URSI-RCRS 2024, ARIES/GEHU, Bhimtal, India, 22 - 25 October, 2024

A Dual Band Polarization Insensitive Metasurface Absorber for Terahertz Applications

Ajeet Singh Verma*, Somak Bhattacharyya
Department of Electronics Engineering, Indian Institute of Technology (BHU) Varanasi, India-221005
ajeetsinghverma.rs.ece23@itbhu.ac.in, somakbhattacharyya.ece@iitbhu.ac.in

Abstract

This paper presents a dual-band graphene based metasurface absorber in terahertz region with tunable characteristics. The proposed structure comprises three layers consisting of a top graphene layer with slotted square ring pattern grown over a thick silicon dioxide (SiO_2) layer backed by a bottom gold layer. The proposed structure offers absorptivity greater than 90% over two distinct frequency bands, offering bandwidth of 1.1 THz ranging from 3.98 THz to 5.08 THz with peak absorptivity at 4.42 THz and 4.02 THz ranging from 6.55 THz to 10.57 THz respectively. The second absorption band contains two absorption peaks at 7.34 THz and 10.22 THz. The proposed structure is polarization-independent due to its four-fold symmetric design. The proposed structure works up to 50^o oblique incidences for both TE and TM-polarized electromagnetic waves. The structure offers periodicity of ~λ/13 with reference to the lowermost frequency of absorption and the thickness of the structure is ~λ/11, satisfying the condition of effective homogeneity for the metasurface. The structure offers its applications towards sensing, spectroscopy and futuristic 6G communications etc.

Keywords: Absorber, Tunability, Polarization Insensitive, Terahertz

1. Introduction

Metasurfaces (MS) are the 2D versions of metamaterials (MTMs) having the capabilities to enhance the response of electromagnetic (EM) wave encountered on its surface [1],[2],[3]. MS-based structures have gained the interest in recent years due to the exotic electromagnetic properties in various domains including, radio astronomy, holography, sensing, mobile communication, spectroscopy and other biomedical applications [4], [5], [6], [7], [8], [9]. Absorbers are the specifically designed structures to reduce the transmission and reflection coefficient of the incident EM wave [3]. MS absorbers with single band, multi band and broad band characteristics have been reported to operate in microwave, millimeter wave and terahertz regions [10]. The conventional MS absorbers reported are multi layered, thick or bulky making them unsuitable and difficult to realize; thereby demanding the requirement of thin structure with a simple design [10], [11], [12]. The structures reported tin litratures have complex unit cell geometry making them unsuitable for realization and fabrication. Hence a simple unit cell geometry is always desired.

In this article, a three-layered graphene-based MS absorber is proposed. The unit cell consists of a layer of amorphous silicon dioxide (SiO_2) sandwiched between the top layer of patterned graphene meta-structure and the bottom gold layer. The structure offers absorptivity more than 90% over the frequency ranges 3.98 to 5.08 THz and 6.55 to 10.57 THz; thereby exhibiting dual band operation with absorption windows of 1.1 THz and 4.02 THz respectively. The proposed structure is polarization insensitive over the entire operating range due to the fourfold symmetry of design. The structure works well up to 50^o oblique incident angles for both TE and TM polarizations. The structure can have application towards antenna test range detections, 6G communications, sensing etc.

2. Design of the structure

The geometrical design for the meta-structure is shown in Figure 1. The unit cell is a three-layer structure with periodicity of 6 μm × 6 μm. The top graphene patch with thickness 0.01 μm and chemical potential 0.8 eV has square shape geometry of 5 μm × 5 μm with rectangular slots. Amorphous SiO_2 has been used as substrate with thickness 7 μm. The structure has bottom gold layer of thickness 0.1 μm. The top and side views of unit cell are illustrated in Figures 1(a) and 1(b) respectively. The complex conductivity of top graphene layer is modelled using Kubo's equations [13]. The dielectric properties for SiO_2 substrate layer modelled as per the data available in [14]. The bottom gold layer is modelled having metallic properties as mentioned in [15].

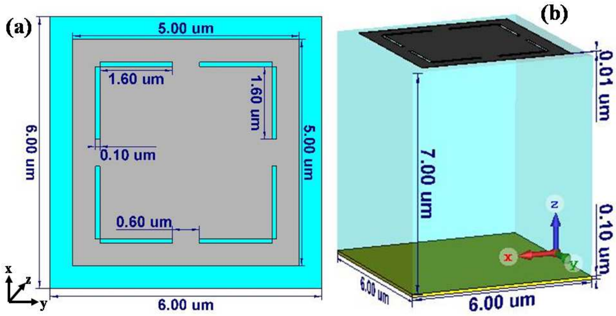

Figure 1. (a) Top and (b) side views of the unit cell of the proposed graphene-based metasurface absorber structure.

The absorption mechanism for EM wave encountered on top graphene layers can be explained by [3], [11]. The transmission coefficient for the incident EM wave is completely eliminated by the bottom gold layer visualizing absorption completely dependent on reflected wave [1], [3]. The top graphene layer deposited along the *xy*-plane acts as the matching circuit with impedance similar to free space impedance. The EM wave is allowed to incident on the top graphene meta-structure through an open, space-added boundary along the *z*-direction. The structure is simulated using CST Microwave Studio with the periodic boundary conditions [16]. The bottom layer placed at a distance ~λ/4 apart from the top graphene layer to encounter scattering and reflections enables the whole structure to act as a Fabry-Perot cavity [3], [10]. The structure possesses the perfectly matched boundary conditions to eliminate the non-specular radiations from edges of the structure and enhancing absorption phenomena. The simultaneous minimization of transmission and reflection coefficient for the proposed structure leads to maximized absorptivity.

3. Simulations and Results

The co and cross polarized reflection coefficients for the designed MS absorber structure are depicted in Figure 2(a) and 2(b) respectively. It is clear from Figure 2(a) that three distinct co-polarised reflection coefficient minima are present at 4.42 THz, 7.34 THz and 10.22 THz while cross polarized reflection coefficient is below -55 dB over the entire range of operation. The absorptivity response for proposed structure is accordingly computed and illustrated in Figure 2(c). The structure exhibits absorptivity greater than 90% over two frequency bands ranging 3.98 THz to 5.08 THz and 6.55 THz to 10.57 THz offering respective bandwidths of 1.1 THz and 4.02 THz.

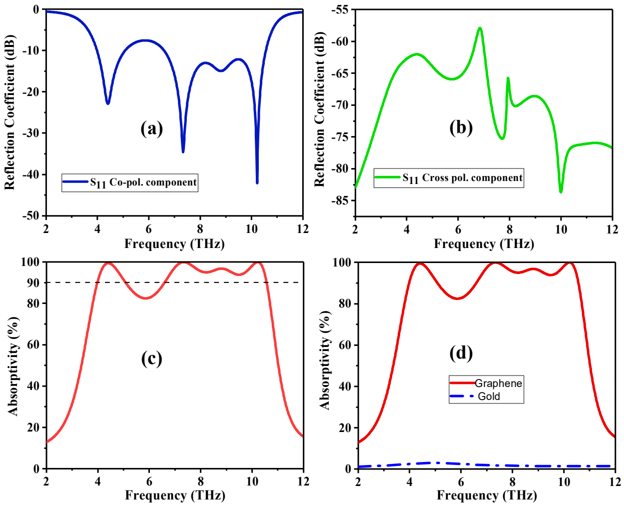

Figure 2. (a) Co-polarized and (b) cross-polarized reflection coefficient responses of the proposed structure along with (c) absorptivity response (d) comparison with gold-based metasurface at the top layer.

The proposed structure was initially simulated using CST microwave studio by modelling top layer with gold meta-atom structure with identical geometrical dimensions of that of the graphene layer, having metallic properties as mentioned in [15]. It was observed that structure offers hardly any absorption in such cases, as visualized in Figure 2(d). The absorption performance has been improved significantly with the incorporation of graphene patches in the top layer meta-atom design.

The field analyses have been carried out at the frequencies of interest to describe the absorption characteristics of the MS absorber. A strong confinement of electric field distribution has been observed at the peak absorption frequencies viz., 4.22 THz, 7.34 THz and 10.22 THz.

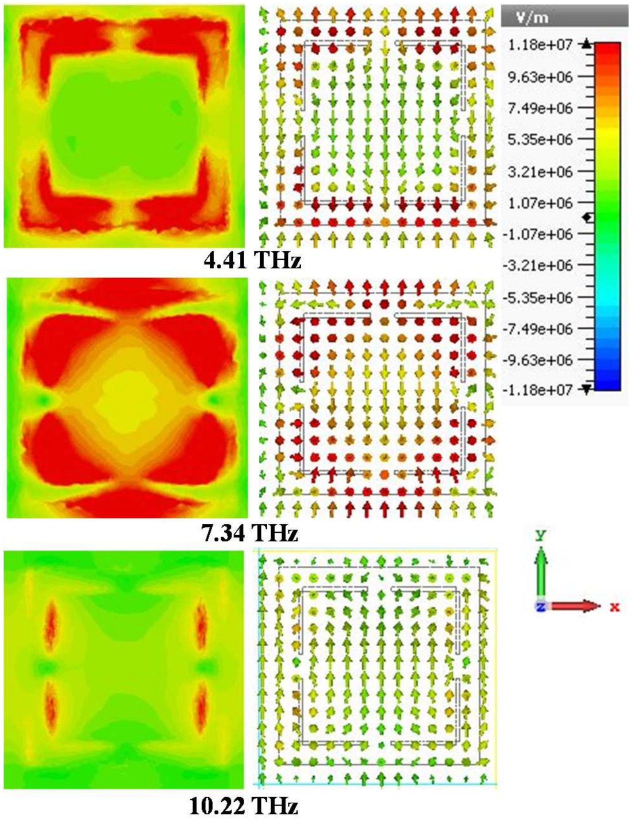

Figure 3. Electric field distributions in the unit cell at 4.41 THz, 7.34 THz and 10.22 THz

Refereeing to Figure 3, a dense and strong confinement of the electric field variation is observed along the horizontal slotted edge of the graphene patch at 4.41 THz. However, due to the mutual coupling among all the faces of the slotted Rectangular sections, the electric field is highly concentrated, expressing self-coupled resonant behaviour at 7.34 THz. Resonating behaviour of structure due to vertical rectangular slots offers confinement of electric field at 10.22 THz as illustrated in Figure 3.

The behaviour of the proposed MS absorber is also verified with the analyses of surface current distributions. The distributions of surface current for top graphene layer at 4.41 THz, 7.34 THz and 10.22 THz are illustrated in Figure 4(a) while the same for bottom gold layer is depicted in Figure 4(b). Observing both the figures simultaneously, it could be concluded that surface currents for top and bottom layers at 4.41 THz and 7.34 THz are antiparallel to each other yielding magnetic excitation. On the contrary, at 10.22 THz surface currents at top graphene layer and bottom gold layer are parallel to each other offering induced electrical excitation.

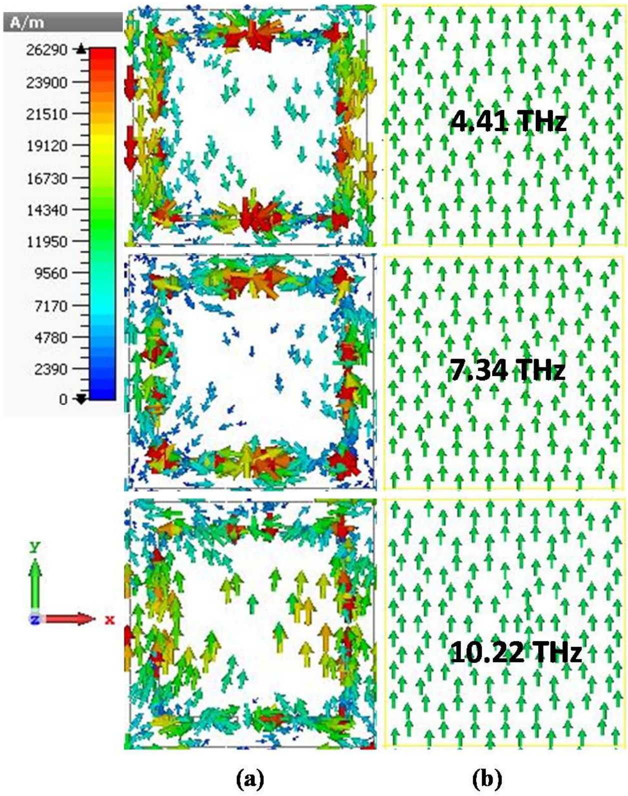

Figure 4. Surface current distributions at (a) top graphene layer and (b) bottom metallic layer of the proposed structure at 4.41 THz, 7.34 THz, and 10.22 THz respectively.

The complex conductivity of graphene depends on its chemical potential (μ_c). Thus the variation in the numeric values of μ_c offers controlled tunability in the EM absorption responses over its range of operation as depicted in Figure 5.

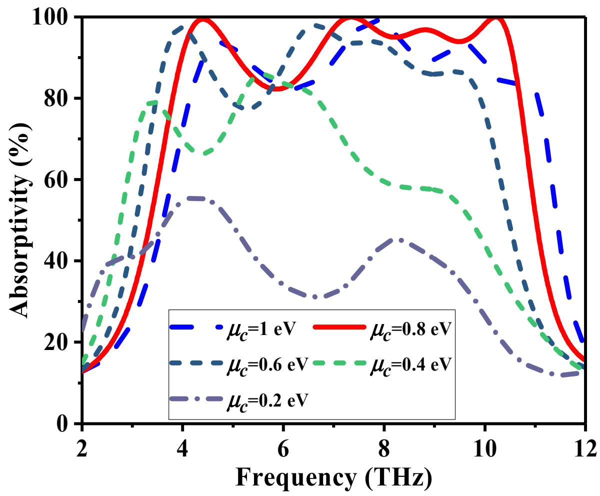

Figure 5. Absorptivity responses of the structure under the variation of chemical potential of graphene.

4. Response under polarization angle variation and oblique incidents

The proposed structure is simulated for various polarization angle variations and the behaviour of absorptivity response for ϕ=0º to ϕ=45º is depicted in Figure 6. It is clearly observed that due to fourfold symmetry of the structure, the proposed design is polarization insensitive in nature.

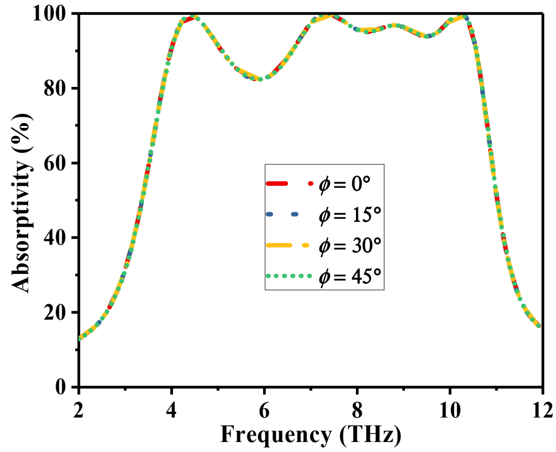

Figure 6. Absorptivity responses of the proposed structure under variation of polarization angles.

The simulated EM responses for absorptivity of the proposed structure are depicted in Figure 7(a) and 7(b) for both TE and TM polarizations on oblique incidences. The proposed structure behaves as absorber up θ=50º as noticed from Figure 7.

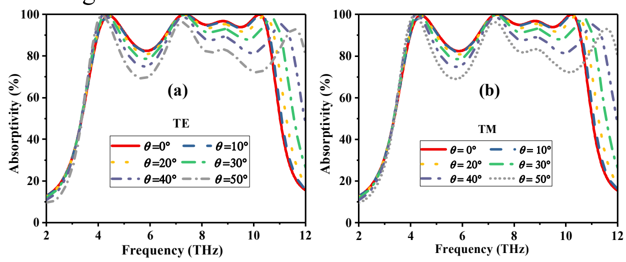

Figure 7. Absorptivity responses of the proposed structure under (a) TE polarization and (b) TM polarization of the incident wave.

Table I. Comparison with similar graphene based MS Absorber structures.

Absorber structure	Frequency range (THz)	Bandwidth (Total) A≥90%	Unit cell Period	Thickness
Dual Band [17]	4.15-4.40 5.85-6.15	0.25 THz 0.30 THz	~λ/14	~λ/8
Dual Band [18]	0.93-2.03 4.16-5.30	1.70 THz 1.14 THz	~λ/22	~λ/10
Single Band [19]	4.7-6.7 THz	2 THz	~λ/10	~λ/2
Dual Band [20]	1.1-1.2 THz 1.4-1.6 THz	0.1 THz 0.2 THz	~λ/18	~λ/9
This work	**3.98-5.08** **6.55-10.57**	**1.10 THz** **4.02 THz**	**~λ/13**	**~λ/11**

The proposed dual-band graphene-based MS absorber has been compared with state-of-the-art designs, as shown in Table I. It is evident that the proposed structure features an ultrathin geometry and exhibits enhanced performance of absorption compared to those reported in the literature.

5. Conclusion

A unique, polarization insensitive graphene based MS absorber with tunable features has been presented in this article. The proposed structure offers absorptivity greater than 90% over two distinct frequency bands of 1.1 THz and 4.02 THz. It shows near unity absorptions at 4.41 THz, 7.34 THz and 10.22 THz. The designed structure works well up to 50º incident angles for both TE and TM polarizations of the incident EM wave. The structure is ultrathin in nature having thickness ~λ/11 and periodicity of ~λ/13 with respect to lowermost frequency of absorption. The structure can be very promising towards sensing, spectroscopy and 6G Communications, and beyond for terahertz applications.

6. Acknowledgements

The work is partially funded by SERB, Govt. of India and ISRO

7. References

[1] S. Bhattacharyya, "Metamaterials and metasurfaces for high-frequency applications," in *Photonics, Plasmonics and Information Optics*, CRC Press, 2021, pp. 31–65.

[2] C. Caloz and T. Itoh, Electromagnetic metamaterials: transmission line theory and microwave applications. John Wiley & Sons, 2005.

[3] B. A. Munk and J. Wiley, "Frequency Selective Surfaces Theory and Design A Wiley-Interscience Publication," 2000.

[4] S. K. Ghosh, V. S. Yadav, S. Das, and S. Bhattacharyya, "Tunable Graphene-Based Metasurface for Polarization-Independent Broadband Absorption in Lower Mid-Infrared (MIR) Range," *IEEE Trans. Electromagn. Compat.*, vol. 62, no. 2, 2020, doi: 10.1109/TEMC.2019.2900757.

[5] L. Nama, S. Bhattacharyya, and P. K. Jain, "A metasurface-based, ultrathin, dual-band, linear-to-circular, reflective polarization converter: easing uplinking and downlinking for wireless communication," *IEEE Antennas Propag. Mag.*, vol. 63, no. 4, pp. 100–110, 2021.

[6] A. Paul, S. Bhattacharyya, and S. Dwivedi, "Design and mathematical analysis of a metasurface-based THz bandpass filter with an equivalent circuit model," *Appl. Opt.*, vol. 60, no. 22, pp. 6429–6437, 2021.

[7] M. Chandra, D. Samantaray, M. Thottappan, and S. Bhattacharyya, "A broadband transmissive type metasurface cross-polarization converter for EMC application," *IEEE Trans. Electromagn. Compat.*, vol. 65, no. 1, pp. 186–194, 2022.

[8] S. Kavitha, K. V. S. S. S. S. Sairam, and A. Singh, "Graphene plasmonic nano-antenna for terahertz communication," *SN Appl. Sci.*, vol. 4, no. 4, p. 114, Apr. 2022, doi: 10.1007/s42452-022-04986-1.

[9] S. Asgari and T. Fabritius, "Numerical Simulation and Equivalent Circuit Model of Multi-Band Terahertz Absorber Composed of Double-Sided Graphene Comb Resonator Array," *IEEE Access*, vol. 11, pp. 36052–36063, 2023, doi: 10.1109/ACCESS.2023.3265804.

[10] H.-T. Chen, A. J. Taylor, and N. Yu, "A review of metasurfaces: physics and applications," *Reports Prog. Phys.*, vol. 79, no. 7, p. 76401, 2016, doi: 10.1088/0034-4885/79/7/076401.

[11] R. Alaee, M. Albooyeh, and C. Rockstuhl, "Theory of metasurface based perfect absorbers," *J. Phys. D. Appl. Phys.*, vol. 50, no. 50, p. 503002, 2017, doi: 10.1088/1361-6463/aa94a8.

[12] A. I. Kuznetsov *et al.*, "Roadmap for optical metasurfaces," *ACS photonics*, vol. 11, no. 3, pp. 816–865, 2024.

[13] F. Jabbarzadeh, M. Heydari, and A. Habibzadeh-Sharif, "A comparative analysis of the accuracy of Kubo formulations for graphene plasmonics," *Mater. Res. Express*, vol. 6, no. 8, p. 86209, 2019.

[14] T. Fujii, A. Ando, and Y. Sakabe, "Characterization of dielectric properties of oxide materials in frequency range from GHz to THz," *J. Eur. Ceram. Soc.*, vol. 26, no. 10–11, pp. 1857–1860, 2006.

[15] M. Walther, D. G. Cooke, C. Sherstan, M. Hajar, M. R. Freeman, and F. A. Hegmann, "Terahertz conductivity of thin gold films at the metal-insulator percolation transition," *Phys. Rev. B*, vol. 76, no. 12, p. 125408, 2007.

[16] CST Studio Suite Team, "CST Microwave Studio 2010 - Workflow and Solver Overview," *CST Stud. Suite Inc.*, p. 392, 2010.

[17] Z. Wu, J. Tian, and R. Yang, "A graphene based dual-band metamaterial absorber for TE polarized THz wave," *Micro and Nanostructures*, vol. 168, p. 207331, 2022, doi: https://doi.org/10.1016/j.micrna.2022.207331.

[18] M. Fu, Z. Liu, Y. Duan, F. Zhou, and Y. Li, "Graphene-based terahertz tunable double-broadband perfect absorber," *Opt. Commun.*, vol. 563, p. 130534, 2024.

[19] M. H. Mazaheri, H. Maab, and A. A. Rahim, "Graphene-based metamaterial absorber for energy harvesting in the Terahertz range," *J. Opt.*, 2024, doi: 10.1007/s12596-024-01685-5.

[20] N. R. Sabaruddin *et al.*, "Designing a Broadband Terahertz Metamaterial Absorber Through Bi-Layer Hybridization of Metal and Graphene," *Plasmonics*, 2024, doi: 10.1007/s11468-024-02219-2.