Dual-band tunable perfect metamaterial absorber in the THz range

Gang Yao,1 Furi Ling,2,* Jin Yue,1 Chunya Luo,1 Jie Ji,1 and Jianquan Yao1,3
1Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China
2School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
3College of Precision Instrument and Opto-electronics Engineering, Tianjin University, Tianjin 300072, China
*lingfuri@mail.hust.edu.cn

Abstract: In this paper, a dual-band perfect absorber, composed of a periodically patterned elliptical nanodisk graphene structure and a metal ground plane spaced by a thin SiO2 dielectric layer, is proposed and investigated. Numerical results reveal that the absorption spectrum of the graphene-based structure displays two perfect absorption peaks in the terahertz band, corresponding to the absorption value of 99% at 35μm and 97% at 59μm, respectively. And the resonance frequency of the absorber can be tuned by controlling the Fermi level of graphene layer. Furthermore, it is insensitive to the polarization and remains very high over a wide angular range of incidence around ±60°. Compared with the previous graphene dual-band perfect absorption, our absorber only has one shape which can greatly simplify the manufacturing process.

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References and links
Introduction

Metamaterial perfect absorbers (MPAs), as a branch of metamaterials (MMs), with the subwavelength scale unit cell, currently provoke extensive interests since the first experimental demonstration was given by Landy et al. in 2008 [1], in which the incident electric and magnetic fields are independently absorbed by two MM resonators printed on the top and the bottom sides of a substrate. Since then, MPAs, having been widely investigated and demonstrated promising applications in bolometers, chemical and biomedical sensing, photodetector, photothermal conversion, and so on, have received considerable attention and many MPAs have been proposed. One of the hottest research direction in this area is to realize tunable MPAs due to their great flexibility in practical application [2–4]. Currently, most designs are focused on the absorption strength modulation rather than the resonance frequency modulation [5, 6]. Another research direction aims to find an effective approach to achieve multiband or broadband absorption [7]. One method is to combine two or more resonators with different sizes together to form a super-unit-cell [8–10]. Another method is to stack multiple layers of the resonators with different geometric dimensions separated by dielectric layers with appropriate thicknesses [11, 12]. Although the multiband or broadband and tunable absorptivity behaviors are very desirable, combining those two characteristics is a very difficult task, which greatly hampers their practical application.
Because of its unique electrical, mechanical, and thermal properties, graphene, a single layer carbon atom arranged in a honeycomb structure, has attracted considerable attention [13–15]. Due to the tunability of its carrier mobility and conductivity, numerous reports have focused on the theoretical research of absorber based on graphene metamaterials. New class of frequency-tunable metamaterial perfect absorbers based on graphene micro-ribbons [16, 17], graphene nanodisk [18], graphene heterostructures [19] as well as the combination graphene wire and gold cut wire [20] have been studied and explained. However, these research results indicate that perfect absorber has single or narrow band absorption. Then, much broadband graphene absorbers based on multilayered graphene structures [21, 22] and multiple graphene nanoresonators [23] operating at far-IR region is proposed. However, these perfect absorbers are polarization dependent in the far-IR region, and the the manufacturing process is very complex, which hampers their potential applications. Dualband metamaterial absorber based on graphene/MgF2 multilayer [24] and graphene hyperbolic metamaterial [25] have been designed in the mid-IR range. From above, few previous works have paid attention to tunable dualband absorber based on graphene metamaterial with polarization insensitive in the terahertz (0.1-10THz) region.

In this paper, we proposed a dynamically lambda-tunable graphene-based terahertz metamaterial absorber, which consists of a single-layer periodically patterned graphene electric resonant structure and a metal ground plane spaced by SiO2 dielectric layer. Because the conductivity of the graphene layer can be varied via the applied electric fields or chemical doping, the absorption of the proposed dual-band single-layered graphene absorber can be conveniently modulated. The absorber exhibits unique characters including ultrathin, dual-band absorption, insensitivity to polarizations and wide incident angles of electromagnetic wave. Obviously, the most important one of our dualband absorber is that it only has one shape of single-layered graphene, which can greatly simplify the manufacturing process compared other multiband and broadband absorber. Furthermore, we demonstrate that our proposed device can be used as a localized surface plasmon resonance (LSPR) sensor. Benefit from the relaxation time of electrons in graphene influenced by the surrounding environment such as placing organic molecules, the dualband MPA presented here can detect rather relative intensity change at two tunable lambda, differing from the existing LSPR sensors which only can measure a fixed frequency [26].

**Design and simulation of the graphene perfect dualband absorber**

The proposed structure is shown in Fig. 1. It consists of a graphene elliptical disk array on the top of a metallic ground plate separated by a thick SiO2 dielectric spacer. The top graphene layer is a single layer of elliptical graphene nanodisk array, where a denotes the length of each nanodisk’s minor elliptical axis, b represents the length of the nanodisk’s major axis. It is periodic in two direction (x, y) with periodicity d = 2.5μm. We assume the relative permittivity of the SiO2 dielectric \( \varepsilon_r = 3.9 \) [19]. The ground plate is made of gold with a conductivity \( \sigma_{gold} = 4.7 \times 10^4 \text{Sm}^{-1} \), which is perfect reflection in the frequency domain of interest (Far-infrared regime).
Fig. 1. Schematic of the graphene elliptical perfect absorber. The geometrical parameters of the proposed structure are \( d = 2.5 \mu m, b = 1.8 \mu m, a = 1 \mu m \), the thickness of SiO2 is \( d_{SiO2} = 3.3 \mu m \) and the thickness of gold is \( t_g = 0.2 \mu m \).

In these simulations, The surface conductivity of graphene \( \sigma \) is calculated according to the Kubo formula [27, 28]:

\[
\sigma(\omega, E_f) = \sigma_{\text{int,\nu}} + \sigma_{\text{int,\sigma}} = \frac{e^2}{\pi h^2} \left( \frac{1}{(\omega - 2\Gamma)^2} \right) \int_0^\infty \left( \frac{\partial f_\nu(\epsilon)}{\partial \epsilon} - \frac{\partial f_-\nu(\epsilon)}{\partial \epsilon} \right) d\epsilon - \int_0^\infty \frac{f_\nu(\epsilon) - f_-\nu(\epsilon)}{(\omega - 2\Gamma)^2 - 4\epsilon^2/h^2} d\epsilon
\]

(1)

Here, \( \sigma_{\text{int,\nu}} \) and \( \sigma_{\text{int,\sigma}} \) originate from the interband and intraband transitions respectively, \( \omega \) is the radian frequency, \( E_f \) is the Fermi energy level, \( \Gamma \) (\( \Gamma = h/\tau \), \( \tau \) is electron-phonon relaxation time) is the phenomenological scattering rate, \( T \) is the absolute temperature of the environment, and \( e \) is the charge of an electron, \( k_B \) is the Boltzmann’s constant, \( h \) is the reduced Planck’s constant. For lower THz frequency and at room temperature, the interband contribution of graphene conductivity can be safely neglected according to Pauli exclusion principle, so the graphene’s complex surface conductivity can be described as

\[
\sigma_{\text{gr}} = \frac{e^2}{\pi h^2} \frac{E_f}{(\omega + i/\tau)}
\]

(2)

Practically the Fermi level can be changed by electrostatic gating by approximately \( \pm 0.5 eV \), so we consider \( E_f = 0.5 eV \) as the Fermi level value where we expect the maximal absorption, while \( \tau = 0.5 \text{ ps} \) is initially considered and their influences will be analyzed later [20, 29]. In addition, the lambda dependent conductivity of graphene at the selected values of the Fermi level are shown in Fig. 2(a) and 2(b). Because of the spectral shift of the resonance determined by \( \text{Im}\left( \sigma_{\text{gr}} \right) \), and the amplitude modulation of the resonance controlled by \( \text{Re}\left( \sigma_{\text{gr}} \right) \), the absorption can be tuned by controlled the Fermi level via the applied electric fields or optical pump. In this study, the model calculations have been checked by the finite elements method (FEM) realized in COMSOL [30, 31], and the graphene can be considered as the surface current boundary condition. The reflection \( R(\omega) = |S_{11}|^2 \) and absorption \( A(\omega) = 1 - R(\omega) \) are obtained from S-parameters.
Fig. 2. Graphene conductivity: (a) real part (b) imag part.

Results and discussions

Figure 3 shows the calculated absorption spectra of the graphene-based metamaterial absorbers under normal incidence excitation, and the incident electric filed along the x-axis, with $E_i = 0.5eV$ and $\tau = 0.5\,ps$. Dual-band absorber will be obtain when elliptical disk array distribute as shown in the Fig. 1. According to simulation results in Fig. 3(a), a dipolar plasmon resonance of periodic arrays with only one elliptical nanodisks is observed at $35\mu m$ under normal incidence when the minor of elliptical along the x-axis. Another dipolar plasmon resonance is found at $59\mu m$ with the major of elliptical along the x-axis, as shown in the Fig. 3(b). Here, it is worth noting that the electric field polarized must be remained along the x-axis in the simulation. Then, four half graphene elliptical nanodisks are placed in one period, as shown in Fig. 3(c). And the polarization of the electric field is chosen to be parallel to x-axis. It can be seen from Fig. 3(d) (solid line) that the absorption spectrum of the graphene-based structure displays two perfect absorption peaks due to the minor (b) and major axis (a) of elliptical nanodisks, corresponding to the absorption value of 99% at $35\mu m$ and 97% at $59\mu m$.
Fig. 3. The absorption spectra for periodic arrays with only one elliptical nanodisks, (a) the minor of elliptical along the x-axis, the insert color map represents the corresponding z component distributions of the electric field of the graphene elliptical nanodisk at the transmission peak wavelength of $39\mu m$, (b) the major of elliptical along the x-axis, the insert color maps represent the corresponding z component electric field distributions of the graphene elliptical nanodisk at the transmission peak wavelength of $59\mu m$. (c) periodic arrays with four half elliptical nanodisk, (d) the absorption spectra for a (red dash line), b (blue dash line), and c (solid line).

The physical origin of dual-band perfect absorption in our structure is related to the electric dipolar resonance in the elliptical nanodisk array due to localized surface plasmon resonance and the magnetic dipolar resonance between the elliptical nanodisk array and gold film. To understand the nature of the electric and magnetic resonance, the field distribution on the top graphene nanodisk of unit cell, as shown x0y plane in the insert in Fig. 4(a) and 4(b), and the magnetic distribution on the cross-section of the structure are calculated at resonance wavelengths $\lambda_1 = 35\mu m$ and $\lambda_2 = 59\mu m$, respectively. The electric and magnetic field distributions at the absorption peak for dual-band are illustrated in Fig. 4. As shown in the Fig. 4(a), fields concentrate mostly on the vertex of minor axis (a), corresponding to absorption spectra of minor axis for periodic arrays with only one elliptical nanodisks (red dash line in the Fig. 3(a), which results in the near perfect absorption at resonance wavelengths $\lambda_1 = 35\mu m$. This electric dipole is greatly coupled with its own image, which oscillates in antiphase on the metallic film. Consequently, a magnetic polariton is formed, which induces a strong magnetic response and causes a resonant peak at $\lambda_1 = 35\mu m$ in the absorption spectrum. In order to better understand the confined electromagnetic energy, the magnetic field distributions ($|H|$) in the cross-sections along minor axis at the resonance wavelengths $\lambda_1 = 35\mu m$ is shown in Fig. 4(c), as shown e plane in the insert in the Fig. 4(c).
The enhanced magnetic fields are confined between the top graphene elliptical nanodisks and the bottom gold mirror. The result for the case of the resonance wavelength $\lambda = 59\mu m$ is presented in Fig. 3(b) and Fig. 4(b) and 4(d), manifesting significant dipolar resonance (see Fig. 4(b)) resulting from the major axis (b) of elliptical nanodisks and the magnetic field (see Fig. 4(d)) gathering in the middle of the top graphene elliptical nanodisks and the bottom gold mirror. However, we also find the dual-band perfect absorption at the resonance wavelength $\lambda = 59\mu m$ has a difference with periodic arrays that only has one elliptical nanodisks, as shown in Fig. 3(b), which results from the couple of the field distributions in the major (b) and minor axis (a) of elliptical nanodisks.

In this paper, we eliminate the polarization affinity by carefully arranging the elliptical nanodisks in a two-dimensionally symmetric structure. The dependencies of the absorption spectra on polarizations are shown in Fig. 5 for different incident angles, where the azimuthal angle is fixed at 0 degree. The two red strips in the Fig. 5 indicate the two angle-independent
high absorption bands. From Figs. 5(a) and 5(b) one can see that the proposed absorber can still work over a wide range of incident angle up to 60 degrees for both TE and TM polarizations, more than 95% absorption is still obtained for both of the two resonance peaks while maintaining the center frequencies. Nevertheless, there are two additional peaks at 41\(\mu m\) and 46\(\mu m\) appearing with the increasing of the incident angles, high as 0.38 and 0.45 respectively when \(\theta = 60^\circ\). This is because of the parasitic resonances of some parts of the structure which enhance sharply as \(\theta\) increases.

![Fig. 5. The simulated absorption efficiencies as a function of wavelength and angle of incidence under (a) TE and (b) TM polarization.](image)

The simulated distribution of electric field for \(\theta = 60^\circ\) at 41\(\mu m\) is given in Fig. 6(a). Contrast the Fig. 6(a) with Fig. 4(a), electron began to concentrate on the vertex of major axis (b) when angle of incidence increased to 60 degree, which result in additional parasitic resonances between the the major (b) and minor axes (a) of elliptical nanodisks and this cause additional peaks at 41\(\mu m\). As expected, the electric field distribution \(|E|\) become more stronger when the angle of incidence increased to 70\(^\circ\), such as Fig. 6(c). The situation at 46\(\mu m\) is similar with the one at 41\(\mu m\).
Tunability of the graphene perfect multiband absorber

The surface conductivity of graphene relates largely to the Fermi level $E_F$, which can be controlled by electrostatic and chemical doping. Figure 7(a) plots the absorption spectra for different values of $E_F$ at normal incidence. The physical origin of the near perfect absorption is the localization of electric and magnetic dipole resonances that can be expressed by $\omega = \sqrt{LC}$, where $L$ and $C$ are the effective inductance and capacitance [10], respectively. When the Fermi level changes from $0.5\text{eV}$ to $0.3\text{eV}$, two absorption peak experiences a redshift and the absorption maximum decrease simultaneously. The absorption variation can be understood as follows: the dimension of the unit cell structure is smaller than the wavelength of the incident light, so the graphene ellipse resonator can be regarded as a dipolar antenna. The relationship between the length of the dipolar antenna $L_{\text{red}}$ and its resonant wavelength $\lambda_{\text{red}}$ can be given by $2L_{\text{red}} = \lambda_{\text{red}}$. The resonant wavelength can be expressed as $\lambda_{\text{red}} = \alpha + \beta^* n_{\text{red}}$, where $\alpha$ and $\beta$ are the coefficients closely related to the device geometry and surrounding dielectric properties [32, 33]. As the Fermi level increases, the effective index of the graphene SPs decreases, resulting in an increase in the resonant frequency, that is, an increase in resonant wavelength, as shown in Fig. 7(a). The higher-wavelength absorption peak shows a greatly redshift than the lower-wavelength one due to the larger change of $\text{Im}(\sigma_g)$, as reported in [34].
The relaxation time of electrons in graphene, which is expressed as $\tau = E_f \mu / (e\nu_F)$ with the Fermi velocity $\nu_F = 10^6 \text{ m/s}$, and $\mu$ the carrier mobility, can be used to control the absorption strength. Through changing the surrounding environment such as placing organic molecules on graphene [35], the carrier mobility will be significantly enhanced, leading to the increasing of relaxation time. Figure 7(b) shows the absorption spectra for different $\tau$, with Fermi level $E_f = 0.5eV$. The location of absorption peaks remains unchanged while the peak value becomes weaken as $\tau$ increases. When $E_f = 0.5eV$ and $\tau = 0.5\text{ ps}$, the charge carriers contributed to the plasma oscillation absorption become saturated. As the relaxation time increases, most energy will be reflected, resulting in the decreased absorption.

**Conclusion**

In conclusion, a dual-band perfect absorber based on graphene elliptical nanodisks array and gold film plane has been designed and theoretically demonstrated. Numerical simulations demonstrate that the designed dual-band perfect absorber shows two near perfect absorption peaks at resonance wavelength $\lambda_{\text{res}} = 35\mu\text{m}$ and $59\mu\text{m}$ when Fermi level $E_f = 0.5eV$. These two absorption peaks are insensitive to the polarization and the near-perfect absorption efficiency is slightly affected by large incidence angles up to 60 degrees. Two absorption peaks are realized because the strong electric and magnetic dipole resonances make the impedance of the absorber match to that of the free space. It should be mentioned that the proposed dual-band single-layered graphene absorber is not only electrically tunable but also optically tunable. The knowledge that a multiband absorber can be constructed with only single-layered graphene can facilitate the development of many related applications.

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