The design of a graphene-based wideband tunable metamaterial absorber in THz regime

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Abstract. Metamaterial absorber (MMA) has great potential application in many scientific and technical fields due to its perfect absorption characteristics. For most practical applications, the absorption bandwidth is one of the most important performance metrics. In this paper, we demonstrate a design of wideband tunable MMA based on graphene. The proposed absorber shows tunable wideband absorption at different externally applied voltage. The simulated absorption exceeds 90% from 7.6 THz to 8.5 THz and the full width at half maximum is 75% (from 7.505 THz to 8.705 THz), which is achieved by using a single layer of multiple SRRs. Further study demonstrates that the absorption wideband can be greatly tuned by applying different externally applied voltage. The absorption band shifts to lower frequency with the increasing of externally applied voltage. This work opens up the possibility for designing intelligent terahertz active filter.

1. Introduction
Metamaterial absorber (MMA) which is an important branch of metamaterial-based devices has attracted great interest and made great progress in the past several years [1–11]. Landy et al experimentally demonstrated the first MMA in 2008, in which two resonators were printed on the top and bottom sides of substrate [1]. Since then, MMA which was based on metal-insulator-metal structure with zero transmission and reflectance [2] has been extended to THz [3], infrared [4], and optical frequencies [5]. But the absorption bandwidth of above MMA is often narrow since resonance is utilized in the process of absorption, this limits its better practical application. To realize the wideband absorption, a simple approach is to increase the loss of MMA, such as loading lumped resistors [6, 7] or employing resistive ohmic sheets [8]. The second approach is to utilize multi-resonance by incorporating multiple resonators within one unit cell [9]. The third approach is to utilize multi-layer structure [10, 11]. However, these perfect absorbers usually work at limited frequency band due to their resonance features and may not suit many practical applications that have tunable bandwidth requirements.

In this work, we implement a wideband tunable MMA based on graphene in Terahertz regime which is achieved by using a single layer of multiple split-ring resonators (SRRs). Terahertz spectrum has many important technological applications, such as imaging [12], security detection [13], or wireless communication [14] which all require perfect absorber to efficiently gather wave energy. Artificial THz MMA was firstly designed in 2008 by Tao H using a two-layer metal resonator that
was implemented at 1.3 THz with 70% absorption[15], and later the same authors enhanced the angle performance of their THz MMA by an ELC metamaterial array[16]. In 2010, Ye Y Q et al proposed a three-layered metal-cross structure to acquire a relatively large band of THz absorption[17]. Similar stacking designs have also been proposed using other types of metallic elements to improve the bandwidth of THz absorber[18–20]. In our model, wideband absorption is obtained by using a single layer of multiple SRRs and its wideband can be tunable by applying externally different voltage at graphene layer. It has the advantages of simple to prepare and so on. It can be fabricated by electrical etching way. Our work opens up the possibility for designing intelligent terahertz active filter.

2. Model design

MMA is usually composed of sub-wavelength structures based on metal-insulator-metal structure. By manipulating the magnetic resonance and the electric resonance simultaneously, the effective impedance of MMA will match well with the free space impedance once the MMA satisfies the condition

\[ Z_u = \frac{\mu_0}{\varepsilon_0} \]

As a result, the reflection is minimized, thus resulting in perfect absorption of incident waves. Generally, the geometric configuration and the geometric parameters of unit cell determine the resonance frequency of MMA. From this view, we can place multiple SRRs with different sizes in one layer, which will result in multiple absorption dips and increase the absorption bandwidth.

The electromagnetism response of the MMA can be actively controlled through external excitation. To realize the tunability of MMA, the typical methods currently used are to employ the inclusion of semiconductor to alter the capacitance of resonators or change the property of surrounding media through optical, electrical, magnetic or thermal means. However, those tunable methods manifest serious limitations in the modulation range and are complex to fabricate, which hinders the practical applications of tunable MMA.

With the rapid development in the fields of fundamental physics and enormous applications, graphene can serve as a good platform for tunable MMA because its permittivity can be tunable by applied external electric field [21]. Graphene can be considered as a two-dimensional material and described by a surface conductivity \( \sigma_g \), which is related to the radiation frequency \( \omega \), chemical potential \( \mu_c \) (Fermi level \( E_f \)), environmental temperature \( T \) and relaxation time \( \tau \). The conductivity of monolayer graphene can be expressed by [22]:

\[
\sigma_g(\omega, u_c, \tau, T) = i\frac{e^2 k_B T}{\pi \epsilon^2 (\omega + i \tau^{-1})} \left\{ \frac{\mu_c}{k_B T} + 2\ln[\exp(\frac{\mu_c}{k_B T}) + 1] \right\}
+ i\frac{e^2}{4\pi^2} \ln[2|\mu_c| - \eta(\omega + i \tau^{-1})]
+ i\frac{2|\mu_c| + \eta(\omega + i \tau^{-1})}{2|\mu_c| + \eta(\omega + i \tau^{-1})}
\]

In this formula, \( e \) is the electron charge, \( \eta \) is the reduced Planck’s constant, and \( k_B \) is the Boltzmann’s constant. The first and second terms of the above equation are attributed to the intraband transition and interband transition respectively.

The dielectric constant of graphene layer can be expressed as [23]:

\[
\varepsilon_g = 2.5 + j \frac{\sigma_g}{\omega \varepsilon_0 \Delta}
\]

Where \( \Delta \) is the thickness of graphene layer and \( \varepsilon_0 \) is the permittivity of free space. In fact, the Fermi level \( \mu_c \) can be changed by the bias voltage \( V_g \) which is applied to graphene layer. The relationship of \( \mu_c \) with the bias voltage \( V_g \) can be approximately expressed by [24]:

\[ \mu_c = \frac{e V_g}{n_k^2} \]

where \( n_k \) is the effective mass of the electron.
From this view, we can achieve tunable MMA by employing the inclusion of graphene as surrounding media.

According to the above designing view, the schematic of our THz wideband tunable MMA and the unit cell structure are shown in Figure 1. The unit cell is composed of multiple SRRs, graphene layer, dielectric substrate and metal film. The multiple SRRs is made of silver with the thickness of 0.05μm, its optimized size dimensions are: \(a=b=23\mu m\), \(c=20\mu m\), \(d=15\mu m\), \(e=10\mu m\), \(w=2.6\mu m\), \(w1=2.4\mu m\), \(f=1\mu m\); the second layer is 10-layers graphene (chemical potentials \(\mu_c = 0.53 eV\), thickness \(\Delta = 0.6\mu m\), environmental temperature \(T = 300K\) and relaxation time \(\tau = 4.8 \times 10^{-12} \mu s\); the dielectric substrate is FR4 dielectric with the thickness of 0.5μm; the metal film is also made of silver with the thickness of 0.1μm. The lateral lattice constant is smaller than the largest wavelength discussed here.

Numerical simulation of our THz wideband tunable MMA is performed with Microwave Studio CST. In the simulation process, the x and y directions are set as unit cell boundary condition, the z direction is set as open, the all-floquet ports are used to simulate the incoming and outgoing waves. The electromagnetic parameters are calculated by using frequency domain electromagnetic solver.

\[
\mu_c = \eta \sqrt{\mu_v \gamma_v} 
\]

(3)

Figure 1. Schematic of our THz wideband tunable MMA (a) side view of the structure; (b) top view of the structure; (c) oblique view of unit cell.

3. Result and discussion

As the metal film of unit cell prevents the incident wave penetrating, the transmittance is \(T(w) = |S_{12}|^2 = 0\). The absorption should be calculated by \(A(w) = 1 - R_{x,x}(y,y) - R_{x,y}(y,x)\) with \(R = |S_{11}|^2\). The calculated absorption is shown in Figure 2. We can see from Figure 2 that the unit cell presents nearly perfect absorption above 90% with absorption ranging from 7.6THz to 8.5THz; its width is 0.9THz.
According to the calculation formula of absorption $A(\omega) = 1 - R(\omega) = 1 - \left| \frac{Z(\omega) - Z_0}{Z(\omega) + Z_0} \right|^2$, the perfect absorption of incident wave is achieved when the input impedance of MMA with free space is equal [25]. According to the parameters extracted by simulation, the normalized impedance $(Z(\omega)/Z_0)$ is calculated by scattering parameter method [26], the result is shown in Figure 3. We can see from Figure 3 that the normalized impedance between 7.6THz and 8.5THz is close to one, it indicates that the good impedance match of unit cell with free space is achieved; the perfect absorption can be realized in this case.

Figure 2. Simulated absorption spectra of unit cell.

Figure 3. Simulated normalized impedance of unit cell with free space.

To better understand the resonant mechanism and wideband absorption of the proposed wideband tunable MMA, we investigated the magnetic field distributions at different resonant frequency, as shown in Figure 4. Two resonances whose absorption is close to one are calculated at $f_1=7.91$THz, $f_2=8.44$THz respectively. Obviously, each resonance is localized in a specific patch. It is found that the power loss accumulates at resonances, where the energy is significantly reinforced and subsequently converted into thermal energy, thus leading to a perfect absorption. The magnetic field distributions further indicate that the perfect absorption of the unit cell is mainly attributed to the mechanism of local electromagnetic coupling resonance. The overlap of different resonant frequency leads to wideband absorption.
Figure 4. Distributions of the magnetic field at resonance frequency of 7.91THz and 8.44THz. (a) 7.91THz; (b) 8.44THz

Here, we discuss the effect of parameters $w$ and $w_1$ on the absorption property, respectively. First, in Figure 5, we change the parameter $w$ from 2.6 $\mu$m to 3.2 $\mu$m with other parameters fixed. We can see that the absorption property is sensitive to the parameter $w$, the absorption decrease with the increasing of $w$. Figure 6 shows the absorption with parameter $w_1$ changing from 2.2 $\mu$m to 2.8 $\mu$m. From the picture, the absorption band is sensitive to the parameter $w_1$. The absorption band shifts to upper frequency with the increasing of $w_1$; the reason is $\omega \propto 1/\sqrt{LC}$, with the increasing of $w_1$, the capacitance decreasing.

Figure 5. Simulated absorption spectra of unit cell with different $w$.

Figure 6. Simulated absorption spectra of unit cell with different $w_1$. 
According to the research result of Elton J. G. Santos [27], the perpendicular dielectric constant values ($\varepsilon_{\perp}$) of ten-layer graphene with different perpendicular electric field ($E_{\text{ext}}^{\perp}$) is shown in Figure 7.

![Figure 7](image1.png)

**Figure 7.** The dependence of graphene perpendicular dielectric constant values on electric field.

Figure 8 shows the absorption of unit cell with different externally applied voltage ($V_g$). We can see from Figure 8 that the perfect absorption band shifts to lower frequency with the increasing of $V_g$. The reason is that the electromagnet resonant frequency satisfies the relation of $\omega_e \propto c / 2L \sqrt{\varepsilon_{\text{eff}}}$ where $c$ is the speed of light in vacuum, $L$ is the equivalent side length of unit cell, $\varepsilon_{\text{eff}}$ is the effective permittivity of surrounding medium. The permittivity of graphene gradually increases with the increasing of $V_g$, the resonant frequency gradually moves toward lower frequency.

![Figure 8](image2.png)

**Figure 8.** The absorption spectra of unit cell with different externally applied voltage.

4. **Conclusions**
In conclusion, a THz wideband tunable MMA based on multiple SRRs and graphene has been designed and numerically verified. The simulated absorption exceeds 90% from 7.6 THz to 8.5 THz, the full width at half maximum is 75% and the absorption band can be tuned by changing the externally applied voltage. The structure unit is very simple to prepare. It opens up the possibility of designing intelligent terahertz active filter and so on.
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Statement
The authors (Liansheng Wang, Changlin Ding, Dongyan Xia, Xueyong Ding and Yuan Wang) declare that there is no conflict of interest regarding the publication of this paper.

References
[1] Landy N I, Sajuyigbe S, Mock J J, Smith D R and Padilla W J 2008 Phys. Rev. Lett. 100(20) 207402
[2] Hao J, Wang J, Liu X, Padilla W J, Zhou L and Qiu M 2010 Appl. Phys. Lett. 96(25) 251104
[3] Grant J, Ma Y, Saha S, Lok L B, Khalid A and Cumming D R S 2011 Opt. Lett. 36(8) 1524–1526
[4] Koechlin C, Bouchon P, Pardo F, Jaeck J, Lafosse X, Pelouard J L and Haidar R T 2011 Appl. Phys. Lett. 99(24) 241104
[5] Zhu P and Guo L J 2012 Appl. Phys. Lett. 101(24) 241116
[6] Li S, Gao J, Cao X, Li W, Zhang Z and Zhang D 2014 J. Appl. Phys. 116(4) 043710
[7] Yang J and Shen Z X 2007 IEEE Antennas Wireless Propag. Lett. 6(11) 388–391
[8] Li M, Xiao S, Bai Y Y and Wang B Z 2012 IEEE Antennas Wireless Propag. Lett. 11 748–751
[9] Sun J, Liu L, Dong G and Zhou J 2011 Opt. Express 19(22) 21155–21162
[10] Wang Y, Liu B S, Bian R B, Mao W Z, Liu C X, Ma B and Chen L 2014 J. Appl. Phys. 116(9) 094504
[11] Ding F, Cui Y, Ge X, Jin Y and He S 2012 Appl. Phys. Lett. 100(10) 103506
[12] Darmo J, Tamosiunas V, Fasching G, Kröll J, Unterrainer K, Beck M and Debbage P 2004 Opt. Express 12 1879–1884
[13] Federici J F, Schulkin B, Huang F, Gary D, Barat R, Oliveira F and Zimdars D 2005 Semicond. Sci. Technol. 20 S266
[14] Fergusson B and Zhang X C 2002 Nature Mater. 1 26–33
[15] Tao H, Landy N I, Bingham C M, Zhang X, Averitt R D and Padilla W J 2008 Opt. Express 16 7181–7188
[16] Tao H, Bingham C M, Strikwerda A C, Pilon D, Shrekenhamer D, Landy N I and Averitt R D 2008 Phys. Rev. B 78 241103R
[17] Ye Y Q, Jin Y and He S 2010 J. Opt. Soc. Am. B 27 498–504
[18] Ma Y, Chen Q, Grant J, Saha S C, Khalid A and Cumming D R 2011 Opt. Lett. 36 945–947
[19] Grant J, Ma Y, Saha S, Khalid A and Cumming D R S 2011 Opt. Lett. 36 3476–3478
[20] Cheng Y, Nie Y and Gong R 2013 Opt. Laser Technol. 48 415–421
[21] Zhao Y T, Wu B, Huang B J and Cheng Q 2017 Opt. Express 25(7) 7161–7169
[22] Li H J, Wang L L, Sun B, Huang Z R and Zhai X 2014 Journal of Applied Physics 116(22) 224505
[23] Wang B, Zhang X, Yuan X and Teng J 2012 Appl. Phys. Lett. 100 131111
[24] Valmorra F, Scalari G, Maissen C and Fu W Y 2013 Nano Lett. 13(7) 3193–3198
[25] Claire M W, Liu X L and Willie J P 2012 Adv. Mater. 24 98–120
[26] Smith D R and Schultz S 2002 Phys. Rev. B 65 195104
[27] Santos E J G and Kaxiras E 2013 Nano Lett. 13 898–902