Tunability in Graphene Based Metamaterial Absorber Structures in Mid-Infrared Region

Shashank Kumar Gupta and Palash Kumar Basu

***Abstract*—Tunable conductivity of graphene, makes it a promising material for metamaterials. There are various graphene tunable metamaterial absorbers in the mid-infrared region, whose absorption spectrum can be dynamically tuned by varying the Fermi potential of graphene. However, graphene absorbers working in the low mid-infrared region (4–7 μm) has limited tuning. In this work, the spectral tuning efficiency of a graphene based metal disc pattern and a graphene ribbon pattern metamaterial absorber is studied using FDTD simulation. The tunability in absorption spectrum achieved by metal disc absorber is 2–4%, which increased to 5–20% for graphene ribbon absorber with more than 85% absorption rate. Thus, the graphene pattern absorber significantly improves the tunability and provides broad tuning in 4–7 μm wavelength range. However, the graphene ribbon absorber is polarization dependent due to its non-symmetric shape. Hence, a new type of nano square hole (NSH) graphene absorber is proposed, which can easily be externally biased and provide polarization independent absorption. The NSH graphene absorber has wide tunability of 5–20% and high absorption rate of 85% similar to the graphene ribbon absorber. These results are very helpful to design tunable sensors and multispectral devices for gas sensor and biosensor applications.**

***Index Terms*—Absorber, Graphene, Metamaterial, Mid-infrared region, Tunable.**

I. Introduction

METAMATERIAL absorbers (MMAs) are artificially designed material which shows near perfect absorption of the light wave. The unique structure and properties of metamaterial have attracted great attention of researchers in the development of various applications, such as optical detectors, sensors, modulators, and communication [1]. MMAs exhibit high absorption due to the excitation of surface plasmon resonance (SPR) in the periodic array structure. The top periodic layer act as an electric dipole resonator, which absorbs all the incident electromagnetic fields at the resonance. Progress in metamaterials has enabled variety of absorbers for narrowband, multi-band, and broadband absorption [2]. However, conventional metamaterial design works only for the fixed operating frequency and absorption rate. It is because, the absorption properties of MMA depend on the geometry of the unit cell structure which cannot be modified once the structure is fabricated. This limits their use in many practical applications. Hence, the development of tunable MMAs is required to improve the performance of devices and extended their working to multi-functional applications.

Recently, graphene based MMAs have drawn the attention of researchers, which has shown the ability to dynamically tune the peak absorption without reconstructing or modifying the geometry [3]. The adjustable surface conductivity of graphene by varying the Fermi potential has facilitate the development of tunable absorbers and grown its demand for the design of variable metamaterial absorbers [4], [5].

Graphene is a two-dimensional (2D) material, consist of a monolayer of carbon atoms arranged in the hexagonal lattice structure. The unique electronic band structure of graphene offers magnificent properties such as optical transparency, high electron mobility, flexibility, and tunable conductivity [6]. The most significant property of graphene is its dynamic tunable surface conductivity, which can be done by varying the Fermi potential (E_f) through externally applied voltage. This property of graphene has made it a promising material for tunable MMAs. The advancement in graphene based MMAs has enabled various absorber structures, that are mainly configured in two ways; 1) graphene added in metal pattern absorber, 2) graphene pattern absorber. The metal pattern absorbers are designed with multiple shapes such as patch, circle, cross, ribbon, etc [7]–[9], with graphene sheet added to provide spectral tunability. Whereas in graphene pattern absorber, graphene is structured in different shapes such as ribbon, cross, disc, etc [10], [11], which act as a primary source of SPR and can be simultaneously tuned by varying Fermi potential.

So far, many graphene based MMAs have been reported in the mid-infrared region. However, most of the absorbers have an operating range above 7 μm wavelength, and very few absorbers are reported for low mid-infrared wavelength (4–7 μm). Even though the graphene absorbers which are reported for 4–7 μm wavelength range, has small spectral tunability [12], [13]. The reason for limited tunability in the region is the low surface conductivity of graphene and the small shift in conductivity at different values of Fermi potential. The surface conductivity of graphene depends on the operating wavelength and E_f [9].

In the mid-infrared region, the conductivity increases with the increase in wavelength, and the shift in conductivity by E_f also increases with increasing wavelength. Thus, at lower wavelengths (4–7 μm), the change in conductivity with respect to E_f is less, which limits the tuning ability of absorbers in the region. Some applications, such as gas sensors or biosensors,

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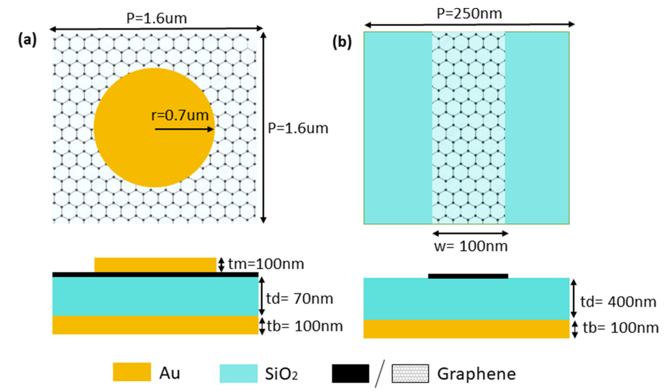

Fig. 1. (a) Unit cell structure of metal disc metamaterial absorber, (b) Unit cell structure of graphene metamaterial absorber.

operating in 4–7 μm wavelength range need a wide range tunable absorber. Therefore, graphene based tunable MMAs with large tunability are highly desirable in the region.

This paper investigates the spectral tuning of both types of graphene based MMAs and compares the tunability performance of both absorbers in the 4–7 μm wavelength range. A graphene sheet added metal disc absorber and ribbon shape graphene absorber are presented in the paper, and finally proposed a new type of polarization independent nano square hole (NSH) graphene metamaterial absorber. The absorber design using patterned graphene has greater spectral tunability than the absorber using graphene sheet for the same E_f change. Thus, a graphene pattern absorber can provide large spectral bandwidth compared to a design using graphene sheets. However, the graphene ribbon absorber is polarization dependent due to its non-symmetric shape. Therefore, a simple NSH pattern graphene absorber structure is proposed, which is polarization independent and spectrally tunable. The absorber structure consists of nano square hole (NSH) graphene over a silicon dioxide (SiO_2) dielectric and placed on a continuous metal plane. The absorption characteristic of all the structures is studied by the Finite Difference Time Domain (FDTD) method.

II. Structure Design and Simulation

For the analysis, the structures are designed to achieve a single wavelength narrowband absorption. Out of various graphene based absorber structures, a disc shape is selected for metal pattern type MMA due to its perfect symmetricity, and graphene is added for tuning the absorption. For graphene pattern type absorber, a ribbon pattern shape is selected due to ease in biasing the graphene externally from the fabrication perspective. The unit cell structures of metamaterial absorbers are illustrated in Fig. 1. Both the structures are designed with the same base layer and material, where the bottom is metallic gold plate and in middle SiO_2 dielectric layer. The metal disc absorber consists of a graphene sheet sandwich between the dielectric and top gold pattern layer, as shown in Fig. 1(a), and (b) shows the graphene ribbon absorber whose top layer is the pattern graphene ribbon. The dimensions of the metamaterial absorbers as labelled in Fig. 1 are as follow- metal disc absorber: tm = 100 nm, td = 70 nm, r = 0.7 μm, P = 1.6 μm, tb = 100 nm; graphene ribbon absorber: td = 400 nm, w = 100 nm, P = 250 nm, tb = 100 nm.

Graphene used in the design is a two-dimensional material that supports SPR in the mid-infrared region. The SPR shown by graphene enables huge concentration of optical energy and produces enhanced light absorption, which can be controlled by its Fermi potential. This important characteristic of graphene to adjust the Fermi level depends on the surface conductivity, which is described by Kubo's formula [14]:

$$\sigma_g = \sigma_{intra} + \sigma_{inter} = \frac{2e^2 k_B T}{\pi \hbar^2} \frac{i}{\omega + {}^{i}/_{\tau}} \times; ln\left[2cosh\left(\frac{E_f}{2k_B T}\right)\right] + \frac{e^2}{4\hbar^2} \left[\frac{1}{2}tan^{-1}\left(\frac{\hbar\omega - 2E_f}{2k_B T}\right) - \frac{i}{2\pi} ln\frac{(\hbar\omega + 2E_f)^2}{(\hbar\omega - 2E_f)^2 + 4(k_B T)^2}\right] \tag{1}$$

where E_f, ω, τ, are the Fermi potential, angular frequency, and the relaxation time, and T, k_B, $\hbar$ are the operating temperature, Boltzmann constant and reduced Planck's constant, respectively. The first and second term in Eq. (1) are intraband conductivity and interband conductivity respectively. In the mid-infrared region, when the photon energy is less than the Fermi potential $\hbar\omega << E_f$, the interband transition becomes negligible compared to the intraband transition. Thus, in the region, interband conductivity is neglected and the surface conductivity of graphene is described by Drude like model of intraband conductivity as [15]:

$$\sigma_g \approx \frac{e^2 E_f}{\pi \hbar^2} \frac{i}{\left(\omega + {}^{i}/_{\tau}\right)} \tag{2}$$

The light absorption on any surface depends on the material property, which in case of graphene can be varied by its Fermi potential. The relative permittivity of graphene depends on the surface conductivity which can adjust the electric medium property of the material. Whenever the conductivity of graphene is changed, it modifies the medium property and changes the optical response of the material to the incident light. The electric permittivity of graphene having a certain thickness tg has been numerically modelled and can be calculated as [16]:

$$\varepsilon_g = 1 + i\frac{\sigma_g}{\varepsilon_0 \omega t_g} \tag{3}$$

where σg, ε_0, tg, and ω are the graphene surface conductivity, vacuum permittivity, graphene thickness, and angular frequency. It can be observed from the Eq (2) and Eq (3) that the change in the surface conductivity by Fermi potential can modify the effective medium property of graphene to the incident light wave. This Fermi potential change is accomplished by bias voltage which is expressed as [16]:

$$E_f = \hbar v_f \sqrt{\frac{\pi \varepsilon_r \varepsilon_0 V_g}{e t_s}} \tag{4}$$

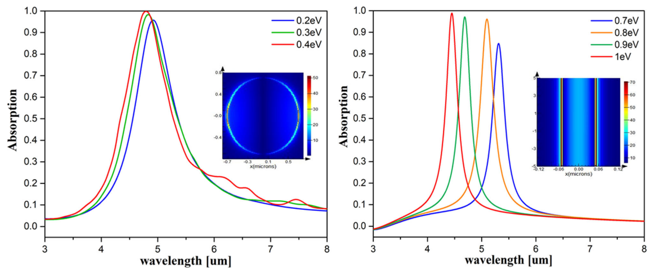

Fig. 2. Tunability performance at mid-infrared wavelength for shift in Fermi potential. (a) Metal disc absorber, (b) Graphene ribbon absorber (Inset shows the electric field distribution for Ex polarized plane wave).

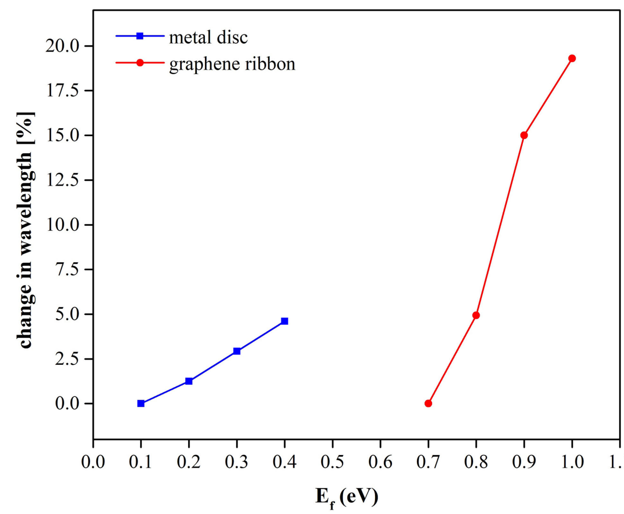

Fig. 3. Relative wavelength shift in absorption peak of both type of metamaterial absorbers due to the variation in Fermi potential.

where vf, Vg, ε_r, and ts are the Fermi velocity, external applied bias voltage, relative permittivity, and thickness of the middle dielectric layer. Thus, the output characteristics of graphene based MMA can be externally controlled by varying the bias voltage without modifying the geometry.

To study the absorption characteristic of metamaterial absorbers, numerical simulation is performed in FDTD Lumericals. In the simulation, the operating temperature is fixed at room temperature 300 K, and the relaxation time of graphene is set to be 0.5 ps [10]. The structures are simulated with different boundary conditions (bc). For metal disc absorber, periodic bc is used in both x- and y-direction, and for graphene ribbon absorber, anti-symmetric in x- and periodic bc in the y-direction. The perfectly matched layer (PML) boundary condition is defined in z-direction for both. The structures are illuminated by a plane wave light source, which is set to propagate in the z-direction. Absorption rate of the metamaterial absorber can be calculated as A = 1-R-T, where A is absorption, R is reflection, and T is a transmission. The thickness of the bottom metal plate was set higher than the skin depth of the THz wave such that the transmission is zero. Thus, the absorption can be simply calculated as A = 1-R.

III. Result and Discussion

The simulation is performed with the TE polarized plane wave to analyze the absorption characteristics of the absorbers. Fig. 2(a) and (b) shows the tunability curve for the metal disc absorber and the graphene ribbon absorber, respectively. For metal disc absorber, the maxima has been observed at 4.78 μm wavelength at 0.4 eV E_f with absorption efficiency of 99.9%. Whereas the graphene ribbon absorber has maxima at 4.46 μm wavelength at 1 eV E_f with similar absorption efficiency. Other important observations from the tunability curve are the red shifting of absorption peak and the reduce in absorption rate by decreasing the E_f. The drop in the absorptivity is due to change in the material property at different E_f, which causes impedance mismatching of the material medium to the surrounding. Additionally, the electric field distribution of metal disc and graphene ribbon absorber at resonance wavelength is also shown in inset of Fig. 2(a) and (b), respectively. The enhanced electric field shown by the structures at the interface is due to the surface plasmon excitation at resonance wavelength. The top periodic layer in the absorber structures act as a metal plasmons which gets excited at resonance wavelength when the incident light frequency equal to the resonance of conducting electrons. This phenomenon is known as localized surface plasmon resonance (LSPR). In a metal disc absorber, the enhanced absorption is due to the periodic metallic layer, and in the graphene ribbon absorber, the patterned graphene layer locally generates surface plasmon at resonance wavelength and produces enhanced absorption.

Further, the spectral shift in both the absorber structures are examined by plotting the change in wavelength as a function of Fermi potential shown in Fig. 3. The relative wavelength shift in the resonance wavelength is defined as- $\delta\lambda(\%) = 100 \times |\lambda_p - \lambda_r|/\lambda_p$, where λp is the resonance wavelength at the first absorption peak, and λr is the resonance wavelength at other peaks.

From Fig. 3, it can be observed that compared to metal disc absorber, graphene ribbon absorber has significant shift for same per 0.1eV change in E_f of graphene. The spectral shift achieved by varying E_f in graphene ribbon absorber is 5–20%, whereas metal disc has only 2–4% shift. This large shift of resonance wavelength in graphene ribbon can be explained by the plasma resonance frequency of graphene. Unlike the metals, graphene plasma frequency depends on the Fermi potential (E_f) which is described as [17]-

$$\omega_p = \left[\frac{2e^2 k_B T}{\pi \hbar^2 \varepsilon_0 \Delta} ln\left(2cosh\frac{E_f}{2k_B T}\right)\right]^{1/2} \tag{5}$$

Since in graphene ribbon absorber, graphene acts as a plasmonic layer, so when E_f is modified, its plasma resonance frequency directly gets changed and generates a new absorption peak. Whereas, in the metal disc absorber, the metal plasmonic layer has a fixed plasma frequency and does not vary with the graphene E_f. The tunability achieved in metal disc structure is due to the change in medium property of the material by graphene Fermi potential (from Eq 3), which causes a less spectral shift in resonance wavelength compared to patterned

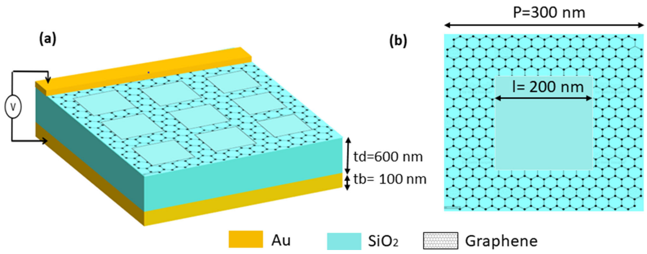

Fig. 4. (a) Schematic of the tunable metamaterial absorber composed of nano square hole (NSH) graphene meta-layer, a SiO_2 dielectric layer and a gold substrate, (b) Top-view of unit cell of NSH graphene meta-layer.

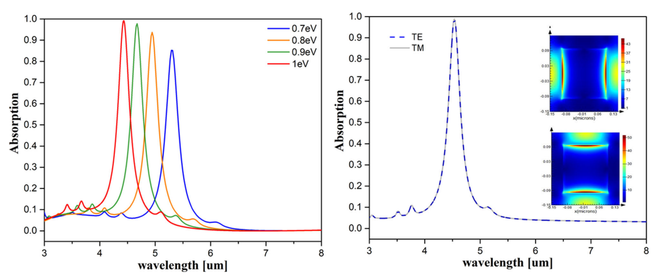

Fig. 5. Absorption characteristics of NSH graphene metamaterial absorber (a)Tunability performance at mid-infrared for shift in Fermi potential, (b) Polarization dependency for TE and TM polarized mode (Inset shows the electric field distribution for TE mode, TM mode).

graphene structure. Thus, we can say that the absorber designed with patterned graphene has better tunability for a wide spectral range and thereby, are more suitable for low mid-infrared region devices.

The graphene ribbon absorber discussed above has an advantage over the other tunable metamaterial absorbers, but absorption in the structure is polarization dependent due to its non-symmetric shape. Many other shapes of graphene pattern absorbers have been reported which are symmetrical, but the structures are practically not feasible. It is because, graphene requires electrical biasing for tuning the device and creating the contacts with all the patterned graphene are difficult to realize from fabrication perspective. Hence, to overcome the constrain, a new type of polarization independent nano square hole (NSH) graphene pattern tunable MMA is proposed. The proposed structure provides flexibility in biasing and is practically realizable.

Fig. 4(a) illustrates the design of the proposed absorber. The NSH graphene metamaterial absorber is designed using a graphene sheet as a top plasmonic layer with periodic square shaped holes in the layer. The dimensions of the unit cell structure are- tm = 100 nm, td = 600 nm, l = 200 nm, P = 300 nm shown in Fig. 4(b). The unit cell structure is symmetric in both the x and y direction and consequently, polarization insensitive to the normal incident plane wave. Fig. 5(a) shows the tunability curve for the absorber. From the curve it can be observed that the NSH graphene absorber has similar absorption characteristics as of graphene ribbon. The absorber has the maximum absorptivity at 4.43 μm wavelength at $E_f = 1$eV with an absorption efficiency of 99.7%. Consequently, the structure has shown wide tunability for E_f from 0.7eV to 1eV with 5–20% spectral shift and absorption rate more than 85%. To check the polarization independency, the unit cell structure is simulated for TE and TM polarizations. Fig. 5(b) and the inset in the figure shows the absorptivity curve and the electric field distribution under both polarization modes respectively. From the curve, it can be observed that by changing polarization from TM to TE both the absorptivity and resonance wavelength remains same. Furthermore, it can be observed from Fig. 5(a) that the absorption curve has multiple small resonance peaks. It is due to the higher mode of plasmonic oscillation in the graphene layer. The NSH absorber structure can be modified to utilize these modes for multi-band applications [19].

Hence, we can infer that the proposed absorber is insensitive to the polarization. In the paper, although the analysis is done for low mid-infrared region (4–7 μm) but the results are applicable for higher mid-infrared region wavelengths also (>7 μm). The tuning range and spectral shift obtained by the structures will further enhance at higher wavelength due to the increase in graphene surface conductivity and large shift in conductivity with E_f (discussed in Section I). However, the spectral shift will always remain greater for graphene pattern structure compared to metal pattern structure. Moreover, it is evident from the proposed nano-hole structure that the design exhibits the tunable plasmonic response and can be realized using nanoimprint lithography fabricating technique [18]. Thus, from the study we can say that the proposed metamaterial absorber can be used as a wide range tunable metamaterial absorber in the mid-infrared region and would be the better option for the design of tunable absorbers for various gas and bio sensor applications.

IV. Conclusion

We have compared the spectral efficiency of two different configurations of graphene tunable MMAs in the low mid- infrared region (4–7 μm), and propose a new type of NSH graphene metamaterial absorber working in the region. The proposed absorber design has great tuning efficiency and overcomes the limitation of both types of graphene absorbers i.e., metal pattern type and graphene pattern type absorber. Moreover, the simplicity of structure facilitates the fabrication of the device for practical applications. Simulation results show that the graphene added metal disc pattern absorber has less spectral tunability for varying E_f compared to the graphene ribbon absorber. It is due to the low surface conductivity of graphene and the fixed plasmon frequency of the metal pattern structure. The modulation achieved in the absorption spectrum of metal disc absorber is 2-4% only, while graphene ribbon absorber can achieve modulation depth of 5–20% with more than 85% absorption rate. Graphene ribbon pattern absorber has wide spectral tunability, but the absorption is polarization dependent due to its non-symmetric structure. Thus, a new type of NSH graphene metamaterial absorber design is developed which can easily be externally biased and can achieve a practically implementable polarization independent absorber. The absorber has great tunability of more than 85% absorption rate and 5-20% modulation depth similar to graphene ribbon pattern. The wide range tunability of the proposed design makes it suitable for various applications such as optical gas sensors, bio-chemical sensing, and thermal imaging.

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