Design of an ultra-thin hepta-band metamaterial absorber for sensing applications

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Abstract
An ultra-thin metamaterial absorber (MMA) comprises of a split-ring-cross (SRC)-shaped resonator coupled with graphene and dielectric layer backed by metallic ground plane is presented theoretically and numerically for hepta-band applications. The proposed absorber demonstrates multiple absorption peaks at 2.33, 5.24, 7.74, 8.25, 10.05, 10.97, and 12.61 THz with average absorption of more than 96%. The physical mechanism of the hepta-band absorption is analyzing by electric field distribution and attributed to the combination of dipolar and LC resonance. Furthermore, the effect of geometric parameters is analyzed to validate the optimal selection of the structural parameters. In addition, the proposed MMA is analyzed for different incident and polarization angles suggesting that absorption response is insensitive to polarization angles. Compared with the previously reported MMAs, the proposed design is ultra-thin (0.036λ) and compact (0.21λ) at the lowest operational frequency. The absorptivity at 12.61 THz is 99.81% and the corresponding quality (Q) factor is 31.52 for a bandwidth of 0.40 THz. The proposed absorber can be potentially utilized in detection, sensing, and imaging. Moreover, the sensing performance of the proposed MMA has been investigated using overlayer thickness and overlayer permittivity.

Keywords Graphene · Hepta-band · Metamaterial absorber · Overlayer · Polarization insensitive · Sensor
1 Introduction

Metamaterials have drawn significant attention due to their unique electromagnetic (EM) properties that natural materials do not possess (Shelby et al. 2001; Cai et al. 2007; He et al. 2017). Recently, several applications including antennas (Jain et al. 2017, 2018), superlenses (Zhang and Liu 2008), solar cells (Wang et al. 2012), cloaking (Cai et al. 2007), and absorbers (Jain et al. 2020b) have been extensively studied utilizing the exotic properties of the metamaterials in the range of microwave to terahertz (THz) frequencies. Metamaterial absorber (MMA) has drawn significant attention in the THz range due to its perfect absorption properties which are difficult to find in natural materials. The first MMA was demonstrated by Landy et al. which attracts considerable attention (Landy et al. 2008) and since then, different kinds of MMAs have been proposed including single (Yan 2019), dual- (Li et al. 2019; Jain et al. 2019), triple- (Huang et al. 2018b), quad- (Wang 2017), penta-band (Zhang et al. 2019b), broadband (Ding et al. 2012), tunable (Jain et al. 2020a) and polarization insensitive (Li et al. 2019) absorbers. Among these, multi-band MMA with polarization insensitive characteristics have found great attention due to their use in applications such as materials detection (Senesac and Thundat 2008), sensing of harmful gas (Ritari et al. 2004), and spectroscopic imaging (Rodrigues et al. 2014).

Several efforts have been proposed to increase the absorption peaks such as stacking of metallic resonators (Ding et al. 2012; Tran et al. 2019; He et al. 2015), or integrating different sized resonators in a single unit cell (Wang et al. 2015; Bhattacharya et al. 2015). Recently, dual-, triple- and quad-band absorbers based on dual- (Yan and Li 2019), triple-square loop (Shen et al. 2011), and quad-square loop (Wang et al. 2015), respectively, were proposed utilizing dipolar resonance. However, these approaches suffer from technical difficulties while manufacturing at higher frequencies due to larger size and thickness which in turn leads to impracticality in practical applications (Wang et al. 2015; Chaurasiya et al. 2016; Yoo et al. 2016). Furthermore, multi-band absorption can also be achieved using a combination of dipolar and LC resonance in a single design structure, such as T-shaped (Meng et al. 2018), ring-strip (Zhao et al. 2018), cave-ring (Huang et al. 2018b), and #-shaped (Hu et al. 2016) resonator. But these designs are sensitive to polarization angles which will limit their practical applications (Yan et al. 2012). Thus, it is necessary to design a polarization-insensitive absorber with tunable characteristics. Recently, a tunable absorber was proposed by varying the position of metallic patch on a fixed substrate which is quite impractical once fabrication is done (Watts et al. 2012; Wang et al. 2014).

Recently, graphene has drawn intense attention due to its excellent optical and electrical properties which makes it a suitable material to design tunable absorbers (Yi et al. 2019b). The single- and dual- frequency dynamic adjustments have been realized in a tunable absorber utilizing ring and cross-shaped graphene patterns (Chen et al. 2017). To achieve operation at multiple frequency bands, Wang et al. designed a dual-band tunable absorber composed of two sizes of single-layer graphene nanodisks (Wang et al. 2018). A polarization independent MMA realized by Zhang et al. consists of a cross-shaped resonator with graphene wires on top and bottom of metallic resonator for THz frequencies (Zhang et al. 2014). A tunable THz MMA was demonstrated using monolayer graphene on top of SiO2 dielectric layer and metallic ground plane exhibiting perfect absorption (Zhang et al. 2015). Further, a broadband tunable MMA utilizing four patch resonators with a total thickness of 0.76 μm has exhibited reflection coefficient
less than −10 dB from 22.02 to 36.61 THz (Xiong et al. 2018). In addition, the tunability of MMA has been demonstrated by loading a graphene layer into the structure which manipulates the graphene’s Fermi energy (Chen et al. 2020).

Here, a compact and ultra-thin terahertz absorber is designed with polarization characteristics for hepta-band applications. The proposed absorber shows multiple absorption peaks at 2.33, 5.24, 7.74, 8.25, 10.05, 10.97, and 12.61 THz. Further, electric (e) field distribution is also evaluated to understand the absorption phenomenon with normalized impedance ($Z$) and constitutive EM parameters. Furthermore, parametric analysis has been done to optimize the dielectric thickness and unit cell dimensions. Compared to earlier reported work, the proposed MMA has multiple advantages like simple structure design, compact in size, less thickness, and polarization insensitive characteristics suggesting potential applications in stealth technology, detection, sensing, and imaging. Finally, the influence of overlayer (OL) thickness and permittivity is investigated on the absorber to analyze the sensing application.

2 Design and simulation

The single unit cell of proposed MMA is simulated utilizing finite element method (FEM) based ANSYS HFSS software applying periodic boundary conditions in both x- and y-directions, and Floquet periodic port in the z-direction. The EM waves polarizing along y-direction is normally incident on the surface of absorber at z-direction while simulation. The proposed structure consists of a split-ring-cross (SRC)-shaped resonator coupled with graphene and dielectric (SiO$_2$) layer backed by metallic plane as illustrated in Fig. 1a. The relative permittivity ($\varepsilon_r$) of the SiO$_2$ layer is 3.9 (Yi et al. 2019b) with the thickness of 3 μm and conductivity ($\sigma$) of gold is $4.09 \times 10^7$ S/m with the thickness of top and bottom layers are 0.2 and 0.5 μm, respectively, as illustrated in Fig. 1b. The absorption is $1 - |S_{11}|^2 - |S_{21}|^2$, where $S_{11}$ and $S_{21}$ represent the reflection and transmission coefficients, respectively. The thickness of the ground plane is larger than that of its skin depth such that the transmission coefficient can be reduced to zero ($S_{21} = 0$), thus the absorption can be simplified as $1 - |S_{11}|^2$. The geometric dimensions of the absorber are $a = 22$, $d = 20$, $b = 1.7$, $r = 7$, $w = 1$, $g = 2$ (all dimensions are in μm). The dimensions were optimized after several simulations and the chosen values were the best ones for the proposed design. The permittivity of graphene is calculated by $\varepsilon_g = 1 + \omega \sigma_g / \omega_0 \varepsilon_0 l_g$, where $\varepsilon_0$ and $l_g$ are the vacuum permittivity and graphene thickness, respectively, and $\sigma_g$ is the conductivity of graphene estimated by Kubo formula (Yan and Li 2019; Yi et al. 2019a, b). The absorption performance of the graphene-based MMA can be easily tuned by adjusting the electric conductivity and relative dielectric constant of the graphene by changing the external bias voltage that is not possible in metallic structures which however requires variations in position of metallic patches on the substrate. The absorption peak position in Graphene MMA can be altered easily with the change in $E_g$ of graphene varying from 0.2 to 0.8 eV (Zhai et al. 2019; Yan and Li 2019; Wu and Li 2019; Jain et al. 2020a).

The fabrication of the proposed MMA can be carried out with electron-beam evaporation of Cr/Au (5/100 nm) onto the back side of SiO$_2$ substrate. After that suitable technique such as mechanical exfoliation/chemical vapor disposition will be utilized to deposit the monolayer of graphene flake/film onto the top of the substrate. Thereafter, a 2D array of periodic disk-shaped structures, i.e., split ring and the cross-shaped geometries, can easily be patterned on the graphene film surface using standard
photolithography technique following the Cr/Au (5/100 nm) deposition and lift-off process creating a metamaterial structure with an operating area of a few cm² (Tung and Tanaka 2018). The proposed MMA utilizes a continuous single graphene layer which makes fabrication easier for practical THz applications unlike other graphene MMAs having hollow petal structure (Wu and Li 2019) and dumbbell-shaped structure (Yan et al. 2020).

The equivalent circuit model (ECM) of the absorber has been analyzed using a transmission line model (Meng et al. 2018) in advanced design system (ADS) software, as demonstrated in Fig. 2a. The top metallic pattern is represented by RLC circuits in parallel, whereas bottom metallic plane is represented as a short transmission line. To obtain the \( R, L \), and \( C \) component values, curve fitting technique is utilized similar to given method in previous works (Deng et al. 2018; Zeng et al. 2018; Huang et al. 2018a). The reflection coefficient (\( \text{Im} (Z_{\text{in}}) = 0) \)) is \( \Gamma = (\text{Re}(Z_{\text{in}}) - Z_0) / (\text{Re}(Z_{\text{in}}) + Z_0) \), where \( Z_{\text{in}} \) and \( Z_0 \) are the MMA impedance and free space impedance (\( \approx 377 \Omega \)), respectively. The \( Z_{\text{in}} \) equals to \( Z_0 \) at the resonance frequency results into zero reflection and perfect absorption in the absorber.
3 Results and discussions

The finite-element method (FEM) is used to demonstrate multiple absorption peaks at 2.33 ($f_1$), 5.24 ($f_2$), 7.74 ($f_3$), 8.25 ($f_4$), 10.05 ($f_5$), 10.97 ($f_6$) and 12.61 THz ($f_7$) with absorption coefficients of 93.76, 98.90, 97.31, 95.56, 94.12, 94.75 and 99.81%, respectively, as shown in Fig. 1c. The full width at half maximum (FWHM) bandwidth at $f_1$ is 0.50 THz and $f_7$ is 0.40 THz and the corresponding quality factor ($Q = f_c/\text{FWHM}$, where $f_c$ is the center frequency of the resonance) is 4.66 and 31.52, respectively, which is better than previously reported absorbers (Fan 2019). The thickness and compactness of the proposed MMA are 0.036$\lambda$ and 0.21$\lambda$, respectively, at the lowest operational frequency. The theoretical and simulated absorption characteristics is shown in Fig. 2b, and is in well accordance with each other except some slight shift as theoretical results don’t take the approximations and boundary conditions into account.

The normalized impedance ($Z$) of the MMA can be estimated as (Bhattacharyya et al. 2013)

$$Z = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} = \frac{1 + S_{11}}{1 - S_{11}} \quad \text{(for } S_{21} = 0) \quad (1)$$

The real and imaginary normalized impedance should be nearly one and zero, respectively, as the impedance of the MMA must be equal to free space impedance to achieve perfect absorption (Yan 2019; Chaurasiya et al. 2016). The obtained $Z$ is 1.46 + j0.42, 1.14 + j0.17, 0.76 − j0.15, 0.82 + j0.35, 1.55 − j0.27, 0.93 + j0.44 and 0.96 − j0.01 at 2.33, 5.24, 7.74, 8.25, 10.05, 10.97 and 12.61 THz, respectively, as illustrated in Fig. 3a. To achieve unity impedance, effective permittivity ($\varepsilon_{\text{eff}}$) and effective permeability ($\mu_{\text{eff}}$) must be equal to effective permeability ($\mu_{\text{eff}}$), as $Z = \sqrt{\mu_{\text{eff}}/\varepsilon_{\text{eff}}}$. Figure 3b, c demonstrates the $\varepsilon_{\text{eff}}$ and $\mu_{\text{eff}}$ of the proposed MMA which are extracted by employing the S parameter retrieval method (Kalraiya et al. 2019). Table 1 shows that the real ($Re$) and imaginary ($Im$) values of normalized impedance are close to one and zero at perfect absorption, respectively. The values of real and imaginary values of EM parameters are found similar at perfect absorption as structure impedance equals free space impedance.
Figure 4a, b illustrate the simulated absorption response at different polarization angles varying from $0^\circ$ to $90^\circ$ suggesting that the absorber is polarization insensitive due to the symmetric shape of the structure. Such characteristics have various potential applications such as sensing, detection, and optoelectronic applications. In addition, the proposed MMA is demonstrating with different incident angles as shown in Fig. 5a, b,
Table 1 Comparison of real and imaginary values of normalized impedance and constitutive EM parameters

| Frequency (THz) | Absorption rate (%) | Re (Z) | Im (Z) | Re ($\varepsilon_{\text{eff}}$) | Re ($\mu_{\text{eff}}$) | Im ($\varepsilon_{\text{eff}}$) | Im ($\mu_{\text{eff}}$) |
|----------------|---------------------|--------|--------|-------------------------------|------------------------|------------------------|------------------------|
| 2.33           | 93.76               | 1.46   | 0.42   | 2.53                         | −2.56                  | 5.39                   | 12.48                  |
| 5.24           | 98.90               | 1.14   | 0.17   | 1.49                         | 0.33                   | 3.24                   | 4.33                   |
| 7.74           | 97.31               | 0.76   | −0.15  | 0.39                         | 1.34                   | 3.33                   | 1.91                   |
| 8.25           | 95.56               | 0.82   | 0.35   | 2.05                         | 0.16                   | 2.50                   | 1.97                   |
| 10.05          | 94.12               | 1.55   | −0.27  | 0.83                         | 1.43                   | 1.21                   | 3.14                   |
| 10.97          | 94.75               | 0.93   | 0.44   | 1.75                         | 0.17                   | 1.56                   | 1.70                   |
| 12.61          | 99.81               | 0.96   | −0.01  | 0.88                         | 1.12                   | 1.50                   | 1.63                   |

Fig. 4 a Absorption response at different polarization angles ($\phi$) from 0° to 90°. b Absorbance as a function of frequency and polarization angle at the normal incidence

Fig. 5 a Simulated absorption response at different incident angles ($\theta$) from 0° to 60°. b Absorbance as a function of frequency and incident angle
which suggests that the absorber is sensitive to the incidence angles, similar to previously reported work (Zhang et al. 2019c).

To understand the physical phenomenon of the hepta-band absorber, e-field distribution of the proposed MMA is analyzed at 2.33, 5.24, 7.74, 8.25, 10.05, 10.97, and 12.61 THz, as shown in Fig. 6. It is obvious from Fig. 6a, c, e, e-field is mainly accumulated on the outer side of the SRC resonator, hence, these modes \( f_1, f_3 \), and \( f_5 \) are attributed to the dipole response. Furthermore, Fig. 6b, d suggest e-field distributions are mainly focused on gaps of SRC resonator for mode \( f_2 \) and \( f_4 \) which can be attributed to LC resonance of the structure. Besides for modes \( f_6 \) and \( f_7 \), the e-field distribution can be found in the cross as well as in gaps of the SRC resonator, see Fig. 6f, g, which is due to the combination of the dipole response and LC resonance of the structure. The optimized structure of the proposed MMA, i.e., SRC-shaped resonator, along with combination of dipolar and LC resonance from the metallic structure in Fig. 6a–g enables the hepta-band absorption characteristics.

To analyze the effect of substrate thickness and unit cell dimensions (\( d \)), parametric analysis is carried out as shown in Fig. 7a, c, respectively. The absorption response is analyzed with the change in substrate thickness from 4.7 to 5.0 \( \mu m \) suggesting a red shift phenomenon with the increase in thickness as the resonating frequency is inversely proportional to the substrate thickness (Zhang et al. 2019b). The absorption peaks shift towards the lower frequencies with the increase in unit cell dimension as the wavelength is directly proportional to the unit cell dimension. Further, Fig. 7b, d shows the color graph having absorbance as a function of frequency with substrate thickness and unit cell dimension, respectively.

The sensing performance of the proposed MMA is demonstrated using overlayer thickness and permittivity where overlayer is the material that is to be added on top of the structure. For the first step, OL thickness has been changed from 0 (corresponds to air) to 2.5 \( \mu m \) and the permittivity is set to 3.9. Figure 8a, b show the absorption response for various OL thickness demonstrating the blue shift with the increase in thickness. The shift in the resonating frequencies can be attributed to the increase in the capacitance of the structure as the thickness increases (Wang et al. 2015, 2016; Jain et al. 2021). The frequency shifts with their respective peaks are 310 GHz (\( f_1 \)), 930 GHz (\( f_2 \)), 890 GHz (\( f_3 \)), 1030 GHz (\( f_4 \)).

![Fig. 6 Electric field distribution on the top layer at a 2.33 THz, b 5.24 THz, c 7.74 THz, d 8.25 THz, e 10.05 THz, f 10.97 THz, g 12.61 THz](image-url)
Fig. 7  
(a) Dependence of the absorption response of the proposed absorber with different substrate thickness ranging from 4.7 to 5.0 μm, 
(b) absorbance as a function of frequency and substrate thickness, 
(c) dependence of the absorption response of the proposed absorber with different unit cell dimension from 27.2 to 28.8 μm, 
(d) absorbance as a function of frequency and unit cell dimension

Fig. 8  
(a) Dependence of the absorption response with the change in thickness of the overlayer ranging from 0 to 1.5 μm, 
(b) absorbance as a function of frequency and overlayer thickness
(f₄), 1240 GHz (f₅), 850 GHz (f₆), and 1100 GHz (f₇) when the thickness is increased from 0 to 2.5 μm. The result suggests that these characteristics can be utilized to make a pressure sensor (Wang et al. 2015); in particular, the resonating frequencies f₄, f₅, and f₇ will offer a high-sensitive OL thickness sensing (Wang et al. 2016). For the second step, the thickness was set to 1.5 μm and permittivity has been changed from 1 (corresponds to air) to 4, to analyze the absorption response. The resonating frequency decreases with the increase in permittivity as demonstrated in Fig. 9a, b. The permittivity of the overlayer is increased from 1 to 4, the shift in frequency with their respective peaks are 190 GHz (f₁), 790 GHz (f₂), 640 GHz (f₃), 820 GHz (f₄), 750 GHz (f₅), 350 GHz (f₆) and 660 GHz (f₇).

Table 2 demonstrates the comparison of previously reported studies with proposed MMA in terms of thickness, unit cell size, and resonating frequencies which suggests that the proposed MMA is ultrathin (0.036λ) and compact (0.21λ) utilizing a single metallic structure. In refs. (Li et al. 2019; Wang 2017; Zhang et al. 2019b; Wang et al. 2015), multiband absorbers were proposed by utilizing multiple resonators of different sizes. However, these approaches suffer from technical difficulties due to larger size and thickness which

| References            | Lowest frequency (THz) | Unit cell size (μm) | Dielectric thickness (μm) | Resonances |
|-----------------------|------------------------|---------------------|---------------------------|------------|
| Wang et al. (2015)    | 0.77                   | 0.583 λ₀            | 0.109 λ₀                  | Quad       |
| Hu et al. (2016)      | 1.09                   | 0.254 λ₀            | 0.041 λ₀                  | Quad       |
| Meng et al. (2018)    | 1.12                   | 0.283 λ₀            | 0.029 λ₀                  | Quad       |
| Wang (2017)           | 1.85                   | 0.431 λ₀            | 0.043 λ₀                  | Quad       |
| Huang et al. (2018b)  | 6.53                   | 0.435               | 0.07                      | Triple     |
| Zhang et al. (2019b)  | 3.95                   | 0.466 λ₀            | 0.066 λ₀                  | Penta      |
| Li et al. (2019)      | 4.58                   | 0.036 λ₀            | 0.071 λ₀                  | Dual       |
| Zhang et al. (2019a)  | 3.5                    | 0.35 λ₀             | 0.05 λ₀                   | Dual       |
| Yan (2019)            | 0.48                   | 0.432 λ₀            | 0.084 λ₀                  | Single     |
| Proposed work         | 2.33                   | 0.21 λ₀             | 0.036 λ₀                  | Hepta      |
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limits practical applications. In addition, the proposed absorber utilizes a single metallic structure demonstrating seven absorption peaks (2.33, 5.24, 7.74, 8.25, 10.05, 10.97, and 12.61 THz) with polarization insensitive characteristics which is better than previously reported MMA (Yan 2019; Zhang et al. 2019a; Huang et al. 2018b; Meng et al. 2018; Hu et al. 2016). The proposed MMA, i.e. split-circular ring joined diagonally, along with higher order of resonances from the metallic structure in Fig. 6a–g enables the multi-band absorption characteristics which is better than that of the above mentioned previous studies.

4 Conclusions

A simple design of hepta-band MMA comprised of a split-ring-cross (SRC)-shaped resonator deposited on continuous graphene/SiO2/Au was presented numerically and theoretically for the terahertz applications. The multiple absorption peaks were found at 2.33, 5.24, 7.74, 8.25, 10.05, 10.97, and 12.61 THz with absorptivities more than 90%. The hepta-band absorption was mainly originated from the combination of the dipolar and LC resonances of the metallic resonator which is explained by analyzing the e-field distribution. The proposed hepta-band MMA is compact, ultra-thin and polarization insensitive, which are significant advantages suggesting potential applications in various fields including sensing, imaging, and detection. The sensing performance of the proposed MMA was also studied with different overlayer thickness and permittivity.

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Availability of data and materials All data generated or analyzed during this study are included in this article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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