Perfect light absorption in graphene by two unpatterned dielectric layers and potential applications

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In the spectral range from ultraviolet to near infrared, graphene lacks the capability to support plasmon polaritons, and has low optical absorptivity for applications due to its extremely small thickness. Many photonic structures based on sophisticated nanofabrication or metal plasmonics have been adopted to conquer this limitation, but they suffer from high expenses or metal parasitic losses. Here, a single-channel coherent perfect absorber simply based on two unpatterned dielectric layers is proposed to reach ~100% light absorption in monolayer and few-layer graphene. The schemes for narrowband and broadband perfect absorption in graphene are systematically demonstrated, and their potential applications on fibre-integrated narrowband perfect absorbers, high-performance optical sensors, electro-optic modulators and broadband perfect absorbers are also investigated. Our research provides a simple and cost-effective method to completely trap the light from ultraviolet to near infrared in a sub-nanometre scale for a lot of high-performance photonic and optoelectronic devices based on graphene and potentially other 2D materials.

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1. Introduction

The family of 2D materials has generated significant interest in the field of photonics and optoelectronics owing to their novel properties for light-matter interactions, which is totally different from those of their 3D counterparts [1,2]. Along with the recent emergence of 2D lateral heterostructures [3,4], the study of light trapping in sub-nanometre 2D materials has become more and more significant in photo-detection, photovoltaics, photoluminescence, Raman microscopy, optical sensing and optical modulation [5–8]. As the most popular representative of 2D materials, graphene has attracted tremendous attention in the optical communities of research and industry, and has been systematically studied for the spectral range from ultraviolet (UV) to terahertz [9,10]. In the spectral range from mid-infrared to terahertz, graphene is capable to support effects of plasmon polaritons, which can lead to strong light-matter interaction by a plasmonic coupling [11]. In contrast, for the range from UV to near-infrared (NIR), graphene acts as a lossy conductive surface, and suspended graphene only absorbs a very small fraction of the normal incident light (only 2.3% in the visible-NIR range) due to an atomic layer structure with an extremely small thickness [12]. In order to enhance the optical absorption in graphene from UV to NIR, plentiful efforts have been made on combining graphene with various photonic structures, such as dielectric waveguides, photonic crystals, plasmonic metamaterials, dielectric metamaterials and integrated microcavities [13–17]. However, most of these methods need a sophisticated fabrication process with subwavelength patterning inside or outside graphene layers. Such a fabrication process will not only increase the manufacture complexity and cost, but also introduce possible fatal degradation of the electronic and photonic performance of graphene, because as a 2D material graphene is usually sub-nanometre thin and has the band structure very sensitive to atom-scale damage and environmental contaminant. Particularly, for UV applications, precise fabrication of nanoscale features on graphene might be much more difficult due to patterning with smaller subwavelength sizes. Previous efforts have aimed to achieve high optical absorption in graphene by using an unpatterned graphene/dielectric/metal structure with polarization
and angular manipulation [18]. However, these efforts have been focused on the UV range only, and significant loss in the metal is not negligible for applications from UV to NIR. In order to completely couple light into sub-nanometre-thick graphene by an efficient and cost-effective way, an innovative design of photonic structure from UV to NIR is quite in demand.

In this paper, we propose a simple photonic structure with two unpatterned dielectric layers for complete optical absorption in graphene. Our approach adopts a scheme in combination with optical total reflection and coherent perfect absorption, and this avoids the use of high-lossy materials and complicated nanofabrication for the photonic structure. In order to achieve perfect optical absorption in graphene for various applications, we perform a systematic study on structural design, material selection, angle and polarization of incident light for the UV-NIR range. Our methods demonstrate promising potential of graphene for photonic applications on high-performance devices of photo-detection, photovoltaics, optical communication, photo-thermal emission, chemical and biomedical sensing.

2. Theoretical model and research method

In this study, we adopt a single-channel coherent perfect absorber for complete light absorption in graphene with a thickness of sub-nanometre. The proposed photonic structure consists of two lossless dielectric layers, in combination with graphene, as shown in Fig. 1(a). The refractive index \( n_1 \) and \( n_2 \) for both of the dielectric layers are larger than the air refractive index \( n_3 \). Layer 2 has a thickness of \( d_2 \), and the location of graphene on Boundary A (interface of Layer 1/Layer 2) or Boundary B (interface of Layer 2/Layer 3) is investigated. The incident light is introduced from Layer 1, and its incident angle and polarization are manipulated with the design of material and structure, in order to achieve perfect optical absorption in graphene. An analytical method based on characteristic matrices of multilayer thin films is used to calculate and optimize the optical absorption in graphene [19]. Full wave numerical simulation using a finite element method (Comsol Multiphysics 5.2a) is also adopted to confirm the analytical optimization and provide a more comprehensive physical picture [20]. Floquet periodic boundary conditions are used in the simulation, the detailed method is included in the supplementary material. In this study, we mainly focus on graphene with a sub-nanometre thickness, which is much smaller than the wavelength of light and only induces the in-plane carrier transport for optical excitations. A wavelength-dependent surface conductivity \( \sigma \) is used to describe the optical response of graphene. The Fano model for the many-body effects and the Kubo formalism for an independent particle are combined to describe the optical conductivity of graphene from UV to NIR [21,22]. The Fano model for the excitation of high optical energy can be expressed as below,

\[
\sigma_{\text{Fano}}(\lambda) = \frac{\sigma_{\text{CN}}(\lambda) \cdot (q + \varepsilon)^2}{1 + \varepsilon^2}
\]

where \( q = \frac{\hbar c}{\lambda - E_r} \) is the normalized energy by the Fermi-Dirac distribution function. The NIR conductivity of plural form by the Kubo formalism can be expressed by the following equations,

\[
\sigma(\omega, \mu_c, \Gamma, T) = \sigma_{\text{intra}} + \sigma_{\text{inter}}
\]

\[
\sigma_{\text{intra}} = \frac{2e^2}{\pi h^2 (\omega - j2\Gamma)} \int_0^\infty \left( \frac{\partial f_d(\xi, \mu_c, T)}{\partial \xi} - \frac{\partial f_d(-\xi, \mu_c, T)}{\partial \xi} \right) d\xi
\]

\[
\sigma_{\text{inter}} = \frac{2e^2}{\pi h^2 (\omega - j2\Gamma)} \int_0^\infty \left( f_d(\xi, \mu_c, T) - f_d(-\xi, \mu_c, T) \right) d\xi
\]

\[
f_d(\xi, \mu_c, T) = \left( e^{(\xi - \mu_c)/k_BT} + 1 \right)^{-1}
\]

Here, \( \sigma_{\text{intra}} \) and \( \sigma_{\text{inter}} \) represent the optical conductivity contributions from the intraband and interband transitions, respectively. In the equations, \( h, k_B, \) and \( e \) denote the reduced Plank constant, Boltzmann constant, and electron charge, respectively, \( T, \xi, \mu_c \) and \( \omega \) represent Kelvin temperature, electron energy, chemical potential and angular frequency, respectively, \( \Gamma \) is scattering rate and is taken as 16.67 ps\(^{-1}\), \( f_d(\xi, \mu_c, T) \) is the Fermi-Dirac distribution function. The wavelength-dependent conductivity of graphene from UV to NIR is shown in Fig. 1(b). Compared with the real part of complex conductivity, the imaginary part is extremely small (close to zero) and can be negligible in this spectral range (see Fig. S1 in the supplementary material). The band-to-band transition would play a more significant role in this spectral range.

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**Fig. 1.** (a) Schematic drawing of the proposed photonic structure with two dielectric layers, including Layer 1 and Layer 2, where \( n_1 \), \( n_2 \) and \( n_3 \) represent the corresponding refractive index. (b) Optical conductivity of graphene, and insets are the atomic structure and band structure of graphene, where the symbol M denotes the saddle point singularity. (A colour version of this figure can be viewed online.)
dominant role for optical absorption in graphene. Based on the optical conductivity, graphene monolayer can also be considered as a lossy dielectric material with a thickness $d_g$ of 0.35 nm [23].

The proposed photonic structure can be assumed as a two-port optical network with both a dielectric channel (Layer 1) and an air channel (Layer 3). The relationship between input and output waves is described by the following equation,

$$\begin{pmatrix} b_1 \\ b_3 \end{pmatrix} = S \begin{pmatrix} a_1 \\ a_3 \end{pmatrix}, \quad S = \begin{pmatrix} r_{11} & r_{13} \\ t_{31} & t_{33} \end{pmatrix}$$

(7)

Here, the complex scalars $a_i$ and $b_i$ represent the input and output wave amplitudes in the $i$-th layer, respectively, as shown in Fig. 1(a); $r_{ij}$ are the reflection coefficients and $t_{ij}$ are the transmission coefficients. The scattering matrix $S$ is derived from Maxwell's equations by using the method of characteristic matrices, and it depends on the material optical constants, the thickness of Layer 1, and the photonic structure. When the photonic structure is solved photonic structure is posed photonic structure is incident on the boundary A from Layer 1 to Layer 2, and obtain the equation

$$\sin(\theta_1) = \sin(\theta_2) = \sin(\theta_3)$$

(8)

Hence, the critical angle of total optical reflection for the proposed photonic structure is $\theta_1 = \theta_2 = \arcsin(n_2/n_1)$, which is only determined by the refractive indexes $n_1$ and $n_2$, regardless of the refractive index and thickness of Layer 2. This propagation property is independent from light polarization, as shown in Fig. 2(a) and (b), where $n_1 = 1.46$, $n_2 = 1.77$, $n_3 = 1$, and $\theta_c = \arcsin(n_2/n_1) = 43.2^\circ$. On the condition for an incident angle $\theta_1$ smaller than $43.2^\circ$, light can be transmitted from Layer 1 to Layer 2, and the photonic structure is a two-port system with incidence, reflectance and transmittance. As observed in Fig. 2(a) and (b), when the incident angle $\theta_1$ is larger than $43.2^\circ$, light transmission from Layer 1 to Layer 3 is totally blocked (i.e., $\theta_1 = 0$), the bottom surface of Layer 2 plays a role of perfect reflecting mirror, and the optical network acts as a one-port system with only incidence and reflectance. Furthermore, when the graphene monolayer is introduced to the location of Boundary A or Boundary B as shown in Fig. 1, it does not change the critical angle $\theta_c$ of total reflection for the entire structure under both s- and p-polarizations (see Fig. S2). This is because graphene can be considered as an extremely thin intermediate layer of lossy dielectric material between Layer 1 and Layer 3, and it doesn’t change $\theta_c$ determined by $n_1$ and $n_3$.

Next, based on the condition of incident angles larger than $\theta_c$ for $\theta_3 = 0$, we discuss how to make the reflection coefficient $r_{11}$ equal to zero for perfect absorbance ($A = 1 - |r_{11}|^2 = 1$) in the proposed structure with graphene in Boundary A or Boundary B. The layers of dielectric and air are assumed to be lossless, so, all the optical dissipation is attributed to the loss in graphene if the perfect

![Fig. 2. Optical transmittance of the dielectric/dielectric/air layers, as a function of wavelength and incident angle, where $n_1 = 1.46$, $n_2 = 1.77$, $n_3 = 1$, $d_g = 40$ nm. (a) Incidence of s-polarized light. (b) Incidence of p-polarized light. (A colour version of this figure can be viewed online.)](image-url)
absorption (i.e. \( r_{11} = 0 \)) is possible. In this study, graphene is assumed as a two-dimensional lossy film with surface optical conductivity and vanishing thickness, which slightly influences the value of \( \theta_s \) for total reflection on the entire structure. The local optical absorption is induced by the in-plane Ohmic dissipation on the graphene surface, and it is determined by the wavelength-dependent conductivity and the local electric field component parallel to the graphene surface, as shown below,

\[ A(\lambda) = \frac{\sigma(\lambda)}{2} |E_p(\lambda)|^2 \]  

(9)

where \( E_p \) denotes the parallel component of wavelength-dependent electric field on the graphene surface. When the incident angle is larger than \( \theta_s \), the electric field of \( p \)-polarized light is not parallel to the graphene surface, but the electric field of \( s \)-polarized light is always parallel to the graphene surface. Hence, only \( s \)-polarized light has the possibility to achieve absolute optical absorption based on equation (9), and we only need to focus on the discussions of \( s \)-polarized incidence for the next investigations. The tilted optical admittance in Layer 1 for \( s \)-polarized light with an angle \( \theta_i \) can be expressed as \( \eta_l = H_l \cos \theta_i |E_p| \), where \( H_l \) and \( E_l \) represent the magnetic field and electric field in Layer \( i \), respectively. The phase factor of the positive-going wave in Layer 2 is denoted as \( \delta_2 = 2 \pi n_2 d_2 \cos \theta_i \lambda \), and the phase factor in graphene is expressed as \( \delta_g = (2 \pi / \lambda) d_g (n_2^2 - k_0^2 - n_1^2 \sin^2 \theta_1 - 2 j n_1 k_0) / \lambda^2 \), where \( N_g = n_2 + jk_0 \) is the effective complex refractive index of graphene. The characteristic matrix of Layer 2 and the characteristic matrix of graphene are expressed as below,

\[
M_2 = \begin{bmatrix}
\cos \delta_2 & j \sin \delta_2 / \eta_2 \\
-jn_2 \sin \delta_2 & \cos \delta_2
\end{bmatrix}
\]

(10)

\[
M_g = \begin{bmatrix}
\cos \delta_g & j \sin \delta_g / \eta_g \\
-jn_g \sin \delta_g & \cos \delta_g
\end{bmatrix}
\]

(11)

and the reflection coefficient of the proposed structure is shown as below,

\[ r = \frac{\eta_l - Y}{\eta_l + Y} \]

(12)

where \( Y \) represents the tilted optical admittance of the assembled material layers except Layer 1. It can be written as below,

\[
Y = \begin{cases}
M_g M_2 \begin{bmatrix} 1 \\ \eta_3 \end{bmatrix}, & \text{if graphene is in Boundary A.} \\
M_2 M_g \begin{bmatrix} 1 \\ \eta_3 \end{bmatrix}, & \text{if graphene is in Boundary B.}
\end{cases}
\]

(13)

As observed from equation (10) to equation (13), the reflection coefficient \( r \) is a function of the refractive index and thickness of Layer 2, the incident angle and the lossy term of graphene’s complex refractive index. In order to achieve perfect optical absorption, the reflectance \( R = |r|^2 \) should equal to zero. Therefore, when all the materials are fixed, the conditions for perfect absorption are mainly determined by the thickness of Layer 2 and the incident angle. Based on equation (8), the condition of \( n_1 > n_2 \) is impossible for equation (12) to get close to a zero value, so we next focus on the condition of \( n_1 < n_2 \) for perfect absorption in graphene.

3. Results and discussions

As shown in Fig. 3(a) and Fig. 3(b), regardless of graphene on Boundary A or Boundary B, the perfect absorbance in monolayer graphene can be reached for a fixed thickness of Layer 2 by using an appropriate coupling angle. As the thickness of Layer 2 increases from 35 nm to 143 nm, the central wavelengths of absorption bands have a red shift from the UV range (\( \lambda = 268 \) nm and \( \lambda = 270 \) nm for graphene on Boundary A and B, respectively) to the NIR range (\( \lambda = 1100 \) nm and \( \lambda = 1100 \) nm for graphene on Boundary A and B, respectively). Besides, graphene on boundary A (Fig. 3(a)) excites broader absorption bands than graphene on Boundary B (Fig. 3(b)). The analytical results based on the method of characteristic matrices demonstrate good consistency with the results from simulations based on the finite element method. If there is no Layer 2 (or Layer 1) with graphene, no obvious absorption peak is observed in the spectrum, especially in the visible and near-infrared range (see Fig. S3 in the supplementary material). The perfect absorbance in graphene is attributed to the coherence effects from the incident and reflective light waves between the upper and lower interfaces of Layer 2. Thus, the proposed structure with graphene can be considered as a single-channel coherent perfect absorber. The coherent perfect absorption is induced by the light wave coupling within Layer 2 under a certain angle, and almost all the light energy dissipates inside graphene for a wavelength determined by the thickness of Layer 2. Graphene on Boundary A has smaller coupling angles and central wavelengths for perfect absorption than graphene on Boundary B, as shown in Fig. 3(a) and (b). Based on equation (9), the optical absorption is determined by the optical conductivity of graphene and the electric field intensity on it. The conductivity of monolayer graphene around \( \lambda = 268 \) nm is about 3.3 times of that at \( \lambda = 700 \) nm. In comparison, as observed by the electric field distributions in Fig. 3(c) and (d), on the coupling conditions for coherent perfect absorption, the electric field amplitude at \( \lambda = 700 \) nm is about 1.82 (3.31/1.82) times of that at \( \lambda = 268 \) nm. These electric field distributions also confirm that the perfect light absorption originates from the enhancement of in-plane electric field on the graphene surface under s-polarized light incidence.

Next, we further discuss the factors that influence the perfect light absorption of graphene. As shown in Fig. 4(a) and Fig. 4(b), for a fixed thickness of Layer 2, the incident light energy is efficiently coupled into the absorption inside graphene around a certain coupling angle, which is close to 90°, especially for monolayer graphene with a lower optical conductivity. Due to the optical path difference, graphene on Boundary B (Fig. 4(a)) has a smaller angle range for high absorbance compared with graphene on Boundary A (Fig. 4(b)). Despite the absorption bandwidth for wavelengths and incident angles, the locations of graphene on Boundary A and Boundary B have very similar optical response, because the single-channel light coherence is attributed to the optical dissipation on the upper or lower interfaces of Layer 2. For a fixed wavelength, the perfect absorption can be engineered and maintained by tuning both the thickness of Layer 2 and the refractive index of Layer 1, as shown in Fig. 4(c). The coherent perfect absorption is determined by the phase factor of Layer 2 as below.

\[
\delta_2 = 2 \pi n_2 d_2 \cos \theta_2 / \lambda = (2 \pi / \lambda) d_2 \left( n_2^2 - n_1^2 \sin^2 \theta_1 \right)^{1/2}
\]

(14)

When \( \lambda, n_2 \) and \( \theta_2 \) are fixed, the term \( d_2 (n_2^2 - n_1^2 \sin^2 \theta_1)^{1/2} \) should be constant, in order to achieve the perfect absorption based on equations from (10) to (13). So the thickness of Layer 2 increases as the refractive index of Layer 1 becomes large. As observed in Fig. 4(d), the central wavelength of perfect absorption band depends on the thickness of Layer 2, and it linearly increases as the thickness of Layer 2 becomes large, because \( \lambda \) is proportional to \( d_2 \) in order to keep \( \delta_2 \) constant for perfect absorption based on equation (14). When the thickness becomes larger, multiple
absorption bands appear due to high order coherence modes, as shown in Fig. 4(d). Fig. 4(e) indicates multiple coherence modes with high absorbance ratios can be achieved by increasing the thickness of Layer 2 up to 1 μm, and the high order modes have narrower absorption bands and smaller operational angles of incidence for high absorbance ratios. Hence, one can tune the thickness of Layer 2 for different absorption bands, multiple absorption bands and operational angle of incidence. Even though Fig. 4(c)–(e) demonstrate the optical properties for graphene on Boundary A only, similar optical properties can also be found for graphene on Boundary B. Unlike the optical waveguide design for long-distance light attenuation in graphene [13], the proposed coherent perfect absorber depends on the superposition of electric field vectors on graphene from the incident light and the reflective light, according to equation (9). By studying the optical response of the layered structure as a function of the area (see Fig. S6 in the
supplementary material), we find that the reflectance and absorbance spectra keep the same for different layer areas. Thus, the coherent perfect absorption is independent from the area of the layered structure. This is because the superposition of electric field vectors for perfect absorption is determined by the amplitude and phase conditions of in-plane electric fields (parallel to the graphene surface) from the incident and reflective light waves, and these conditions are independent from the area of the layered structure and rely on the light polarization, incident angle, refractive index and thickness of Layer 2. Based on above analysis, the coherent perfect absorption is determined by the light polarization, incident angle, refractive index and thickness of Layer 2, regardless of the area of the layers. The angular dependent optical properties of graphene could be applied to implement narrowband perfect absorption, as shown in Fig. 4(f), where an angled optical fibre tip with alumina and graphene coatings is used to completely absorb the optical signal. In view of the fabrication process, the angled optical fibre tip can be accomplished by the polishing through the Fibre Lensing Machine, which is efficient for producing accurate end profiles on the regular optical fibre tip [25]. Additional fabrication procedures, such as super-smooth finishing and ion processing [26,27], might be applied in order to further reduce the roughness of the surface. The alumina can be coated by the atomic layer deposition or sputtering, and the graphene layer can be transferred onto the alumina surface [28]. According to the technique requirements, the grazing angle could be further engineered and reduced for practical applications (see Fig. S8 in the supplementary material). Such a design might facilitate the photonic integration in combination with graphene and fibres on many applications for optical communications and optoelectronic devices.

The perfect absorption features of the proposed structure can be also adopted for a new optical sensing mechanism. As well known, the surface optical conductivity of graphene is very sensitive to slight environmental contamination, partial chemical bonding or carrier doping [29–32], hence the change of the surface optical conductivity on the 2D material is a critical criterion for sensing applications. As shown in Fig. 5(a), a prism-based structure is used to detect the change of surface optical conductivity on the hexagonal boron nitride (hBN) layer. For instance, localized chemical bonding to the carbon atoms of graphene by the oxygen atom or hydroxyl could reduce the optical conductivity, which can be measured by the reflectance spectra. Such a scheme seems similar to the Kretschmann configuration for surface plamon resonance sensing [33], which uses p-polarized light to excite surface plamons on a novel metal film. However, our scheme uses s-polarized light and maximizes the interaction between the 2D material and the electric field on the sub-nanometre layer by an appropriate coupling angle. The change of optical conductivity due to surface contamination, bonding or doping can be simply detected by measuring the reflectance ratios for a certain wavelength, as shown in Fig. 5(b). For a fixed incident angle, the intensity of reflection signal is very sensitive to the change of the surface optical conductivity (from σ to 0.05σ), which implies its promising potential for single molecule spectroscopy. This detection allows for the use of visible light, whose detectors are very popular and inexpensive in various sensing platforms. In addition, such detection method is non-destructive and avoids any contact problem by using electrodes for measuring electrical conductivity on the 2D material [34].

Since the electric-optic modulation of graphene is of great importance in optical communication [35], we next investigate modulation effects of the proposed photonic structure in the NIR range. As show in Fig. 6, the intensity of optical reflectance for graphene on Boundary B or Boundary A is modulated by changing the chemical potential of graphene, which can be implemented by electronic gating on graphene [36]. It is observed in Fig. 6(a) and (c), the optical reflectance ratios around λ = 1550 nm can be tuned by changing the chemical potential μc from 0.3eV to 0.65eV. Around λ = 1550 nm, the reflectance of μc = 0.3eV is close to zero due to the effects of coherent perfect absorption, whereas the reflectance of μc = 0.65eV is very large (up to 87.6% and 88% for graphene on Boundary A and Boundary B, respectively. The reflectance differences are attributed to the significant reduction of optical conductivity based on equation (9). Comparing Fig. 6(a) and (c), we find that graphene on Boundary B has a higher quality factor for the reflectance dip than graphene on Boundary A. In order to evaluate the modulation effects, we define the optical contrast of reflectance by (Ron − Roff)/Roff [37], where Ron and Roff represent the reflectance for μc = 0.65eV and μc = 0.3eV, respectively. For graphene on Boundary B (Fig. 6(b)) and Boundary A (Fig. 6(d)), the optical contrasts around λ = 1550 nm are extremely high, and the modulation efficiency for graphene on Boundary A (9969 at λ = 1553 nm) is much higher than that for graphene on Boundary B (1879 at λ = 1550 nm). This indicates the promising potential of the proposed photonic structure for developing high-performance electric-optic modulators based on graphene.

The above achievements will facilitate the applications on perfect absorption of single-wavelength signal, electric-optic modulation and optical sensing based on graphene, but they depend on the high optical absorption of a narrow band. In order to bring about broadband high absorption, graphene with more atomic layers can be introduced on both Boundary A and Boundary B. As shown in Fig. 7 (a) and Fig. 7(b), broadband high absorbance is obtained in the visible range, when the incident angle is larger than

![Fig. 5. (a) Optical sensing structure for localized chemical bonding based on graphene, hBN and a prism. (b) Reflectance spectra as a function of optical conductivity of graphene by using the prism-based structure, where the incident angle and the thickness of hBN are 89.1° and 30.9 nm, respectively. (A colour version of this figure can be viewed online.)](image-url)
the critical angle of $43.2^\circ$. These two Figures also demonstrate that the maximum absorbance ratios above 95% are focused around $\lambda = 520$ nm, which is determined by the fixed thickness of Layer 2. The absorbance above 60% can be maintained for the wide ranges of wavelengths and incident angles. In contrast, the absorbance ratio is significantly reduced for the incident angle below the critical angle of $43.2^\circ$. The broadband optical absorption is of great importance for developing many optical devices based on graphene, such as solar cells, light emitters and photothermal therapy [38–40]. Based on the modelling theory, this angle can be tuned by changing the ratio of refractive index between Layer 3 and Layer 1. The reconfigurable light response based on angular manipulation might be applied on broadband optical switching and broadband filtering of different angular signals. Compared to graphene with three atomic layers in Fig. 7(a), graphene with four atomic layers in Fig. 7(b) maintains broadband high absorbance for a larger range of incident angle. In this structural configuration, Layer 2 is sandwiched by two graphene layers, and it acts as an optical cavity with light energy dissipation on both Boundary A and Boundary B. The use of graphene with more atomic layers reduces the quality factor of the cavity, and induces more broadband optical absorption for more incident angles.

4. Conclusions

We have proposed a simple photonic structure with two unpatterned dielectric layers, in order to achieve perfect light absorption in the spectral range from UV to NIR. This structure acts as a single-channel coherent perfect absorber induced by the self-interference mode, and it avoid the fussy patterning on graphene or the use of complicated coherent light beam systems. The perfect light absorption can be implemented by an angled optical fibre tip, which will facilitate the combination between graphene and integrated optical systems. The extremely high light-matter interaction

Fig. 6. (a) Reflectance as a function of $\lambda$ and $\mu_c$, and (b) reflectance contrast between $\mu_c = 0.65$ eV and $\mu_c = 0.3$ eV, where graphene is on Boundary B and $\theta_1 = 89.6^\circ$. (c) Reflectance as a function of $\lambda$ and $\mu_c$, and (d) reflectance contrast between $\mu_c = 0.65$ eV and $\mu_c = 0.3$ eV, where graphene is on Boundary A and $\theta_1 = 89.1^\circ$. The parameters $n_5, n_3$ and $d_2$ are 1.46, 1.77 and 201 nm, respectively. (A colour version of this figure can be viewed online.)

Fig. 7. (a) Absorbance as a function of $\lambda$ and $\theta_1$, in which both Boundary A and Boundary B have graphene with three atomic layers. (b) Absorbance as a function of $\lambda$ and $\theta_1$, in which both Boundary A and Boundary B have graphene with four atomic layers. Here, Layer 1 is silica ($n_1 = 1.46$), Layer 2 is alumina ($n_2 = 1.77$), Layer 3 is air ($n_3 = 1$), and $d_2$ equals to 64.8 nm. (A colour version of this figure can be viewed online.)
and narrowband absorption will enable ultrasensitive sensing and high-performance optical modulation based on graphene. Broadband high optical absorption can also be reached with the effects of angular selectivity. Our research provides a comprehensive physical picture for the simple scheme of light trapping on graphene in the UV-NIR range, and also paves the way for various new applications based on graphene in the optics and optoelectronics community.

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Appendix A. Supplementary data

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