Polarization and Wide Incident Angle Insensitive Metal Free Superwideband Absorber For Terahertz and Infrared Spectrum

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Research Article

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Abstract

A circular slot loaded octagonal metal free graphite based absorber for superwideband applications at terahertz and infrared spectrum is proposed. The absorber comprises a circular slot loaded octagonal graphite slab at the top layer, silicon dioxide as substrate and square graphite slab as the bottom layer. This absorber is operating over a frequency spectrum of 6 THz to more than 80 THz (ratio bandwidth of > 12:1 and fractional bandwidth of > 172.093%) for absorption more than 90% with unity peak absorption. The absorber dimensions are 5 µm × 5 µm × 7.04 µm. The thickness of the substrate is only ~ λo/26 and the periodicity of absorber is ~ λo/10 at 6 THz. The performance of the absorber is found to be insensitive to changes in polarization angle (Φ). Furthermore, the performance of the absorber is observed to be unaffected by incident angle (θ) variations from 0° to 60°. The metal-free geometry along with insensitiveness to Φ and 0° ≤ θ ≤ 60° makes the proposed absorber suitable for compact terahertz/infrared micro/nanoscale systems.

I. Introduction

Terahertz (THz) spectrum has received much interest from academia and industry in the last two decades for its vast applications in communication, imaging, medical, radar, sensing, spectroscopy, and other fields. The field of absorbers has been determined to be the most practical use of the THz spectrum. Researchers have recently reported several single and multilayered geometry-based terahertz absorbers having narrowband, multi-band, wideband, and frequency-dependent reconfigurable performance [1–34]. Different techniques leading to the excitation of multiple resonances are used to design multi-band absorbers. The merging of these multiple resonances leads to wideband performance. Multilayered or multiple stacked systems provide wide bandwidth; however, they are challenging to implement. The easy to implement single layer structures provide limited operating frequency range. Therefore, a major challenge is to design a broadband absorber having single layer of substrate without any stacking of metallic/graphene layers.

Another challenge faced during absorber designing is the limited performance at higher frequencies due to the metals’ limited electrical properties and high-temperature sensitivity, which is mainly responsible for incident power absorption in metal/dielectric multi-layered absorbers [27, 28]. Few researchers have reported absorbers based on vanadium oxide, a temperature-sensitive & phase change material [21, 29]. They provide desired wideband performance even at high temperatures, but these high temperatures affect the functioning of other nano-scale components. All the above-discussed broadband absorbers have complex fabrication techniques, thick geometries, and temperature-dependent performance. Thus, there is a need to design broadband absorbers whose fabrication is easy, the substrate thickness is negligible, and the performance is temperature independent. According to the available literature, metal-free absorbers like graphite/dielectric-based absorbers and semiconductor grating-based absorbers have provided temperature-independent performance [26, 30, 31]. The major reason for the usage of graphite in flexible electronics components like THz antennas and high-frequency absorbers is its better temperature stability [21]. These broadband metal-free absorbers can cover only a small portion of the terahertz spectrum. The future requirements require the coverage of both terahertz and infrared spectrum.

This paper presents the design and analysis of a metal-free graphite/dielectric-based super wideband absorber. The combination of circular slot-loaded octagonal graphite slab, silicon dioxide dielectric material, and square graphite slab resulted in an operating frequency range from 6 THz to more than 80 THz with the absorption of more than 90% for the normal incidence of electromagnetic waves. In two frequency bands of 7.85–13.05 THz and 22.47 THz to more than 80 THz, the absorption is found to be more than 95%. In the frequency spectrum of 25.35–28.71 THz, 44.68–74.65 THz, and 79.52 THz to more than 80 THz, the absorption is more than 99%. The proposed absorber's overall volume is significantly lesser than several dielectric, metamaterial, and grating-based structures. The advantageous features of planar metal-free geometry with miniaturized dimensions, low volume, insensitivity to polarization angle, and wide
incident angle range make this absorber compatible with the future nanoscale super wideband terahertz and infrared systems.

II. Absorber Design

The proposed antenna geometry, shown in Fig. 1, is a three layered structure. In the proposed absorber, a 1.54 µm thick silicon dioxide substrate is sandwiched between two graphite slabs. The top graphite slab is octagonal in shape. It is loaded with a central circular slot. During the simulation of the proposed absorber structure by using finite integration technique (FIT)-based CST Microwave Studio (CST MWS), periodic boundaries are fixed along x- and y-axis. Along the z-axis i.e. transmission direction, open boundary conditions are fixed. This absorber is designed in three stages i.e. initially only graphite ground is analyzed. In second stage, the combination of graphite ground and substrate is analyzed. In the last stage, the circular slot loaded octagonal graphite, substrate material and graphite ground plane are analyzed together.

III. Results And Discussion

The magnitudes of reflectance ($S_{11}$) and transmittance ($S_{21}$) for all absorber designing stages are shown in Fig. 2. It is observed that for each stage the magnitude of transmittance is almost zero i.e. $|S_{21}| \approx 0$. The reflectance for first stage is decreasing linearly from 1 to 0.7 in the frequency range of 1 to 80 THz without any resonance. For second stage, two resonance at the frequencies of 22.79 and 69.85 THz with $|S_{11}|$ of 0.55 and 0.23 are observed. In the last stage, the reflectance is observed to be sharply decreasing from 1 to 0.1 with three resonances. For the frequency range of 6.33 THz to more than 80 THz, the reflectance magnitude is less than 0.3. By using these values of reflectance and transmittance in the absorption equation, $A = 1 - |S_{11}|^2 - |S_{21}|^2$ the values of absorption are calculated for each designing stage. Since $|S_{21}|=0$, therefore the above equation is reduced to $A = 1 - |S_{11}|^2$. The absorption values for each designing stage are shown in Fig. 2 (c). For first stage, a maximum absorption of 50% is achieved. In second stage, two peaks having absorption of 70% and 95% are observed at resonance frequencies. In the last stage, absorption of more than 90% is achieved in the frequency spectrum of 6THz to more than 80 THz. Figure 3 illustrates a good agreement between the absorption in both modes i.e. transverse electric (TE) and magnetic (TM) for the proposed absorber.

To analyze the polarization sensitiveness of this absorber, the polarization angle ($\Phi$) is varied from 0° to 90°. Due to the geometrical symmetry, this absorber is insensitive to the variations in polarization angle as shown in Fig. 4.

Table 1 illustrates that the proposed absorber has widest bandwidth (6 THz to more than 80 THz) along with minimum volume of 176 µm$^3$ among the compared structures. The proposed absorber is covering terahertz frequency spectrum from 6–10 THz and infrared region from 10 THz to more than 80 THz whereas the operating band of other absorbers is covering only a narrow portion of the terahertz spectrum. In addition to this, this absorber is polarization angle and wide incident angle insensitive.
### Table 1
Comparison of proposed absorber with other absorber structures

| Reference | Geometry                                | Material                                | Unit cell dimensions (µm × µm × µm) | Absorption operating range in THz / (Absorption criteria in %) | % BW               | Polarization insensitivity | Incident Angle (θ°) (for A > 90%) |
|-----------|-----------------------------------------|-----------------------------------------|-------------------------------------|---------------------------------------------------------------|-------------------|-----------------------------|----------------------------------|
| [6]       | Multiple square patches resonators      | Copper and SiO2                          | 20×20×0.7                           | 6.23–7.08 THz / (80) 6.24–7.04 THz / (90)                     | 12.772            | yes                         | 12.048                           |
| [7]       | Multiple stacked bars resonators        | Polyimide and Gold bars                  | Not available                       | 0.8-1.368 THz / (80) 0.8 to 1.28 THz / (90)                   | 52.399            | no                          | 40 40                            |
| [8]       | Hybrid Structure                        | Polyimide and Gold                       | 376×376                             | 0.13 THz(80) 0.22–0.33 THz / (90)                             | 46.154            | yes                         | 45 45                            |
| [9]       | Sectional asymmetric structure          | Au and Si3N4                              | 19.4×19.4                           | 4.6–5.1 THz / (80)                                            | 10.309            | No                          | 30 30                            |
| [10]      | Fractal cross resonators                | Polyimide and Gold                       | 40×40×11.24                         | 3.01–4.84 THz / (80)                                          | 46.624            | -                           | 45 45                            |
| [11]      | Stacked cross resonators                | Parylene, Gold, Aluminium and Silicon    | 80×80×12                            | 7.1-8 THz / (80)                                              | 11.921            | -                           | - -                              |
| [12]      | Nested circular rings                   | Copper and polyimide                     | 30×30×10.2                          | 1.6–2.6 THz / (80) 0.896 THz / (90)                           | 47.619            | Yes                         | 60 60                            |
| [13]      | Truncated pyramid structure             | SU8 polymer and gold                     | 95×95×21                            | 0.75–1.5 THz / (80)                                           | 66.667            | Yes                         | 30 70                            |
| [14]      | Grating structure                       | Doped Silicon                            | 100×100×500                         | 0.58–2.58 THz / (90)                                          | 126.582           | Yes                         | 45 55                            |
| [15]      | Multiple I-shaped strips                | Polyimide and gold                       | 78×78×8.5                           | 0.87–0.97 THz / (80)                                          | 10.87             | Yes                         | 60 60                            |
| [16]      | Pythagorean tree fractal structure      | Polyimide and gold                       | 69×69×22.2                          | 7.5–10 THz / (90)                                             | 28.571            | No                          | 0 0                              |
| [17]      | Multiple diamond array                  | Dielectric and diamond                   | 170×170×310                         | 1.3 THz / (90)                                                | 95.65             | No                          | 45 40                            |
| Reference | Geometry | Material | Unit cell dimensions \((\mu m \times \mu m \times \mu m)\) | Absorption operating range in THz / (Absorption criteria in %) | % BW | Polarization insensitivity | Incident Angle \((\theta^o)\) (for A > 90%) |
|-----------|----------|----------|-------------------------------------------------|---------------------------------------------------------------|-------|--------------------------|-------------------------------------|
| [18]      | Slot loaded rectangular structure | Metal and Dielectric | 88×88×14 | 1.3–2.7 THz / (90) | 70 | No | - |
|           |          |          |                                                  | 1.24–2.86 THz / (50)                                          |       |                          |                                      |
| [19]      | three-layer structure, comprising square-, cross-, and circular-shaped | Metal, dielectric and graphite | 58×58×50 | 0.55–3.12 THz / (90) | 140 | Yes | 15 45 |
| [20]      | square ring and multiple T-shaped resonators | Metal and dielectric | 120×120×22 | 4.904–6.632 THz / (90) | 29.95 | Yes | 0 0 |
| [21]      | L shaped resonators | VO2 and dielectric | 50×50×26 | 1.2–3.2 THz / (90) | 90.90 | No | 50 50 |
| [22]      | Cross shaped resonators | Metal and dielectric | 225×225×325 | 0.65–2.45 THz / (90) | 116.12 | Yes | 40 40 |
| [23]      | Rectangular ring loops | Metal,dielectric and nitride | 70×70×24 | 1.17–2.99 THz / (90) | 87.5 | Yes | 30 30 |
| [24]      | wheel hub-like | Metal | 200×200×90 | 1.6–5 THz / (90) | 103 | Yes | 45 70 |
| [25]      | Multiple circular resonators | Metal, dielectric and graphite | 80×24×28 | 1.6–3.2 THz / (90) | 63.91 | No | 50 - |
| [26]      | Annular ring | Dielectric and graphite | 85×85×50.2 | 0.65–3.03 THz / (90) | 129.34 | Yes | 50 50 |
| Proposed Absorber | Octagonal Annular Ring | Dielectric and graphite | 5×5×7.04 | 6 THz to more than 80 THz (90)/ 4.8 THz to more than 80 THz (80) | > 172.093 | Yes | 60 60 |

**Iv. Conclusion**

A superwideband absorber based on dielectric and graphite material for operation at terahertz and infrared frequency spectrum is investigated. It has an operating bandwidth of more than 74 THz starting from 6 THz for absorption more than 90%. Due to the presence of only graphite as conducting material, this absorber will be insensitive to the
temperature variations. Since the absorber geometry is symmetrical, it has insensitiveness to polarization angles. It is insensitive to a wide range of incident angle variations up to 60°.

Declarations

* Ethics approval: Not Applicable

* Consent to participate: Not applicable

* Consent for publication: Not applicable

* Availability of data and materials: Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Please include the sub-sections below of Compliance with Ethical Standards section.

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* Research involving Human Participants and/or Animals: Not applicable

* Informed consent: Only single author is there

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Figures
Figure 1
Geometry of proposed absorber (a) top view, (b) side view (all dimensions are in µm)

Figure 2
Performance of design stages (a) reflectance magnitude, (b) transmittance magnitude and (c) absorption
Figure 3

Absorption in TE and TM modes

Figure 4

Absorption of proposed absorber with variations in polarization angle
Figure 5

Absorption of proposed absorber with variations in incidence angle in TE mode

Figure 6

Absorption of proposed absorber with variations in incidence angle in TM mode