Tunable Ultra-Broadband Terahertz Waveband Absorbers Based on Hybrid Gold-Graphene Metasurface

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Abstract. In this paper, we propose a tunable ultra-broadband terahertz absorber based on hybrid gold-graphene resonator to achieve an ultra-broadband, ultra-thin, and tunable metasurface, which has not only the high absorption rate of gold metamaterials but also the tunable properties of graphene metamaterials, compared with the traditional single gold-based and graphene-based methods. By simulating the response frequencies by the finite element method, we found that the absorber achieves a broadband 2.68-7.48 THz range (absorption>80%) absorbance with a relative bandwidth of 94.5%, where the center frequency is \( f_c = 5.08 \text{THz} \). The physical mechanism of the absorber was analyzed using the electric field of the surface plasmon resonance, due to the design structure presents periodic geometric symmetry, the polarization angle and large angle incidence both present better advantages. The dynamic tuning of the metamaterial absorber is achieved by changing the Fermi energy level of graphene by adjusting the bias voltage to effectively control the metamaterial absorption intensity and resonant frequency. Our proposed absorber has important application prospects in sensing, optical communication, detection, and optical devices.

1. Introduction

Metamaterials are artificial structures composed of periodic resonant elements with electromagnetic properties beyond those of natural materials, and are the most influential new materials after polymers and nanomaterials, and are the basis for the realization of optical devices such as slow light [1] and negative refractive index [2], and are also widely followed by experts in the fields of stealth and communication [3-5] for their feasibility. However, perfect absorbers are another important branch of metamaterials. Since After Landy [6] and others first proposed thin and nearly perfect absorbing metamaterials in 2008, metamaterial absorbers (MAs) have started a vigorous development. Due to the difficulty of finding strong frequency selective terahertz absorbers [7], so that MAs have received focused attention in the terahertz band. Terahertz refers to 0.1 THz-10 THz, the high frequency and short pulse of terahertz has a high time-domain spectral signal-to-noise ratio, and the low photon
energy and strong penetration is less destructive to matter and human body, thus compared with X-ray, terahertz imaging technology has more advantages, and the unique nature has a broad prospect in protein composition analysis [8], imaging devices [9], broadband communication [10], etc.

In this work, we propose a design method for a tunable ultra-wideband absorber based on a hybrid gold-graphene metasurface. According to the designed structure, the amplitude of the electromagnetic wave resonance is controlled by changing the graphene Fermi energy level through the biased ion-gel top grid dielectric, and it is found that the gold-graphene metasurfaces in the structure can achieve a broadband highly absorbing absorber. Our designed absorber has the advantages of ultra-broadband, miniaturized fabrication, and adjustable degrees of freedom compared with recently published absorbers, validating the superiority of the gold-graphene hybrid absorber. This has better prospects for future terahertz technologies such as detectors, communications, optoelectronic devices, and sensing.

2. Materials and Methods

The schematic diagram of our proposed metamaterial absorber consists of an upper double-ring gold, a dielectric layer, a mesh graphene layer, a dielectric layer and an ideal electrical conductor, as shown in Figure 1(a), with a top view of the cell in Figure 1(b). The dielectric constant of dielectric spacer material (SiO$_2$) is 2.88 [11] and a thickness of $t_m=9.5\mu m$ and $t_d=3.5\mu m$. The upper double-ring gold with $R_1=6.5\mu m$, ring gap $W_r=0.2\mu m$, $R_2=4.5\mu m$, ring gap $W_r=0.5\mu m$, thickness $t_s=100nm$ and complex refractive index [12]. The gold-graphene metasurfaces are built on the dielectric layer. The incident wave cannot reach on the dielectric layer, so it has no effect on the absorption characteristics. The lower graphene layer is a mesh structure consisting of a square $S=10\mu m$ and a cross $w=2\mu m$ combined. Since graphene is transparent, in order to obtain high absorption according to the mutual effect of adjacent unit cells, we optimize the structure with a period of $Q=20\mu m$, graphene thickness of $t_g=0.5nm$, and Fermi energy level corresponding to 0.72eV.

![Figure 1. Schematic of a gold-graphene hybrid ultra-wideband terahertz absorber. (a) 3D view of the unit; (b) Top view of the unit; (c) Side view of the unit;](image)

The conductivity of graphene is provided by the Kubo equation, which determines the intra-band and inter-band jumps from both together [13-15]

$$\sigma_G(\omega, \mu, \tau, T) = \sigma_{\text{intra}} + \sigma_{\text{inter}}$$

$$\sigma_{\text{intra}} = \frac{2k_B T e^2}{\pi \hbar^2} \times \text{ln}(2 \cosh \frac{E_f}{2k_B T}) \times \frac{i}{\omega + i \tau^{-1}}$$

$$\sigma_{\text{inter}} = \frac{e^2}{4\hbar} \left[ \frac{H(\frac{\omega}{2}) + i \times 4 \omega}{\pi} \times \int_0^\infty \frac{H(\Omega) - H(\frac{\omega}{2})}{\omega^2 - 4\Omega^2} d\Omega \right]$$

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Here \( H(\Omega) = \sinh\left(\frac{h\Omega}{k_B T}\right) \left[ \cos\left(\frac{E_f}{k_B T}\right) + \cosh\left(\frac{E_f}{k_B T}\right) \right] \). In the terahertz band, when \( E_f >> 2k_B T \), it is mainly the intra-band jumps that contribute, while the inter-band jumps in the graphene conductivity are neglected, and the conductivity is at this time, the above calculation formula for graphene conductivity is simplified as:

\[
\sigma_\parallel(\omega) = \frac{e^2}{\pi\hbar^2} \times \frac{i}{\omega + i\tau^{-1}}
\]

\[
\lambda = \frac{2\pi\hbar c}{e \sqrt{\omega(\varepsilon_0 + \varepsilon)\varepsilon_0}}
\]

3. Results and Discussions

3.1. Broadband Absorption

In order to investigate the absorption characteristics of the double-ring gold mesh graphene absorber, we simulated the absorption spectrum and field distribution under normal incidence. Figure 2 shows the absorption spectrum of TE polarization at \( E_f = 0.72\text{eV} \). It can be seen from the absorption spectrum that the absorption bandwidth of TE polarization is in the range of 2.68-7.48THz (absorption>80%) absorption rate, where the center frequency \( f_c = 5.08\text{THz} \), and \( \frac{\Delta f}{f_c} \) is used to calculate the relative bandwidth of 94.5%, as shown in the blue curve in Figure 2. Figure 1(a) schematic diagram is a periodic symmetrical structure, with reflection \( R(\omega) \) almost approaching 0 and extremely small reflection in a relatively large bandwidth. Therefore, the total reflection of incident waves is small, and most of the reflected wave is consumed by the incident wave. An ideal electrical conductor is used as a reflective layer of gold film to the ground to minimize the transmission coefficient. The results show that the transmission coefficient of the gold layer is 0, that is, the green curve in Figure 2.
3.2. Electronic Field
In order to further reveal the physical mechanism of the absorber we designed, the resonance absorption spectra of three high absorption electric fields at low (3.06 THz) in Figure 3(a)-(b) shows the gold and graphene surface electric field distribution, medium (4.60 THz) in Figure 3(c)-(d) shows the gold and graphene surface electric field distribution, and high (7.02 THz) in Figure 3(e)-(f) shows the gold and graphene surface electric field distribution, numerical analysis revealed the hybridization of gold and graphene metasurface plasmon-polaritons. It can be seen from Figure 3(a)-(b) and Figure 3(e)-(f) that the electrical energy of 3.06/7.02THz is basically concentrated on the metasurface. It can be seen from Figure 3(c)-(d) that the electrical energy of 4.60THz is mainly concentrated on the metasurface of the inner ring of gold, which has a strong coupling between the gold and graphene and improves the resonance of the graphene surface. The extremely wide band energy of the gold double ring trapped on the gold-graphene metasurface will interact with each other, and the coupling and superposition will also offset each other.

Figure 3. Absorption spectrum electric field distribution, (a)-(b) shows the electric field distribution of gold and graphene (3.06 THz), (c)-(d) shows the electric field distribution of gold and graphene (4.60 THz), (e)-(f) shows the electric field distribution of gold and graphene (7.02 THz).

3.3. Parameter discussion
In order to test the performance of the absorber, the influence of different thickness of the dielectric layer of the structure (tm/td) on the absorption spectrum was studied. The results are shown in Figure 4(a) and (b). The simulation results show that the best absorption performance can be obtained when tm = 9.5μm and td = 3.5μm. As can be seen from Figure 4(a), with the increase of tm, the absorption bandwidth decreases gradually. When tm exceeds 10μm, the absorption rate in 6THz-7THz band decreases gradually, and the effect is best in the band of 9-10μm. It can be seen from Figure 4(b) that td thickness has little effect on absorption rate. Repeated experiments show that the absorption efficiency and bandwidth at 3.5μm are the best. By measuring the thickness of the dielectric layer, it is known that the dielectric layer parameter between the gold-graphene metamaterials is very important for the absorption characteristics of our designed absorbers.
Graphene, as a tunable material, changes the status quo of gold materials where the properties remain unchanged after the structure is fixed, and enables dynamic modulation by applying a bias voltage, allowing greater freedom of the absorber. As the Fermi level increases, the resonant frequency increases slightly, as shown in the Figure 5 and Equation (5). With the adjustment of the Fermi energy level by 0.1eV-1eV, the position of the absorption resonance peak becomes broader and the absorption becomes more effective. When by changing the chemical potential from 0.1eV-0.7eV, the 2THz-3THz and 7THz-8THz absorptions are significantly increased to 80%.

Numerical simulations were carried out to measure the absorption characteristics of our absorbing structure at different polarization and oblique incidence angles. Figure 6(a) is a numerical simulation in different polarization angle (Φ) absorption spectra super unit structure, the Figure 6(a) shows that tuning (Φ) from 0 to 90° polarization angle of absorption of TE and TM mode remains unchanged. The results show that the absorption rate is completely independent of polarization under normal incident condition, which means that the structure is insensitive to polarization angle, because the structure is periodic symmetric. In practical applications, the incident light is usually irradiated at an oblique incident angle. The oblique incident angle ranges from 0 to 45° in our simulation, and the absorption modes of TE and TM polarization are basically consistent. Figure 6(b) shows TE polarization, whose electric field is always perpendicular to the incident plane. Figure 6(c) shows TM polarization, whose magnetic field is always perpendicular to the incident plane. The results show that our structure has high absorption performance and ultra-wideband.
4. Conclusion
In summary, we propose an ultra-wideband, ultra-thin, adjustable ultra-surface terahertz absorber based on a gold-graphene hybrid resonator. We designed the device to be implemented in the 2.68-7.48THz range (absorption > 80%), the center frequency is $f_c=5.08$THz, and the relative bandwidth is 94.5%. The physical mechanism of the absorber is analyzed by using the electric field of surface plasmon resonance. The hybridized gold-graphene patterns enhance the metasurface field. By adjusting the bias voltage to change the Fermi level of graphene, the absorption intensity and resonance frequency of the metamaterial can be effectively controlled, and the dynamic tuning of the metamaterial absorber can be realized.

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