Electrically tunable absorber based on nonstructured graphene

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Abstract

We demonstrate numerically that a tunable absorber with absorption of 99.94% in the far infrared range can be obtained using a nonstructured graphene. The mechanism originates from a nonstructured graphene film supported on a periodical dielectric array that can show Fermi level modulation periodically and produce plasmonic resonances in the far infrared range. The nonstructured graphene can avoid the unexpected edge effects and does not influence the unique properties of graphene, which will be helpful in practice to achieve the unity absorption and facilitate the development of many related applications.

Keywords: absorber, nonstructured graphene, tunable

1. Introduction

Because of its unique properties, graphene has attracted significant interest in photonic applications, such as photodetectors [1, 2], modulators [3–6], polarizer [7], reflectors, and filters [8, 9]. Of late, graphene has become one of the most promising materials in the design of tunable absorbers that can operate in both THz and infrared spectral ranges because the carrier mobility and conductivity of graphene are tunable [10–19]. Graphene absorbers have been extensively studied and a variety of structures have been proposed such as graphene disks [10], ribbons [11], anti-dots [12], fishnets [20], and multilayers [21]. All these structures can achieve a near-unity absorption in theory and simulation. Unfortunately, the near-unity absorption of these structures has not been demonstrated experimentally. One possible reason is that all these structures are based on nanostructured graphene, which produce plasmonic resonances when excited by an incident wave. However, the edge effects of the nanostructured graphene [22, 23] might lead to diffuse scattering and destroy the destructive interference, thus rendering it difficult to achieve the unity absorption in practice. Recently, some researchers have found that combining a nonstructured graphene with metasurface comprising plasmonic structures [24] or stacking nonstructured multilayer graphene sheets on quartz substrates backed with a ground plate [25] can also act as the perfect absorber.

In this article, we demonstrate that using a nonstructured graphene, thus avoiding the unexpected edge effects and not influence the unique properties of graphene, can also obtain the unity absorption. We first analyze the physical mechanism of the proposed absorber and then run a numerical simulation in the infrared spectral range.

2. Methods and results

Figure 1(a) presents a schematic of the absorber we designed. The absorber consists of a single flake of graphene supported on a 1D periodical dielectric array and a doped semiconductor substrate with thickness ts on top of a thick piece of metal. The 1D periodical dielectric array is structured by alternately ranking two kinds of dielectric material with relative

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permittivity $\varepsilon_{d1}$ and $\varepsilon_{d2}$ ($\varepsilon_{d2} > \varepsilon_{d1}$). The thickness and period of the dielectric array are $t_d$ and $P$, respectively. The width of high permittivity dielectric ($\varepsilon_{d2}$) is labeled as $W$. A bias voltage is imposed between the graphene and the doped semiconductor substrate to electrically dope the graphene. As we know, applied gate voltage on graphene leads to a carrier density change [17, 26–29] and consequently shift the Fermi level ($E_F$) according to the following formula (for single layer graphene)

$$|E_F| = h\nu_F (\pi N)^{1/2},$$

where $\nu_F \approx 1 \times 10^6$ m s$^{-1}$ is the Fermi velocity, and $N$ is the total carrier density [3]. For simplicity, a simple electrostatic parallel capacitor model is adopted to provide the required voltage $V_{bias}$ dependence on the spacing of dielectric layer, where the total carrier density $N$ is expressed as

$$N = e_0 \varepsilon_r |V_{bias}|/q \varepsilon_b,$$

where $q$ is the elementary charge, $t_d$ is the thickness of the dielectric layer of electrostatic parallel capacitor model, $\varepsilon_r$ is the relative permittivity of dielectric layer, and $\varepsilon_0$ is the permittivity of free space. Therefore, equation (1) can be written as

$$|E_F| \approx h\nu_F (\pi 0.5 |V_{bias}|/q t_d)^{1/2} \propto \varepsilon_t^{1/2}. \quad (3)$$

From equation (3), we can find that Fermi levels are determined by the relative permittivity of dielectric layer when a fixed applied gate voltage $V_{bias}$ is applied. Therefore, the nonstructured graphene film supported on a periodical dielectric array (as shown in figure 1(a)) can periodically show Fermi level modulation of $E_{F2}$ and $E_{F1}$ ($E_{F2}/E_{F1} = (\varepsilon_{d2}/\varepsilon_{d1})^{1/2}$) and be regarded as a periodic array of graphene ribbons [30, 31]. It is well known that doped graphene ribbons can produce sharp plasmonic resonances when excited by an electric vector perpendicular to the graphene ribbons [18]. In this model, the thick piece of metal not only acts as an electrode, but also suppresses the transmission channel. If this plasmonic resonance together with the fields reflected from the dielectric film and the thick metal can cause the destructive interference of total reflected wave, the only possible outcome is absorption, which leads to near-unity absorption.

To verify our prediction, we conducted the full-wave numerical simulations using the commercial finite integration package CST MICROWAVE STUDIO. In the simulation, we regard the graphene as an anisotropic effective media of thickness $t_g$ of 1 nm with the in-plane component of relative complex permittivity as $\varepsilon_{x1} = \varepsilon_{x1} = 2.5 + i \sigma(\omega)/(\omega \varepsilon_0 \gamma_1)$ [3], and the surface normal component as $\varepsilon_{z2} = 2.5$, where $\sigma(\omega)$ is the optical conductivity calculated within the local random phase approximation as in [32, 33]

$$\sigma(\omega) = \frac{2e^2 k_B T}{\pi h^2} \left( \frac{i}{\omega + i \tau} \right) \log \left( 2 \cosh \left( \frac{E_F}{2k_B T} \right) \right) + \frac{e^2}{4h} \int_0^\infty H(\omega/2 + i \omega) \left( \frac{\omega}{\omega^2 - 4\Omega^2} \right) d\Omega,$$

where $H(\omega) = \sinh(h\omega/k_B T)/[\cosh(E_F/k_B T) + \cosh(h\omega/k_B T)]$, $\omega$ is the frequency of incident light, $E_F$ is the Fermi level, $e$ is the charge of an electron, $\tau$ is the Drude relaxation rate, $T$ is the temperature, $h$ is the reduced Planck's constant, and $k_B$ is the Boltzmann constant. In equation (4), the first and second terms describe the intraband response and the interband transitions of graphene, respectively. The dielectric material was considered to be nondispersive with relative permittivity $\varepsilon_{r1}$ and $\varepsilon_{r2}$ 1.0 and 4.0, respectively. The doped semiconductor substrate is taken to be a nondispersive dielectric material with relative permittivity 11.56, and the metallic material, with thickness $t_m$, is Au, which is treated as a dispersive medium following the Drude model [34, 35]. The relative permittivity is derived from $\varepsilon(\omega) = \varepsilon_{\infty} - \omega_p^2/(\omega^2 + i \gamma)$. The values of $\varepsilon_{\infty}$, $\omega_p$, and $\gamma$ are 1.0, $1.38 \times 10^{16}$ rad s$^{-1}$, and $1.23 \times 10^{13}$ s$^{-1}$, respectively.

First, we consider the case where the period $P$, width $W$, the thickness $t_d$, $t_s$, $t_m$ and Fermi level $E_{F1}$ and $E_{F2}$ are 300, 140, 15, 760, 200 nm, 0.45, and 0.90 eV, respectively. It should be stressed that, for the reason of simplicity in the simulations, and to keep the concepts easily and intuitively understandable, we have assumed the sharp inhomogeneity in

\[\text{Figure 1. (a) Schematic model of electrically tunable absorber, consisting of a single flake of graphene supported on a 1D periodical dielectric array and a doped semiconductor substrate on top of a thick piece of metal. (b) A unit cell of absorber structure. The period of unit cell is } P. \text{ The thickness of dielectric layer, substrate layer, dielectric layer, and metal is } t_d, t_s, \text{ and } t_m. \text{ The width of the high permittivity dielectric is } W.\]
Fermi level distributions of the two neighboring sections of a single flake of graphene. However, our ideas of designing an absorber using nonstructure graphene will still be valid and applicable even when the Fermi level inhomogeneity between the two sections is reasonably smooth in the form of a transition region.

Figure 2(a) shows the absorption spectra for the incident polarization with the electric vector that is perpendicular to the periodical dielectric grating under normal incidence excitation. From figure 2(a), we can see that the absorption is 99.94% at the frequency of 28.74 THz. This results from the fact that the perpendicular component can excite the local plasmonic resonance. The electric field patterns for the frequency of 28.74 THz are also given in figure 2(b). From figure 2(b), we can find that the frequency of 28.74 THz corresponds to a strong first order local plasmon resonance.

To study the electrically tunable effects of this absorber, we varied the Fermi level $E_{F1}$ ($E_{F2}$) between 0.3 eV (0.6 eV) and 0.55 eV (1.10 eV), even as fixing $P = 300$ nm, $W = 140$ nm, $t_d = 15$ nm, and $t_s = 760$ nm. Figure 3 shows the absorption as a function of the Fermi level. From figure 3, we can find a blue shift of the operation frequency with the increased Fermi level, which implies that the operation frequency can be tuned by the Fermi level. This is because the near-unity absorption of this type of absorber is closely related to the graphene plasmon resonance (the maximum absorption frequency-slightly red-shifts with respect to the plasmon resonance [10]), and simultaneously, the plasmonic resonance frequency of the electrically doped graphene increases with increased Fermi level [36–38].

Next, we consider the situation where Fermi level $E_{F1}$ ($E_{F2}$) is fixed at 0.45 eV (0.90 eV) and the width $W$ and the thickness $t_d$ and $t_s$ are varied. Figure 4(a) shows the calculated absorption curves with varying $W$, even as fixing $P = 300$ nm, $t_d = 15$ nm, and $t_s = 760$ nm. As can be seen from figure 4(a), a red shift of the absorption maximum is evident with increased $W$. The reason for this corresponds to the fact that the increased $W$ leads to an increased effective refractive index of the plasmon resonant mode [28, 39]. Figures 4(b)–(d) show the effect of the thickness $t_d$ and $t_s$ on the performance of the absorber where the period $P = 300$ nm and width $W = 140$ nm. From figure 4(b) and (c), we can find a blue shift of the absorption maximum with increased $t_d$. This can be understood through the following qualitative analysis. The increased $t_d$ leads to a decreased electric field energy of the plasmon resonant mode distribution in the high refractive index material (doped semiconductor substrate). Therefore, the corresponding effective refractive index of the plasmon resonant mode becomes smaller and a blue shift of the absorption maximum occurs. In addition, a decrease of the absorption maximum with increased $t_s$ from 15 to 45 nm can also be found, as shown in figures 4(b) and (d), which results from the fact that the phase-matching condition is destroyed as $t_d$ increases. Contrarily, as shown in figure 4(c), the operation frequency of the absorption maximum are approximately insensitive to $t_s$ when $t_s$ varies from 500 to...
1000 nm. The reason for this corresponds to the fact that the electric field energy of the plasmon resonant mode is limited in half plasmon wavelength range, which is much smaller than 500 nm. Therefore, when $t_s$ varies from 500 to 1000 nm, the plasmon resonant frequency does not vary significantly and thus the operation frequency of the absorption maximum is approximately insensitive to $t_s$.

In order to investigate the absorption sensitivity to the oblique incidence plane wave, we vary the incident angle $\theta$ (defined as the angle between the incident wave and positive z-direction (see figure 1)) while the period $P$, width $W$, the thickness $t_d$, $t_s$, and $t_m$, and Fermi level $E_{F1}$ and $E_{F2}$ are fixed at 300, 140, 15, 760, 200 nm, 0.45 eV, and 0.90 eV, respectively. Figure 5 shows the calculated absorption as a function of frequency and incident angle while maintaining the electric field vector perpendicular to the 1D periodic dielectric grating. It can be observed that the incidence-angle absorption dependence is relatively weak when the incidence angle varies between $0^\circ$ and $30^\circ$.

Figure 4. (a) Calculated absorption curves with varying width of dielectric grating, when the thickness $t_s$ and $t_d$ and Fermi level $E_{F1}$ ($E_{F2}$) is 760, 15 nm, and 0.45 eV (0.90 eV), respectively. (b) Calculated absorption curves with varying thickness of periodical dielectric array, when $t_s$ = 760 nm. (c) Frequency corresponding to the absorption maximum and (d) absorption curves with varying thickness $t_s$ and $t_d$. The period $P$, and the Fermi level $E_{F1}$ ($E_{F2}$) are 300 nm and 0.45 eV (0.90 eV), respectively.

Figure 5. Calculated absorption as a function of frequency and incident angle. The period $P$, width $W$, thickness $t_d$, $t_s$ and $t_m$ and Fermi level $E_{F1}$ and $E_{F2}$ are 300, 140, 15, 760, 200 nm, 0.45, and 0.90 eV respectively.
Obviously, the proposed absorber is polarization dependent because of the asymmetric periodical dielectric array. Figure 6(a) gives the absorption spectra of two polarization components, where fixing $P = 300$ nm, $t_d = 15$ nm, and $t_r = 760$ nm. From figures 6(a), we can find that the absorption of the polarization with the electric vector perpendicular to the dielectric grating is 99.94%, and the other component is only 2.79% at the frequency of 28.74 THz, which implies that the absorber can be used as a polarizer. Figure 6(b) gives the calculated result of polarizing extinction ratio with varying Fermi levels. The polarizing extinction ratio can be as high as 32 dB at the frequency of 28.74 THz, which is shown clearly in figure 6(b).

3. Summary

In summary, we proposed an absorber based on a nonstructured graphene film supported on a 1D periodical dielectric array. Numerical simulations demonstrate that the absorption of 99.94% can be obtained at the frequency of 28.74 THz. The proposed absorber can be used as a polarizer with polarizing extinction ratio of 32 dB because the 1D periodical dielectric array is polarization-dependent. It is worth emphasizing that an absorber that is polarization-independent can be easy to obtain by replacing the 1D periodical dielectric grating with a 2D periodical dielectric array. The absorber based on nonstructured graphene will be helpful in practice to achieve the unity absorption and facilitate the development of many related applications because the nonstructured graphene can avoid destroying the unique properties of graphene.

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