Multiband Polarization Insensitive and Tunable Terahertz Metamaterial Perfect Absorber Based on The Heterogeneous Structure of Graphene

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Research Article

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Abstract
In this paper, we present and investigate a multi-band metamaterial perfect absorber (MPA) based on the heterogeneous structure of graphene with Cu and SiO\textsubscript{2} substrates. The top layer of structure consist of one graphene disk at the center and four graphene solid triangle with semicircular cuts on them that surround the central disk. This heterogeneous structure causes us to achieve 97.06%, 94.71%, 99.7% and 99.5% perfect absorptions peaks at 28239.7 nm, 31048.9 nm, 50898.6 nm and 70689.1 nm, respectively. The absorption mechanism based on electric fields has been investigated. We can shift the wavelength of absorption peaks to our required wavelength by changing the Fermi level (µc) of graphene. Two absorption peaks of this absorber remain unchanged in different incident angle. In addition, very important point about this structure is that it is not sensitive to polarization and this feature makes the proposed absorber very suitable for applications such as imaging, filtering, sensing and detecting applications.

Key word: Metamaterial perfect absorber, Multi-band, Graphene, Tunable, Polarization insensitive, Terahertz.

Introduction
With the increasing development of communication technology and the use of frequency in the terahertz range, the need for tools and equipment in this frequency range is inevitable. This need drew the attention of all terahertz range researchers to metamaterials. A metamaterial is any material engineered to have a property that is not found in naturally occurring materials [1]. Metamaterials have special properties such as negative refraction [2, 3], cloak [4, 5] superlunary [6, 7] and backward wave [8, 9], and for this reason, they have been highly regarded by researchers in the field of electromagnetism. One of the most important and practical metamaterials is graphene. Graphene is a metamaterial made of graphite, and graphite itself is made up of layers of carbon atoms arranged hexagons. Each of these layers is fastened together with a strong bond. By breaking these bonds according to Fig. 1, we can reach the graphene metamaterial, which is a single layer of carbon atoms, and because of this, it is called a two-dimensional metamaterial [10].

Graphene has received a great deal of attention in the construction of antennas and alternating structures, including absorbers, electromagnetic shields, and electromagnetic sensors, due to its small size, two-dimensionality, high conductivity and its adjustable conductivity [11, 12]. In the last decade, we have done research and development in the field of design and improvement of graphene structures. Due to the use of graphene in antennas has brought us significant benefit such as extreme miniaturization, monolithic integration with graphene RF Nano-electronics, efficient dynamic tuning, and even transparency and mechanical flexibility [13], the idea of designing graphene antennas has been a step to ahead.

Fig. 1 Exfoliation of graphite to create graphene

Since we can change the chemical potential of graphene by external bias voltage or chemical doping, graphene is an adjustable metamaterial [14]. We used this graphene capability to design the antennas with performance in far-field and terahertz range central frequency due to control its polarization just by changing the Fermi energy level of the graphene [15-18]. Another application of graphene is the design and construction of absorbers that operate in the microwave [19, 20] and terahertz [21, 22] range. Electromagnetic absorbers are specifically selected or designed materials that can inhibit the reflection or transmission of electromagnetic radiation. Features that are important in absorbers are full absorption (close to 100% adsorption), insensitivity to polarization and incident angle of radiation.
Absorbers that use metamaterials in their design and have absorption close to 100% are called metamaterial perfect absorbers (MPA) [23-26]. There are two types of absorbers: resonant absorbers [27-29] and wideband absorbers [30-32]. Terahertz band absorbers have many applications such as sensing, imaging, modulating, detection, filtering, etc. [33-35].

The mechanism of absorption of multilayer absorbers is such that the underlying conductive layer does not allow radiation to pass through the structure. In addition, the intermediate dielectric layer and the metamaterial placed on the dielectric must also be designed so that the waves reflected from inside the structure have a phase difference aiming to neutralize each other, in order to the structure reach to the perfect absorption.

One of the characteristics that makes the absorber structure unique for different applications is the insensitivity of the structure to polarization [36] and incident angle [37].

In this paper, we present a multi-band perfect metamaterial absorber that has one graphene disk at the center and four graphene solid triangle with semicircular cuts on them that surround the central disk. The dielectric of the middle layer and the conductive of underlying layer of the structure are SiO\(_2\) and Cu, respectively. One of the advantages of this structure is in its construction, because in this structure, copper conductor is used in the lower layer to prevent radiation transmission, which is more economical than structures in which gold is used in the lower layer [38-41]. The proposed absorber is a resonant absorber that has four perfect absorption peaks, which are 97.06%, 94.71%, 99.7% and 99.5% at wavelengths of 28239.7 nm, 31048.9 nm, 50898.6 nm and 70689.1 nm, respectively.

**Structure and Design**

As shown in Fig. 2(a), we present a three-layer absorber. The bottom layer of the absorber is a cube with dimensions \(L \times L\) (\(L = 3\) \(\mu\)m) and a thickness of 0.5 \(\mu\)m. The material of this substrate is copper with conductivity of \(\sigma_{Cu} = 5.813 \times 10^7\) S/m [42]. This conductor has the task of reducing the radiation transmission from the structure to zero. Our middle layer is a cube with the same dimensions \(L \times L\) and a thickness of 4.9 \(\mu\)m. In addition, its dielectric material is SiO\(_2\) with a relative permittivity of \(\epsilon_r = 3.9\) [43, 44].

As mentioned, graphene is a two-dimensional material that is placed on our SiO\(_2\) layer. According to Fig. 2 (b), the central graphene disk has a radius of \(R = 0.55\) \(\mu\)m. The four triangles that surround the central disk are equal in size. The height of each triangle is \(w = 0.95\) \(\mu\)m and the base of each of them is equal to \(L = 3\) \(\mu\)m. We also cut each triangle into a semicircle so that all the semicircles are equal and have a radius \(R = 0.55\) \(\mu\)m.

**Simulation Results**

We performed the simulations at room temperature (\(T = 300\) K) using the CST Studio Suite software.

As shown in Fig. 3, by setting the parameters of graphene to \(\mu_c = 0.8\) eV and \(\tau = 1.6\) ps, the structure has four perfect absorption peaks, which are 97.06%, 94.71%, 99.7% and 99.5% at 28239.7 nm, 31048.9 nm, 50898.6 nm and 70689.1 nm, respectively.
This structure is tunable; it means that we can shift the frequency of absorption to a required frequency for the intended application or increase and decrease the amount of absorption at the desired frequency by changing Fermi level or relaxation time of graphene. We changed the Fermi level of graphene to different values, and you can see the frequency changes of the absorption peaks in Fig. 4(a). We also changed the relaxation time of graphene in Fig. 4(b), where you can see the changes in the absorption peaks of the structure.

As you can see in Fig. 5, one of the good advantages of this structure is that we can increase the number of absorption peaks by changing the Fermi level of graphene (for example changing it to 0.5 eV) and changing the relaxation time of graphene (for example changing it to 0.5 ps). By this setting our structure has six absorption peaks, four of those are above 90%, one of those is above 85% and the other one is above 75%. This setting is used for applications where the number of absorption peaks takes precedence over the absorption rate.

One feature that is very important in absorbers is the insensitivity of the structure to polarization. As you can see in Fig. 6(a), the absorber presented in this paper is polarization insensitive because the absorption peaks remain unchanged at different angles of polarization. This feature makes the proposed absorber very suitable for applications such as imaging, detecting, filtering, sensing, etc.

As shown in Fig. 6(b), it is obtained that the absorption peaks at wavelengths 28239.7 nm and 50898.5 nm with different incident angles (From 0 to 45 degrees) remain almost unchanged. Especially at the 28239.7 nm peak, the absorption rate increases slightly with increasing incident angle. This makes the proposed absorber more widely used in various applications.

**Discussion and Comparison**

The absorption mechanism of this absorber is such that the bottom layer of copper does not allow radiation to pass through the structure. In addition, the middle layer of SiO$_2$ and graphene placed on the layer of SiO$_2$ is also designed in such a way that the waves reflected from inside the structure have a phase difference and neutralize each other, thus the structure reaches four full absorption peaks.
Fig. 6  Absorption spectra of structure for (a) different polarization angles and (b) different incident angles.

Fig. 7  Electric field [real (Ez)] distributions in the normal incidence of TE waves at wavelengths of (a) $\lambda = 28239.7$ nm (b) $\lambda = 31048.9$ nm (c) $\lambda = 50898.6$ nm (d) $\lambda = 70689.1$ nm

As a result, the second resonance at wavelength of $\lambda = 31048.9$ nm can be considered due to the graphene resonance at these points. A similar analysis of Fig. 7 (c) shows that the electric field is concentrated on a part of the surface of graphene triangles located in the y direction along the semicircular cuts and the graphene disk, and this concentration extends to the edges of the graphene disk. So the third resonance at the wavelength of $\lambda = 50898.6$ nm is attributed to the resonance of these points. Finally, in Fig. 7 (d), it is clear that the electric field is concentrated in the lower two corners and along the sides of the triangles located in the x direction. Therefore, we can conclude that the fourth resonance at wavelength of $\lambda = 70689.1$ nm is due to resonance at these points.
Table 1  Comparison between the features of the absorber structure of different articles with the features of the proposed absorber structure in this paper

| Feature | Absorption freq. / wavelengths (THz/nm) | Absorption peaks (THz/nm) | Polarization sensitivity | Incident angle sensitivity |
|---------|----------------------------------------|---------------------------|--------------------------|----------------------------|
| References | | | | |
| [45] | 0.60 THz | 99.10% | Sensitive to polarization | No analysis has been done |
| | 0.80 THz | 99.90% | | |
| | 1.74 THz | 98.77% | | |
| | 2.33 THz | 98.82% | | |
| | 2.75 THz | 99.99% | | |
| | 3.63 THz | 99.63% | | |
| [46] | 4.95 THz | 99.8% | No analysis has been done | No analysis has been done |
| | 9.2 THz | 99.6% | | |
| [47] | 1.054 THz | 90.6% | Sensitive to polarization at three absorption peaks | Insensitive to incident angle (at a wide angle) |
| | 2.16 THz | 97.2% | | |
| | 3.59 THz | 93.95% | | |
| | 3.87 THz | 99.61% | | |
| [48] | 0.8 THz | 99.43% | Polarization insensitive | Insensitive to incident angle (at a wide angle) at two absorption peaks |
| | 1.72 THz | 99.92% | | |
| | 3.38 THz | 99.58% | | |
| [49] | 0.245 THz | 97.5% | Polarization insensitive | Insensitive to incident angle (at a wide angle) |
| [50] | 0.114 THz | 97.9% | Polarization insensitive | Insensitive to incident angle (at a wide angle) |
| | 0.181 THz | 99.8% | | |
| [51] | 1.16 THz | 99.6% | Polarization insensitive | Insensitive to incident angle (at a wide angle) at two absorption peaks |
| | 2.73 THz | 99.8% | | |
| | 4.57 THz | 99.5% | | |
| [52] | 0.80 THz | In an average of 97.54% | Polarization insensitive | No analysis has been done |
| | 2.89 THz | | | |
| | 3.98 THz | | | |
| | 4.36 THz | | | |
| [53] | 1.92 THz | 98.4% | No analysis has been done | No analysis has been done |
| | 4.62 THz | 98.3% | | |
| | 8.81 THz | 99.6% | | |
| [54] | 2.59 THz (OS) | Larger than 90% | Polarization insensitive in both TS and OS | Sensitive to incident angle in both TS and OS |
| | 3.03 THz (OS) | | | |
| | 6.54–7.10 THz (OS) | | | |
| | 3.12 THz (TS) | | | |
| | 6.00–7.21 THz (TS) | | | |
| [55] | 1085.03 nm | 95.88% | Insensitive to polarization in TM mode | Insensitive to incident angle (at a wide angle) in TM mode |
| | 1131.48 nm | 99.81% | | |
| | 1187 nm | 97.44% | | |
| | 1365.35 nm | 95.30% | | |
| Proposed absorber | 28239.7 nm | 97.06% | Polarization insensitive | Insensitive to incident angle (at a wide angle) at two absorption peaks |
| | 31048.9 nm | 94.71% | | |
| | 50898.6 nm | 99.7% | | |
| | 70689.1 nm | 99.5% | | |
As mentioned, more absorption peaks, high absorption rate, insensitivity to polarization and incident angle of incident wave are some of the features that distinguish the metamaterial absorber. For this purpose, in Table 1, we have compared the metamaterial absorber presented in this paper with some of the metamaterial absorbers presented in recent years in terms of having or not having these properties.

As it is known, the proposed absorber has more absorption peaks than some of the compared absorbers and has a higher absorption rate than some of them. In addition, the proposed absorber in comparison with some of the absorbers presented in Table 1 has the advantage of insensitivity to polarization and the incident angle at its two absorption peaks. As a result, the proposed absorber is more flexible and suitable for many applications such as imaging, detecting, sensing, filtering, etc. due to multi-band absorption, complete absorption, insensitivity to polarization and insensitivity to the incident angle at its two absorption peaks.

Conclusion
In recent years, many terahertz absorbers have been introduced. The absorber presented in this paper is a multi-band metamaterial perfect absorber that has the ability to adjust and increase the absorption peaks only by changing the Fermi level or the graphene relaxation time, without the need for structural change. In addition, this absorber is insensitive to polarization and its two absorption peaks remain almost unchanged in various incident angles (from 0 to 45 degrees). All these features make the absorber very suitable for applications such as imaging, detection, sensing and filtering.

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Authors’ Contributions
Amirhossein Norouzi Razani: conceptualization, methodology, software, result analysis, writing - original draft, writing—review and editing. Pejman Rezaei: validation, data curation, writing—review and editing, supervision.

Data Availability
All data generated or analyzed during this study are included in this published article.

Compliance with Ethical Standards
Competing Interests The authors declare that they have no conflict of interest.

Ethical Approval
We declare that this article is original, has not been published before, and is not currently considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

Consent for Publication
Written informed consent for publication was obtained from all participants.

Consent to Participate
Written informed consent for participate was obtained from all participants.

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Figure 1

Exfoliation of graphite to create graphene.
Figure 2

(a) Unit cells structure from three-dimensional view. (b) Dimensions of the absorber structure from a two-dimensional view. (These figures were prepared using COMSOL Multiphysics software).
Figure 3

Absorption spectra of structure with $\mu_c = 0.8$ eV and $\tau = 1.6$ ps.
Figure 4

Absorption spectra of structure for (a) different Fermi level $\mu_c$ at $\tau = 1.6$ ps and (b) different relaxation time $\tau$ at $\mu_c = 0.8$ eV.
Figure 5

Increasing the number of absorption peaks by setting $\mu c=0.5 \text{ eV}$ and $\tau =3 \text{ ps}$.

Figure 6

Absorption spectra of structure for (a) different polarization angles and (b) different incident angles.
Figure 7

Electric field [real (Ez)] distributions in the normal incidence of TE waves at wavelengths of (a) $\lambda = 28239.7$ nm (b) $\lambda = 31048.9$ nm (c) $\lambda = 50898.6$ nm (d) $\lambda = 70689.1$ nm