Physica E: Low-dimensional Systems and Nanostructures 103 (2018) 93–98

Contents lists available at ScienceDirect

Physica E: Low-dimensional Systems and Nanostructures

journal homepage: www.elsevier.com/locate/physe

Plasmonic absorption characteristics based on dumbbell-shaped graphene metamaterial arrays

Chunlian Cen[a,b], Jiajia Chen[a,b], Cuiping Liang[a,b], Jing Huang[a,b], Xifang Chen[a,b], Yongjian Tang[a,b], Zao Yi[a,b,**], Xibin Xu[c,***], Yougen Yi[d,*], Shuyuan Xiao[e]

[a] Joint Laboratory for Extreme Conditions Matter Properties, Southwest University of Science and Technology, Mianyang, 621010, China
[b] Sichuan Civil-Military Integration Institute, Mianyang, 621010, China
[c] Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang, 621010, China
[d] College of Physics and Electronics, Central South University, Changsha, 410083, China
[e] Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Keywords:
Graphene plasmon
Metamaterial
Absorber
Far-infrared and terahertz
FDTD

ABSTRACT

In this paper, we proposed a theoretical model in the far-infrared and terahertz (THz) bands, which are dumbbell-shaped graphene metamaterial arrays with a combination of graphene nanobelt and two semisphere-suspended heads. We report a detailed theoretical investigation on how to enhance localized electric field and the absorption in the dumbbell-shaped graphene metamaterial arrays. The simulation results show that absorption characteristics can be changed by changing the geometrical parameters of the structure and the Fermi level of graphene. Furthermore, we have discovered that the resonant wavelength is insensitive to TM polarization. In addition, we also find that the double-layer graphene arrays have better absorption characteristics than single-layer graphene arrays. This work allows us to achieve tunable terahertz absorber and may also provide potential applications in optical filter and biochemical sensing.

1. Introduction

Graphene, a single layer of carbon atoms in plane with a honeycomb lattice, is a kind of two-dimensional material. Because of its peculiar electrical and optical properties [1–3], there are broad application prospects in the fields of optoelectronic such as transparent electrodes [4–6], optical modulators [7–9] and photodetectors [10–13]. Moreover, graphene can support surface plasmons (SPs) in the infrared and THz window through proper doping and facilitate active plasmonic devices [14–17]. Compared with SPs of the traditional metal, graphene shows better performances, such as the limit of the electromagnetic energy constraints, low loss and high tunability. The SPs of graphene both in theory and experiment have attracted great interest. Recently, many articles have proposed extremely diverse arrays of graphene, such as graphene strips, disks, rings and cross structures [18–22]. In recent years, due to their unique active tunability [23,24] plasmonic metamaterial structures have been very attractive.

In the far infrared and THz regimes, graphene shows a strong plasmonic response. The localized surface plasmon resonances (LSPR) is excited in patterned graphene structures, which greatly enhances the plasmonic absorption characteristics [18,25–27]. In the near-infrared or visible regime, metal plasmonic structures [28–30], photonic crystals [31–33] or optical cavities [34–36] are introduced to enhance the near field resonance of the neighboring graphene, which increases the strength of the interaction between graphene and the incident electromagnetic wave, thereby improving its absorption. Strong resonance would cause strong absorption enhancement, but a narrow bandwidth, which is harmful in broadband applications. The design of different sizes of plasmonic elements can partially expand the bandwidth [37,38]. However, there is still limitations such as narrowband for current THz absorbers. We proposed that the dumbbell-shaped graphene metamaterial arrays can obtain the ideal optical properties through the configuration of geometrical parameters, beyond the intrinsic properties of the material.

In this research, we introduce the dumbbell-shaped graphene metamaterial arrays and study on the plasmonic absorption characteristics. Through the finite difference time domain (FDTD) method, the absorption characteristics of arrays are numerically calculated. Compared with other shapes, geometric parameters of the dumbbell-shaped structure can be changed more flexibly to adjust the absorption. Changing the geometrical parameters of the dumbbell-shape has a great impact on the absorption

* Corresponding author.
** Corresponding author. Joint Laboratory for Extreme Conditions Matter Properties, Southwest University of Science and Technology, Mianyang, 621010, China.
*** Corresponding author.
E-mail addresses: yizaomy@163.com (Z. Yi), dodolong@csu.edu.cn (X. Xu), yougenyi@csu.edu.cn (Y. Yi).

https://doi.org/10.1016/j.physe.2018.05.033
Received 13 March 2018; Received in revised form 17 May 2018; Accepted 27 May 2018
Available online 29 May 2018
1386-9477/

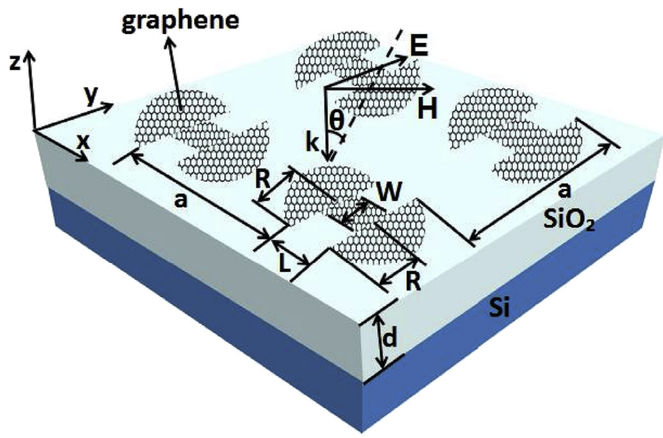

Fig. 1. The schematic diagram of geometric structure is designed as follows: the dumbbell-shaped graphene metamaterial arrays with period a, length L and a width W and radius R of two semisphere-suspended heads. The arrays are supported on a Si substrate coated by a thin SiO_2 layer with thickness d. The incident angle is θ.

characteristics. It is also encouraging that, under TM polarization, the absorption characteristics of arrays show excellent stability. The dynamic tunability of Fermi level is also studied. Through the study of the system, the mechanism of the absorption of electric field distribution and charge density distribution is revealed. The high absorption rate is due to the near-field enhancement caused by the surface plasmonic mode on the interface. The absorption of double-layer graphene arrays is also researched. The proposed absorber in plasmonic sensors, modulator and all-optical switch has potential application prospects.

2. The geometric structure and numerical model

Fig. 1 shows the structure we proposed, which consists of graphene nanobelt and semispheres constructing a dumbbell-shaped graphene metamaterial arrays with the period a, length L, width W and radius R of two semisphere-suspended heads. The graphene array is attached to the silicon substrate and dissociated by a thin SiO_2 filler piece with thickness d. The incident angle from the air to the plane is θ. The incident plane is the x-z plane.

The graphene conductivity is derived using the random-phase approximation (RPA) in the local limit, including both the intraband and interband processes [39,40].

$$\sigma_g = \sigma_{\text{intra}} + \sigma_{\text{inter}} = \frac{2e^2 k_B T}{\pi\hbar^2}\frac{i}{\omega + i\tau^{-1}}\ln\left[2\cosh\left(\frac{E_F}{2k_B T}\right)\right] + \frac{e^2}{4\hbar}\left[\frac{1}{2} + \frac{1}{\pi}\arctan\left(\frac{\hbar\omega - 2E_F}{2k_B T}\right) - \frac{i}{2\pi}\ln\frac{(\hbar\omega - 2E_F)^2}{(\hbar\omega - 2E_F)^2 + 4(k_B T)^2}\right] \quad (1)$$

where e is the charge of an electron, k_B is the Boltzmann constant, T is the operation temperature, $\hbar$ is the reduced Planck's constant, ω is the angular frequency of the incident light, τ is the carrier relaxation time and E_F is the Fermi level.

In the lower THz range, the interband contributions can be completely ignored. Because of Pauli exclusion principle, the surface conductivity can be approximated as a Drude-like model [41–43].

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

Here in the relaxation time $\tau = (\mu E_F)/(ev_F^2)$ depends on the electron mobility $\mu = 10000\ \text{cm}^2/\text{V·s}$, the Fermi level E_F (the unit of E_F is eV) and the Fermi velocity $v_F = 10^6$ m/s.

The simulations are based on the FDTD method, which is a famous method for solving Maxwell's equations in time domain. The equation for Maxwell's source free zone are given as [44].

$$\nabla \times E = -\mu\frac{\partial H}{\partial t} \quad (3)$$

$$\nabla \times H = -\varepsilon\frac{\partial E}{\partial t} \quad (4)$$

where E and H are the electric and magnetic fields, respectively. ε is the permittivity and μ is the permeability of the medium. In FDTD method, Maxwell's equations are quantized based on the time and space. The method of solving Maxwell's equations is based on the material parameters and initial conditions and calculates the electromagnetic field number at each time point. The incident electric field (E) is in the x direction and the plane of incidence is x-z. The absorption is calculated by A = 1-T-R formula, where T and R represent the transmission and reflection, respectively.

3. Results and discussions

We studied the absorption characteristics of rectangle (the length is 1.2 μm and the width is 0.4 μm), nanobelt (It is composed of rectangle and two semicircles, the length and width are the same as the rectangle are 1.2 μm and 0.4 μm, respectively. The width of the two semicircle is the same as the width of the rectangle is 0.4 μm), circle (the radius is 0.4 μm) and dumbbell-shaped (the radius of the two semispheres are the same as that of the circle radius, which is 0.4 μm. The length and width are the same as the rectangle are 1.2 μm and 0.4 μm). Through FDTD simulation calculations, we can obtain the absorption maximum of the rectangle is 0.129, the absorption maximum of the nanobelt is 0.133, the absorption maximum of the circle is 0.127 and the absorption maximum of the dumbbell-shaped is 0.142 as shown in Fig. 2(A). By comparing the absorption maximum of these four structures, it is obvious that the absorption characteristics of the dumbbell-shaped is better than those of the other three structures. This phenomenon can be understood by the electric field diagram shown in Fig. 2(B). By comparing the electric fields of the four structures, we find that the electric

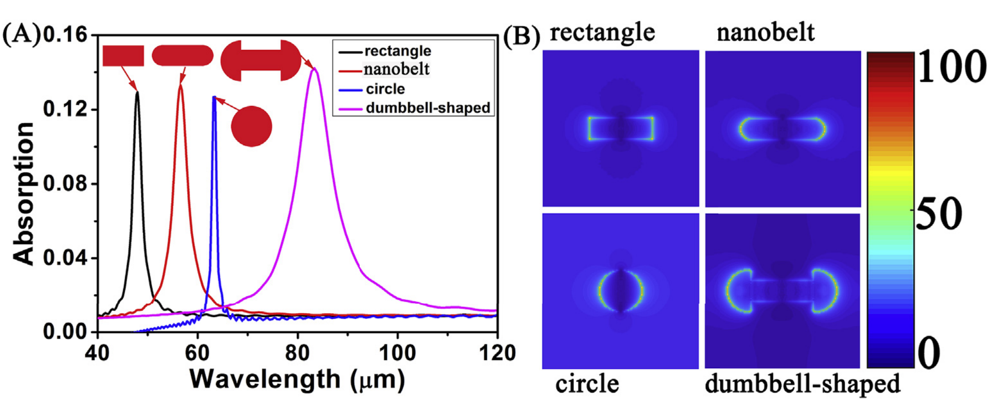

Fig. 2. (A) The absorption spectra of the four structures of rectangle (the length is 1.2 μm and the width is 0.4 μm), nanobelt (the length, width and width of the two semicircle are 1.2 μm 0.4 μm and 0.4 μm, respectively), circle (the radius is 0.4 μm) and dumbbell-shaped (the radius of the two semispheres, length and width are 0.4 μm, 1.2 μm and 0.4 μm, respectively). (B) The electric field distribution of four different structures at absorption peak.