Equivalent circuit model of graphene chiral multi-band metadevice absorber composed of U-shaped resonator array

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Abstract: In this study, we have designed an equivalent circuit model (ECM) by use of a simple MATLAB code to analyze a single-layered graphene chiral multi-band metadevice absorber which is composed of U-shaped graphene resonator array in terahertz (THz) region. In addition, the proposed metadevice absorber is analyzed numerically by the finite element method (FEM) in CST Software to verify the ECM analysis. The proposed device which is the first tunable graphene-based chiral metadevice absorber can be used in polarization sensitive devices in THz region. It is single-layered, tunable, and it has strong linear dichroism (LD) response of 94% and absorption of 99% for both transverse electric (TE) and transverse magnetic (TM) electromagnetic waves. It has four absorption bands with absorption >50% in 0.5-4.5 THz: three absorption bands for TE mode and one absorption band for TM mode. Proposed ECM has good agreement with the FEM simulation results. ECM analysis provides a simple, fast, and effective way to understand the resonance modes of the metadevice absorber and gives guidance for the analysis and design of the graphene chiral metadevices in the THz region.

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1. Introduction

Chiral metadevices are in two categories of three dimensional (3D) [1] and two dimensional (2D) [2]. Chiral metadevices have attracted great attention due to their properties such as circular dichroism (CD) [3], circular conversion dichroism (CCD) [4], and/or linear dichroism (LD) [5] in terahertz (THz) frequency range. Many chiral metadevices, including graphene-based devices, have been proposed recently to achieve chirality responses such as CD, CCD, and/or LD which could be controlled [1–10].

Graphene, a 2D layer of carbon atoms arranged in a honeycomb lattice, has fascinated remarkable heads in photonics and optoelectronics [11] because it can support electromagnetic waves in THz region and its possible to control the electromagnetic waves actively by just altering the applied electric bias voltage without need to refabricate the metadevices [4,6–8]. Nowadays, many kinds of graphene-based devices such as filters [12,13], logic gates [14,15], demultiplexers [16,17], and absorbers [18–21] are proposed and designed in the THz and mid-infrared (MIR) regions. In the case of graphene, the chirality responses such as CD, CCD, and/or LD become actively tunable and controllable by its Fermi energy which is not possible by other commonly used materials such as dielectrics or metals. Basically, this means that by varying the bias voltage of graphene, its spectral properties can be tuned without need to refabricate the device.

2D graphene chiral metadevices composing of single- and double-layered graphene resonator array with tunable chirality responses of CD and/or CCD have recently been designed and proposed in THz region [4,6–8,22–24]. These reported devices are made of graphene, having CCD and CD respectively up to 20% and 60%. However, chiral tunable devices with strong chirality responses of CD, CCD, and/or LD are more desirable.
Recently, some chiral absorbers are designed and proposed [25–30] but none of them are tunable and controllable with single or dual band absorptions. There is a lack of simple multi-band absorber concepts with excellent absorption properties. That is because simplified geometry tends to limit the number of absorption bands. Conventional multi-band absorbers are based either on the combination of multiple resonators with different sizes into one super unit cell [31,32] or stacking the resonators as a multilayer structure with resonators with different geometrical parameters and separate them with dielectric spacers [32]. The graphene-based multi-band simple or chiral metamaterial absorber based on the above frequency superposition methods has a complicated structure requiring of high precision preparation technique. Thus, it is necessary to find a new method to realize graphene-based multi-band metamaterial absorber with simple geometry and few layers. So, implementation of tunable multi-band perfect metamaterial absorber with single-layered simple geometry is very beneficial to save material, cost, and time.

The future THz communication systems, where it is necessary to obtain more information through multi-band and multi-beam absorbers to promote multi-task systems, are potential applications for multi-band THz absorbers [33–36]. Similar kind of needs might be found in the sensing applications as well [37–39].

Theoretical and numerical simulations are not convenient to be used for engineering driven metamaterial design because of their complexity. That is why a simple, fast, and efficient equivalent circuit model (ECM) approach is proposed for a tunable graphene chiral multi-band metadevice absorber composed of tunable single-layered graphene U-shaped resonator array which has very strong LD response, working in THz region. Our proposed multi-band metadevice absorber with ECM model is expected to accelerate the development of such metadevices for some other potential applications such as polarization filter, converter, and biological sensor in the THz region.

2. Device, material, and equivalent circuit model

The 3D schematic view of the proposed tunable graphene-based chiral multi-band metadevice absorber consisted of periodically patterned graphene-based U-shaped resonator array is shown in Fig. 1(a). The substrate is made of quartz with refractive index of 1.96 ($\varepsilon_{d2}=3.84$) [6]. The conductivity of gold layer is $4.56\times10^7$ S/m [40]. Based on the penetration depth of the THz electromagnetic waves, the thickness of $0.5 \mu m$ for the gold reflector is chosen to ensure that the incident electromagnetic wave cannot transmit through it [40]. The ion gel layer is described by a nondispersive permittivity of $\varepsilon_{d1}=1.82$ [41], which is overlaid on the graphene U-shaped resonator array, with a thickness of $0.5 \mu m$ for electrostatic bias of the graphene resonator array. Then, a gold electrode is manufactured on the ion gel layer. Simulations are done in CST Microwave Studio Software [6,7,42,43]. The chiral metadevice absorber (Figs. 1(a) and 1(b)) is composed of U-shaped graphene resonator array (USGRA). The USGRA is given in Fig. 1(c).

The substrate thickness $d_2$ has considered to be $7 \mu m$ in all simulations. The length of the U-shaped resonator is $L=20 \mu m$. The length and width of the gap are respectively considered $l=7.5 \mu m$ and $w=1.5 \mu m$. The considered values for the parameters of the proposed metadevice absorber are summarized in Table 1.

The thickness of the monolayer graphene is considered as $\Delta=0.335$ nm [44]. The relative permittivity of graphene is [42,45]:

$$\varepsilon = 1 - \frac{j\sigma}{\omega\varepsilon_0\Delta}, \quad (1)$$

in which $\sigma$, $\omega$, and $\varepsilon_0$ are respectively the surface conductivity of the graphene, angular frequency, and vacuum permittivity. $\sigma$ consists of the inter- and intra-band electron transition contributions.
Fig. 1. (a) Three dimensional schematic view of the tunable graphene chiral multi-band metadevice absorber array composed of graphene U-shaped resonators (b) View of the unit cell of the metadevice absorber. (c) Front view of the U-shaped graphene resonator array (USGRA). The substrate is made of quartz dielectric with refractive index of 1.96. Gold reflector with conductivity of $4.56 \times 10^7$ S/m is used beneath the structure to prevent the wave transmission. For uniform electrostatic biasing of graphene U-shaped resonators, ion gel with refractive index of 1.35 is used.
Table 1. Considered values for the parameters of the chiral multi-band metadevice absorber of Fig. 1.

| Parameter                                             | Value |
|-------------------------------------------------------|-------|
| Unit cell dimension in x direction ($P_x$)            | 20 µm |
| Unit cell dimension in y direction ($P_y$)            | 20 µm |
| Thickness of the ion gel layer ($d_1$)                | 0.5 µm|
| Thickness of the quartz dielectric spacer ($d_2$)     | 7 µm  |
| Thickness of the gold reflector ($d_3$)              | 0.5 µm|
| The length of the U-shaped resonator ($L$)            | 15 µm |
| The length of the gap ($l$)                           | 7.5 µm|
| The width of the gap ($w$)                            | 1.5 µm|
| graphene Fermi energy ($E_f$)                         | 0.8 eV|

by assumption of the incident electromagnetic wave as $e^{j\omega t}$; as follows [46]:

$$\sigma = \sigma_{\text{intra}}(\omega) + \sigma_{\text{inter}}(\omega),$$

(2a)

$$\sigma_{\text{intra}}(\omega) = \frac{2ke^2T}{\pi\hbar^2} \ln \left[ 2\cosh \left( \frac{E_f}{2k_B T} \right) \right] \frac{j}{jT^{-1} - \omega},$$

(2b)

$$\sigma_{\text{inter}}(\omega) = \frac{e^2}{4\hbar} \left[ H\left( \frac{\omega}{2} \right) - 4j\omega \int_0^\infty \frac{H(\zeta) - H(\frac{\omega}{2})}{\omega^2 - 4\zeta^2} d\zeta \right],$$

(2c)

$$H(\zeta) = \sinh \left( \frac{\hbar \zeta}{k_BT} \right) \left[ \cosh \left( \frac{E_f}{k_BT} \right) + \cosh \left( \frac{\hbar \zeta}{k_BT} \right) \right],$$

(2d)

in which $\hbar$ is the reduced Plank’s constant, $k_B = 1.38 \times 10^{-23}$ J/K is the Boltzmann’s constant, $e = 1.6 \times 10^{-19}$ C is the electron charge, $T$ is the temperature equals to 300 K, and $\zeta$ is the integral variable. $\tau$ is the relaxation time as [42,47]:

$$\tau = \frac{\mu E_f}{e v_f^2},$$

(3)

in which $v_f = 10^6$ m/s is the Fermi velocity and $\mu = 1.25$ m²/(V.s) is the carrier mobility. In the THz band, we have: $\hbar \omega \ll E_f$. So, the inter-band transition is assumed to be negligible and the intra-band transition dominates [42].

The propagation constant of the electromagnetic wave on graphene-vacuum configuration can be calculated by [48]:

$$\beta = k_0 \sqrt{1 - \left( \frac{2}{\eta_0 \sigma} \right)^2},$$

(4)

where $\beta$, $k_0$, and $\eta_0$ are respectively the propagation constant of electromagnetic wave on graphene-vacuum configuration, the wave vector of incident light wave, and the vacuum impedance. The spectra of the real part of the propagation constant $\beta$, of the graphene layer for three different values of $E_f$ are calculated and given in [42]. As the $E_f$ increases, the real part of the $\beta$ decreases. External bias voltage should be applied between the graphene U-shaped resonator array and the
bottom gold reflector for manipulating of the $E_f$. The relationship between $E_f$ and bias voltage ($V > 0$) is approximately considered as [49]:

$$E_f = \hbar v_F \sqrt{\frac{\pi \varepsilon_0 \varepsilon_d V}{ed_2}}, \quad (5)$$

Transverse magnetic (TM) and transverse electric (TE) polarized electromagnetic waves are launched separately to the metadevice absorber composed of U-shaped resonator array in THz region. The ECM of the metadevice absorber differs for TM polarized wave and TE polarized wave which proves the chirality nature (lack of mirror symmetry) of the proposed metadevice.

For the TE polarized incident wave, the U-shaped graphene resonator array (USGRA) of Fig. 1(c), is modeled with RLC circuit and the gap of the resonator is modeled by a parallel capacitance. In this case, the incident electric field is normal to the gap, the ECM is depicted in Fig. 2(a). The gap of the resonator is modeled by a capacitance which is calculated by:

$$C_{\text{gap}} = \varepsilon_{\text{eff}} \frac{l}{W}, \quad (6)$$

which is 158 pF based on the parameters given in Table 1, where

$$\varepsilon_{\text{eff}} = \varepsilon_0 \frac{\varepsilon_d \varepsilon_1 + \varepsilon_d \varepsilon_2}{2}, \quad (7)$$

**Fig. 2.** The equivalent circuit models (ECMs) of the U-shaped graphene resonator array (USGRA) of Fig. 1(c), when (a) TE and (b) TM electromagnetic waves are launched to the multi-band metadevice absorber.

For the TM polarized incident wave, the U-shaped resonator array could only be modeled with RLC circuit. However, $C_{\text{gap}} = 0$ because the incident electric field is parallel to the gap. The ECM of this case is shown in Fig. 2(b).

The ECM approach is based on the ABCD matrix and the S-parameters [50]. The ABCD matrices of ion gel/substrate (IG/S) and U-shaped graphene resonator array (USGRA) respectively are obtained by [50]:

$$[T_{\text{IG/S}}] = \begin{bmatrix} \cos(\phi_{\text{IG/S}}) & jZ_{\text{IG/S}} \sin(\phi_{\text{IG/S}}) \\ \frac{j}{Z_{\text{IG/S}}} \sin(\phi_{\text{IG/S}}) & \cos(\phi_{\text{IG/S}}) \end{bmatrix}, \quad (8)$$

$$[T_{\text{USGRA, TM}/\text{TE}}] = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_{\text{USGRA, TM}/\text{TE}}} & 1 \end{bmatrix}, \quad (9)$$
in which the electrical length and the impedances of IG/S are as follows:

\[ \phi_{IG/S} = \frac{\omega}{c} \sqrt{\varepsilon_r IG/S}, \]  
\[ Z_{IG/S} = \frac{Z_0}{\sqrt{\varepsilon_r IG/S}}, \]  

The ABCD matrix of the graphene chiral metadevice absorber without considering ion gel and gold reflector can be obtained by [50]:

\[ [T_{USGRA&S, TM/TE}] = [T_{USGRA, TM/TE}][T_3] = \begin{bmatrix} A_{USGRA&S, TM/TE} & B_{USGRA&S, TM/TE} \\ C_{USGRA&S, TM/TE} & D_{USGRA&S, TM/TE} \end{bmatrix}, \]  

where \( \omega, c, \) and \( Z_0 \) are respectively the angular frequency, speed of light, and impedance of vacuum.

In order to calculate \( Z_{USGRA, TM/TE} \), we use the field reflection coefficients of TM/TE modes for the structure containing USGRA and substrate, \( r_{USGRA&S, TM/TE} \), which are calculated by finite element method (FEM) simulations [50]:

\[ r_{USGRA&S, TM/TE} = \frac{A_{USGRA&S, TM/TE} + B_{USGRA&S, TM/TE}}{A_{USGRA&S, TM/TE} + D_{USGRA&S, TM/TE}} - Z_0 C_{USGRA&S, TM/TE} - D_{USGRA&S, TM/TE} \]

So, \( Z_{USGRA, TM/TE} \) is calculated by:

\[ Z_{USGRA, TM/TE} = \frac{Z_0 (1 + r_{USGRA, TM/TE}) (Z_0 \cos(\phi_s) + jZ_0 \sin(\phi_s))}{(1 - r_{USGRA, TM/TE}) (Z_0 \cos(\phi_s) + jZ_0 \sin(\phi_s)) - Z_0 (1 + r_{USGRA, TM/TE}) (\cos(\phi_s) + j \left( \frac{\omega}{c} \right) \sin(\phi_s))}. \]  

For calculation of \( Z_{g, TE} \), we have:

\[ Z_{USGRA, TE} = Z_{g, TE} Z_{gap} \Rightarrow Z_{g, TE} = \frac{Z_{gap} Z_{USGRA, TE}}{Z_{gap} - Z_{USGRA, TE}}. \]  

For the state of TM mode, we have:

\[ Z_{USGRA, TM} = Z_{g, TM}. \]  

After calculation of \( Z_{USGRA, TM/TE} \), we calculate the ABCD matrix of the total metastructure \( T_{tot, TM/TE} \), which is composed of ion gel (IG), U-shaped graphene resonator array (USGRA), and substrate (S):

\[ [T_{tot, TM/TE}] = [T_{IG}][T_{USGRA, TM/TE}][T_3] = \begin{bmatrix} A_{tot, TM/TE} & B_{tot, TM/TE} \\ C_{tot, TM/TE} & D_{tot, TM/TE} \end{bmatrix}, \]  

The ECMs of the proposed chiral multi-band metadevice absorber for TE and TM modes are respectively given in Figs. 3(a) and 3(b).
Fig. 3. The ECMs of the graphene chiral multi-band metadevice absorber when (a) TE and (b) TM electromagnetic waves are launched to it.

The input impedances of TM and TE modes of the chiral metadevice absorber $Z_{\text{in},\text{TM/TE}}$ (shown in Fig. 3) is calculated by [50]:

$$Z_{\text{in},\text{TM/TE}} = \frac{A_{\text{tot,TM/TE}}Z_{\text{Gold}} + B_{\text{tot,TM/TE}}}{C_{\text{tot,TM/TE}}Z_{\text{Gold}} + D_{\text{tot,TM/TE}}}, \quad (18)$$

where $Z_{\text{GOLD}}$ is the impedance of the ground plate. The ground plate acts as a short circuit. So, we set $Z_{\text{Gold}}$ to zero. Then, Eq. (18) is simplified to [50]:

$$Z_{\text{in},\text{TM/TE}} = \frac{B_{\text{tot,TM/TE}}}{D_{\text{tot,TM/TE}}}, \quad (19)$$

which is equal to:

$$Z_{\text{in, TM/TE}} = \frac{\left(jZ_S \sin(\phi_S) \cdot \left(\cos(\phi_{IG}) + \left(jZ_{IG} \sin(\phi_{IG}) \cdot \frac{1}{Z_{\text{USGRA,TM/TE}}}\right)\right) + (jZ_{IG} \sin(\phi_{IG}). \cos(\phi_S))\right)}{\left(jZ_S \sin(\phi_S) \cdot \left(\frac{jZ_S}{Z_{USGRA,TM/TE}} \sin(\phi_{IG}) + \left(\cos(\phi_{IG}). \frac{1}{Z_{\text{USGRA,TM/TE}}}\right)\right) + (\cos(\phi_{IG}). \cos(\phi_S))\right)}, \quad (20)$$

Then, the reflection of the total metastructure $r_{\text{tot,TM/TE}}$ is calculated by [50]:

$$r_{\text{tot,TM/TE}} = \frac{Z_{\text{in, TM/TE}} - Z_0}{Z_{\text{in, TM/TE}} + Z_0}. \quad (21)$$

Finally, the total absorption of the chiral metadevice absorber is calculated by [50]:

$$A_{\text{TM/TE}} = 1 - |r_{\text{tot,TM/TE}}|^2, \quad (22)$$

We can promote our ECM for the oblique incident angle (angle respect to -z axis in Fig. 1(b) which is not zero.) of $\phi_{\text{inc}} \neq 0$, as well. In this regard, $Z_{IG/S}$ (Eq. (11)) for TE and TM modes are
not equal, and they should respectively be replaced with [51]:

\[ Z_{TE}^{IG/S} = \frac{Z_{IG/S}}{\cos(\phi_{inc})}, \] (23)

\[ Z_{TM}^{IG/S} = Z_{IG/S} \cos(\phi_{inc}), \] (24)

Also, the electrical length (Eq. (10)) for the oblique incident angle should be modified as [51]:

\[ \phi_{IG/S} = \beta_\perp d_2, \] (25)

in which:

\[ \beta_\perp = \beta_0 \sqrt{\varepsilon d_2 - \sin^2(\phi_{inc})}, \] (26)

where \( \beta_\perp \) and \( \beta_0 \) are respectively the normal component of the wave number and the propagation constant of vacuum.

3. Results and discussion

Numerical simulations were performed in CST Microwave Studio Commercial Software by use of finite element method (FEM) with a frequency domain solver [52,53]. We have applied periodic boundary conditions in x and y directions, and open boundary condition in z direction in our simulations. In addition, tetrahedral mesh type is used for meshing of the structure. Our proposed structure is excited by the z-polarized transverse electric (TE) and transverse magnetic (TM) incident electromagnetic lightwaves.

In order to obtain the absorption spectra of TM/TE modes for the whole absorber structure of Fig. 1 by the ECM approach, the impedance of the U-shaped graphene resonator array \( Z_{USGRA, TM/TE} \) should be calculated. For calculation of \( Z_{USGRA, TM/TE} \) (as given in Eq. (14)), the field reflection coefficients of TM/TE modes for the structure containing of USGRA on substrate, \( r_{USGRA&S, TM/TE} \), are needed. The structure containing USGRA on substrate (Fig. 4) with simulation parameters given in Table 1 is simulated and \( r_{USGRA&S, TM/TE} \) are obtained. The obtained \( r_{USGRA&S, TM/TE} \) which are given in Figs. 5(a) and 5(b) are put in Eq. (14) and \( Z_{USGRA, TM/TE} \) are determined. \( Z_{USGRA, TM} \) (Fig. 3(b)) is containing of RLC elements. The gap is not modeled by a capacitance in TM mode because the incident electric field is parallel to the gap. \( Z_{USGRA, TE} \) (Fig. 3(a)) is containing of RLC elements parallel with \( C_{gap} \) element. The gap is modeled by a capacitance in TE mode because the incident electric field is normal to the gap. Those RLC elements in Figs. 3(a) and 3(b) for TE and TM modes are respectively shown by \( Z_{g, TE} \) and \( Z_{g, TM} \).

The real parts of \( Z_{g, TE} \) (Eq. (15) and Fig. 3(a)) and \( Z_{g, TM} \) (Eq. (16) and Fig. 3(b)) of the USGRA are respectively plotted in Figs. 5(c) and 5(d). In addition, the imaginary parts of \( Z_{g, TE} \) (Eq. (15) and Fig. 3(a)) and \( Z_{g, TM} \) (Eq. (16) and Fig. 3(b)) of the USGRA are respectively given in Figs. 6(a) and 6(b). By increasing of \( E_f \), the resonance frequencies of the absorber increase, which tends to exhibit a blueshift. It is because the real part of the \( \beta \) in Eq. (4) decreases as the \( \mu_c \) increases (shown in [42]) [54]. Therefore the resonance values of the real and the imaginary parts of the impedances increase by the increase of \( E_f \). At the same time, the losses of the TM and TE waves supported by the graphene decrease with the \( E_f \) increase. So, the absorption of the absorber increases correspondingly with the \( E_f \) increase (shown in [42]) [54]. Therefore the values of the real and the imaginary parts of the impedances increase by the increase of \( E_f \).

The absorption spectra of the proposed tunable graphene-based multi-band metadevice absorber for TE and TM modes by considering of \( E_f = 0.8 \) eV are given in Fig. 7. As depicted, there are four resonances in 1.18, 2.21, 3.1, and 4.13 THz for TE mode and two resonances in 1.78 and 3.74 THz for TM mode. In fact, there are three absorption bands for TE mode and one absorption band for TM mode with absorption >50% in 0.5-4.5 THz. The absorption spectrum of TE is
not coincided with that of TM which shows the chiral (asymmetrical) nature of the introduced metadevice absorber. In addition, the chirality nature of the device could be sensed by the ECMs of the USGRA in both TE and TM modes which are respectively given in Figs. 2(a) and 2(b). The gap is modeled by a capacitance in TE mode because the incident electric field is normal to the gap.

The observed chiral asymmetry nature of the proposed metadevice absorber can also be demonstrated by its electrical field distributions. The electric field distributions of the proposed graphene chiral metadevicer absorber of Fig. 1 under TM and TE incident lightwaves at the two different resonance frequencies of 1.78 and 2.21 THz are displayed in Fig. 8. The distributions show a clear dependence on the polarization of the incident light, resulting in a difference in the absorption of TM and TE lightwaves. The field distributions of the absorber for TM and TE normal incident illuminations (illuminations are in -z direction in Fig. 1(b)) are given in Figs. 8(a) and 8(b). They are not equal. The maximum absorption occurs for TM mode in 1.78 THz resonance frequency (shown in Fig. 7). So, the electric field is stronger in this resonance frequency for TM mode compared with TE mode (shown in Figs. 8(a) and 8(b)). The same as for the electric field distributions for 2.21 THz resonance frequency in Figs. 8(c) and 8(d). Maximum absorption occurs for TE mode in 2.21 THz (shown in Fig. 7). So, the electric field is stronger for TE mode compared with TM mode in 2.21 THz (shown in Figs. 8(c) and 8(d)).

The absorption obtained by simulation (FEM method) and ECM (Eq. (22)) methods, for the proposed graphene chiral metadevice absorber when the structure is illuminated normally (illumination in -z direction) by TM and TE polarized incident waves for three different values of $E_f = 0.6, 0.7, \text{and } 0.8 \text{eV}$ are compared and depicted in Figs. 9(a) and 9(b), respectively.

The results of the both ways for the different values of $E_f$ are in good agreement. As it can be seen, by increasing $E_f$, the resonance frequency increases with a tendency to exhibit a blueshift. Also, the absorption increases. The reason for this is the same as given for Figs. 5 and 6. The input impedances of the absorber are matched with the normalized vacuum impedance at the resonance frequencies which results in maximum absorption.

Fabrication of perfect graphene patterns is challenging, and defects decrease the mobility of the graphene [55]. In order to predict the device performance in the case of different mobilities of graphene, absorption characteristics of the device is obtained by FEM and ECM (Eq. (22)) methods when the structure is illuminated normally by TM and TE polarized incident waves.
Fig. 5. Reflection spectra of the structure of Fig. 4 for (a) TE and (b) TM modes. Real parts of (c) $Z_{g, TE}$ (Fig. 3(a)) and (d) $Z_{g, TM}$ (Fig. 3(b)) of the structure of Fig. 4.
Fig. 6. Imaginary parts of (a) $Z_{g, TE}$ (Fig. 3(a)) and (b) $Z_{g, TM}$ (Fig. 3(b)) of the structure of Fig. 4.

Fig. 7. Absorption spectra of the proposed multi-band metadevice absorber of Fig. 1 considering $E_f = 0.8$ eV, for TE and TM modes.

with three different mobility values of $\mu = 0.85$, 1.15, and 1.45 m$^2$/V.s when $\mu_c = 0.7$ eV in Figs. 10(a) and 10(b), respectively. As depicted, the carrier mobility does not affect the resonance frequencies of the TE and TM absorption spectra. Increase in carrier mobility results in an increase in the absorption peaks of the TE and TM absorption spectra. The reason of enhanced absorption by increase of carrier mobility $\mu$ (increase of $\mu$ results in increase of the relaxation time $\tau$; Eq. (3)) is that the contribution of carrier to plasma oscillation increases with the increase of $\mu$ (or $\tau$), so that the absorption increases [56].

In addition, the TE and TM absorption spectra of the proposed absorber of Fig. 1 for oblique incident angle of 40° with both methods of FEM and ECM are respectively given in Figs. 11(a) and 11(b). Good agreement between the FEM and ECM results indicates that the proposed ECM can predict the absorption spectra, even at oblique incidences.

To make a comparison between TE and TM absorption spectra of 0° (illuminated by the incident lightwave in -z direction) and 40° (the angle between the illuminated lightwave and -z
**Fig. 8.** Electric field distributions of the proposed graphene chiral metadevice absorber of Fig. 1 for (a) TM in 1.78 THz, (b) TE in 1.78 THz, (c) TM in 2.21 THz, and (d) TE in 2.21 THz.

**Fig. 9.** Comparison of FEM and ECM results of the proposed graphene chiral multi-band metadevice absorber composed of U-shaped resonator array for normal incident wave (illumination in -z direction) for different values of $E_f$ for (a) TE and (b) TM modes.
Fig. 10. Comparison of FEM and ECM results of the proposed graphene chiral multi-band metadevice absorber composed of U-shaped resonator array for normal incident wave (illumination in -z direction) for different values of $\mu$ when $\mu_c=0.7$ eV for (a) TE and (b) TM modes.

Fig. 11. Comparison of FEM and ECM results of the proposed graphene chiral metadevice absorber for oblique incident angle of $40^\circ$ for (a) TE and (b) TM modes.
Fig. 12. Comparison of FEM results of the proposed graphene chiral metadevice absorber for normal and oblique 40° incident angles for (a) TE and (b) TM modes.

direction) oblique incident waves, TE and TM simulated absorption spectra by FEM for the both mentioned states are respectively given in Figs. 12(a) and 12(b). For TE mode (Fig. 12(a)), by increasing of the incident lightwave angle to 40°, the resonance frequencies are unchanged and stable, but the absorption values are decreased. For TM mode (Fig. 12(b)), by increasing of the incident angle to 40°, the first and second resonance frequencies respectively increase and decrease slightly, and the absorption values for the first and second resonances are respectively unchanged and increased. As a consequence, the overall performance of the absorber structure for both TE and TM modes are maintained by change of the 0° incident angle to the oblique 0°-40° ones.

The characteristics of our proposed tunable graphene chiral absorber are compared with other published chiral absorbers. The comparison is given in Table 2. All the reported works are tunable by change of geometrical parameters or incident angle. Graphene chiral absorber (our work) is also tunable by change of bias voltage which is a beneficial feature to serve material, cost, and time. Also, the characteristics of our proposed graphene chiral metadevice are compared with other graphene chiral metastructures in Table 3. Comparison of our multi-band graphene chiral absorber with other previously published multi-band graphene absorbers is given in Table 4.

Even though the fabrication of the proposed metastructure is out of the scope of this paper, the implementation feasibility is necessary to be considered. Usually the quality of graphene in such devices is lower than expected in theoretical and numerical calculation due to the imperfections caused by fabrication process. The consequence of those defects is the lower carrier mobility of graphene [55]. Fabrication procedure of the proposed chiral metadevice absorber could be as follows: The quartz dielectric is transferred on gold metal reflector through thermal evaporation. The graphene layer is coated on the quartz dielectric by chemical vapor deposition (CVD). The graphene U-shaped resonator array is written by electron beam etching [61,62]. The ion gel dielectric is transferred on graphene resonator array through thermal evaporation. The proposed
Table 2. Comparison of the characteristics of the chiral metadevice absorber of Fig. 1 with other chiral absorbers.

| Tunability by change of geometrical parameters & incident angle | [25] | [26] | [27] | [28] | [29] | [30] | This work |
|---------------------------------------------------------------|------|------|------|------|------|------|-----------|
| Tunability by change of bias voltage                          | yes  | yes  | yes  | yes  | yes  | yes  | yes       |
| Number of layers                                              | two  | one  | one  | two  | one  | one  | one      |
| Number of resonators in unit cell                             | eight| one  | one  | eight| one  | six  | one      |
| Unit cell dimension                                           | $10 \times 10$ mm$^2$ | $320 \times 420$ nm$^2$ | $300 \times 450$ nm$^2$ | $80 \times 80$ µm$^2$ | $235 \times 335$ nm$^2$ | $380 \times 700$ nm$^2$ | $20 \times 20$ µm$^2$ |
| Theoretical approach                                         | no   | no   | no   | no   | no   | no   | yes       |
| Max. absorption (%)                                          | 93.2 | 80   | 50   | 97   | not reported | 85 | 99       |
| Number of absorption bands                                     | one  | two  | two  | two  | two  | one  | four     |
| Max. CD (%) / based on transmission                           | 86 / transmission | 50 / absorption | 12 / absorption | 70 / transmission | 88 / (0) / reflection (transmission) | 50 / absorption | 0 / absorption |
| Max. CCD (%) / based on transmission                          | N/A  | N/A  | N/A  | N/A  | 0 (15) / reflection | N/A | 0 / absorption |
| Max. LD (%) / based on                                         | N/A  | N/A  | N/A  | N/A  | N/A  | N/A | 94 / absorption |

Table 3. Comparison of the characteristics of the graphene chiral metadevice absorber of Fig. 1 with other graphene chiral metastructures.

|                | [4]  | [6]  | [7]  | [8]  | [22] | [23] | [24] | [42] | This work |
|----------------|------|------|------|------|------|------|------|------|-----------|
| Number of layers                                      | one  | one  | one  | one  | one  | one  | three | two  | one      |
| Unit cell dimension                                   | $1.6 \times 1$ µm$^2$ | $80 \times 80$ µm$^2$ | $0.25 \times 0.3$ µm$^2$ | $2 \times 4$ µm$^2$ | $0.27 \times 0.27$ µm$^2$ | $4.4 \times 3.65$ µm$^2$ | $46 \times 46$ µm$^2$ | $22 \times 22$ µm$^2$ | $20 \times 20$ µm$^2$ |
| Theoretical approach                                  | no   | no   | no   | no   | no   | no   | no   | yes  | yes      |
| Max. absorption (%)                                    | N/A  | 45   | N/A  | N/A  | N/A  | N/A  | N/A  | 90   | 60       |
| Max. CD (%) / based on transmission                     | N/A  | Not possible | 0 / transmission | 0 / transmission | 0 / transmission | 0 / transmission | 60 (60) / absorption (reflection) | 20 / absorption | 0 / absorption |
| Max. CCD (%) / based on transmission                    | N/A  | Not possible | 6 / transmission | 4 / transmission | 20 / transmission | 19 / transmission | 0 (0) / absorption (reflection) | N/A | 0 / absorption |
| Max. LD (%) / based on transmission                     | N/A  | Not possible | N/A  | N/A  | N/A  | N/A  | N/A  | N/A | 94 / absorption |
metamaterial model assumes that all the layers are fabricated without any defects or imperfections. The fabrication of the proposed device and its influence on metamaterial performance needs further investigation.

4. Conclusion

In this paper, equivalent circuit modeling (ECM) approach of a tunable graphene-based chiral metadevice absorber composed of U-shaped resonator array by use of a simple and fast MATLAB code is proposed, designed, and analyzed in terahertz (THz) region. Simulation results are done by the finite element method (FEM) in CST Microwave Studio Software which are in good agreement with the ECM ones. Our proposed ECM approach could also be used for modeling of other chiral metadevices. Our proposed absorber structure is tunable, single-layered, containing one resonator in each unit cell, having strong linear dichroism (LD) response of 94%, absorption of 99% for both of TE and TM electromagnetic waves, and having three absorption bands for TE mode and one absorption band for TM mode. Also, the proposed device could find some other potential applications in controllable polarization sensitive devices such as polarization filter and biological sensor in the future.

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Disclosures

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