Research Article

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An electrically switchable wideband metamaterial absorber based on graphene at P band

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Abstract: Graphene has the capability of dynamically tuning its conductivity through gate voltage. Based on this fact, an electrically switchable wideband metamaterial absorber at low frequencies is presented and investigated in this paper. Our calculated results show that its absorption is over 90% from 400 to 1,000 MHz with the Fermi level of graphene being at 0 eV and the absorption band can be switched by adjusting the Fermi level of graphene without changing its physical structure. Moreover, the surface current distribution enables us to reveal the switchable wideband absorption characteristics of our designed metamaterial absorber. At last, we prove that its absorption property is polarization-insensitive due to the rotational symmetry of the structural unit. This work may provide a further step in the development of switchable sensors and absorbers at low frequencies.

Keywords: metamaterial absorber, graphene, switchable, wideband, low frequency

1 Introduction

Metamaterials, due to their novel electromagnetic responses which are designable and tunable, give us a more effective way to control the electromagnetic waves and have extensive applications in many areas like optical imaging, optical

storage, microwave engineering, medical imaging, and military technology [1–3]. A metamaterial absorber is a kind of special structural absorbing material. The basic design principle of the metamaterial absorber is to achieve a good impedance match with the free space by optimizing the structural unit of the metamaterial. In this state, the incident electromagnetic wave can be absorbed by the metamaterial almost without reflection [4]. Compared with traditional absorbing materials, a metamaterial absorber has the advantage of simple structure, being controllable, adjustable, and providing high absorption [5].

The frequency of electromagnetic waves at the P band is from 0.23 to 1 GHz and is mainly used on long-range warning radar [6]. The long wavelength of the electromagnetic wave at the P band carries great challenges on the electromagnetic parameter setting and to control the thickness of the absorbing material. It has great military significance for the study of advanced and efficient metamaterial absorbers for P-band radar. A metamaterial absorber working on the P band can realize electromagnetic stealth of P-band radar. In the aspect of metamaterial absorber research at P band, Liu et al. [7] designed a circuit resonant metamaterial absorber. The structural unit of the metamaterial absorber was composed of conductive metal wire loaded with resistors, FR4 dielectric layer, air layer, and metal plate. The absorption of the optimized structure was more than 90% from 840 to 960 MHz. Zuo et al. [8] designed a metamaterial absorber with three layers of metal square rings, and the absorption was more than 90% at UHF band (300–3,000 MHz). Buitung et al. [9] designed an hourglass-shaped metamaterial absorber at P band; its absorption was over 90% at 375 MHz. Nie et al. [10] designed a composite metamaterial absorber by superimposing the resonant metamaterial and the metamaterial was loaded with resistance film. The absorption of the designed structure was greater than 90% from 1 to 7 GHz.

At present, there are few reports on wideband switchable metamaterial absorber at P band. Based on the tunable conductivity of graphene, an electrically switchable

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wideband metamaterial absorber at P band is presented and investigated in this paper. Our calculated results show that its absorption is over 90% from 400 to 1,000 MHz with the Fermi level of graphene being at 0 eV and the absorption band can be switched by adjusting the Fermi level of graphene without changing its physical structure. Our work may provide a further step in the development of switchable sensors and absorbers at low frequencies.

2 The tunable conductivity of graphene

Graphene is a two-dimensional planar crystal that is composed of single-layer carbon atoms. Graphene has very high electron and hole mobility and its conductivity can be adjusted by changing the bias voltage applied to it [11]. Therefore, graphene is widely used to design switchable metamaterials [12–15]. The surface conductivity of graphene can be expressed by the Kubo formula from microwave to visible light band [16] as follows:

$$\sigma(\omega, \mu_c) = \frac{ie^2(\omega - 2i\Gamma)}{\pi\hbar^2} \left\{ \frac{1}{(\omega - 2i\Gamma)^2} \times \int_0^\infty \varepsilon \left[\frac{\partial f_d(\varepsilon)}{\partial \varepsilon} - \frac{\partial f_d(-\varepsilon)}{\partial \varepsilon} \right] d\varepsilon - \int_0^\infty \frac{f_d(-\varepsilon) - f_d(\varepsilon)}{(\omega - 2i\Gamma)^2 - 4(\varepsilon/\hbar^2)} d\varepsilon \right\}, \quad (1)$$

$$f_d(\varepsilon) = [\exp(\varepsilon - \mu_c)/k_B T + 1]^{-1}. \quad (2)$$

In formulas (1) and (2), k_B is the Boltzmann constant, $\hbar$ is the Dirac constant, $f_d(\varepsilon)$ is the Fermi-Dirac distribution, ε is the energy, μ_c is the Fermi level of graphene, T is the temperature, and Γ is carrier scattering rate [11]. According to formulas (1) and (2), the relationship of graphene's conductivity with its Fermi level is shown in Figure 1 ($T = 300$ K, $\Gamma = 12.2$ meV) [16].

We can see from Figure 1 that the graphene can be regarded as a resistor film with tunable conductivity at microwave band, and its conductivity increases with the increase of Fermi level [12–15, 17]. The relationship of graphene's Fermi level with the applied bias voltage can be expressed as [17]:

$$\frac{\varepsilon_0 \pi \hbar^2 v_F^2}{e} E_{\text{bias}} = \int_0^\infty \varepsilon [f_d(\varepsilon) - f_d(\varepsilon + 2\mu_c)] d\varepsilon. \quad (3)$$

In the formula (3), E_{bias} is the applied bias voltage, $v_F = 10^6$ m/s is the velocity of electrons [16].

Figure 1: The conductivity of graphene at different Fermi levels.

3 Model design

The unit cell of our designed switchable wideband metamaterial absorber based on graphene at P band is shown in Figure 2. The absorber is composed of three layers – copper ring layer loaded with three thousand layers of graphene, FR4 dielectric layer ($\varepsilon_r = 4.3$, $\tan \delta = 0.025$), and copper substrate ($\sigma = 5.96 \times 10^7$ S/m). In the simulation process, the three thousand layers of graphene are set as a resistor film with total thickness of $1 \mu\text{m}$ according to the calculated conductivity of graphene shown in Figure 2. In addition, a narrow-band silver electrode is set at the boundary between the graphene layer and the dielectric layer to apply bias voltage. Assuming that the incident

Figure 2: The diagram of the switchable wideband metamaterial absorber based on graphene at P band: (a) perspective view, (b) front view, and (c) side view.

Figure 3: The absorption of metamaterial absorber at different Fermi levels of graphene.

microwave is perpendicular to the surface of the metamaterial, the absorption of a metamaterial absorber can be calculated by the formula $A = 1 - |S_{11}|^2 - |S_{21}|^2$, where S_{11} and S_{21} are the reflection and transmission of metamaterial absorber, respectively. In order to prevent the breakdown of the dielectric layer by the applied bias voltage, the Fermi level of graphene is limited to 0–0.5 eV in this work. The related structure parameters are: $a = b = 16$ mm, $r = 6$ mm, $c = d = 1$ mm, $t_2 = 0.035$ mm, $t_1 = 1$ μ m, $t_3 = 1$ mm, $t_4 = 0.035$ mm. The above parameters are the optimized parameters obtained during the model designing process based on the best possible absorption spectra. The commercial software CST Microwave studio is used for the full-wave simulation of the designed metamaterial absorber. Throughout the simulation process, the boundary conditions for the x and y directions are set as unit cell and the z -direction is

Figure 4: The normalized input impedance of metamaterial absorber with free space: (a) real part and (b) imaginary part.

Figure 5: The surface current distribution of metamaterial absorber at 0.5 GHz with the Fermi level of graphene 0 eV: (a) the top metal copper ring and (b) the metal substrate.

Figure 6: The surface current distribution of metamaterial absorber at 0.8 GHz with the Fermi level of graphene 0 eV: (a) the top metal copper ring and (b) the metal substrate.

set as open [11]. The All + Floquet ports are used to simulate the incoming and outgoing waves [11]. The electromagnetic parameters are calculated by using frequency-domain electromagnetic solver [11].

4 Results and discussion

The calculated absorptions of the metamaterial absorber at different Fermi levels of graphene are shown in Figure 3. We can see from Figure 3 that the absorption is greater than 90% from 400 MHz to 1 GHz when the Fermi level of

graphene is 0 eV, and the absorption gradually decreases when the Fermi level of graphene increases from 0 to 0.5 eV, thereby realizing the switchable property of the designed wideband metamaterial absorber. According to the formula of modulation depth $M = |A_{\text{bias}} - A_{\text{max}}|/A_{\text{max}}$, the maximum modulation depth of the metamaterial absorber reaches up to 41.7%.

The good impedance match between a metamaterial and the free space is the most important condition to realize any metamaterial absorber. According to the S_{11} and S_{21} parameters extracted from the simulation, we calculate the normalized impedance $(Z(\omega)/Z_0)$ for the Fermi level of graphene of 0 eV through the scattering

Figure 7: The surface current distribution of metamaterial absorber at 0.5 GHz with the Fermi level of graphene 0.5 eV: (a) the top metal copper ring and (b) the metal substrate.

Figure 8: The surface current distribution of metamaterial absorber at 0.8 GHz with the Fermi level of graphene 0.5 eV: (a) the top metal copper ring and (b) the metal substrate.

Figure 9: The absorption of metamaterial absorber at different polarization states with the Fermi level of graphene 0 eV.

parameter method [18], as shown in Figure 4. It can be seen from Figure 4 that the normalized impedance of the metamaterial absorber with the free space from 400 MHz to 1 GHz is close to one, which indicates that a well-acceptable impedance match between the metamaterial absorber and the free space is accomplished; as an outcome, the absorption can be realized in this case.

In order to explore the mechanism of wideband absorption, the surface currents of the absorber at 0.5 and 0.8 GHz with the Fermi level of graphene at 0 eV are monitored. The results are shown in Figures 5 and 6. It can be seen from Figures 5(a) and 6(a) that under the action of electromagnetic wave, the surface currents of the top copper ring and the metal substrate form an antiparallel current, which forms a current loop; this leads to a strong magnetic response, and then produces

Figure 10: The absorption of metamaterial absorber at different incident angles with the Fermi level of graphene 0 eV: (a) TE mode and (b) TM mode.

Figure 11: The absorption of metamaterial absorber under different structure size parameters c .

a strong magnetic resonance at the z -direction [19]. At the same time, the surface currents on the left and right side of the top copper ring are parallel, which leads to the alternating accumulation of current and the formation of electric dipole resonance. Both magnetic resonance and electric resonance are simultaneously realized at 0.5 and 0.8 GHz, respectively, which is the precondition of forming a metamaterial absorber. The superposition of different resonant frequencies results in the wideband absorption of the metamaterial absorber.

In order to explore the mechanism of switchable absorption of the metamaterial absorber, the surface currents of the absorber at 0.5 and 0.8 GHz are monitored when the Fermi level of graphene is at 0.5 eV [11]. The results are shown in Figures 7 and 8. It can be seen from

Figure 12: The absorption of metamaterial absorber under different structure size parameters d .

Figures 7 and 8 that it does not produce magnetic resonance and electric resonance under the action of the incident electromagnetic wave; this leads to the lower absorption of the metamaterial absorber.

In order to meet the practical applications, a metamaterial absorber needs to have high absorption at different polarization states and wide-incident angles. Therefore, the absorption of the metamaterial absorber at different polarization states and different incident angles is calculated (the Fermi level of graphene is 0 eV); the results are shown in Figures 9 and 10. It can be seen from Figure 9 that the absorption property of the metamaterial absorber is polarization-independent. It can be seen from Figure 10 that the absorber can still maintain high absorption in a wide range of incident angles at TE mode and TM mode. This is very important for practical applications.

Figures 11 and 12 show the absorption of the metamaterial absorber with different structure size parameters c and d . It can be seen from Figure 11 that the absorption gradually decreases with the increasing of structure size parameter c . It can be seen from Figure 12 that the absorption of the metamaterial absorber under different structure size parameters d stays unaltered [11].

5 Summary

Metamaterial absorber at P band has great military significance for P-band radar. An electrically switchable wideband metamaterial absorber based on graphene at P band is presented in this paper. The absorption of the metamaterial absorber is over 90% from 400 to 1,000 MHz with the Fermi level of graphene 0 eV and the absorption band can be switched by adjusting the Fermi level of graphene. The absorber offers the advantages of being based on a simple structure, providing wideband absorption at low frequencies, and being polarization-independent. It has great application value as switchable sensors and absorbers at low frequency.

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