A Novel Tunable Graphene Based Terahertz Absorber with Polarization Insensitive

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Abstract **─** A novel design of the four-band graphene based terahertz (THz) absorber is presented. The pattern is formed by a graphene ring and orthogonal elliptical sheets on the top of a ground plate separated by a dielectric layer. Numerical results reveal that the graphene based absorber has four absorption peaks whose peaks are all over 99%. Besides, the absorption coefficient of the proposed absorber is insensitive to the polarization of the incident wave. And also, variation of geometrical parameter gives considerable freedom to change the resonance frequencies of the absorber. Moreover, the results reveal that the absorption spectra can be extended by tuning the chemical voltage of the graphene layer.

Index Terms **─** Absorber, grapheme, polarization insensitive, terahertz (THz), tunable.

I. INTRODUCTION

With recent ongoing progress in the next generation communications, absorbers attract more attention [1], [2]. Recently, THz absorbers have been used in applications such as security, medical imaging, and communications. Besides, graphene has attracted more consideration owing to its unique electrical, mechanical, and optical properties. Graphene is a two dimensional material with hexagonal structure which has excellent properties such as high electron mobility and flexibility. Furthermore, the Fermi energy of the graphene sheet can be controlled by electrochemical potential. In fact, owing to its impedance variation by tuning bias voltage, it can be used in electromagnetic devices such as absorber [3]. Researchers have been working on graphene based absorbers such as [4] and [5]. In [4], a narrow bandwidth absorption spectra is obtained by using a stack of graphene-dielectric-grounded metal. In order to expand the bandwidth, two or more layers are employed in [6] and [7-9].

New group of graphene based absorbers such as graphene nano disk [10], micro ribbons [11], and hereterostructures [12] have been studied. Since, these papers mentioned above indicate that the bandwidth of the absorbers are narrow, so, the broadband functionality is more attracted. Therefore, more broadband graphene based absorbers such as multiple graphene nano resonators [13] are proposed. Although, the broadband attitude of the absorber is practical, the tunable of absorption is more important in many applications. In order to control the tunability, the voltage control technique is suitable. The bias voltage controls the absorption energy of the absorber over a narrow frequency band [14, 15]. Recently, both multiband and broadband tunable absorbers were investigated [16, 17]. However, no design focused on tuning the narrowband to broadband through changing various bias voltages in multiband graphene based absorber with polarization insensitive in the terahertz region. In particular, converting narrowband to broadband in absorbers promises application opportunities in terahertz sensor network such as [18] and communications.

In this paper, a dynamically frequency-tunable graphene based terahertz absorber is presented, which consists of a single layer periodically patterned graphene structure over a metal ground plane separated by a polyamide dielectric layer. In order to obtain polarization insensitive and wideband frequency bandwidth, the structure should be symmetrical and curved, respectively. Due to structure of the proposed absorber, an identical absorption spectra is obtained for both TE and TM incident EM wave. By suitable parametric study, average absorption coefficients greater than 99% for the four distinct absorption peaks can be achieved. The distinguish property of the proposed absorber is expanding the bandwidth of the absorption spectra by tuning the applied bias voltage. The absorber with these performances has sufficient potential in medical imaging, communications, sensing, and most practical applications.

II. DESIGN AND CONFIGURATION

The proposed four-band THz absorber based on graphene is shown in Fig. 1; which unit cell consists of two orthogonal concentric elliptical graphene rings at the center and quarter orthogonal concentric elliptical graphene sheets at the corners. The pattern is on the metallic ground plate separated by a thick dielectric

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layer. The pattern is periodic in x- and y-direction with periodicity of W_{cell} = 150 um and L_{cell} = 150 um. All the optimized parameters are specified as follows: R_1 = 60 um, R_2 = 30 um, R_3 = 27 um, R_4 = 12 um, w = 5 um, h = 25um, t = 0.4 um. The refractive constant of the dielectric polyamide layer is $1.68+i0.06$ [8]. The thickness of the metal (Gold) layer is set to $t = 0.4\ \mu m$ whose frequency independent conductivity is $\sigma = 4.5\times10^7\ S/m$.

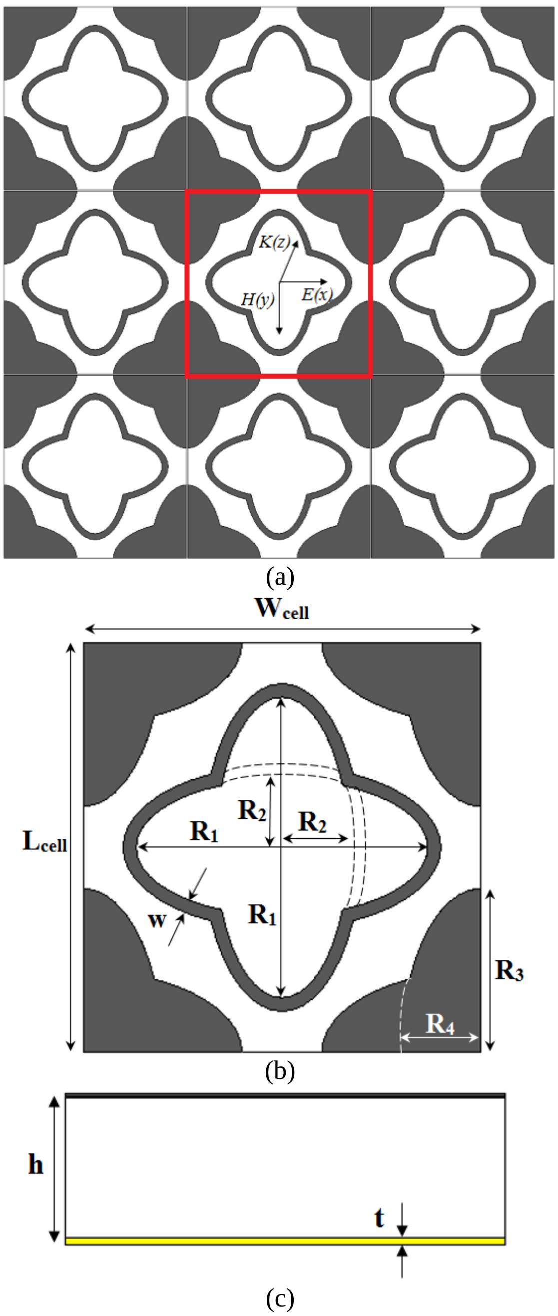


Fig. 1. (a) Structure schematic of the proposed four-band graphene based THz absorber. (b) Red line is presented a unit cell. (c) Cross sectional view of a unit cell.

Graphene can be electromagnetically investigated by modeling a single layer as ultrathin surface characterized by a two dimensional complex surface conductivity. In this study, the complex conductivity of graphene can be calculated by Kubo formula as [18]:

$$\sigma\left(\omega,E_f\right)=\frac{je^2\left(\omega-2j\Gamma\right)}{\pi\hbar^2}\Big[\frac{1}{\left(\omega-2j\Gamma\right)^2}\times \int_0^\infty \varepsilon\left(\frac{\partial f_d(\varepsilon)}{\partial\varepsilon}-\frac{\partial f_d(-\varepsilon)}{\partial\varepsilon}\right)d\varepsilon-\int_0^\infty\frac{f_d(-\varepsilon)-f_d(\varepsilon)}{\left(\omega-2j\Gamma\right)^2-4(\frac{\varepsilon}{h})}d\varepsilon\Big], \tag{1}$$

where ω, E_f, e, ε, h, and Γ are the radian frequency, Fermi energy level, electron charge, carriers energy, reduced Plank's constant, and phenomenological scattering rate, respectively. The Fermi-Dirac function can be calculated as [19]:

$$f_d\left(\varepsilon\right)=\left(1+\exp\left[\frac{\varepsilon-\mu_c}{k_BT}\right]\right)^{-1}, \tag{2}$$

where μ_c, k_B, and T are chemical potential, Boltzmann constant, and temperature, respectively. Besides, for the lower THz band at room temperature, the conductivity of graphene can be described as [19]:

$$\sigma=\frac{e^2E_f}{\pi\hbar^2}\frac{j}{\omega+j/\tau}. \tag{3}$$

Here, τ is the relaxation time. Chemical potential (μ_c) of graphene layer is defined as [19]:

$$\left|\mu_c\right|\approx\hbar\upsilon_F\left\{\pi C_g\left|V_A-V_{Dirac}\right|\right\}^{\frac{1}{2}}, \tag{4}$$

where $V_{Dirac}=0.8V$, $\upsilon_F=106\,m/s$, and V_A are Dirac voltage offset, fermions Fermi velocity, and applied voltage.

III. RESULTS AND DISCUSSIONS

The absorption spectra of the proposed four-band graphene based absorber as a function of frequency for *x*- and *y*-polarized of incident wave is presented in Fig. 2. As shown in Fig. 2, there are four absorption peaks at 1.84 THz (f_1), 2.23 THz (f_2), 2.46 THz (f_3), and 2.61 THz (f_4) whose peaks are average over 99%, for *x*-polarized wave. The bandwidth of resonance frequency defined as full width at half maximum (FWHM), are 0.3 THz, 0.17 THz, 0.19 THz, and 0.2 THZ for mode f_1, f_2, f_3, and f_4, respectively. Owing to the narrowband absorption obtained by above results, the four-band graphene based absorber has potential in imaging and sensing applications. Besides, the absorption spectra for the *y*-polarized wave is shown in Fig. 2. It is found that, the proposed absorber has the same resonance frequencies as in *x*-polarized case. Therefore, the absorption spectra of the proposed graphene based absorber is not limited to the polarization of the incident wave.

The sensitivity of the absorption spectra on proposed graphene based absorber at various angles of incident TE and TM polarized wave from 25° to 40° is shown in Figs. 3 (a) and (b). As shown in Figs. 3 (a) and (b), it is found that the presented four-band absorption is not limited to the normal incident wave. Besides, the proposed absorber remains almost stable for both TE and TM polarized incident wave to 40°.

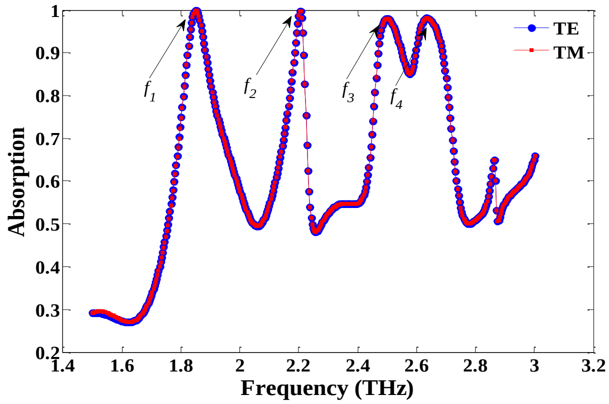
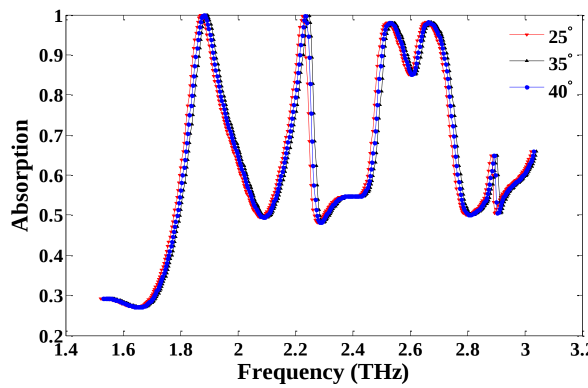
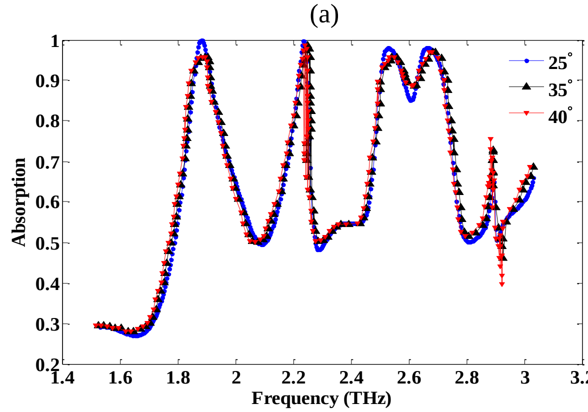


Fig. 2. The absorption spectra of the proposed terahertz absorber for TE and TM polarization.



(a)



(b)

Fig. 3. Dependence of the absorption spectra on different incident angles for: (a) TE and (b) TM configurations, respectively.

In order to reveal the better understanding of the multi band absorption mechanism, the electric field (|E| and real E_z) distributions corresponding to four-band absorption peaks, are presented in Fig. 4. As shown in Fig. 4 (a_1), at 1.84 THz (mode f_1) the electric field is mainly focused on the outer edges of the quarter orthogonal concentric elliptical graphene sheets. Great enhancement of electric field on the corners of the pattern provides the large accumulation of opposite charges on the edges of the orthogonal elliptical pattern, as shown in Fig. 4 (b_1). For mode f_3 (2.46 THz), the electric field distribution is concentrated on the upper and bottom (near the minor axes) of the horizontal elliptical ring, as shown in Fig. 4 (a_2). Besides, the opposite charges are mostly accumulated on both inner and outer edges of the horizontal elliptic (Fig. 4 (b_2)). For mode (f_4), the electric field is focused on the major axes (upper and bottom) of the vertical elliptical ring (Fig. 4 (a_3)). Thus, the opposite charges are accumulated on both inner and outer edges of the pattern (Fig. 4 (b_3)). Owing to the electric field distributions, the fundamental modes are attributed to the main resonance frequency of the orthogonal, horizontal, and vertical elliptical patterns, respectively.

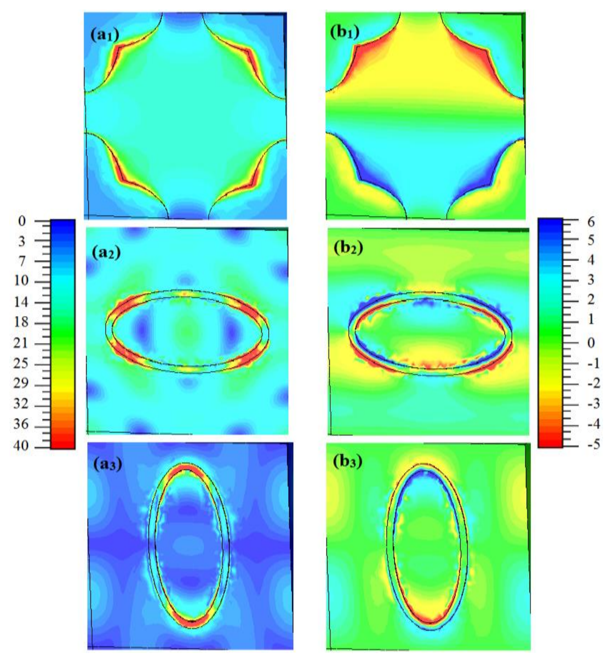


Fig. 4. Distributions of the electric fields (|E| and $|E_z|$) for the quarter orthogonal elliptical nano-disk (a_1 and b_1), horizontal elliptical ring (a_2 and b_2), and vertical elliptical ring (a_3 and b_3) in modes f_1, f_3, and f_4, respectively.

In order to gain the better understanding of the behavior of absorption mechanism of the proposed graphene based four-band absorber, the electric field (|E| and $|E_z|$) distributions, are presented in Fig. 5 and

Fig. 6. The distributions of electric field on the edges of the quarter orthogonal elliptical sheets, provide the accumulation of opposite charges on the edges of the pattern (Fig. 5 (a_1) and Fig. 6 (b_1)). Besides, some weak real ($|E_z|$) electric field distributions can be found on the inner ring. Therefore, the fundamental mode is mainly affected by the quarter orthogonal elliptical sheets. The modes f_2 and f_3 are due to the resonance frequency of the inner ring, because, the electric field distribution is focused on the right and left sides of the ring (mostly near the horizontal axes of the ring), which results the opposite charges accumulation on the inner and outer edges of the ring (Figs. 5 (a_2)-(a_3) and Fig. 6 (b_2)-(b_3)). For mode f_2, the opposite charges are accumulated on the bottom of the elliptical ring, as shown in Fig. 6 (b_2). Furthermore, owing to the large accumulation of opposite charges on the major axes (upper) of the elliptical ring, the mode f_2 is changed to mode f_3, as shown in Fig. 6 (b_3). For mode f_4, the great enhancement of the electric field on the upper and bottom of the ring, provide the large accumulation of opposite charges on the inner edge (Fig. 5 (a_4) and Fig. 6 (b_4)). Therefore, based on the electric field distributions on the structure pattern, the four-band graphene based absorber can be obtained.

Furthermore, in order to verify the explanation of the absorption mechanism, the effect of the geometrical parameter the resonance frequency is investigated. As mentioned above, the resonant frequency of the four-band graphene based absorber mainly depends on the radius of each elliptical pattern. Thus, with the other geometric parameters fixed, the radius variation of the ring can shift or change the modes f_2 and f_3. The effect of the radius R ($R = R_1 + 2.5\ \mu m$ and $R = R_2 + 32.5\ \mu m$) on the resonance frequency of the absorption coefficient, is shown in Fig. 7. The term R indicates the variations of radius R_2 and R_3. It is obvious that the resonant frequencies of the modes f_3 and f_4 gradually decreases with the increase of radius R, while the frequency changes of the modes f_1 and f_2 are neglected. Therefore, the geometrical parameter variation of the structure pattern provides the considerable freedom to control the resonance frequency of the proposed absorber.

In order to achieve the frequency tunability of the proposed graphene based absorber, the absorption spectra in terms of frequency is depicted in Fig. 8 for different values of the chemical potential. From (4), the graphene's chemical potential in various applied bias voltages is tabulated in Table 1. As shown in Fig. 8, when the chemical voltage increases, the bandwidth of the near unity absorption spectra at low frequencies becomes wide from 1.5 THz to 2.1 THz (with FWHM of 0.87 THz). Therefore, the absorber with tunability property is desirable in sensing applications.

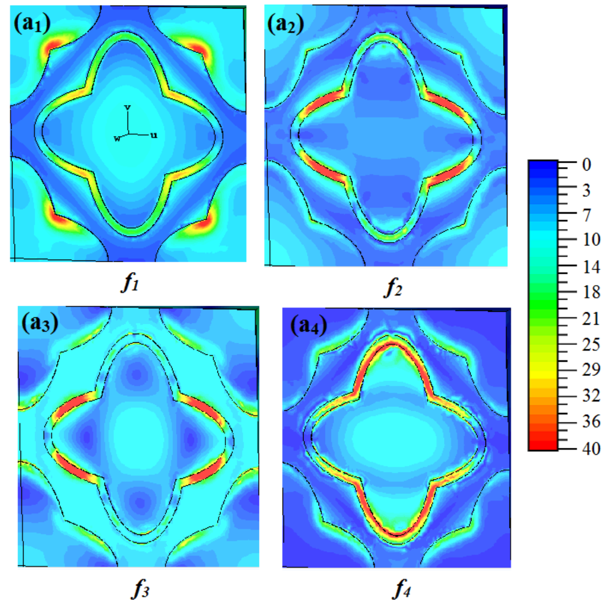


Fig. 5. (a_1)-(a_4) show the distributions of the electric fields $|E|$ for the proposed four-band THz absorber at modes f_1, f_2, f_3, and f_4, respectively.

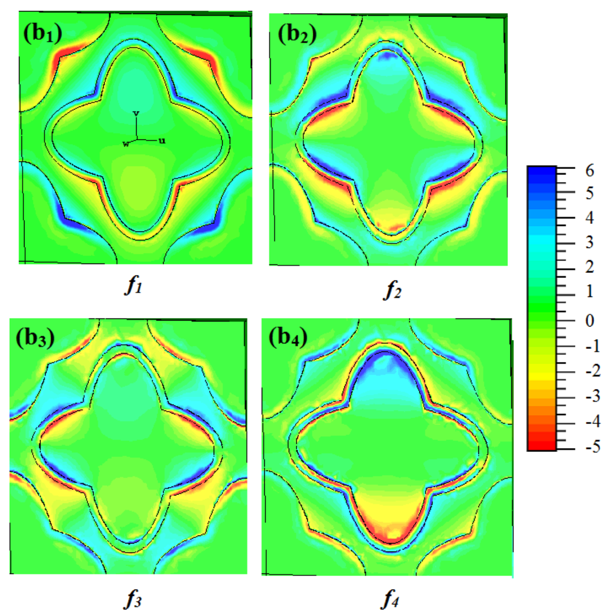


Fig. 6. (b_1)-(b_4) show the distributions of the electric field real $|E_z|$ for the proposed four-band THz absorber at modes f_1, f_2, f_3, and f_4, respectively.

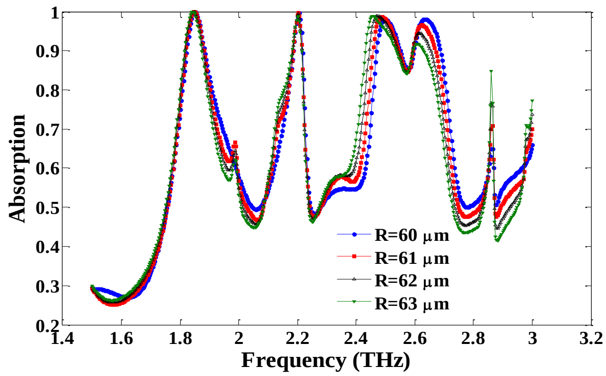


Fig. 7. Dependence of the absorption spectra of the proposed four-band THz absorber on the size changes of the R.

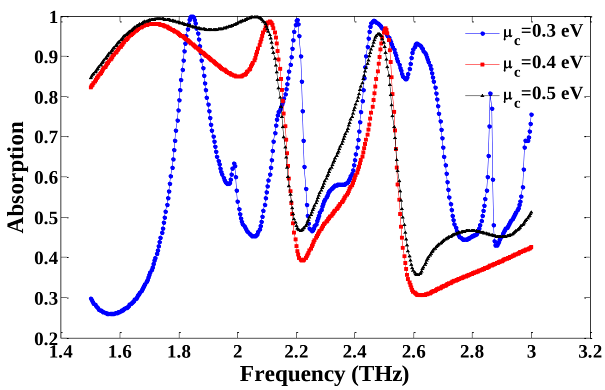


Fig. 8. Dependence of the absorption spectra of the proposed four-band THz absorber on the variation of the chemical potential.

Table 1: Chemical potential of the graphene layer

$\mu_c\,(eV)$	0.3	0.4	0.5
$V_A\,(V)$	6.3	8.5	10.3

IV. CONCLUSION

In conclusion, we proposed a near unity graphene based THz absorber. Four distinct absorption peaks are found at 0.3 THz, 0.6 THz, 0.816 THz, and 2.52 THz with the average absorption over 99% when the Fermi energy is $E_f = 0.2$ eV. The results show that the absorption spectra is insensitive to the incident polarization. Moreover, the bandwidth of the absorption coefficient can be expanded by applying different biasing voltages. The proposed absorber with these performances can be used in imaging and sensing applications.

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