{iD_{\text{xy}}}{\pi (\omega + \eta/\hbar)}$$  \hspace{1cm} (3)

where $\sigma_{\text{BPX}}$ and $\sigma_{\text{BPY}}$ are defined as AC and ZZ direction conductivity of BP, respectively. $\omega$, $\eta = 10$ meV and $h$ are angular frequency, scattering rate and Planck constant, respectively. $D_{\text{xy}} = \pi e^2 \tau/m_{\text{xy}}$ is the Drude weight along the AC and ZZ direction, $e$ is the electron charge, $n$ is the carrier density in monolayer BP, $m_x$ and $m_y$ represent the effective mass of in-plane electrons near the $\Gamma$-point in the Hamilton model \(^{[45]}\). We can write as $m_x = \hbar^2/(2\gamma^2 + \eta_k)$ and $m_y = \hbar^2/2\nu_x$, where the four conduction band parameters $\gamma = 4\mu/\pi$ eV m, $\Delta = 2 eV$, $\eta_k = \hbar^2/(4.0\,m_b)$, $\nu_x = \hbar^2/(1.4\,m_b)$ \(^{[46]}\). $a = 0.223$ nm is the width of the Brillouin zone and $m_0 = 9.109 \times 10^{-31}$ kg is the standard electron rest mass \(^{[44]}\).

The conductivity $\sigma_G$ of graphene is given as \(^{[47]}\):

$$\sigma_G(\omega) = \frac{i\epsilon^2 E_F}{\pi \hbar^2 (\omega + i\tau^{-1})}$$  \hspace{1cm} (4)

where $\epsilon$, $\hbar$ and $\omega$ have the same meaning as in the previous formula. $E_F$ is Fermi level of graphene.

$\tau = \mu E_F/(\epsilon v_F^2)$ is the time of carrier relaxation \(^{[17, 48]}\), the $\mu = 1.00$ m$^2$ (V$^{-1}$ s$^{-1}$) is carrier mobility, and the $v_F = 10^5$ m s$^{-1}$ is Fermi velocity of graphene.

The system is in a state of energy conservation. Therefore, we can obtain a set of relations for resonant models as follows:

$$B_{\text{in}} = D_{\text{out}} e^{i\varphi}, \quad D_{\text{in}} = B_{\text{out}} e^{i\varphi}$$  \hspace{1cm} (5)

$$B_{\text{out}} = B_{\text{in}} - \tau_{e_1}^{1/2} e_{\text{b}}$$  \hspace{1cm} (6)

$$D_{\text{out}} = D_{\text{in}} - \tau_{e_2}^{1/2} d_{\text{b}}$$  \hspace{1cm} (7)

where $\varphi = \text{Re}(\beta)d_1$ represents the phase shift of the resonant B and D mode. The light incident on the system is completely reflected by the gold mirror at the bottom. Therefore, the system transmittance $T = 0$, and have equation $D_{\text{in}} = D_{\text{out}} e^{i2\phi}$. The $\phi = \text{Re}(\beta)d_2$ is the phase shift of the resonant D and gold mirror. From equations (2)–(7), we can obtain the complex absorption coefficient of plasmonic structure.

$$r = \frac{B_{\text{out}}}{B_{\text{in}}} = e^{i2\varphi} e^{-i2\psi} - \left(\tau_{e_1}^{1/2} e^{i2\varphi} + \tau_{e_2}^{1/2} d_{\text{b}}\right) \frac{\chi_1 S_2 - \chi_2 S_3}{\chi_1 S_2 - \chi_2 S_1}$$

$$- \frac{\chi_1 S_0 - \chi_3 S_2}{\chi_2 S_1 - \chi_1 S_2}$$

where $\chi_1 = \gamma_B - \tau - 1eB e^{i2\varphi} e^{-i2\psi}$, $\chi_2 = -i\mu_{BD} - \tau - 1eB e^{i2\varphi} e^{-i2\psi} - \tau - 1/2eB\tau - 1/2eDe^{i2\psi}$, and $\chi_3 = -\tau - 1/2eB - \tau - 1/2eBe^{i2\varphi} e^{-i2\psi}$, $\chi_4 = -i\mu_{BD} - \tau - 1/2eB - \tau - 1/2eDe^{i2\psi}$, $\chi_5 = -i\mu_{BD} - \tau - 1/2eB - \tau - 1/2eDe^{i2\psi}$, $\chi_6 = -\tau - 1/2eB - \tau - 1/2eDe^{i2\psi}$, and $\chi_7 = -\tau - 1/2eB - \tau - 1/2eDe^{i2\psi}$. Therefor the reflectivity rate is expressed as $R = |r|^2$. Thus the absorbance of the system can be obtained from $A = 1 - T - R$.

3. Results and discussion

In the system, BP ribbons and graphene sheets are placed in the upper and lower layers of the structure, respectively. We investigate the respective effects of dual 2D metamaterials in PIT formation. Numerical simulations of absorption spectrum based on incomplete structures and complete structures are shown in figure 3(a). Among them, the incomplete structure by the short black line and the long grey line in the illustration, respectively, that there is only BP ribbon in the structure and only graphene sheet in the structure. The complete structure by the coexistence of short black line and long grey line. In this simulation, the carrier density of BP is set to $n = 1.0 \times 10^{14}$ cm$^{-3}$, and the Fermi level of graphene is set to $E_F = 1.0$ eV. When the 2D metamaterials in the system only have the upper layer BP ribbons, the absorption
Figure 3. (a) Numerical simulation absorption spectrum of the proposed dual 2D metamaterial structure for PIT, when \( n = 1.0 \times 10^{14} \text{ cm}^{-2} \) in BP and \( E_F = 1.0 \text{ eV} \) in graphene. The olive-line is an absorption curve for only the graphene sheet in the structural system. The navy-line is an absorption curve for only BP ribbons periodically arranged in the structural system. The red-line is an absorption curve of the whole structure. (b)–(e) Electric field distribution diagram corresponding to the marked position of the absorption spectrum in (a), respectively.

Spectrum is a single peak navy-line with excellent absorption. The electric field distribution at the absorption peak top (b) is concentrated on the BP ribbons, as shown in figure 3(b). There is a strong interaction between the BP ribbons and the incident light with a wavelength of 8 \( \mu \text{m} \), and the surface plasmons of BP are excited. When the 2D metamaterials in the system only have the lower layer graphene sheet, the absorption spectrum is olive-line. The graphene sheet in the structure cannot be coupled with the incident light, and the absorption spectrum has no response. When the BP ribbons and graphene sheets are completely present in the structure, the absorption spectrum is red-line with two excellent absorption peaks and a transparent valley. The electric field distribution diagram of the three tops (c)–(e) on the red-line absorption spectrum are shown in figure 3(c–e). The wavelength of the induced transparent window (d) position is almost equal to the absorption peak (b) position. At the induced transparent window, the upper BP ribbons interact with the incident light to excite surface plasmons. At the same time, the surface plasmon wave excites the lowly layer graphene sheet. The destructive interference of these two excitation modes leads to the generation of the induced transparent window, and the energy is concentrated in the lower layer graphene sheet.

Based on the above simulation and analysis, the proposed structure can be realized excellent dual-channel absorption of PIT with the excitation of plasmonic resonances. However, a detailed study of structural geometric parameters and excellent absorption dynamic adjustment is necessary. The numerical simulation and theoretical analysis results in the absorption spectrum are represented by the navy solid line and the red dotted line, respectively. When one of the parameters is studied, the other parameters are consistent with figure 3(a).

The absorption spectrum of the various upper and lower layer spacings \( d_1 = 120, 110, 100, 90, \) and \( 80 \) \( \text{nm} \) are shown in figure 4(a). Compared with the two absorption lines, the numerical simulation results are in good agreement with the theoretical calculation results. With the decrease of \( d_1 \), the resonance positions of the two main peaks shift away from the induced transparent window. Still, the absorption efficiency remains at 100%. The position of the induced transparent window did not change, but the window depth became deeper as \( d_1 \) decreased. The close distance between the BP ribbons and the graphene sheet results in increased destructive interference. As a result, the transparent window becomes deeper. In addition, to further investigate the relationship among \( d_1 \), the resonance wavelength, and the absorption efficiency of the proposed structure. CMT calculates the theoretical absorption rate of the structure, and the results are shown in figure 4(c). We can see more clearly that as \( d_1 \) decreases, the transparent window becomes deeper and broader.

The absorption spectrum of the various carrier density \( n = 1.2, 1.1, 1.0, 0.9, 0.8 \times 10^{14} \text{ cm}^{-2} \) in BP, and various Fermi level \( E_F = 1.2, 1.1, 1.0, 0.9, 0.8 \text{ eV} \) in graphene are shown in figure 4(b). The results of FDTD simulation at different carrier density in BP ribbons and different Fermi levels in the graphene sheet are consistent with the results of CMT calculation. Dynamic carrier density in BP can be obtained by adjusting the bandgap of the monolayer BP through the bias voltage [43]. It is straightforwardly to realize the Fermi level in graphene sheet dynamic tuning by gate voltage [49]. When both the carrier density of BP and the Fermi level of graphene are reduced, the position of the resonant valley induced transparent window and the positions of the two absorption peaks are red-shifted. Therefore, the overall response wavelength position of the system is red-shifted. In addition, to further investigate the relationship among carrier...
density $n$ in BP, Fermi level $E_F$ in graphene, the resonance wavelength and the absorption efficiency of the proposed structure. CMT calculates the theoretical absorption rate of the structure, and the results are shown in figure 4(d). The figure clearly shows that the system’s absorption response and induced transparent window response is red-shifted. The absorption efficiency of the system not affected by the change of the responsible position, and it still maintains 100% excellent absorption performance. Therefore, the system can dynamically adjust to achieve excellent absorber at a wide response wavelength.

It is combined with the electric field distribution at the position of the induced transparent window to the absorption spectrum of figure 4(a), we can clearly understand the mechanism in the resonance state. The electric field distribution of these positions is shown in figure 5(a)–(e), respectively. Obviously, the greater the distance between BP band and graphene sheet, the more localized energy on the material. This is consistent with the absorption performance at the induced transparent window. Comparing the electric field distributions of the induced transparent window at $d_1 = 120$ nm and $d_1 = 80$ nm. Destructive interference is enhanced as the excitation distance of the two modes decreases. The strong destructive interference results in the decrease of photon energy absorbed by the upper BP band. Therefore, the energy absorbed and localized by the whole system is reduced.

**Figure 4.** The navy solid line and the red dotted line are the results of FDTD simulation and CMT calculation, respectively. (a) The absorption spectrum of the proposed structure when $d_1 = 120, 110, 100, 90, 80$ nm. The $n = 1.0 \times 10^{14}$ cm$^{-2}$ in BP and $E_F = 1.0$ eV in graphene is set to a fixed value. (b) The absorption spectrum of the proposed structure when $n = 1.2, 1.1, 1.0, 0.9, 0.8 \times 10^{14}$ cm$^{-2}$, and $E_F = 1.2, 1.1, 1.0, 0.9, 0.8$ eV. The $d_1 = 100$ nm is set to a fixed value. (c) The functional relationship between wavelength and absorptance by CMT calculation when $d_1$ varies. (d) The functional relationship between wavelength and absorptance by CMT calculation when $n$ in BP and $E_F$ in graphene varies.

**Figure 5.** (a)–(e) Electric field distribution diagram corresponding to the induction window position of the PIT absorption spectrum in figure 4(a).
According to the previous research, it is found that BP and graphene in the proposed structure generate surface plasmons. The investigative show that the structure of plasmonic metamaterials can achieve high sensitivity to light [12]. Therefore, we add a layer of channels above the proposed structure that can pass through the biogas. The change in gas concentration causes the refractive index of the sensing medium layer to be changed. The schematic diagram of the plasmonic biosensing structure is shown in figure 6(a). In this system, we can get the theoretical phase change based on the theoretically calculated reflection coefficient: $\varphi = \text{arg}(r)$. The absorption spectrum and phase change of the system with the refractive index of the sensing medium layer $n_s = 1.0$, are shown in figure 6(b). The absorption spectrum is the navy curve corresponding to the left ordinate. The phase change is the red curve corresponding to the right ordinate. The phase of the system is rapidly reversed at the two excellently absorbing positions. The tremendous phase change that occurs at the surface plasmon resonance wavelength is the basic principle of plasma biosensing applications. We give the evolution of the absorption spectrum, and phase versus wavelength with the different refractive index of the sensing medium layer $n_s = 1.00$ (navy-line), $n_s = 1.05$ (red-line) and $n_s = 1.10$ (olive-line) are shown in figures 6(c)–(d). We found that the absorption changes of navy-line and red-line were $\Delta A_1 = 0.19$ and $\Delta A_2 = 0.14$, respectively. The wavelength changes were $\Delta \lambda_1 = 0.12$ and $\Delta \lambda_2 = 0.15$, respectively. The phase changes of navy-line and red-line were $\Delta \varphi_{\theta 1} = 87$ and $\Delta \varphi_{\theta 2} = 128$, respectively. Sensitivity is expressed as the ratio of the dependent variable and the independent variable. Therefore, the intensity sensitivity of maximum absorption, wavelength and phase are calculated as $S_A = \Delta A/\Delta n = 3.8$ /RIU, $S_\lambda = \Delta \lambda/\Delta n = 3.8$ /RIU, and $S_\varphi = \Delta \varphi_{\theta} /\Delta n = 2560$ /RIU, respectively (Here $\Delta n = 0.05$). Phase sensing sensitivity is significantly better than absorption and wavelength sensitivity. According to the above discussion, the proposed structure has good phase sensing performance. Our design guides the development of 2D metamaterial plasmonic biosensors.

4. Conclusion

In summary, we propose a plasmonic nanostructure composed of BP ribbons and graphene sheets. The surface plasmon resonance of BP and graphene results in the clear induced transparent window in the absorption spectrum, forming a PIT phenomenon. The upper and lower layer spacings $d_1$ affects the intensity of the destructive interference between the two radiation modes. The proposed structure can dynamically adjust the wavelength of two excellent absorption peaks without affecting the absorption efficiency. A suitable plasmonic biosensor is obtained by adding a gas channel layer at the top of the structure. We describe the spectrum of absorption and phase changes when the refractive index of the sensing medium is 1.0 and 1.05. The results show that the obtained phase shifts have visibility better than...
the spectral phase shift. In terms of structural design, both BP and graphene are continuous structures without patterns. This simple structure is conducive to dynamic adjustment and experimental implementation. This structure can provide some theoretical guidance for the realization of the dual-channel excellent absorber and plasmonic biosensor.

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