

Design of a Polarization Insensitive Wideband Absorber Using Graphene Based Metasurface

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Abstract—In this paper, we demonstrate the design of a polarization-independent wideband absorber of light that consists of a perforated graphene sheet on top of a lossless dielectric spacer placed on a metallic reflector. The single layer absorber is duly designed based on impedance matching concept. The simulated results indicate that the structure produces 0.98 THz broad absorption from 1.80 THz to 2.72 THz with absorptivity larger than 90% at the normal incidence. The electromagnetic (EM) field distributions and the plots of surface power loss density have been illustrated to explain the absorption mechanism of the structure. The variation of chemical potential from 0.8 to 1.2 eV keeps 90% absorption bandwidth as much as 1 THz band. The polarization-insensitive feature and the properties under oblique incidence are also investigated. Finally, the interference theory is used to analyze and interpret the broadband absorption mechanism.

1. INTRODUCTION

The design of low profile and wideband absorbers is a challenging task as low profile and wideband are two conflicting parameters [1]. Several techniques have been applied by different researchers towards the development of a thin and wideband absorber [2–4].

Nowadays, electromagnetic metamaterials have been widely employed to design microwave absorber and become the replacement of conventional absorber due to their ultra-thin thickness, near unity absorption characteristics, and less design complexity [5]. An ultra-thin broadband metamaterial absorber has been reported in [6] where the use of a large number of metallic circular patch elements merely provides relative full width at half maximum (FWHM) bandwidth of 25%. In [7], destructive interference mechanism has been applied over a multi-layered split ring resonator (SRR) structure whereas multi-reflection interference theorem has been employed in [8] to design a resistive-high impedance surface metamaterial absorber.

Terahertz spectrum is more demanded due to its potential applicability in medical imaging, environmental monitoring, remote sensing, stealth technology, cloaking, etc. [9]. Therefore, it is always desirable to design a single layer broadband electromagnetic absorber at THz frequency with the minimum design complexity. Graphene, a honeycomb lattice structure of single layer carbon atoms, exhibits unique properties, such as flexibility, optical transparency, high electron mobility, and conductivity, which can be tuned by electrochemical potential via electrostatic gating or optical excitation [10]. It has been theoretically demonstrated that graphene can support surface plasmon polaritons at terahertz frequency [11] and can be used as the building materials for metasurface and metamaterial that provide diverse characteristics than a continuous graphene sheet. Although stacking of multilayered patterned graphene patches [12–14] over a gold backed substrate has widened the

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absorption bandwidth, the alignment of multiple layers at THz frequency is a tedious task. Therefore, the design of a single layer THz absorber with broadband characteristics is highly desirable.

In this paper, a metasurface based broadband absorber is proposed at THz frequency which is designed using a perforated graphene sheet and a gold-backed silicon dioxide dielectric. Patterning of periodic pores over a continuous graphene sheet has modified the absorption characteristics significantly. The absorption bandwidth can be controlled by the size of a pore or metallic width between pores. Absorption spectra can also be shifted by the bias voltage applied over the graphene sheet. The resonance mechanism of the absorber has been analyzed using field distribution. The response of proposed absorber is found insensitive to the incidence angle as well as types of polarization.

2. STRUCTURE DESIGN

In this paper, a metasurface, shown in Figure 1, is designed using a silicon dioxide (SiO_2) substrate which is layered by a gold material on one side and a graphene monolayer sheet, perforated with periodic pores on the reverse side. The unit cell is simulated with master slave boundary conditions and floquet port excitation using ansys high frequency structure simulator (HFSS). To analyze the characteristics of the metasurface absorber (MSA), at first graphene's surface conductivity is estimated with the help of Equation (1). Thereafter, considering a single layer graphene structure, its surface impedance is manipulated for different chemical potentials (μ_c) which is depicted in Figure 2(a). Here, the graphene sheet is characterized by a complex surface impedance which is adjusted to change the gate voltage, and the interaction in a graphene dielectric stack is formed by plane-wave reflection. Initially the surface impedance of the graphene sheet for a particular chemical potential can be estimated with the help of Equation (2). Afterwards, the surface impedance (Z_{MS}) of the metasurface has been estimated with the help of Equation (3) [15]. In Equation (3), S_{11} and S_{21} are S -parameters of the terahertz metasurface absorber. The dimension to design the MSA is mentioned in the figure's caption. The complex surface conductivity of a continuous graphene sheet can be expressed according to [16].

$$\sigma(\omega) = \frac{\sigma_0}{1 + j\omega\tau}, \sigma_0 = \frac{q^2 K_B T \tau}{\pi \hbar^2} \left[\frac{\mu_c}{K_B T} + 2 \ln \left(1 + \exp \left(-\frac{\mu_c}{K_B T} \right) \right) \right] \quad (1)$$

$$Z_s(v_b) = \frac{1}{\sigma(\omega)} = R_s(v_b) + jX_s(v_b), \mu_c = q\alpha v_b \quad (2)$$

$$Z_{MS} = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \quad (3)$$

In the above equations, q is the electron charge, \hbar the reduced Planck's constant, h the plank constant, K_B the Boltzmann's constant, μ_c the chemical potential, T the temperature, ω the operational frequency, and τ the electro-phonon relaxation time. To realize the surface conductivity of graphene, we set $\tau = 0.05$ ps, $T = 300$ K, and other parameters in Equation (1) take their usual values. Figure 2(b) exhibits the surface impedance of the 2×2 unit cell structure. It is distinct that for a wide range of frequency, real part of the surface impedance is close to free space impedance (120π), and imaginary part is near zero impedance.

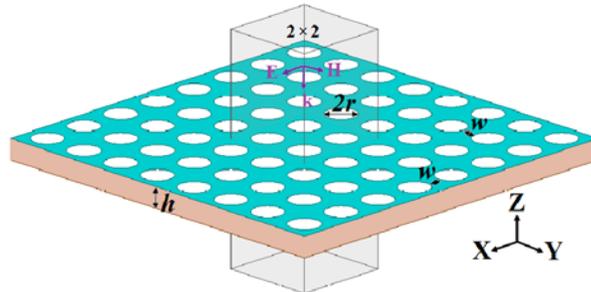


Figure 1. Graphene based metasurface (8×8) with the dimension of $w = 15 \mu\text{m}$, $r = 15 \mu\text{m}$, $h = 20 \mu\text{m}$.

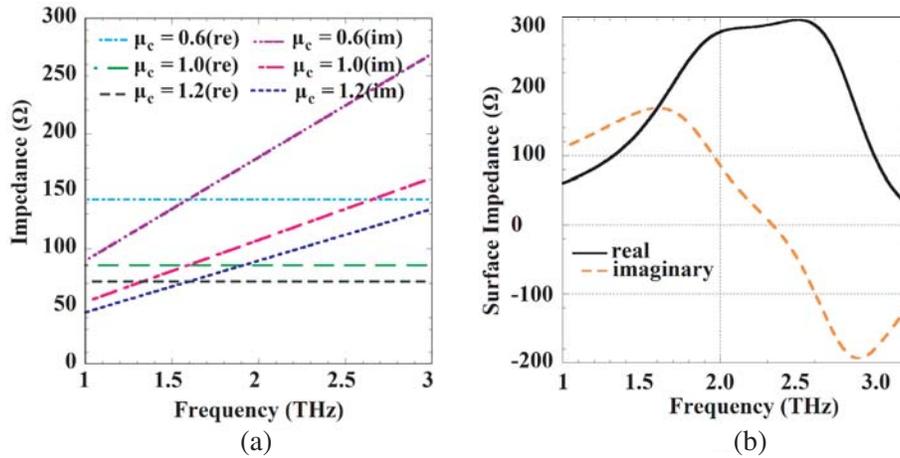


Figure 2. (a) Impedance of a graphene sheet for different μ_c , (b) surface impedance of the metasurface for $\mu_c = 1 \text{ eV}$.

3. NUMERICAL DEMONSTRATION AND PARAMETRIC VARIATIONS

In practice, loss is measured by the amount of absorbed EM power, which is characterized by $A(\omega) = 1 - R(\omega) - T(\omega)$, where $R(\omega)$ is the reflection coefficient, and $T(\omega)$ is the transmission coefficient. Due to the shielding of the gold film, the transmission is zero for all frequency ranges, and thus, reflection is the only factor determining the absorption. Hence, the absorption rate is calculated by $A(\omega) = 1 - |S_{11}|^2$, where S_{11} is the reflection coefficient. Assuming normal incidence of electromagnetic waves above the meta surface, it is found from Figure 3(a) that return loss characteristics have a wide $\geq -10 \text{ dB}$ regime while transmission characteristics show $\geq -50 \text{ dB}$ value for a wide frequency range. This indicates that the metasurface exhibits wide-band absorption of $\approx 1 \text{ THz}$. The introduction of periodic pores over graphene sheet produces some additional absorption band that in turn widens the absorption bandwidth of the perforated graphene structure. Figure 3(b) illustrates the difference in absorption band for the two different cases.

To optimize the geometrical parameter for maximum wide absorption, a parametric variation of pore radius (r) and metallic width between two pores (w) have been investigated. It is noted that the structure provides wide-band absorption for the unit cell dimension of $r = 15 \mu\text{m}$ and $w = 15 \mu\text{m}$ where

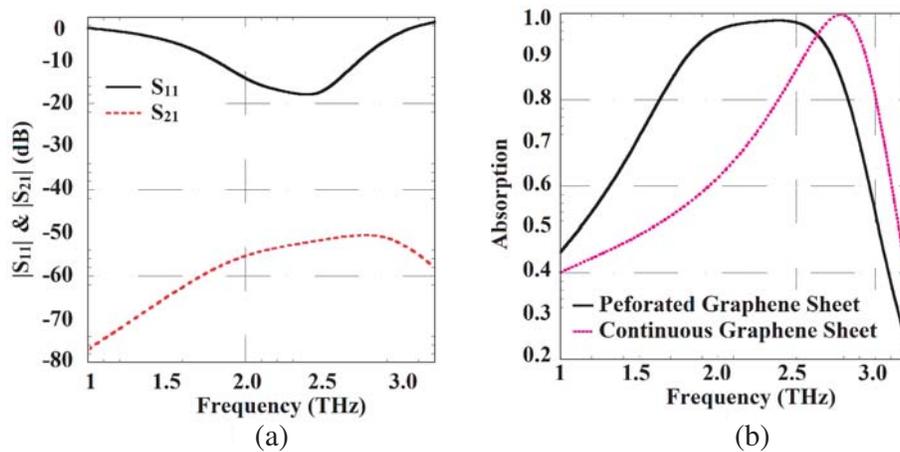


Figure 3. (a) S_{11} and S_{21} characteristics for $\mu_c = 1 \text{ eV}$, (b) comparison with continuous and perforated graphene sheet.

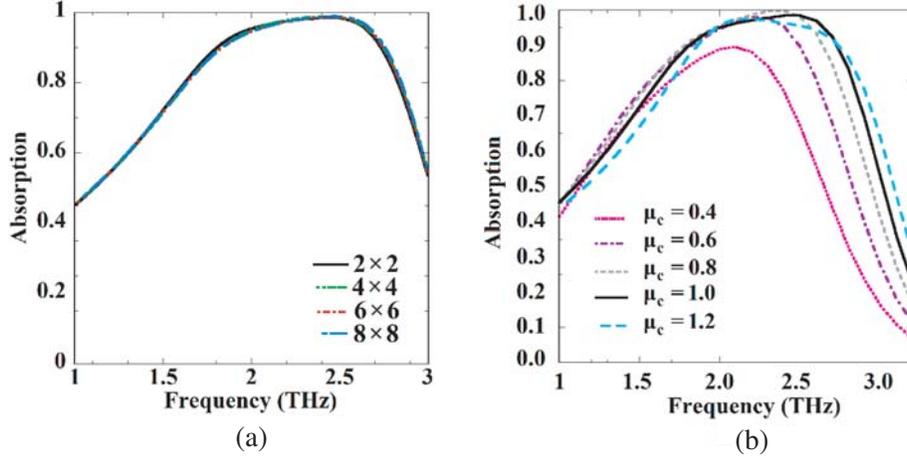


Figure 4. Absorption characteristics of the absorber with the variations of (a) cell size and (b) chemical potential.

chemical potential is considered at 1.0 eV. In Figure 4(a), absorption characteristics of the proposed graphene based meta-surface are illustrated for different numbers of unit cell size. As expected, a larger footprint (8×8) structure produces similar absorption to a smaller unit cell structure (2×2). Thus, this smallest unit cell structure is considered for further validation as well as investigation on the absorption phenomena. A parametric variation on different μ_c is conducted to tune the absorption band. It is observed from Figure 4(b) that the increase of bias voltage ($v_b = \frac{\mu_c}{q\alpha}$) lowers the surface impedance which helps the metasurface structure to impedance match with the free space impedance ($Z_0 = 377 \Omega$). Hence, with the increase of chemical potential (≥ 0.6 eV), a wide-band absorption is observed while a gradual shifting of the absorption band has also been noticed.

Moreover, the incidence angle independence and polarization-insensitive feature are characterized by setting the incidence angle (θ) and polarization angle (ϕ) from 0° to 60° . Figures 5(a), (b) indicate simulation results for the absorber for θ and ϕ variations with $\mu_c = 1.0$ eV. It is apparent that the absorptivity is hardly changed for different θ and ϕ angles, which validates that this absorber is insensitive to incidence angle as well as polarization angle. It must be noted that for variation of polarization angle, the structure is excited by a normal incident wave.

The multiple reflections would generate the interference phenomenon on terahertz metamaterial

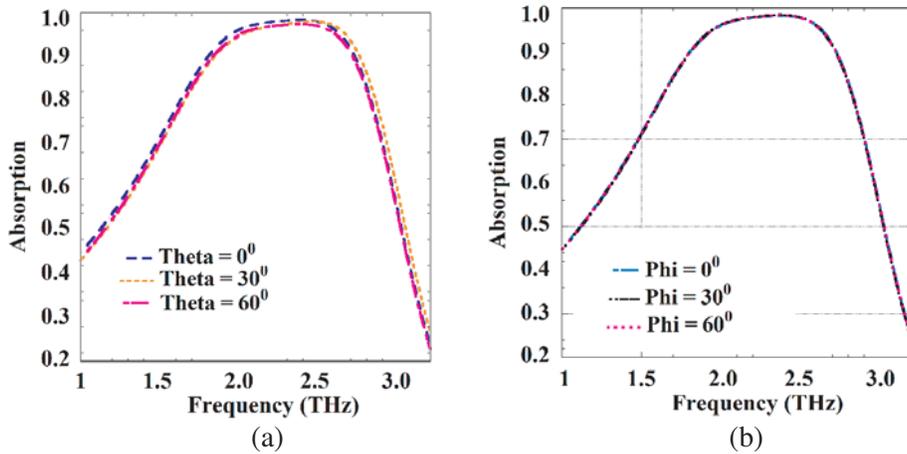


Figure 5. Absorption variations of the graphene absorber with the incidence angle in the direction of (a) theta, and (b) phi.

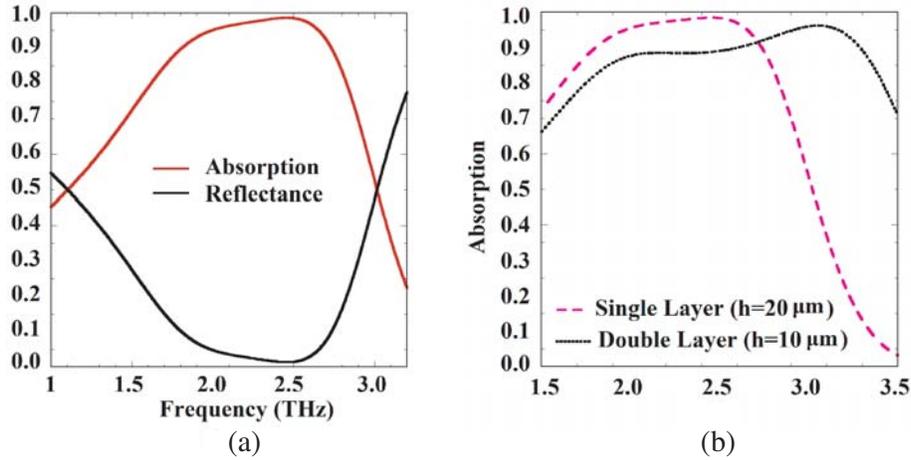


Figure 6. Absorption of the metasurface using (a) interference theory (b) single and double layers.

absorber. In Figure 6(a), (b), the analytical reflection and absorption rates of the proposed metasurface absorber are calculated using the unit structure with the aid of the simulated S_{11} along with the interference model. To quantitatively analyze the broadband absorption mechanism, multireflection interference theory is introduced [8,15,17]. The details of the interference model are considered from [8]. According to the interference theory [8] and due to the ground plane, the overall reflection wave of layer 1 from air back to air is represented by Equation (4), where the parameters are in their usual meanings.

$$S_{11,total} = |S_{11}| e^{j\theta_{11}} - \frac{|S_{12}| |S_{21}| e^{j(\theta_{12} + \theta_{21} - 2\beta)}}{1 - |S_{22}| e^{j(\theta_{22} - 2\beta)}} \quad (4)$$

To comprehend the absorption mechanism, the electric and magnetic field distributions at the absorption peak (2.5 THz) are illustrated in Figures 7(a) and (b), respectively. As depicted in Figure 7(a), the distributions of the electric field at 2.5 THz are mainly focused on the edge of the pores which suggests accumulation of charges on two opposite edges of each pore. The storing of electric charges provides gap capacitance. On the other hand, magnetic fields shown in Figure 7(b) exhibit maximum field intensity on the edge of the graphene sheet which contributes to inductance. Hence according to the equivalent circuit theory, the proposed structure can achieve strong resonance absorption at 2.5 THz. The surface loss and volume loss density distributions are plotted in Figures 8(a) and (b), respectively. It is evident from the plot that the power loss is mainly focused on the resistive graphene surface while volume loss density is very small. Therefore, it can be stated that the surface ohmic loss property of the metasurface mainly provides broadband absorption phenomena.

The absorption performance of the proposed graphene absorber is found far better, and the proposed design is simpler than some other patterned graphene absorbers summarized in Table 1.

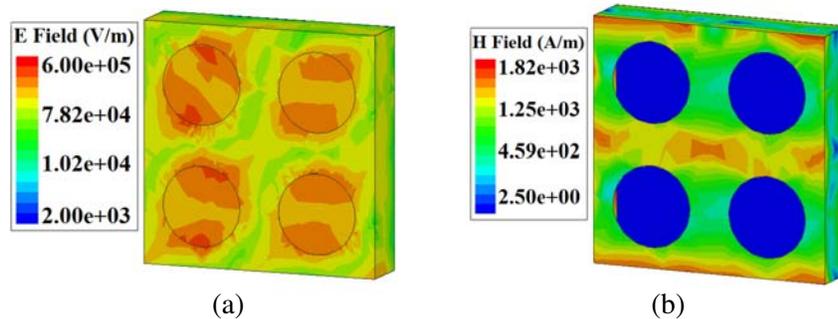


Figure 7. Field distributions over the structure at 2.5 THz for (a) electric field and (b) magnetic field.

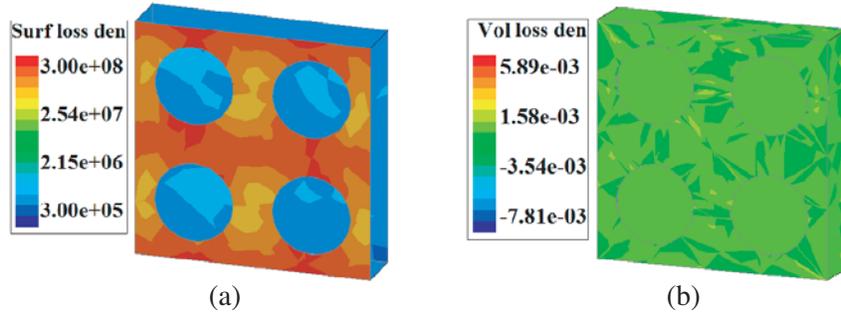


Figure 8. (a) Surface loss, and (b) volume loss density of the absorber at 2.5 THz.

Table 1. Comparison of absorbing performance with some patterned graphene absorber.

References	Near unity absorption bandwidth	Normalized bandwidth (%)
[13]	1.6–2.2 THz = 0.6 THz	31.5
[14]	1.25–1.30 THz = 0.05 THz	3.9
Prop.	2.72–1.80 THz = 0.92 THz	40.7

4. CONCLUSION

In this section, we demonstrate the design and characterization of a broadband MSA based on perforated graphene sheet. Impedance matching concept is adopted to explain the wideband performance of the proposed absorber. The electromagnetic field distributions, plots of surface power loss density, and volume loss density have been analyzed to understand the absorption mechanism. The proposed structure is polarization insensitive due to the design symmetry. The novelty of the presented graphene absorber lies in the single layer configuration, whereas most of the graphene absorbers [9, 10] rely on a multilayer configuration for achieving broad band absorption. The designed MSA might be a good candidate for use in stealth technology since it comes with advantages such as light weight, single layer, broadband, and easy fabrication.

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