IOP Conf. Series: Journal of Physics: Conf. Series **844** (2017) 012037 doi:10.1088/1742-6596/844/1/012037

Tunable mid-infrared absorption of metamaterial integrated with graphene

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Abstract. A metal-isolator-metal (MIM) metamaterial absorber with embedded graphene shows tunable at mid-infrared frequency regime. We report tunable absorption spectra of the MIM structure for different Fermi levels of graphene.

1. Introduction

Metamaterials refer to artificially structured materials with arrays of subwavelength elementary particles (known as meta-atoms) [1]. Much work has been done, especially in creating negative-refraction materials [2-3]. Recently, the metamaterial absorbers based on metal-isolator-metal (MIM) structure have been reported. To realize the tunability of MIMs, several methods have been implemented, including altering the capacitance of the resonators and changing the property of the surrounding media [4-6]. However, those methods are limited in the modulation range and are complicated to implement.

Graphene has drawn enormous attention because of its electrically tunable conductivity from terahertz to mid-IR frequency regime [7]. The coupling of graphene and photo/plasmonic structures could achieve dynamic tunable devices.

In this article, we report the design of a hybrid graphene/MIM device which offers an efficient manner of coupling free-space light into nanoscale plasmonic modes. The electronic control of that coupling process is attained by tuning the Fermi level of graphene. A schematic diagram of the graphene/MIM device is shown in figure 1. The MIM structure consists of three layers: (1) a thick gold layer (thickness H = 100 nm) at the bottom, (2) a 35 nm thick alumina (Al_2O_3) spacer, and (3) a periodic array of gold nanostructures (width d = 1200 nm, thickness W = 30 nm) at the top. A single layer graphene (thickness t = 0.34 nm) is sandwiched between the gold particles and alumina layer to form the graphene/MIM hybrid structure.

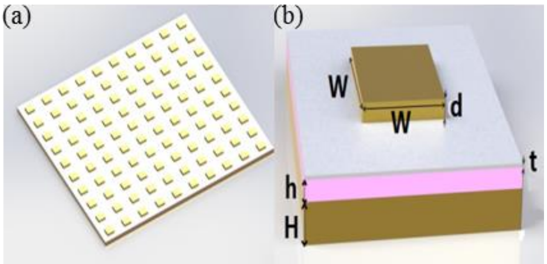

Figure 1. (a) Geometry of graphene/MIM device. (b) Unit cell of absorber. H, d, t, and h represent thickness of gold layer at bottom, gold particle, graphene, and Al_2O_3. W is width of the gold particle. The periodicity of the gold nanostructure array is 1500 nm.

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2. Result and Discussion

The simulation for graphene/MIM nanostructure is performed with commercial COMSOL MULTIPHYSIS software based on the two-dimensional finite elements method. The absorption spectrum is derived using the formula: $A(\lambda) = 1\text{-}R(\lambda)\text{-}T(\lambda)$. Figure 2 (a) shows the simulated absorption spectra, $A(\lambda)$, for different Fermi level of graphene ranging from 200 meV to 400 meV. The resonant frequency changes as the Fermi level is varied. The variation of resonance frequency and corresponding absorption with different Fermi levels is listed in table 1. The peak absorption is 89% (at 5.52 μm) when the Fermi level of graphene is 200 meV. The absorption moves to 87% (at 5.62 μm) when its Fermi level becomes 400 meV. The minimum absorption also changes with Fermi level of graphene. It ranges from 2.7% (at 5.54 μm) to 2.0% (at 5.62 μm) as Fermi level changes from 200 meV to 400 meV. Figure 2 (b)-(g) illustrate the magnetic field for both maximum and minimum absorption corresponding to different Fermi level of graphene.

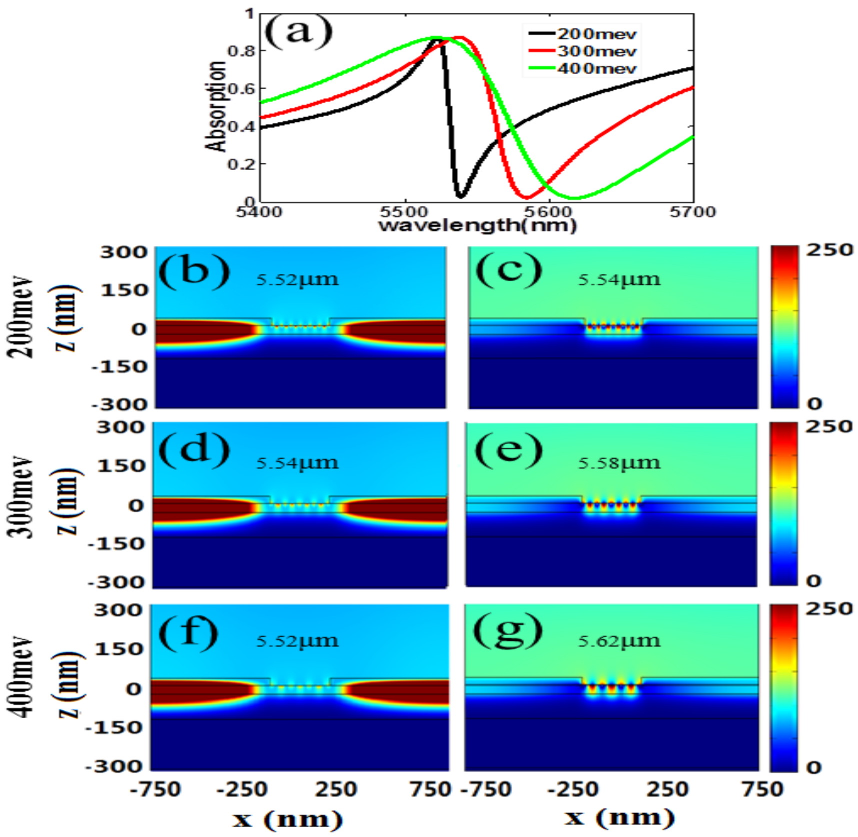

Figure 2. (a) Simulated absorption spectra for different Fermi levels. (b), (d) and (f) represent the magnetic field when the structure reaches maximum absorption. (c), (e) and (g) are also the magnetic field when it reaches minimum absorption.

Table 1. The variation of resonance frequency and corresponding absorption with different Fermi levels

Fermi level (meV)	Maximum Efficiency	Absorption Wavelength	Minimum Efficiency	Minimum Efficiency
200	89%	5.52μm	2.7%	5.54μm
300	87%	5.54μm	2.2%	5.58μm
400	87%	5.52μm	2.0%	5.62μm

In order to understand the absorption properties of these graphene/MIM nanostructure, the electromagnetic field distributions for the resonant modes are thoroughly investigated. Maximum absorption is observed due to the excitation of localized magnetic and electric dipole resonances resulting from the coupling of accumulated charges at the sides of gold particle with their image charges in the gold surface. These strong resonances effectively trap light energy and provide sufficient time to dissipate it by the Ohmic losses within the metals and graphene. [1] It can be noted that Al_2O_3 is lossless in this wavelength regime. There also exists another resonance probably because of standing waves localized on the graphene layer between two gold particles. Here the graphene layer can be considered as a plasmonic metamaterial where the plasmons can be excited at the air-graphene-Al_2O_3 interface. The dispersion of transverse magnetic (TM) plasmons in graphene layer between air and Al_2O_3 with the permittivities ε_1 and ε_2 is described by the dispersion equation [8]

$$\frac{\varepsilon_1}{[q^2(\omega)-\varepsilon_1]^{1/2}}+\frac{\varepsilon_2}{[q^2(\omega)-\varepsilon_2]^{1/2}}+iQ_s(\omega)Z_0=0 \tag{1}$$

Where ε_1 and ε_2 represent permittivity of air and Al_2O_3, $\sigma_s(\omega)$ is the surface conductivity of graphene and $Z_0=\sqrt{\mu_0/\varepsilon_0}$ is the free-space impedance, q (ω) represents the effective index of the graphene plasmon.

3. Conclusion

In this article, we have demonstrated that the graphene/MIM hybrid structure can be tuned by controlling the Fermi level of the graphene. This tunable optical response allows for graphene being an attractive platform for optoelectronic applications such as light modulators, selective thermal emitters.

Acknowledgment

This work is supported by the National Natural Science Foundation of China (grant nos 6142503, 61575177 and 61235007).

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