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Published in:
Optical and Quantum Electronics

Link to article, DOI:
10.1007/s11082-017-1013-8

Publication date:
2017

Document Version
Peer reviewed version

Absorption Enhancement in Graphene with an Efficient Resonator

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***Abstract*—Graphene can be utilized in designing tunable terahertz (THz) devices due to its tunability of sheet conductivity, suffering however with weak light-graphene interactions. In this paper, an absorption enhancement in graphene using a Fabry-Perot resonator is presented, and its performance has been numerically investigated using finite element method (FEM). The Fabry-Perot resonator consists of a continuous layer of graphene film sandwiched between the polymethyl methacrylate (PMMA) and silicon layers on an Au substrate which is covered by periodic gold ribbons. Numerical results show that the absorption performance is significantly enhanced by use of the Fabry-Perot resonator and a narrow band perfect absorption is achieved in THz regime. The influence of structural parameters on the absorption performance is further analyzed, and the absorption peak frequency can be flexibly controlled by adjusting the chemical potential of graphene which could be conveniently achieved by applying a bias voltage. The proposed structure here has a promising potential for developing advanced THz optics-electronics devices.**

Index Terms—Absorber, Graphene, THz

I. Introduction

Graphene as a two-dimensional material has been a hot topic in recent years, since a team led by Novoselov and Geim successfully separated graphene from graphite in an efficient way in 2004 [1]. Graphene is a single layer of carbon atoms arranged in plane with a honey comb lattice. Due to its unique electric and optical properties, such as high carrier mobility, zero-gap bandstructure and tunability of conductivity by applying bias voltage or chemical doping, graphene has become a very promising material [2-4] for the development of modulators and ultrafast lasers. In a wide range of frequencies, the absorption of monolayer graphene amounts to $\pi\alpha\approx 2.3\%$, with $\alpha=1/137$ being the fine structure constant [5, 6]. The weak light-matter interaction leads to 97.7% of light unaffected by the presence of the graphene layer. Consequently, the efficiency of graphene-based optoelectronic devices is strongly limited by the weak light-graphene interactions. In order to improve its absorption efficiency, one has combined graphene into optical cavities [7], dielectric gratings [8], and photonic crystals [9, 10] where electromagnetic wave can be efficiently trapped and absorbed. Recently, there are many work using different shapes of graphene to enhance the absorption of electromagnetic wave, such as graphene nanodisks [11], graphene open micro-ring arrays [12] or graphene micro-ribbon [13] and periodically elliptical nanodisk graphene structure [14].

In this paper, we investigate a simply and efficient perfect absorber by use of Fabry-Perot resonator structure in the THz regime. By changing the geometric parameters of the structure and adjusting the chemical potential of graphene, we can achieve the perfect absorption.

II. Calculation method

The graphene was numerically modeled by a thin layer (with thickness Δ=1nm) with the relative permittivity of $\varepsilon_{GR}=1+i\sigma_g/\omega\Delta\varepsilon_0$, where σ_g is the conductivity of graphene sheet derived using the well-known Kubo formula [15]. The conductivity of the graphene is described with interband and intraband contributions as follows:

$$\sigma_g = \sigma_{intra}(\omega,\mu_c,\Gamma,T)+\sigma_{inter}(\omega,\mu_c,\Gamma,T) \tag{1}$$

$$\sigma_{inter} \approx \frac{-ie^2}{4\pi\hbar}\ln\left[\frac{2|\mu_c|-(\omega-i2\Gamma)\hbar}{2|\mu_c|+(\omega-i2\Gamma)\hbar}\right] \tag{2}$$

This work was supported by 2016 Zhejiang Provincial Natural Science Foundation under Grant No.LY16F010010, in part by 2015 Zhejiang Province Public Welfare of International Cooperation Project under Grant No. 2015C34006.

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$$\sigma_{\text{intra}} = \frac{-ie^2 K_B T}{\pi\hbar^2(\omega - i2\Gamma)}\left[\frac{\mu_c}{K_B T} + 2\ln(e^{-\mu_c/K_B T} + 1)\right] \quad (3)$$

where e, ħ and K_B are electron charge, reduced Plank's and Boltzmann's constant, respectively. ω is the angular frequency, μ_c is chemical potential，T is the temperature and fixed to 300K, and Γ is the scattering rate, which is related to relaxation time τ ($\tau = 1/2\Gamma$).

For THz frequencies, where the photon energy $\hbar\omega \leq E_F$, $E_F \geqslant k_B T$, the interband part is negligible comparing to the intraband part. Therefore, in the THz regime, graphene is well described by the Drude-like conductivity with Eq. (3). In addition, the frequency dependent permittivity of graphene depending on the some selected values of the chemical potential are shown in Fig. 1(a) and 1(b).

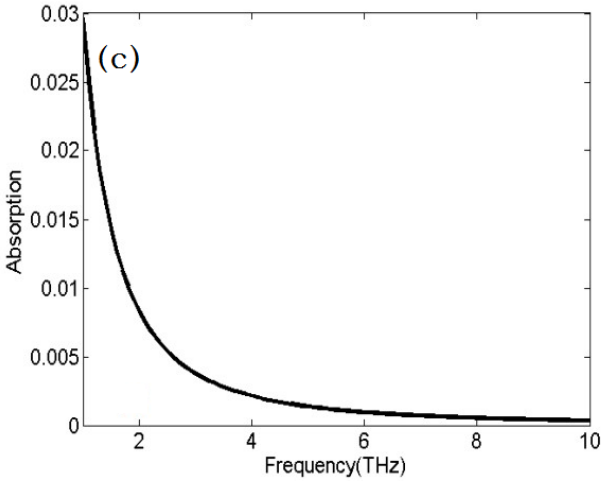
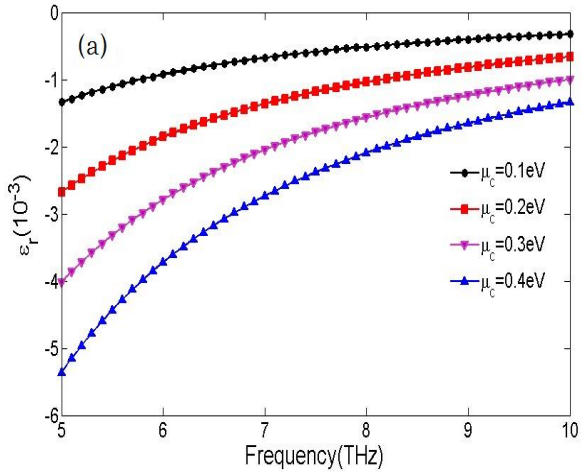


Fig. 1. Real (a) and imaginary (b) parts of the relative permittivity of a 1nm-thickness graphene sheet as function of frequency as well as chemical potential. (c) The absorption efficiency of monolayer graphene in terahertz ranges.



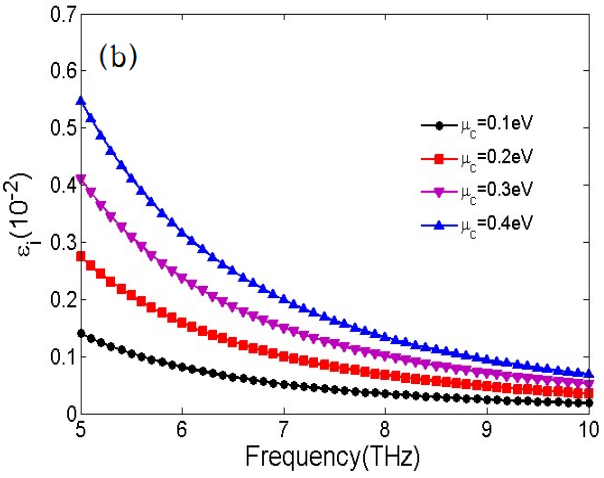


Fig. 1(a) clearly shows that the real part of graphene relative permittivity is negative in the THz range, it means that the graphene sheet have the property of metal. When the chemical potential increases from 0.1eV to 0.4eV, the amplitudes of real part and imaginary part of relative permittivity become larger (the absolute value of the real part becomes larger) as shown in Fig. 1(a) and 1(b), so the chemical potential has a significant effect on graphene. Although graphene owns the property of metal in terahertz regime, the absorbance is still very low as shown in Fig. 1(c). We can see that with the frequency increases, the absorption efficiency decreases obviously in the THz range, it's due to the graphene in high frequency has the smaller dielectric loss. Compared with noble metal, graphene has many excellent properties. For example, graphene suffers lower loss than noble metal because of its smaller imaginary part of relative permittivity. And, even if the geometrical structure is fixed, we can adjust the absorption frequency and amplitude by static voltage. In conclusion, graphene becomes a potential candidate to take the place of noble metal in the THz regime.

III. Simulation Results and Discussion

In this paper, the proposed structure was shown in the Fig. 2(a), the top layer is the periodic Au strips. In order to understand the influence of geometrical parameters on the absorption effect, the width w of top layer Au strip of proposed structure is discussed, ranging from 5.5μm to 7μm. And the thickness of middle layer PMMA is changing from 300nm to 700nm. It's worth noting that the thickness of Au is bigger than skin depth in the THz regime. So the reflection is the only factor limiting the absorption efficiency. In the discussion, we analyze the one parameter under the circumstance of fixing another parameter in order to choose optimal value according to simulation. In the paper, relative permittivity of PMMA and Si

is 2.3 and 11.6 respectively, the conductivity of Au is 4.7×10^7 S/m, which is perfectly reflecting in the THz frequency region. In our calculation, the numerical simulations are conducted using finite element technique in Comsol MultiPhysics. FEM accompanied with periodic boundary condition has been employed to calculate the absorption spectrum of the structure. The total absorption can be calculated by: A=1-T-R (T and R is transmission and reflection coefficient respectively). The incident plane wave is considered to be normal to the proposed structure along the z direction. The absorption enhancement of graphene in the proposed structure can be explained through analyzing electric and magnetic field distributions, as shows in Figs. 3(a)-3(d). At the absorption peak of 6.78THz, |E| is confined in the middle layer PMMA between graphene and metal gold strips as shown in Fig. 3(a). And |H| is between gold ribbons and gold substrate as shown in Fig. 3(b). In contrast, at 6.02THz, as shown in Fig. 3(c) and 3(d), the filed is very low. Our structure can be seen as a Fabry-Perot resonator, which is similar to metal-insulator-metal (MIM) structure [16].

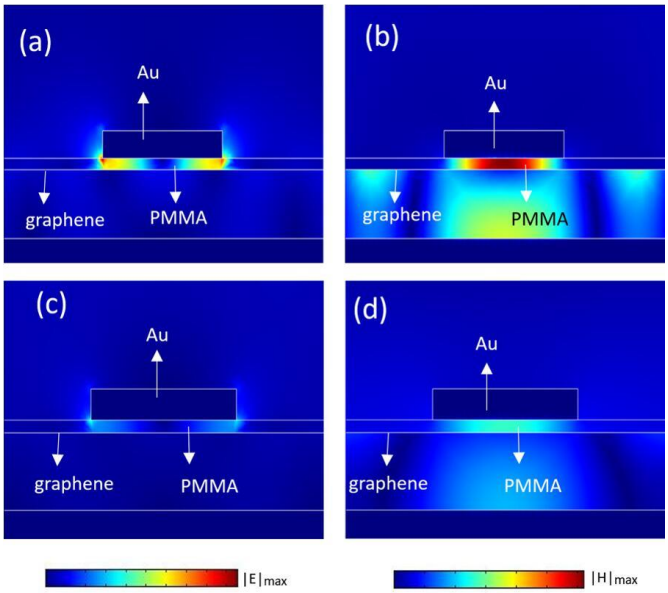


Fig. 3. Field distributions for the TM polarized, where w=7μm, t=0.5μm.

Electric field (a) and magnetic field (b) at f=6.78THz.

Electric field (c) and magnetic field (d) at f=6.02THz.

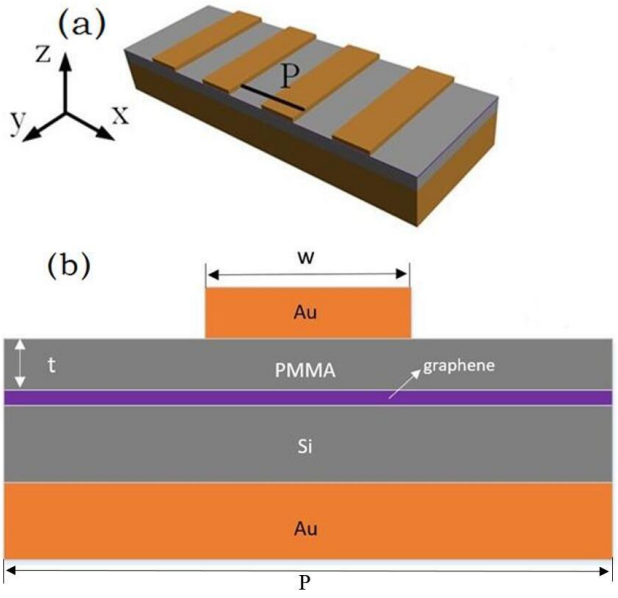


Fig. 2. (a) 3D schematic of the proposed structure and (b) 2D schematic of the proposed structure, with Au 0.5μm thick, Si 3μm thick and periodic P=25μm.

Different from [13], our structure is relatively easy to be fabricated. Because of our structure doesn't need to tailor the graphene strip. Besides, compared to metal-based absorber [13, 18], graphene-based absorber is easily tunable. Fig. 4 shows the absorption performance of the proposed structure at different geometric parameters. Firstly, the width of metal Au strip is discussed when the other geometric parameters is fixed. Fig. 4(a) shows that the absorption spectra of the TM-polarized incident wave with four different widths w of the metal stripes ranging from 5.5μm to 7μm. Here we set the period of the structure as 25μm, and thickness of the PMMA is 500nm. The solid lines represent the absorption spectrum with bottom metallic substrate, and the dashed lines for the case without bottom metallic substrate. From Fig. 4(a) we can see that the absorption efficiency is very low without the gold substrate, the absorption efficiency is just ranging from 30% to 38%. When having the gold substrate, absorption efficiency is enhanced significantly. This is due to the fact that the incident electromagnetic wave is reflected by metallic substrate, so the electromagnetic wave pass through the graphene film with multiple times, thus enhancing the absorption in graphene. As w increases from 5.5μm to 7.0μm, the absorption spectra of graphene are red-shifted. Here the edges of the Au strips act as sources of surface plasmon-polaritons, which are induced by the underlying graphene sheet, and constructive interference results in the resonance dependence on the Au width [19]. That is to say, absorption frequencies of graphene metamaterial can be decided by the width of Au strip. So we can easily tune the absorption peak by changing the width of Au strip.

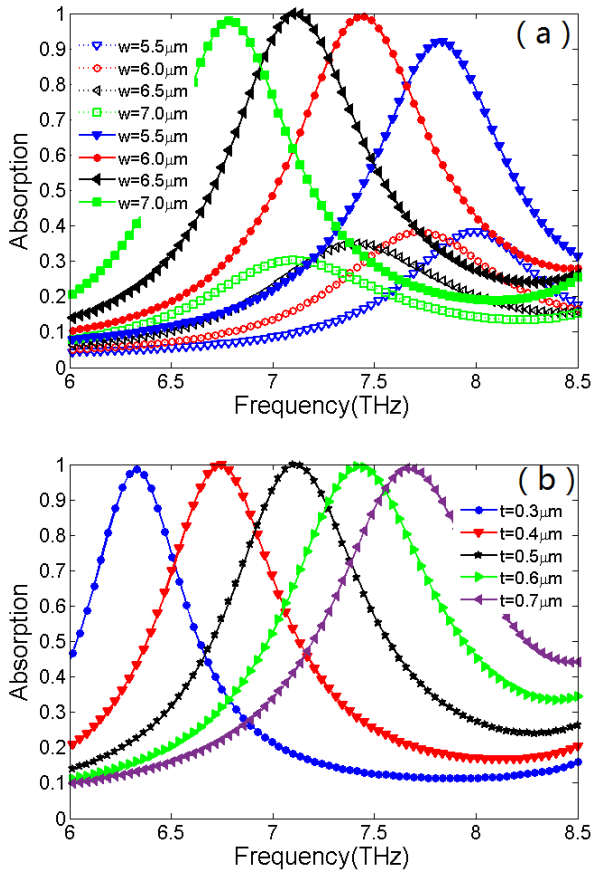


Fig. 4. Absorption spectra where p=25 μm, μ_c=0.1 eV. (a) for different w values with (the solid lines) and without (the dashed lines) the bottom metallic substrate where t=500 nm. (b) for different t values, where w=6.5 μm.

Lastly, we discuss the dependence of absorption spectra on working frequency at different thickness of PMMA. Similar to MIM structure in the optical regime, the absorption spectra of the structure is sensitive to thickness of PMMA. As shown in the Fig. 4(b), as the thickness of PMMA increases from 300nm to 700nm, the absorption spectrum shows obvious resonances peaks, and the peaks shift from 6.35THz to 7.70THz due to the increase of the resonant gap. And the absorption peak is above 90%, the possible reason is that coupling between graphene and metal Au become strong. Near field coupling existing between the graphene and Au strip lead to the energy confined in the middle layer PMMA.

Besides the geometric parameter can affect the absorption peak, we can also tune the chemical potential to change the performance of the proposed structure. As we know, the chemical potential has a great impact on the conductivity of graphene, which can be controlled by electrostatic and chemical doping [20, 21]. As shown in the Fig. 5, absorption spectrum has been calculated at different chemical potential (or Fermi level). The frequency of the absorption resonance experiences the blue shift with the increase of chemical potential. It should be mentioned that almost perfect absorption can be achieved in the tuning range. Therefore, by applying a gate voltage on the graphene layer, the chemical potential and thus the conductivity of graphene can be controlled on purpose.

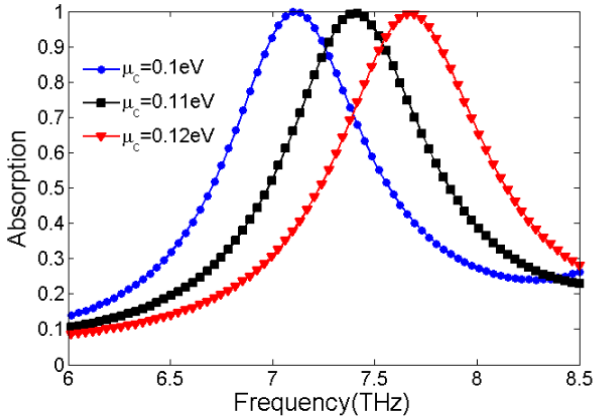


Fig. 5. Absorption spectra at different chemical potential μ_c, where we set P=25μm, w=6.5μm, t=0.5μm

IV. Conclusion

We have proposed a perfect absorber with tunable resonance frequency by employing a Fabry-Perot structure. The absorption performance is numerically investigated by the finite element method, and the absorption efficiency can be improved from 40% to above 90% by the present of the resonator. Simulation results show that the absorption peak frequency can be adjusted in the terahertz frequency by tuning the bias voltage on the graphene layer. The influence of geometrical parameters on the absorption is also analyzed systemically. The research achievements reveal that our work has provided an efficient method to manipulate the THz wave which could be used in many THz devices such as modulators, sensors, and detectors, etc.

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