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Research Paper

Tunable Terahertz Absorber Based on Hexagonal Graphene Disk Array

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Abstract:
In this paper, a tunable absorber structure based on a graphene hexagonal array in the terahertz range is investigated. The graphene hexagonal absorber is simulated by the finite element method. The effects of the geometry, graphene Fermi energy level and incident light angle, and light polarization on the absorptance of the structure are investigated. The results show that the absorptance spectrum of the proposed absorber is tuned from 6.1 THz to 9.1 THz when the Fermi energy increases from 0.4eV to 0.9eV. The absorptance peak shifts to lower and higher frequencies with increasing hexagonal side length and Fermi energy level, respectively. The absorption of the structure is over 90% in the incident light angle range from 0 to 80° for the TE polarization and in the range of 0-40° for the TM polarization. Also, results indicate that the absorption peaks shift to the lower energies with increasing the dielectric constant of the dielectric layer.

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1. INTRODUCTION

Metamaterials are synthetic materials that have properties not found in natural materials [1, 2]. Recently due to their exotic electromagnetic properties such as negative refraction [3], asymmetric transmission [4], and cross-polarization conversion [5] metamaterials have been noticed. Metamaterials have different applications such as polarization converters [6], highly sensitive sensors [7], perfect lenses [21], and perfect absorbers [9]. The perfect absorbers are the most important among them which are used in sensing [10], imaging [11], and cloaking [12].

On the other hand, two-dimensional materials such as graphene are suitable candidates in electrical devices due to their great optical and electronic properties, such as high electron mobility and tunable surface conductivity. Graphene can be used as a suitable absorber that is not limited to one frequency and can be adjusted in a wide frequency range [13, 14, 15, 16]. Recently, the ultra-thin graphene layer has been widely used in the infrared and terahertz (THz) frequency range [17, 18, 19, 20, 21, 22, 23, 24, 44, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39]. Su et al. designed an elliptical graphene disk array in the THz regions. They found that the absorption spectrum reveals two absorption peaks near 50% [40]. Xiao et al. studied a cross-shaped graphene array in the THz regime [41]. They calculated the absorption of this structure and achieve an absorption rate above 90%.

In this work, we propose an absorber consisting of a hexagonal graphene disk array, a thick dielectric spacer, and a gold substrate layer. Effects of the geometry, Fermi level, TE, and Tm polarization on the absorptance of the absorber are investigated. The absorptance tunability is investigated in the frequency range 3-12 THz.

2. THEORY

As shown in Fig.1, the unit cell of the proposed absorber consists of three layers: a graphene disk with hexagonal side length a, a SiO_2 dielectric layer, and a gold substrate layer. This structure is periodic in the x-y plane with p = 3.5 μm where p is the length of the unit cell. The perfectly matched layers are applied in the z-direction. The gold layer thickness and conductivity are d_{Au} = 0.5 μm and $\sigma_{Au} = 4.5\times10^7 s/m$, respectively. The dielectric layer is assumed non-dispersive with a permittivity of 3.9 and thickness $d_D = 4\mu m$. A graphene monolayer is electrically described by its surface conductivity σ(ω), where ω is the angular frequency of the incident wave. Using the Kubo model, the graphene conductivity is $\sigma_g(\omega) = \sigma_{\text{int}ra}(\omega) + \sigma_{\text{int}er}(\omega)$, where the intraband transition ($\sigma_{\text{int}ra}$) and interband transition ($\sigma_{\text{int}er}$) are [42, 43]:

$$\sigma_{\text{int}ra}(\omega) = -i\frac{e^2 k_B T}{\pi\hbar^2(\omega - i\tau^{-1})}\left[\frac{\mu_c}{k_B T} + 2\ln(e^{(-\frac{\mu_c}{k_B T})} + 1)\right] \tag{1}$$

$$\sigma_{\text{int}er}(\omega) = -i\frac{e^2}{4\pi\hbar}\ln\left[\frac{2|\mu_c| - (\omega - i\tau^{-1})\hbar}{2|\mu_c| + (\omega - i\tau^{-1})\hbar}\right], \tag{2}$$

where μ_c is the chemical potential related to electrostatic biasing or chemical doping. k_B is the Boltzmann constant, ħ is the reduced Planck constant, τ is the momentum relaxation time, and e is the charge of an electron,.

In the THz range, the interband contribution is dominant compared to the intraband part, and thus the Kubo formula can be approximately described as a Drude model [44]

$$\sigma_g(\omega) = \frac{e^2\mu_c}{\pi\hbar^2}\frac{i}{\omega + i\tau^{-1}} \tag{3}$$

In our simulations, T and τ are assumed to be 300K and 0.5ps, respectively. Also, the electric field and the magnetic field of the incident electromagnetic THz wave are polarized along the y-axis and x-axis, respectively (see Fig. 1), and the wave vector k is along the z-direction. The 3D finite element method (FEM) is used to solve Maxwell's equations and obtain the absorptance of the structure.

The amplitude modulation and spectral shift of the resonance depend on the real and imaginary parts of the conductivity, respectively [45]. These real and imaginary parts can be adjusted by changing the Fermi level via the optical pump or the applied electric field. Therefore, the graphene conductivity and resulting absorptance spectrum can be tuned by the Fermi energy.

The absorptance is $A(\omega) = 1 - T(\omega) - R(\omega)$, where $T(\omega)$ and $R(\omega)$ represent transmittance and reflectance, respectively.

In our calculations, the thickness of the gold film $d_{Au} = 0.5\ \mu m$ is much larger than the skin depth [46]. So transmittance can be neglected and the absorptance equation becomes $A(\omega) = 1 - R(\omega)$.

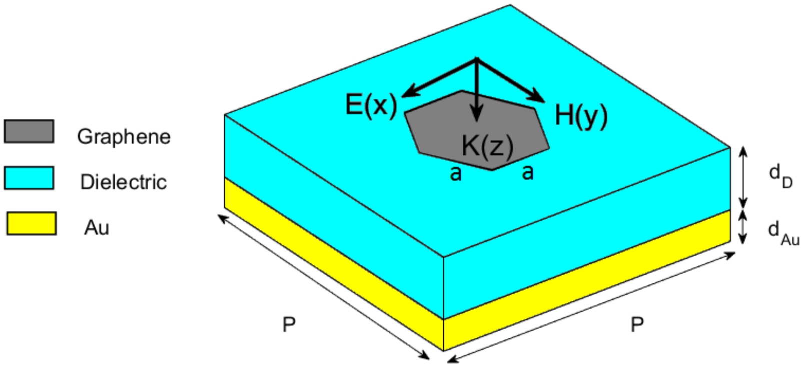

Fig. 1. Schematic diagram of the proposed absorber unit cell.

3. RESULTS AND DISCUSSION

In Fig. 2, the real (Re(σ)) and imaginary (Im(σ)) parts of the graphene conductivity are plotted as a function of the frequency for different values of the Fermi level. This figure shows that Re(σ) and Im(σ) decrease with the frequency and enhance with increasing the Fermi energy, especially at lower frequencies.

The absorptance spectra of the structure for the x-polarized and y-polarized incident light is shown in Fig. 3. This figure indicates that the absorptance spectrum depends on the incident light polarization.

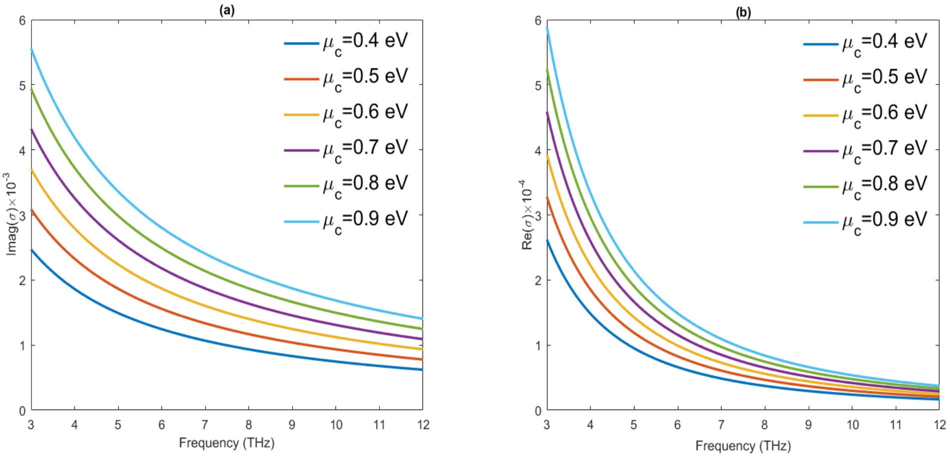

Fig. 2. (a) Real (b) imaginary parts of the graphene electrical conductivity.

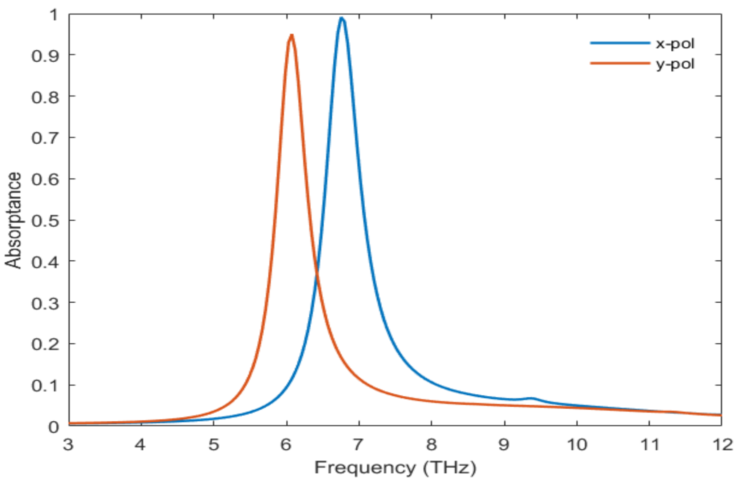

Fig. 3. The absorptance spectra under the x-polarized and y-polarized incident light for μ_c = 0.55 eV and a = 0.8μm.

Fig. 4 shows the absorptance spectra for different types of dielectric materials, SiO2, quartz, polyimide, zircon, rubber, with permittivity of 3.9, 3.7, 3.5, 3.3, and 3.1, respectively. By changing the dielectric constant from 3.1 to 3.9, the absorptance peak shifts to a lower frequency. However, the maximum value of the absorptance remains over 98%. It is also seen that the absorptance peak lies in the range of 6-9 THz.

In Fig. 5, the absorptance is presented versus the frequency and hexagonal side length. In this figure, a narrow dark-red region (line-shape) is seen that denotes the high absorptance. This figure also shows that the peak of the absorptance shifts to the lower frequencies by increasing side length.
Fig. 6 presents the variations of absorptance as a function of both the frequency and Fermi energy. Here, the width of the straight-line shape region increases with the frequency and Fermi energy. Our calculations indicate that the maximum absorptance occurs at μ_c = 0.55 eV.

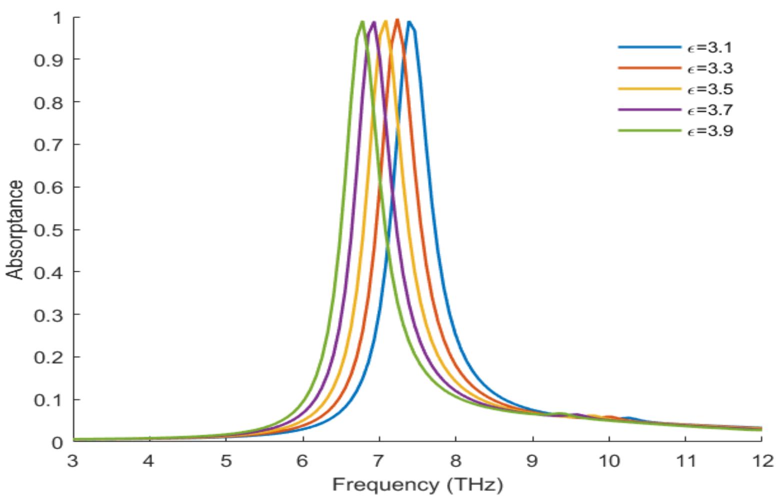

Fig. 4. Absorptance spectra of the absorber for different dielectric constants with μ_c = 0.55 eV and a = 0.8μm.

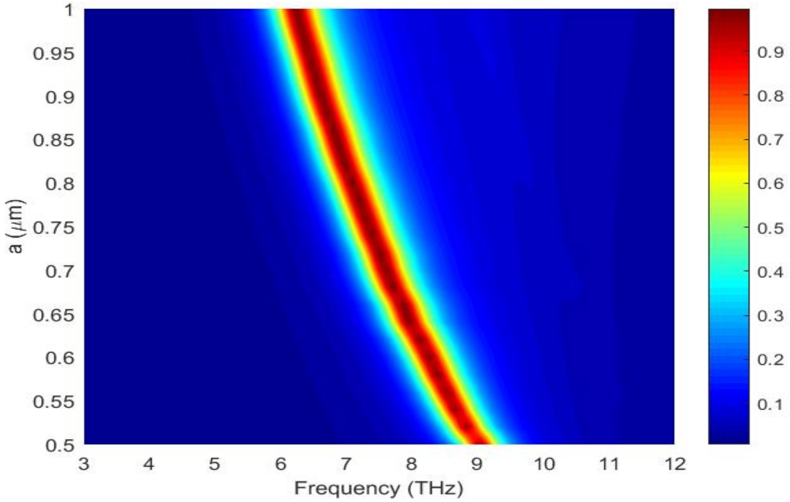

Fig. 5. The absorptance versus the frequency and hexagonal side length for μ_c = 0.55 eV.

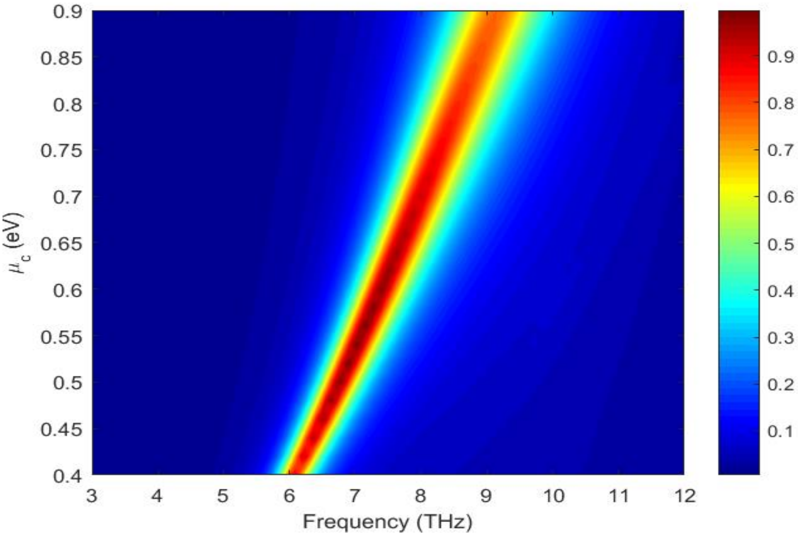

Fig. 6. Absorptance as a function of frequency and Fermi energy for a = 0.8μm.

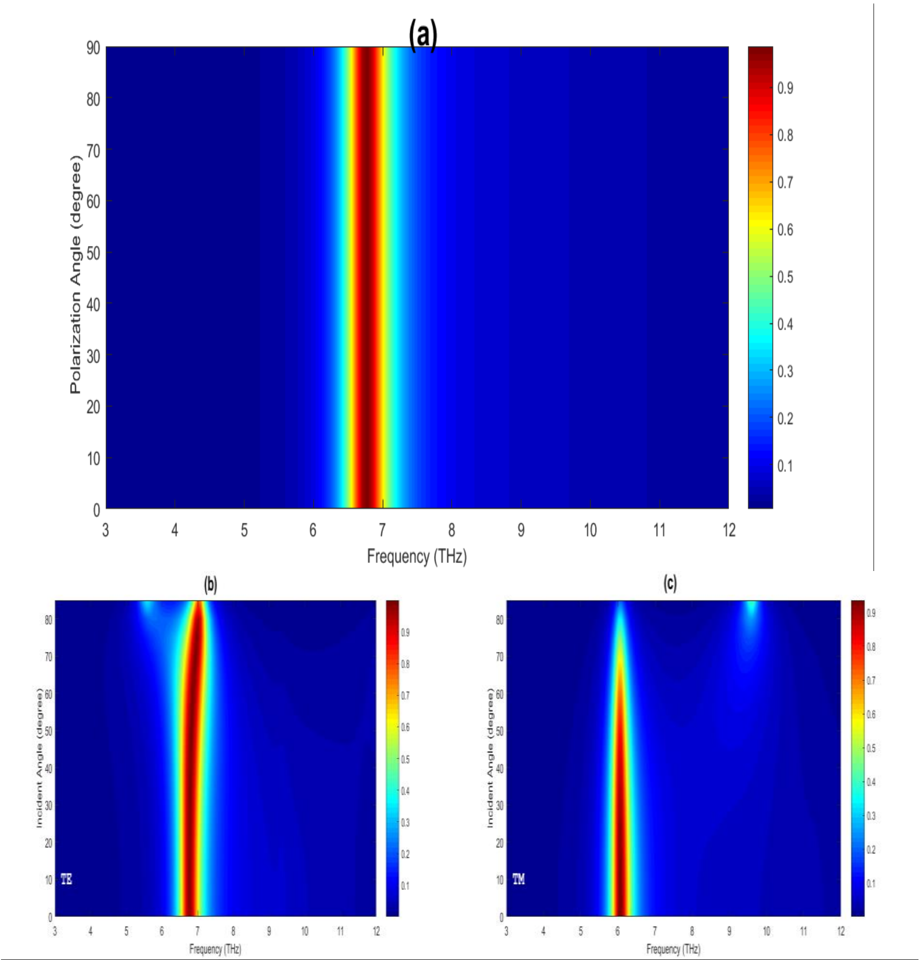

Fig. 7. Absorptance spectrum versus frequency and incident angle for the (a) normal incident light (b) TE polarized and (c) TM polarized wave with μ_c = 0.55 eV and a = 0.8µm.

In Fig.7, the influence of the polarization and incident angle of the light on the absorptance is presented. Fig. 7(a) shows that the absorptance is insensitive to the incident angle for the normal incident light. Fig. 7(b) reveals that the line shape region slightly changes for incident angle over 70°. But for the TM mode

(Fig. 7(c)), the absorptance peak decreases significantly in higher incident angles and shifts to the lower frequencies.

4. Conclusion

In conclusion, we designed a Terahertz absorber consisting of graphene hexagons, a metal layer and a dielectric layer. Results show that an absorptance of about 99.1% in the range of 6-9 terahertz can be achieved by properly selecting the parameters such as Fermi energy and hexagonal side length. The absorptance is insensitive to the incident angle for the normal incident light. This structure can be used in communications, optics, electromagnetic compatibility, and measurement applications. In addition, our approach can be applied to the design, manufacture, and use of graphene-based devices with a similar pattern.

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