Research on Perfect and Tunable Metamaterial Absorber Based on Crosshair-shaped Graphene

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Abstract. Graphene, as a new nano-material, according to the physical properties of electric field localization and selective absorption on light of surface plasmon resonance (SPR), a tunable, multi-band and wide-angle perfect absorber based on crosshair-shaped graphene is devised by using the Finite Difference in Time Domain (FDTD) method. In this paper, the effects of chemical potential, relaxation time, and incident angle of light on the absorptivity of graphene are systematically discussed. The simulation experiment shows that there are two absorption peaks with perfect absorption rate appeared in the study range, and the maximum modulation index can be obtained by changing the relaxation time. Finally, it proves that the absorber is insensitive to wide-angle of light. Thus, it is able to be concluded that the absorber has a great reference value to sensor, wireless communication, biomedical and other fields.

1. Introduction

Graphene[1] is a two-dimensional honeycomb flat film formed of carbon atoms. After considerable researches[2-5], it finds that the graphene which can be made by mechanical exfoliation method, template method, chemical vapor deposition and other methods has excellent properties in the electronic, optics and thermotics domain, which shows the value of it in the field of new energy[6], solar battery[7], biosensor[8] and others.

Surface plasmon polariton[9] (SPP), a type of electromagnetic surface mode, can be excited when the unbound electrons on the surface of metal couple with light. Compared with ordinary metal, the SPP of graphene has better advantages as lower transmission loss, stronger locality and better tunability, which are beneficial to transmute the electromagnetic energy into heat energy and improve the absorptivity. As graphene can make up for the defects of metal as the absorption medium, Wang[10] et al. designed a graphene-based absorber whose maximum absorption rate and modulation index were able to reach 99% and 0.5 respectively. Yuan[11] et al. combined graphene with metal and designed a single-band absorber which was able to achieve perfect absorption in the wide-band range. By designing special structures, Zhang[12] et al. provided an absorber which had two absorption peaks and was able to obtain the absorption rate of 95%.

In this paper, we propose an absorber based on crosshair-shaped graphene. After studying the influence of the chemical potential, the relaxation time, and the incident angle of light on graphene, it is able to be summarized that: compared to above researches, the metamaterial absorber which is...
consisted of graphene and gold not only obtains two perfect absorption peaks (the absorption rate is above 90%), but also has the maximum modulation index of 0.5 and the wide-angle insensitive feature.

2. Materials design and calculation Methods
In the light of figure 1, the 3D structure of the crosshair-shaped graphene absorber is composed of the Graphene arrays on the top, the Silicon Dioxide and the Gold as the dielectric layer, the Silicon as the bottom. In the FDTD method, graphene is a two-dimensional material with zero thickness, and the thickness of Silicon Dioxide (d₁) and Gold (d₂) are set to 0.4 µm and 0.3 µm. The length (L), width (W) and height (M) of four L-shaped structures are set to 1 µm, 0.4 µm and 0.4 µm respectively. The period is defined as P and the incident angle is defined as θ.

![Figure 1. (A) The composition diagram of absorber. (B) The structural diagram of crosshair-shaped graphene.](image)

\[
\sigma_g = \frac{2e^2k_B T}{\pi\hbar^2} \left[ \ln(2\cosh(\frac{\mu_c}{2k_B T})) + i\frac{e^2}{4\hbar^2} \frac{1}{\pi} \arctan\left(\frac{\hbar\omega - 2\mu_c}{2k_B T}\right) \right] - \frac{i}{2\pi} \ln\left(\frac{(\hbar\omega - 2\mu_c)^2}{(\hbar\omega - 2\mu_c)^2 + 4(k_B T)^2}\right)
\]

Where \( e \) is Electron charge, \( T \) is temperature, \( k_B \) is Boltzmann constant, \( \hbar = \hbar / 2\pi \) is reduced Planck constant, \( \omega \) is angular frequency of incident light, \( \tau \) is relaxation time, \( \mu_c \) is chemical potential, \( \mu \) is carrier mobility.

The surface conductivity[13] \( \sigma_g \), which is able to represent the intensity of optical performance of graphene, can be derived from Kubo Equation which is equation (1). In the light of Pauli Exclusion Principle, the Drude model which is equation (2) can be obtained after simplification in Terahertz range.

\[
V_g = \frac{2te}{\epsilon_0\epsilon_r\hbar^2v_F^2} \int \frac{\mu_c}{k_BT} \frac{1}{e^\frac{\mu_c}{k_BT} + 1} dx + k_BT \mu_c \ln(e^{-\frac{\mu_c}{k_BT}} + 1) + k_BT \mu_c \ln(e^{\frac{\mu_c}{k_BT}} + 1)
\]

In equation (3), the chemical potential \( \mu_c \) of graphene can be regulated by changing the applied voltage \( V_g \), and \( d \) is the thickness of isolation layer, \( \epsilon_0 \) is dielectric constant in free space, \( \epsilon_d \) is dielectric constant of isolation layer and \( V_F=10^6\text{m/s} \) is Fermi velocity.
3. Simulation results and discussion

Figure 2. Two absorption peaks from left to right are defined as mode 1 and mode 2. (A) The absorption spectra of crosshair-shaped graphene with different chemical potentials. (B) The electric field distributions of two modes of graphene.

In the light of figure 2, it can be seen that, with the increasing of chemical potential from 0.4 eV to 0.8 eV, the resonance wavelengths of two modes blue shift and the maximum absorption rate of mode 1 increases from 81.8% to 96.1% then decreases to 81.1%. The same data of mode 2 increases from 63.1% to 98.6% then decreases to 83.1%, the absorption rate can remain above 90% in the range of 58-60 μm. In addition, when the chemical potential is 0.4 eV, there is another peak on the far left of figure 2 (A) whose resonance wavelength is 25.63 μm and absorption rate is 57%. Because the surface plasmon resonance (SPR) will be excited when the wave vector of SPR is greater than the wave vector of light. As chemical potential increases to the threshold which is 0.6 eV, the SPR effect and the local electric field intensity get strongest, and the absorption rate increases to the highest. Meanwhile, after the resonance wavelength blue shifts, the wave vector of SPR is less than the wave vector of light, therefore the absorption rate decreases gradually. Above results indicate that, the absorber is able to achieve dynamic regulation and perfect absorption under the condition of 0.6 eV.

Figure 3. The absorption spectra of graphene structure with different relaxation time.

According to \( \tau = \mu \mu_c / e v_F^2 \), in FDTD method, the relaxation time is able to be regulated by adjusting the carrier mobility \( \mu \).

As can be seen from figure 3, with the increasing of the relaxation time, step by step, the maximum absorption rates of mode 1-2 increase from 65.7% to 97.9% and 48.4% to 97.9%, and the resonance wavelengths remain unchanged. The absorber is able to achieve perfect absorption in the range of
35.4-36.2 \( \mu m \) and 57.9-59.4 \( \mu m \) and the modulation indexes of mode 1-2 are 0.3 and 0.5, respectively. The carrier mobility increases with the increasing of relaxation time, which promotes the enhancement of SPR and the absorptivity. Thus, the maximum modulation index can reach over 0.5, which means the reflection index is able to reach 0.5 too.

![Figure 4](image-url)  
**Figure 4.** The absorption spectra of graphene with different incident angles from 0-60 degrees.

It can be seen from figure 4, in this section, we verify the sensitivity of the absorber to the incident angle of light. When the incident angle increases from 0 degrees to 60 degrees, both the resonance wavelength and the maximum absorption rate of two modes remain unchanged, which is caused by the rotational symmetry of the structure. This result supports the conclusion that the absorber has a good absorption effect in the wide-angle range.

### 4. Conclusion

In summary, based on FDTD method, the absorptivity of the perfect absorber graphene-based is studied by changing the chemical potential, the relaxation time, and the incident angle of light. It is proved that we can obtain two prefect absorption peaks in the range of 35.5-36.2 \( \mu m \) and 58-59.5 \( \mu m \) under the condition of setting the chemical potential to 0.6 eV. Meanwhile, the maximum modulation index of 0.5 is able to be obtained by regulating the relaxation time from 0.1ps to 0.5ps. At last, it is verified that the resonant wavelength and absorptivity of graphene are insensitive to wide-angle of light (0-60 degrees). Therefore, in the combined action of higher absorptivity and tunability, the absorber in this paper is beneficial to photoelectric switch and filter and other fields.

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