Dual-band, Dynamically Tunable Plasmonic Metamaterial Absorbers Based on Graphene for Terahertz Frequencies

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1. INTRODUCTION

Metamaterial structures have been extensively applied in microwave frequency bands for providing enhancement in active and passive devices. Metamaterials have been applied to design and improve microwave devices such as transmission lines, antennas, absorbers, etc. [1-5]. After their realization and successful applications in microwave frequencies, tremendous efforts raised to take advantage of their extraordinary features in terahertz and optical frequencies. Terahertz absorbers using metamaterials have been developed due to their wide range of applications in terahertz detectors, sensors, stealth applications and so forth. Recently graphene, one layer of carbon atoms in hexagonal lattice, has received special interest in terahertz and optical frequencies due to its beneficial effects specifically its dynamically tunable property.

A vast amount of researches include the design of metamaterial terahertz absorbers based on either metal or graphene sheets. A four band and polarization insensitive metamaterial absorber is proposed in literature [6]. In this structure gold is used as metal and a relatively thick substrate with 16 µm thickness is applied. A broadband and polarization insensitive terahertz absorber, as well as a metamaterial based perfect absorber using multilayer metamaterial structures, both using gold as metal, are designed in literature [7, 8] respectively. However fabrication of multilayer structures is complicated and challenging. A broadband terahertz absorber and a perfect metamaterial absorber on a single dielectric layer are designed in literature [9, 10], respectively. In these absorbers gold is employed for patterned metallic layer and unit cell's lateral dimensions equal 0.33 and 0.27 wavelengths at the lowest absorption frequency, respectively; which are relatively high. Several complementary planar metamaterials, using gold, on a thick dielectric with 625 µm thickness, are proposed in literature [11].
From metamaterial absorber designs using graphene we can refer to literature [12], where a free standing monolayer metamaterial graphene sheet is investigated and 50% absorption is achieved. A perfect metamaterial absorber made of graphene ribbons is proposed in literature [13]. Ultra-wideband metamaterial graphene ribbons on a thick dielectric with 118 µm thickness, and a tunable graphene based metamaterial absorber on a relatively thick dielectric with 17 µm thickness, are proposed in literature [14, 15], respectively. A broadband tunable terahertz metamaterial absorber based on graphene, is designed in literature [16]. In this structure, with varying graphene’s chemical potential broadband performance changes to a narrowband absorber, albeit there isn’t a direct relation between absorption frequency and graphene’s chemical potential.

Literature survey of metamaterial terahertz absorbers reveals that applying graphene instead of metals results in absorbers with smaller unit cell dimensions and tunable properties. In this paper a dual-band with improved bandwidth tunable metamaterial terahertz absorber based on graphene, with identical unit cell dimensions and similar configurations, on a 5 µm grounded SiO$_2$ substrate is designed and investigated. The designed structure are dynamically controllable with increasing graphene’s chemical potential, through applying a static biasing voltage. The absorbers are thin and compact. Simulations are performed using CST microwave studio.

2. THEORY OF THE DESIGN

The proposed tunable absorber is designed based on graphene. Graphene is a mono-layer of carbon atoms in hexagonal lattice. It is shown that graphene in low terahertz frequencies can support plasmonic excitations, both propagating and localized [17]. Graphene is modeled numerically using a sheet with surface conductivity $\sigma_s$. Its conductivity is affected by interband and intra-band contributions [15]:

$$\sigma_s = \sigma_s^{\text{intra}} + \sigma_s^{\text{inter}} \quad (1)$$

$$\sigma_s^{\text{intra}} = \frac{2\pi\epsilon r^2 c}{m^2} \ln \left( \frac{2\cosh \frac{\eta}{2\beta}}{\cosh \frac{\eta}{2\beta} - 1} \right) \frac{i}{\omega \tau_{\text{intra}}} \quad (2)$$

$$\sigma_s^{\text{inter}} = \frac{-c^2}{4\epsilon h} \left[ H \left( \frac{\omega}{\omega_p} \right) + i \frac{\omega_p}{\omega} \int_{\omega_p^2 - \omega^2}^{\infty} \frac{H(\nu) - H(\omega/2)}{\omega^2 - \nu^2} d\nu \right] \quad (3)$$

where $T$ is temperature in Kelvin; $2\Gamma = h/\tau$ and $\tau$ is electron-phonon relaxation time; $e$, $h$ and $k_B$ are constants and denote electron charge, Planck’s and Boltzmann’s constants respectively; $\beta$ is Fermi energy and can be tuned by applying a static bias voltage [13].

In low Terahertz regime, only the intra-band contribution is considerable and is required to be taken into account. Furthermore for $E_F \gg k_B T$ the intra-band term, with reasonable accuracy, can be simplified according to literature [15]:

$$\sigma_s = \frac{e^2 F_s i}{\pi \hbar^2 \omega + i \tau_{\text{intra}}} \quad (4)$$

Which represents a Drude like property with linear dependency of conductivity on Fermi energy. Thus with varying graphene’s Fermi energy or chemical potential, surface conductivity is dynamically tunable.

As mentioned, graphene in low Terahertz regime has similar properties to metals with the advantage of being tunable with varying chemical potential through applying electrostatic voltage. Interaction of an incident wave with the graphene sheet occurs through excitation of plasmonic resonances. By patterning graphene sheet, surface conductivity is modified and can be tailored to provide plasmonic resonances at desired frequencies. In order to investigate effective surface conductivity of patterned graphene sheet, numerical methods are proposed in literature [15,18]. In this method graphene's surface conductivity is investigated from reflection and transmission coefficients of the structure or the ABCD matrix.

3. METAMATERIAL STRUCTURE DESIGN

The designed metamaterial absorber is depicted in Figure 1. A graphene layer is patterned on a grounded dielectric substrate. The substrate is chosen silicon dioxide, SiO$_2$, which is applied for graphene structures [16]. A 0.5 µm thick gold layer is employed as ground plane. The thickness of gold should be more than the skin depth in terahertz frequencies to eliminate any transmission from the structure. Thus, considering zero transmission, absorption of the structure is defined as follows:

$$A = 1 - |S_{11}|^2 \quad (5)$$

where, $S_{11}$ represents the reflected wave.

In this paper we have assumed a thickness of 1 nm for graphene sheet, which is reasonable [13]. Other parameters of graphene are shown in Table 1.

The unit cell of the metamaterial absorber, as shown in Figure 1(a), consists of four complementary square rings. The unit cell is designed on a complementary configuration in order to provide the possibility of applying graphene’s bias voltage to the whole structure simultaneously. In this regard, four splits are applied on the rings to maintain continuity in graphene sheet.

### Table 1. Parameters of graphene

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness (nm)</td>
<td>1</td>
</tr>
<tr>
<td>temperature (K)</td>
<td>300</td>
</tr>
<tr>
<td>relaxation time (ps)</td>
<td>1</td>
</tr>
<tr>
<td>chemical potential (eV)</td>
<td>0-1</td>
</tr>
</tbody>
</table>
Design parameters of the structure including unit cell dimensions, square ring width and the gap between rings, are illustrated in Figure 1(b). Electric field of the incident wave is set along the y axis. Depending on the parameters, a dual-band absorber as well as an improved bandwidth absorber is designed and investigated. Numerical values of the two designs are shown in Table 2.

In order to investigate and explain the performance of the patterned graphene in the proposed absorber, an equivalent circuit model is developed. Since the graphene sheet is relatively ultra-thin compared to the wavelength (in THz regime), it can be considered as a shunt impedance in circuit model [18]. Figure 2 shows the mentioned equivalent circuit model, where \( Z_d = 120\pi \Omega \) is the free-space impedance, and \( Z_g \) and \( Z_d \) are the surface impedance of graphene and the impedance of SiO\(_2\) dielectric, respectively. The gold layer is represented as a short circuit in the proposed equivalent circuit model.

\[
Z_g = \frac{Z_0 Z(1 + S_{11})}{Z(1 - S_{11}) - Z_0 (1 + S_{11})}
\]

where, \( Z = i Z_d \tan(\phi_d) \) is the input impedance of the dielectric slab as shown in Figure 2.

Figure 3 shows the results of the analytical solution. In this approach, the graphene chemical potential is varied between 0.5 and 1 eV and the distribution of the real and imaginary parts of \( Z_g \) calculated in the frequency range of the designed absorber are illustrated in Figures 3(a) and 3(b), respectively.

As can be observed from Figure 3, the maximum spectra shows a red shift for \( \Re(Z_g) \) and a blue shift for \( \Im(Z_g) \) as the chemical potential is decreased. Furthermore, as shown in Figure 3, by increasing the chemical potential, the lower values of graphene’s impedance spectra is broadened. Moreover, Figure 3(b) also shows that there are frequency bands, over which \( \Im(Z_g) \leq 0 \), implying capacitive impedance behavior for the graphene in the designed absorber.

### 4. SIMULATION RESULTS

Absorption of the dual-band design is plotted in Figure 4. Two 90% absorption at frequencies of 4.92 THz and 5.95 THz is observed, when graphene’s chemical potential is set to 0.5 eV. The unit cell’s lateral dimensions are

\[
\text{TABLE 2. Parameters of the metamaterial absorber}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dual-band</th>
<th>Improved bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h )</td>
<td>5 ( \mu )m</td>
<td>5 ( \mu )m</td>
</tr>
<tr>
<td>( p )</td>
<td>3 ( \mu )m</td>
<td>3 ( \mu )m</td>
</tr>
<tr>
<td>( w )</td>
<td>0.05 ( \mu )m</td>
<td>0.05 ( \mu )m</td>
</tr>
<tr>
<td>( g_h )</td>
<td>0.05 ( \mu )m</td>
<td>0.05 ( \mu )m</td>
</tr>
<tr>
<td>( g_s )</td>
<td>0.025 ( \mu )m</td>
<td>0.025 ( \mu )m</td>
</tr>
<tr>
<td>( g_z )</td>
<td>0.05 ( \mu )m</td>
<td>0.1 ( \mu )m</td>
</tr>
<tr>
<td>( g_t )</td>
<td>0.05 ( \mu )m</td>
<td>0.4 ( \mu )m</td>
</tr>
<tr>
<td>( g_r )</td>
<td>0.05 ( \mu )m</td>
<td>0.05 ( \mu )m</td>
</tr>
<tr>
<td>( \mu_c )</td>
<td>0.5 ev</td>
<td>0.5 ev</td>
</tr>
</tbody>
</table>

Since the dielectric is lossless, the relative permittivity has only a real part (\( \varepsilon_d = 4.41 \)). Thus, the impedance of SiO\(_2\) dielectric is \( Z_d = Z_0 \sqrt{\varepsilon_d} \) and the phase difference experienced by a signal traveling through this dielectric slab with a thickness \( h \) is defined as: \( \phi_d = \beta_d h = \frac{2\pi n_d h}{\lambda_0} \) where \( \beta_d, \lambda_0 \) and \( n_d \) are propagation constant, the free-space wavelength and refractive index of the dielectric, respectively.

Based on the proposed equivalent circuit model, we use transmission line theory to extract the impedance of graphene [18]. Therefore, the graphene sheet impinged by a plane wave normally and by using the finite difference frequency domain (FDFD) numerical method, the calculated reflection coefficient \( (S_{11}) \) at the reference plane; Ref is employed to obtain \( Z_g \) according to the following equation:

\[
Z_g = \frac{Z_0 Z(1 + S_{11})}{Z(1 - S_{11}) - Z_0 (1 + S_{11})}
\]
Figure 3. Distribution of the real part, (a) and the imaginary part, (b) of the graphene impedance ($\Omega$) versus its chemical potential (horizontal axis) and the frequency range (vertical axis)

It is observed that fields are concentrated under the gaps of the complementary rings, which is quite compatible with field plots on graphene surface shown in Figure 5. Graphene’s chemical potential is varied and absorption of the structure is investigated and plotted in Figure 7. The figure demonstrates that with an increment of $\mu_c$, frequencies of both absorption peaks increase and therefore a tunable dual band absorber is achieved.

Effects of incident and polarization angles on absorber performance is investigated and is plotted in Figure 8. With an increasing incident angle, absorption gradually
Figure 7. Absorption of dual-band design versus graphene's chemical potential

degrades and up to Θ=30° dual band absorption peak exists, as shown in Figure 8(a). The increase of incident angle beyond 30 degrees, causes one of the absorption peaks to fall below 90%.

With increasing the polarization angle, absorption also degrades and dual band absorption is observed for incident angles up to 30 degrees. Because of symmetry of the structure, degradation occurs for polarization angle up to 45 degrees as well and beyond that improvement of absorption is observed. However, at polarization angle of 180 degrees the initial dual band behaviour is reached.

With varying parameters of the complementary rings, an absorber with improved bandwidth of 13.2%, for 90% absorption, is achieved. Parameters of the design are shown in Table 2 while absorption of the improved bandwidth design is plotted in Figure 9. For this design, a dynamically tunable absorber is also achieved with changing graphene's chemical potential.

Absorption of the structure with increasing $\mu_c$ is simulated and is demonstrated in Figure 10. It is illustrated that with small increments of graphene's chemical potential, absorption band moves toward higher frequencies. An improvement in absorption bandwidth, with increasing graphene's chemical potential, is also observed.

The absorber's performance with varying incident and polarization angles of the incoming wave is simulated and illustrated in Figure 11.
As shown in Figure 11(a), wide band absorption is preserved until incident angle of 20 degrees, and further increase of incident angle results in reduction of bandwidth. With increasing polarization angle, wide band performance transforms to tri-band absorption. This is compatible with the fact that, wide band performance is provided through three nearby resonances. Although with increasing Φ in excess of 45 degrees improvement of absorption is occurred, for Φ equal to 180 degrees the initial response is reproduced.

5. CONCLUSION

In this paper a tunable metamaterial absorber, in low Terahertz frequency band was designed and investigated. The structure was composed of 0.5 µm thick gold layer, as ground plane, which was covered by a layer of SiO2 with 5 µm thickness, as substrate, and a patterned graphene sheet on the top. The proposed absorber was investigated theoretically and through simulations. Two sets of parameter values with identical unit cell dimensions were studied. The first design provided a dual band absorber with more than 90% absorption. The second design achieved improved bandwidth of 13.2% for 90% absorption. It was shown that both designs provided quite dynamically tunable structures with varying graphene’s chemical potential. Electric field magnitude, on the surface of graphene layer as well as on the structure’s cross section was studied thoroughly. Impact of incident and polarization angles on absorption performance of the two designs were studied and graphically demonstrated.

6. REFERENCES

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چکیده
در این مقاله یک جاذب فراماده پلاسمونی قشره برای فرکانسهای تراهرت پیشنهاد شده و شبیه سازی شده است. جاذب براساس ساختارهای گرافنی فراماده می باشد و از ویژگی قابلیت کنترل جذب گرافن بهره می برد. با استفاده از شکل دیه لاشه گرافن، تنظیم‌های پلاسمونی طوری طراحی شده اند که جذب دو باند، و همینطور جذب با پهنا بالای بهبود دیده است. بنابراین، سلول واحد ساختار طراحی شده، از چهار لایه میکروسیستم تشکیل شده و بهبود می‌یابد. نشان داده شده که با تغییر ابعاد حلقه، لهجه‌ای شکاف دار، جاذب با پهنا بالای بهبود یافته می‌شود. در نتیجه، جاذب با افزایش فرکانس، جذب بهبود می‌یابد. به منظور درک بهتر فرایند دریافت جاذب، گستردگی میدان الکتریکی روی گرافن بررسی شده است. در نهایت، تشدیدهای پلاسمونی در ساختار پیشنهاد شده، کاربردی میدان الکتریکی برای جاذب، و همین‌طور در طول بررسی سلول واحد بررسی شده است.