Gate-tunable nearly total absorption in graphene with resonant metal back reflector

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Abstract – The gate-tunable absorption of graphene layers with a resonant metal back reflector (RMBF) is theoretically investigated. We demonstrate that the absorption of graphene with RMBF can vary from nearly negligible to nearly total by tuning the external gate voltage within the terahertz (THz) spectra range. Total THz absorption is less affected by the incident angle of THz beams. This peculiar nearly total THz absorption can be attributed to the Fabry-Perot cavity effect, which enhances the absorption and reduces the reflection of graphene. The absorption spectra of the graphene-RMBF structure can also be tailored in bandwidth and center frequency by changing the thickness and dielectric constant of the spacer layer. These findings can lead to the development of tunable THz photonic devices and have potential applications in studies on the ultrafast dynamics of Dirac fermions in graphene.

The optical properties of graphene is attracting increased attention because of the abundant potential applications within a wide spectral range from terahertz (THz) to visible frequencies [1–27]. As an ultra-thin two-dimensional (2D) carbon material, graphene is widely used in the transparent electrodes and optical display materials [1–4]. In recent years, THz techniques have been used to study the electric states in graphene [28–33]. Given the ultra-high carrier mobility of graphene, it also has applications in THz optoelectronics such as transformation optics, tunable THz modulators, room-temperature THz detectors, THz optical antennas [26,34–41], etc. In particular, the modulated THz transmission of graphene films $\Delta T/T$ can be as large as 15% by applying an external gate voltage in the experiment [35–37], which have potential applications in tunable THz modulators and detectors. To promote these applications, a gate-tunable nearly 100% absorption is very desired.

In the recent two years, various microstructures have been proposed to get complete absorption in graphene, e.g., the periodically patterned graphene, the microcavity, the graphene-negative permittivity metamaterials, and the attenuated total reflectance, etc. [12–16]. The concept of perfect absorbers has initiated a new research area and has important applications in optoelectronics [12,42–44]. However, fabricating periodically patterned graphene or placing it in an optical microcavity under current technological conditions remains difficult. Recently, Liu \textit{et al.} proposed that the optical absorption of graphene layers on the top of a one-dimensional photonic crystal (1DPC) can be significantly enhanced within the visible spectral range because of photon localization [45]. In a similar manner, the absorption of graphene can also be increased within the THz spectra range [46]. The proposed 1DPC structures can be implemented using existing technologies. However, the photonic band gap (PBG) of 1DPC limits the spectrum bandwidth for the absorption enhancement of graphene.

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In fact, highly conducting metal films such as aluminum, silver, and gold can effectively reflect the electromagnetic wave within a wide spectral range from the middle-infrared region to the microwave region the same as a 1DPC [47]. Different from the 1DPC, the reflection of the metal films within the THz range is nearly invariable with different incident angles. Thus, the metal film can replace the 1DPC to enhance the THz absorption of graphene within a wide spectrum region and different incident angle. Apart from performing as the back reflector, the metal film can also act as the metal gate electrode that can be used to modulate the Fermi energy of graphene and the absorption of graphene.

In this letter, the THz absorption of graphene layer prepared on top of SiO$_2$/p-Si substrate with a resonant metal back reflector (RMBF) is theoretically investigated. We find that the absorption of graphene with an RMBF can be enhanced by about 3.3 times because of Fabry-Perot interference. The full width at half maximum of the absorption spectrum (FWHM) of graphene with an RMBF is much larger than that of graphene on top of a 1DPC. By tuning the applied gate voltage, the THz absorption of graphene layer with an RMBF can vary widely from almost no absorption to almost 100% absorption regardless of the incident angle if this angle is not too large. Our proposal is very easy to implement using the existing technology and has potential important applications in both THz and graphene studies.

The details of the structure are shown in the inset of fig. 1. The spacer layers consist of 300 nm SiO$_2$ layers and a 21.9 μm lightly doped p-type silicon (p-Si) layer with resistivity greater than 100 Ω cm, unless otherwise specified. The graphene layer is prepared on top of the SiO$_2$ layer, and an 86 nm silver film is placed at the bottom of the p-Si layer as the back reflector and metal gate electrode\(^1\). The refractive index of the p-Si (SiO$_2$) layer is 3.418 (2.1) and negligible in THz absorption [48]. The conductivity of graphene can be expressed as [46]

\[
\sigma_g = \frac{e^2}{\pi \hbar} \frac{|\epsilon_F|}{\hbar \Gamma - i\hbar \omega},
\]

where $\hbar$ is the reduced Planck constant, $\Gamma$ is the relaxation rate, $\epsilon_F$ is the Fermi level position with respect to the Dirac point, and $\omega$ is the angular frequency of the incident THz radiation. The permittivity of graphene can given by $\varepsilon_g(\omega) = 1 + \frac{z_0}{\omega_0} = 1 + \frac{z_0}{\omega_0} d_g$ [49], where $\omega_0$ is the vacuum permittivity, $\sigma$ is the conductivity of bulk materials, and $d_g = 0.34$ nm is the thickness of graphene.

To model the THz absorption of graphene in this structure, the transfer matrix method is used [45,50,51]. In the

\(^1\)Changes in THz absorption are negligible if the 86 nm silver films are replaced by Al, Au, or thicker silver films.

Fig. 1: (Color online) The absorbance of graphene as a function of the frequency for different structures: suspended graphene monolayer (black solid line), graphene monolayer with a 1DPC (blue dotted line), and graphene monolayer with an RMBF (red dashed line). The inset shows the schematic of the graphene layer prepared on top of SiO$_2$/p-Si spacer layers with an RMBF.
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the $l$-th layer. For the 1st graphene layer, $d_1 = d_g = 0.34$ nm. Thus, the light in the $(l+1)$-th layer is related to the incident fields by the transfer matrix

$$
\begin{pmatrix}
A_{l+1} \\
B_{l+1}
\end{pmatrix} =
\begin{pmatrix}
t^{l1}_{11} & t^{l1}_{12} \\
t^{l2}_{21} & t^{l2}_{22}
\end{pmatrix}\ldots\begin{pmatrix}
t^{l1}_{11} & t^{l1}_{12} \\
t^{l2}_{21} & t^{l2}_{22}
\end{pmatrix}
\begin{pmatrix}
A_0 \\
B_0
\end{pmatrix} =
\begin{pmatrix}
T^{l1}_{11} & T^{l1}_{12} \\
T^{l2}_{21} & T^{l2}_{22}
\end{pmatrix}
\begin{pmatrix}
A_0 \\
B_0
\end{pmatrix}.
$$

(5)

Thus, we can obtain the absorbance of graphene $A_o$ using the Poynting vector [45]

$$
A_o = (S_{0i} + S_{2i} - S_{0o} - S_{2o})/S_{0i},
$$

(6)

where $S_{0i}$ and $S_{0o}$ ($S_{2i}$ and $S_{2o}$) are the incident and outgoing Poynting vectors in air (in the nearest spacer layer), respectively. Here, $S_{0i} = \beta_0 A_0^2 \cos \theta$, $S_{2o} = \beta_0 B_0^2 \cos \theta$, $S_{2i} = \beta_1 B_0^2 \cos \theta'$, and $S_{0o} = \beta_1 A_0^2 \cos \theta'$. For the TE mode, $\beta_0 = \sqrt{\varepsilon_0/\mu_0}$, $\beta_1 = \sqrt{\varepsilon_o/\mu_o}$; for the TM mode, $\beta_0 = \sqrt{\varepsilon_0/\mu_0}$, $\beta_1 = \sqrt{\mu_0/\varepsilon_o}$, where $\varepsilon_o$ is the dielectric constant of the spacer layer, and $\theta'$ is the propagation angle of light in the spacer layer.

Figure 1 shows the THz absorption of graphene layers under normal incidence in different structures as a function of frequency. In the calculations, $\hbar \Gamma = 2.5$ meV [46] and $\epsilon_F = 0.06$ eV are used. The Fermi energy $\epsilon_F$ is more than twice the thermal energy at room temperature ($\sim$26 meV). The energy of the 1 THz photon is about 4 meV, which is much smaller than $2\epsilon_F$. The absorption induced by the inter-band transition can be negligible due to Pauli blocking. The maximum THz absorbance of the graphene monolayer with an RMBF is about 0.5 (red dashed line in fig. 1). By contrast, for the same frequency ($f \approx 1$ THz), the absorbance of the suspended graphene monolayer is about 0.15 (black solid line in fig. 1). Thus, the absorption of graphene monolayer with an RMBF can be enhanced by about 3.3 times. Similar to graphene with a 1DPC, the graphene layer and the metal film act as the mirrors of the Fabry-Perot Cavity. The THz wave propagates back and forth between these two mirrors, which leads to photon localization and enhances the absorption of graphene [45,51].

In fig. 1, we also show the THz absorption of graphene layers prepared on top of 7.5 period alternating Si and SiO$_2$ layers, i.e., 1DPC. The maximum THz absorbance of the graphene monolayer with a 1DPC is about 0.52 (blue dotted line in fig. 1), which is slightly larger than that of the graphene monolayer with an RMBF. However, the FWHM of the absorption spectrum of graphene monolayer with a 1DPC is only about 0.11 THz limited to the PBG width in 1DPC. By contrast, the bandwidth of absorption in the graphene-RMBF structure can reach 0.45 THz because the metal film can perfectly reflect the electromagnetic wave within the wide spectral range. More importantly, graphene-RMBF structure is much easier to realize than other proposed structures such as 1DPC, periodically patterned graphene, and microcavity. THz spectroscopy is also used to detect electron states and ultrafast dynamics of Dirac fermions in graphene [28–33]. The enhanced THz absorption with an RMBF can promote these studies and may help observe the THz-induced nonlinear dynamics of Dirac fermions in graphene [33,52,53].

The THz absorption of graphene layers can be tuned by varying the gate voltage. The Fermi energy $|\epsilon_F|$ of graphene can be continuously tuned by varying the gate voltage similar to a field-effect transistor. As shown in eq. (1), the conductivity of graphene is expected to increase as the Fermi energy $|\epsilon_F|$ is increased, which enhances the intraband THz absorption of graphene. By using a simple capacitor model, the Fermi energy $|\epsilon_F|$ of graphene in our proposed structure can be written as [5,36]

$$
|\epsilon_F| = h\nu_F \sqrt{\pi |\alpha_c (V_g - V_{E0})|},
$$

(7)

where $\nu_F = 1 \times 10^6$ m/s is the Fermi velocity, $\alpha_c \approx 7 \times 10^{10}$ cm$^{-2}$V$^{-1}$, $V_{E0} = \epsilon_F^2/\hbar^2 v_F^2 |\alpha_c|$, and $\epsilon_{E0}$ is the Fermi energy of graphene with zero gate voltage.

The absorbance and reflectance of graphene monolayer with an RMBF as a function of the light frequency and back gate voltage for $\epsilon_{E0} = 0.06$ eV are shown in fig. 2(a) and (b), respectively. The absorbance of graphene with an RMBF can vary from nearly zero to nearly 100% by tuning the gate voltage. For instance, when $f = 1.26$ THz,
the absorbance (reflectance) of graphene with an RMBF for $V_g = 3.8\text{ V}$, $V_g = 45\text{ V}$, and $V_g = 80\text{ V}$ is about 0.03 (0.96), 0.9 (0.08), and 0.97 (0.02), respectively. Thus, the absorbance and reflectance are very sensitive to the gate-voltage. By contrast, the absorbance of the graphene monolayer without an RMBF as a function of optical frequency and the back gate voltage is shown in fig. 2(c). To remove the Fabry-Perot cavity effect, the thickness of the p-Si layer is set to semi-infinite. The maximum absorbance of graphene without an RMBF is only about 0.2, which is even smaller than that of suspended graphene monolayer (black solid line in fig. 1). Thus, the traditional substrate material reduces the absorption of graphene [54]. In fact, the absorption coefficient of graphene within the THz frequency range is large. The weak absorbance of graphene is due to the fact that most of the incident THz wave is reflected because of the large real and imaginary parts of the conductivity of graphene for a large Fermi energy $|\epsilon_F|$. A resonant back reflector such as 1DPC or metal can reduce the reflection of graphene [51,55] and lead to relatively weak photon localization [45], which are the key points for achieving nearly total THz absorption in graphene.

The absorption spectra of the graphene-RMBF structure in the case of oblique incidence of a THz beam are shown in fig. 3. The resonance condition of a Fabry-Perot cavity can be described as $2L_0k\cos \theta' = 2m\pi$, where $m$ is an integer, $L_0$ is the optical path of the p-Si and SiO$_2$ spacer layers, $k$ is the wave vector of the THz wave, and $\theta'$ is the propagation angle of the THz wave in the spacer layer. According to Snell’s law, $\theta'$ is small even with a large incident angle $\theta_i$ because of the large refractive index of the p-Si layer in the proposed structure. Different from the 1DPC, the reflection of the metal films within the THz range is nearly invariable with increased incident angle. Thus, the THz absorption of graphene with an RMBF is less affected by the incident angle of the THz beams if the incident angle is not too large. For instance, for $\epsilon_F = 300\text{ meV}$, the absorbance of graphene monolayer for $\theta_i = 0^\circ$ and $\theta_i = 30^\circ$ for TE (TM) mode is about 0.956 (0.956) and 0.972 (0.926). Even for incident angle $\theta_i = 60^\circ$, the absorbance of graphene monolayer for the TE (TM) mode is about 0.963 (0.757). Thus, our proposed graphene-RMBF structure can be used in pantoscopic and imageable THz detectors and modulators.

We now consider the adjustability of the THz absorption of graphene by varying the dielectric constant or optical path of the spacer layers. The reflection of the graphene layer is smaller with a lower dielectric constant substrate, and the THz absorption of graphene is enhanced beyond the resonance cavity frequency. The FWHM of the THz absorption spectra increases with decreased dielectric constant of the spacer layers (see fig. 4(a)). For air spacer layers, i.e., the FWHM of the absorption spectrum of graphene monolayer with RMBF can be as large as 1.2 THz. For the normal incidence case, the resonance condition of a Fabry-Perot cavity is $2L_0k = 2m\pi$, which indicates that the center frequency of the absorption spectra can be easily tuned by varying the spacer layers thickness. As shown in fig. 4(b), the center frequency of the THz absorption peak increases with decreased spacer layers thickness. Given that the absorption coefficient of graphene is larger for lower frequency THz waves according to eq. (1), the maximum absorption of graphene increases with increased spacer layers thickness. Thus, the fabrication of the graphene-RMBF structure with a
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Fig. 5: (Color online) The inter-band absorbance of graphene as a function of the frequency for suspended graphene monolayer (black solid line) and graphene monolayer with an RMBF (red dotted line) with 1.09 μm lightly doped p-type silicon.

thickness-tunable air spacer layer (e.g., gate-controlled suspended graphene [56,57]) is also highly desired.

Finally, we discuss the inter-band contributions in the absorption of graphene layers. The optical conductivity caused by the inter-band transition can be described by \( \sigma_I = \sigma'_I + i\sigma''_I \), where \( \sigma'_I = \sigma_0 (1 + \frac{1}{\pi} \text{arctan} \frac{\hbar \omega - 2eF}{\Gamma} - \frac{1}{\pi} \text{arctan} \frac{\hbar \omega - 2eF}{\hbar \omega - 2\gamma}) \), \( \sigma''_I = -\sigma_0 \frac{1}{\pi^2} \ln \left( \frac{2eF + \hbar \omega + \hbar \gamma - 2\gamma}{2eF - \hbar \omega + \hbar \gamma - 2\gamma} \right) \), and \( \sigma_0 = \pi e^2/(2 \hbar) \) [58]. The real part of the optical conductivity \( \sigma'_I \) describes the dissipation of electromagnetic energy (i.e., the absorption) in the graphene layers. For the case of \( 2eF \gg \hbar \omega \) and \( 2eF \gg \Gamma \), as discussed before, \( \text{arctan} \frac{\hbar \omega - 2eF}{\Gamma} \approx -\pi/2 \). The inter-band contributions in absorption is quite small due to \( \sigma'_I \approx 0 \). However, for low \( eF \) and high frequency \( \omega \), the inter-band contributions in absorption is larger than the intra-band contributions. The RMBF can also enhance the inter-band absorbance as shown in fig. 5. The maximum inter-band absorbance of graphene monolayer with an RMBF is about 8.1% at ~19 THz with \( eF = 0 \), which is about 3.5 times larger than that of suspended graphene monolayer.

In summary, the gate-tunable THz absorption of graphene layers with an RMBF is investigated. The THz absorption of graphene with an RMBF is enhanced and can be tuned from nearly zero to nearly total by varying the gate voltage. This peculiar nearly total THz absorption can be attributed to the Fabry-Perot cavity effect, which enhances the absorption of graphene and reduces the reflection of the THz beams. The maximum absorption of graphene is almost unchanged even when the incident angle varies from 0° to 30°. The center frequency and FWHM of the absorption spectra can also be tuned by varying the thickness and dielectric constant of the spacer layers. Using existing technology, the proposed structure is very easy to fabricate not only in laboratory scale but also in industrial scale. Our findings have important implications in the development of THz photonic devices such as THz detectors and modulators, as well as in studies on the ultrafast dynamics of Dirac fermions in graphene.

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