A THz Metamaterial Absorber with Multiple Polarization: Insensitive, Sensitive, and Tunable

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ABSTRACT

Terahertz (THz) absorbers are gaining interest in many applications. In this paper, we present the design and simulation of a multiband metamaterial absorber (MMA) with combined polarization properties and prominent absorption at 2.2 THz and 3.9 THz. The MMA comprises two square split-ring resonators and one square ring resonator placed on top of a polyimide dielectric spacer, offering multiband absorption characteristics with maximum absorptivity of 93.18% and 96.09%, respectively. The most protruding feature of this design is that it displays multiple polarization characteristics, including insensitivity, sensitivity, and tunability, even though the structure is similar to those of conventional absorbers. Firstly, the distinctly visible absorption spectra at 1.8 THz, gradually diminishes with an increase in polarization angle and then completely vanishes for TM polarization. Secondly, the prominent band at 2.2 THz is insensitive to changes in polarization of the incident wave, whereas, at 3.9 THz, the absorption band displays polarization tunability characteristics. Due to the multiple characteristics displayed by the structure, this MMA can be simultaneously used for several applications in the terahertz frequency regime such as imaging, terahertz spectroscopy, sensing, and stealth technology.

Keywords: Metamaterial, Terahertz, Absorber, Polarization, Multiband

1. INTRODUCTION

Electromagnetic absorbers are widely used for applications ranging from microwaves to optical frequencies. Therefore, as a key component in various communication systems, absorbers have been the subject of extensive research for many years. Absorbers are designed to absorb incident electromagnetic energy effectively. To meet such requirements, various classical electromagnetics absorbers have been developed, but their bulky size and design complexity make them impractical for many applications. Owing to the need for present-day communication the research focus has moved toward compact and simple absorbers based on metamaterials. Metamaterials are a new class of ordered composites that exhibit exceptional electromagnetic characteristics not usually observed in nature.

The shortage of electromagnetic spectra in the microwave range and the growing trend of developing various applications in spectroscopy, medicine, earth and space science, defense, communication, material characterization, sensing, and imaging, etc., has led researchers to consider frequency in the range of terahertz (THz = 10^{12} Hz). In recent years, THz technology has gained more attention due to its non-ionizing nature, high penetration with low attenuation, and high-resolution imaging capability. The last decade has witnessed numerous advances in research activities due to the terahertz gap in the electromagnetic spectrum. These THz waves are also called T-rays because of their non-ionizing properties and high penetration with low attenuation. Terahertz devices have attracted tremendous attention due to their broad applications in imaging, remote sensing, astronomical radiation detection, high-resolution spectroscopy, and biomedical analytics.

One of the important aspects of this research field is the development of THz metamaterial absorbers for many important technological applications. In recent years, out of the various designs of absorbers, the most popular is the metamaterial-based absorber (MMA). Metamaterials (MM) are assemblies of metallic and/or dielectric materials, obtaining their exotic properties from composite structural shapes, geometries, size, and arrangements rather than being the main constituents. Each composite element is smaller than a quarter of the guided wavelength impinging, in contrast to naturally available materials whose electromagnetic behaviors are related

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to their constituting atoms and molecules. The distance between atoms and molecules in naturally existing materials is very small compared to the wavelength which is very large in artificial materials. Metamaterials, being artificially structured, demonstrate modified material properties, helping engineers to design unit cells for electromagnetic wave applications. The electromagnetic response of the material relies entirely on the structure rather than its chemical composition [1]. Thus, it is feasible to create an effective medium where both the fundamental parameters, i.e., permittivity (ε) and permeability (μ) are controlled. By designing a proper MM structure, various physical phenomena such as perfect lensing [2], negative refractive index [3], invisibility cloaking [4], and perfect absorbance [5] can be achieved.

In the past few years, metamaterial-based structures have been designed using THz frequencies due to their wide range of applications in THz communications. Researchers are also focusing more on the various designs of metamaterial absorbers in THz [6–12] and their potential applications in sensing, spectroscopy, cloaking, solar cells, and terahertz imaging [13–15]. These designs mostly focus on the development of multiband, broadband, polarization sensibility, and temperature sensing absorbers.

A metamaterial absorber can absorb all kinds of electromagnetic (EM) radiation. The unit cell structure of MMA is made up of a dielectric layer placed between a metallic patch and ground plane. It is a three-layer sandwich structure consisting of those three major components, offering near-unity absorption through the manipulation of the medium's dielectric properties. Due to their resonant nature, EM waves are generally absorbed in the form of a narrow frequency band, yielding narrowband absorption spectra. Two basic theories are involved in achieving perfect absorption in metamaterials: impedance matching and interference. In the former, both the electric and magnetic resonances are designed in a metamaterial, whereby the effective permittivity and permeability can be adjusted to achieve impedance matching with the free space. The theory is based on the interference of multiple reflections inside the dielectric substrate with negligible magnetic resonances.

Landy *et al.* [16] demonstrated the first-ever metamaterial-based perfect absorber in 2008. The absorber consisted of a metallic split-ring structure with a cut wire operating in the microwave frequency regime. This gained much attention due to its absorption characteristics, and seeing this near-unity absorption. Tao *et al.* [17] created a perfect near-unity absorber comprising of SRRs in 2008. Later in 2010, Hao *et al.* [18] experimentally presented a metamaterial absorber on a plasmonic nanostructure in an optical frequency range. Since then, several other designs have been proposed for multitudinous applications. Yen *et al.* [19] proposed the first terahertz metamaterial absorber in 2004. The initial research focused on developing metamaterial absorbers with single-band absorption characteristics.

Gradually the focus shifted to the design of multiband and broadband absorbers [20–23]. Another aspect that has attracted interest is the effect of polarization on the absorption spectra. Based on the absorption properties of incident waves with respect to polarization, there are four types of MMAs, the first of which displays absorption spectra insensitive to variations in the polarization angle. The second type of MMAs displays absorption spectra that appear only for one type of polarization, while vanishing for others. The third type of MMA displays polarization-tunable absorption spectra. Recently, a fourth type of MMA has been designed, displaying multiple characteristics, such as polarization sensitivity in some bands and polarization insensitivity in others. Usually, symmetric structures are insensitive to polarization and have been extensively covered in the existing literature [24–28]. Asymmetric MMAs are insensitive to variations in polarization angles, but usually display the absorption spectra for only one type of polarization. Similarly, MMAs with polarization-tunable absorption spectra have also been reported [29–30]. However, MMAs displaying multiple polarization sensitivity characteristics have not been reported extensively.

To the best of the authors' knowledge, multiple polarization absorption with sensitive, insensitive, and tunable characteristics is not addressed in any of the previous MMA structural designs. In this paper, the authors attempt to design a unique absorber with a thickness of only $5\,\mu$m and multiple polarization characteristics. The novelty of this MMA is that it displays polarization-insensitive, sensitive, and tunable properties, when the structure is simulated by varying the polarization angles. An MMA with polarization-insensitive and sensitive absorption characteristics has tremendous application potential in the field of terahertz imaging and sensing. The other important MMA with the ability to control thermal emissivity is a polarization-tunable absorber. Most of the structures are not versatile in nature. Some are meant only for only polarization-insensitive absorption and others for sensitive, while lacking the other polarization sensitivity characteristics. It is a promising attempt to design such an absorber which is simple and provides various polarization characteristics. It also displays five absorption spectra at different THz frequencies. The idea behind taking the five different frequencies from the entire THz band is to justify the occurrence of bands showing combined properties at a particular frequency band ranging from 1–4 THz for different

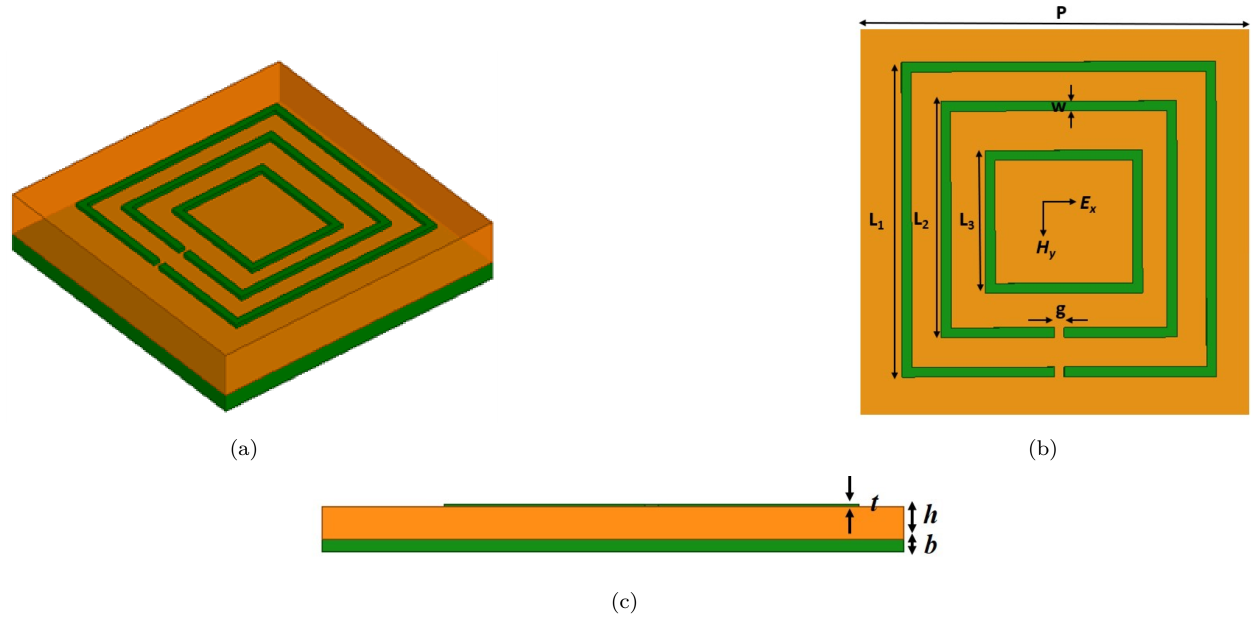


Fig. 1: *Unit cell structure of the absorber (a) 3-D view, (b) top view, and (c) side view.*

polarization angles. Since this proposed MMA is a coupled system, the absorption mechanism depends entirely on the coupling between the two SRRs and a ring-shaped metallic patch. The resultant narrowband absorption peaks are due to the strong coupling between the resonators. The absorption peaks of the MMA, yielding a variety of polarization characteristics, are due to combining the coupling lines between the SRRS and ring structure. Though the ring-shaped patch and SRR structure are very conventional, this proposed MMA has the unique feature of displaying three different kinds of polarization properties in a single graph. The proposed absorber is of great practical significance because of its complex absorption characteristics.

This paper is systematized as follows: Section 2 describes the unit cell structure of the absorber, followed by a performance analysis of the structure and its polarization characteristics in Section 3. Section 4 summarizes the work and contains the conclusion.

2. UNIT CELL STRUCTURE

The three-dimensional schematic design of the presented absorber including the top and side views is shown in Fig. 1. The top layer consists of a three-dimensional metallic patch structure, separated from the bottom metallic surface by an intermediate dielectric material layer. In this paper, a metamaterial absorber is presented with two split rings (inner and outer) and a complete square ring operating in the THz frequency. The absorber has a dielectric thickness of $h = 5\,\mu$m made of polyimide with a dielectric constant of $3 + i0.06$ and copper used as the metal component. Despite Au (gold) being used in most THz applications, the use of copper is not uncommon [31]. The dimensions of the structure taken as a candidate unit cell for the investigation are given as $L_1 = 64\,\mu$m, $L_2 = 48\,\mu$m, $L_3 = 27\,\mu$m, $g = w = 2\,\mu$m, and $P = 90\,\mu$m. The top metallic layer has a thickness of $t = 0.4\,\mu$m. The frequency independent conductivity (σ) of the copper metal considered for the absorber design is 5.80×10^7 S/m. The dimensions are optimally set in such a way that the field coupling between the rings enhances the absorption characteristics. The absorption for the presented metamaterial absorber is calculated using Eq. (1), where A is represented as the total absorption and R as the reflectance. Therefore, the total absorption depends entirely on the reflectance which is given by the square of the reflected power s_{11}.

$$A = 1 - R = 1 - |s_{11}|^2 \tag{1}$$

The thickness of the dielectric spacer is vital since it distresses the absorption peaks for the metamaterial absorber. Here, polyimide is considered as the material for the dielectric layer with the thickness of the layer set to a value of $h = 5\,\mu$m with a dielectric constant of $3 + i0.06$. The thickness of the metallic plane at the bottom is set as $b = 2\,\mu$m. This MMA is usually constructed from periodic structures of sub-wavelength size and their interesting properties are attained by the unit cell. Therefore, the performance of the periodic structures is analyzed by assigning proper boundary conditions to a unit cell. Here, the structure is simulated at a frequency ranging from 1 to 4 THz.

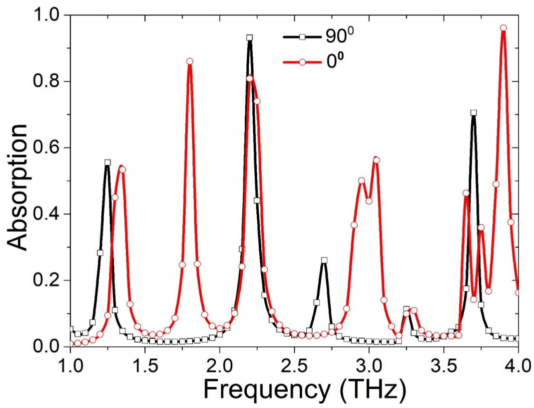


Fig. 2: *Absorption spectra of the proposed absorber.*

3. RESULTS OF SIMULATION ANALYSIS

The metamaterial absorber structure discussed in this section is designed using a high-frequency electromagnetic field simulator (HFSS), based on the finite element method.

Periodic boundary conditions are used for parametric analysis of the design. The EM wave is applied from the z-direction for a normal angle of incidence. The MMA structure is first simulated for 0° and 90° polarization, displaying absorption characteristics as shown in Fig. 2. These simulation values considered are due to its absorption spectra yielding absorptivity of 55.52%, 86.00%, 93.18%, 70.52%, and 96.09% at frequencies of 1.25 THz, 1.8 THz, 2.2 THz, 3.7 THz, and 3.9 THz, respectively. Here, the maximum absorptions shown by the metamaterial absorber are 86.00%, 93.18%, and 96.09% at frequencies of 1.8 THz, 2.2 THz, and 3.9 THz, respectively. This absorber displays good absorption of more than 85%.

To further realize this phenomenon and study the various parameters, the structure is first simulated for different types of polarization; the results of which are shown in Fig. 3. The MMA is simulated from 0° to 90°. Fig. 3(a) shows the plot of various polarization angles. From this figure, the close-up images are then taken for each variation in absorption characteristics shown in Figs. 3(b), 3(c), and 3(d). It can be observed from the figure that in the simulation of various polarization angles, the absorption bands obtained at a frequency of 2.2 THz are polarization-insensitive with respect to incident electromagnetic waves. Even if the angles are varied, there is no change in the absorption spectra at this frequency.

The symmetrical ring structure is responsible for this polarization insensitivity. Therefore, the bands offering this property have the potential for application in detection and stealth technology. The next observation is the peak absorption obtained at 3.9 THz with an absorptivity of 96.09% drifting from a higher to lower frequency with the increase in polarization angle.

The bands are tuned according to the change in angles. Thus, band fluctuation provides a polarization-tunable spectrum which may be helpful in the sensing field. Finally, at 1.8 THz, the absorption bands vanish with the increase in polarization angle. Here, the absorber can be called polarization-sensitive, since, with the change in polarization angle, the bands vanish. This vanishing is due to its sensitivity to the increasing angles. These three types of combined properties occurring at different polarization angles are highlighted in Figs. 3(b), 3(c), and 3(d). Thus, it can be observed that the design offers all three kinds of polarization characteristics in the enlarged view.

In order to justify the unit cell dimension, the period of the unit cell is varied as indicated by the simulated results in Fig. 4. It can be observed from the plot that degradation occurs in the absorption spectrum when P is increased or decreased. Therefore, the maximum absorption of 93.18% at 2.2 THz is observed for a cell dimension of 90 μm but not for 80 μm or 100 μm. Hence, the unit cell period is set to 90 μm to achieve maximum absorption.

Moreover, to understand the mechanism behind the absorption in the MMA, the electric field strength at 1.8 THz, 2.2 THz, and 3.9 THz is investigated, as shown in Fig. 5(a), 5(b), and 5(c). Due to the coupling effect between the loops of the square ring at the center and the inner split ring, the absorption band at 1.8 THz frequency is presented in Fig. 5(a). This also explains the vanishing spectrum displayed at this frequency. Since the structure is almost symmetric but has a gap in its arms, the bands gradually diminish with the increase in polarization angle. Similarly, the absorption band at 2.2 THz frequency for the square ring is placed at the center. Since the square ring is a symmetric structure, the absorption spectrum is insensitive to polarization angles. Both SRRs and the square ring are responsible for the absorption band achieving maximum absorption at 3.9 THz, and thus, this absorption spectrum shifts with the polarization angle.

The magnetic response is shown in Figs. 6(a), 6(b), and 6(c), clearly demonstrating that the resonance is determined solely by the magnetic response. Figs. 6(a), 6(b), and 6(c) presents the magnetic field strength for resonant frequencies of 1.8 THz, 2.2 THz, and 3.9 THz. It can be observed from the plot in Fig. 6(a) that the first absorption is due to magnetic resonance at the inner SRR. The magnetic field induces anti-parallel currents at the wire part of the inner split ring with very little current being induced at the outer SRR. The second absorption peak at 2.2 THz frequency is due to the magnetic resonance at the wire part of the square ring structure. In this case, no current is induced at the two inner and outer SRRs. In the third case, the absorption peak is achieved at 3.9 THz due to the currents induced at both inner and outer SRRs. The magnetic

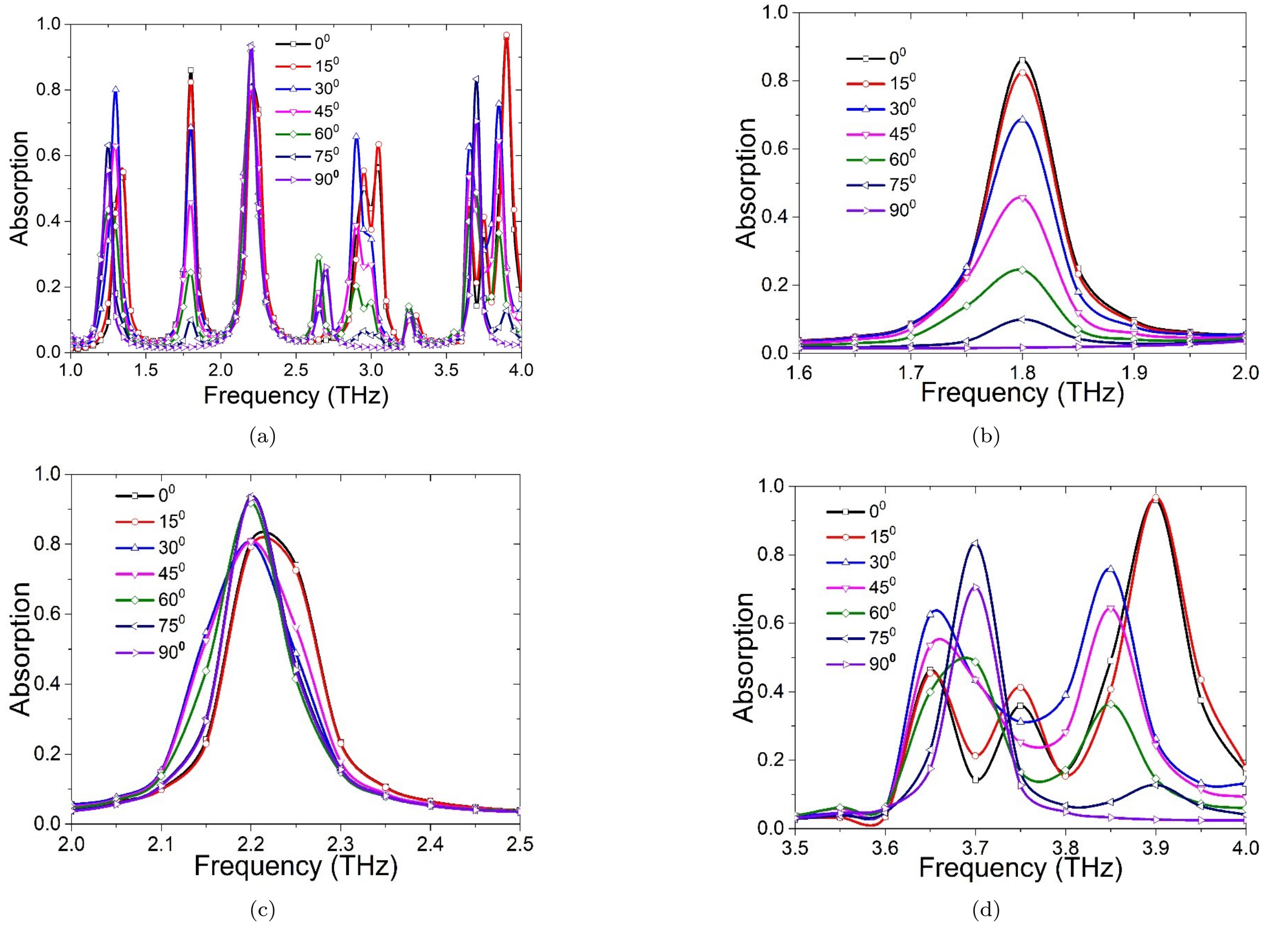


Fig. 3: *(a) Enlarged view of polarization characteristics with respect to different angles, (b) frequency range from 1.6 THz to 2 THz, (c) frequency range from 2 THz to 2.5 THz, and (d) frequency range from 3.5 THz to 4 THz.*

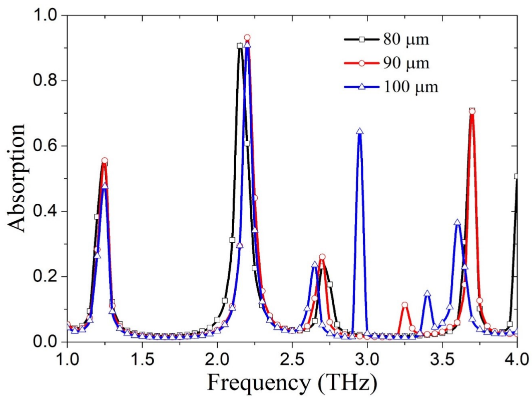
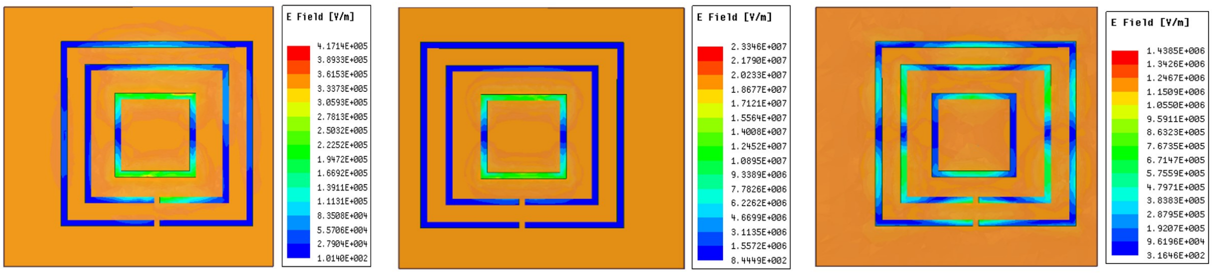


Fig. 4: *Absorption plot for unit cell dimension.*

response of the given MMA is investigated between the top and bottom metallic layers, resulting in the induction of magnetic resonances. Finally, changes in the absorption spectrum with respect to the incidence angle are obtained, as shown in Fig. 7. It is interesting to note that not only is the absorption spectra at 1.8 THz insensitive to polarization angle variation but also to variations in the angle of incidence and so can be used for the absorption of EM wave incidents from angles with any type of polarization. The performance of the proposed MMA with respect to different incidence angles is presented in Table 1. It can be observed that the absorber is capable of achieving a maximum absorption of 96.09% at a 0° angle of incidence, such as a 0° polarization angle.

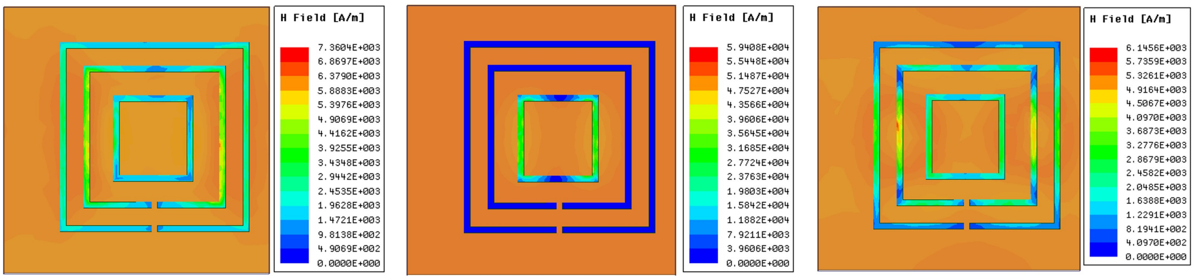
A summary of the recent work is shown in Table 2, displaying a comparison between existing absorbers and the proposed MMA. According to the literature, previous designs displayed only one type of polarization characteristic or a combination of insensitive and sensitive polarization. However, to the best of the authors' knowledge, until now, no such work has been reported which displays three types of characteristics, namely sensitive, insensitive, and tunable polarization.

In [32] shows a modified design of SRR. This MMA structure displays three bands for polarization-insensitive absorption and a single band for insensitive polarization absorption. Though it shows a combination of both insensitive and sensitive



(a) (b) (c)

Fig. 5: *Electric field strength plots for different frequency modes (a)* $f_1 = 1.8$ *THz, (b)* $f_2 = 2.2$ *THz, and (c)* $f_3 = 3.9$ *THz.*



(a) (b) (c)

Fig. 6: *Magnetic field strength plots of different frequency modes (a)* $f_1 = 1.8$ *THz, (b)* $f_2 = 2.2$ *THz, and (c)* $f_3 = 3.9$ *THz.*

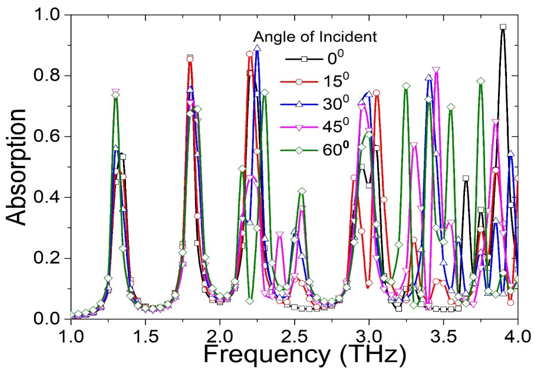


Fig. 7: *Polarization characteristics with respect to angle of incidence.*

Table 1: *Absorption performance of MMA for different incident angle.*

Frequency (THz)	Absorption at different incident angle				
	$\theta = 0°$	$\theta = 15°$	$\theta = 30°$	$\theta = 45°$	$\theta = 60°$
1.80	86.00	85.43	75.26	71.17	67.53
2.20	80.79	87.12	88.95	46.54	N/A
3.70	N/A	N/A	21.85	N/A	N/A
3.90	96.09	N/A	54.28	65.00	15.18

polarization, there is no tunability. The simple SRR design is unable to produce the tunable characteristic. In [33], the MMA exhibited dual-band absorption with polarization-insensitive characteristics. This design shows no sensitivity and tunability characteristics. The dielectric thickness is 25 μm, which is a little bulky in comparison to other compact dielectric spacers. In [34] presented a square-shaped metamaterial absorber structure yielding a dual-band absorption spectrum. Due to its symmetric design, the absorber demonstrated polarization-insensitive characteristics, although no tunability was displayed in the metamaterial structure. In [35] showed two MMAs, one comprising a simple metallic strip or slab and the other a metallic cross. The cross structure displayed polarization insensitivity, while the absorption spectrum was not sensitive to different polarization angles due to its symmetric MMA design.

In [36] and [37] demonstrated a U-shaped resonator structure which displayed near-unity absorption. The two U-shaped MMAs displayed dual-band and quad-band perfect absorption, respectively. Besides, the parametric study of both designs in a near-unity absorption spectrum showed no sign of multiple polarization characteristics. In [38] and [39], the authors demonstrated tunable polarization metamaterial absorbers. The structure mentioned in [38] was a simple design comprising two SRRs. Though the structure was tunable in nature, it did not show any kind of polarization-sensitive or insensitive absorption. Similarly, in [39], the authors

Table 2: *Different types of absorbers reported in literature.*

Absorbers	Unit cell	Dielectric thickness (μm)	Polarization characteristics	No. of bands
B. Appasani *et al.* [32]	Modified SSR	7	Multiple (not tunable)	–
Y. Shan *et al.* [33]	SRR	25	Insensitive	2
X. Li *et al.* [34]	Square	2	Insensitive	2
B.-X. Wang *et al.* [35]	Metallic cross	10	Tunable	2
B.-X. Wang *et al.* [36]	U-shaped	3.7	N/A	2
B.-X. Wang and G.-Z. Wang [37]	U-shaped	27	N/A	4
B.-X. Wang [38]	SRR	7	Tunable	4
B.-X. Wang *et al.* [39]	Metallic mirror and patch	9	Tunable	3
V. K. Verma *et al.* [40]	Elliptical ring resonators	8	Insensitive	8
Proposed	SRRs and square ring	5	Multiple	5

presented a metallic mirror and patch structure, displaying triple band absorption along with tunable polarization characteristics. In [40] proposed an octa-band metamaterial absorber, displaying eight absorption peaks. Since the design of the MMA is symmetric, it demonstrates polarization-insensitive absorption, i.e., the variations in polarization angles do not affect the absorption spectrum.

4. CONCLUSION AND FUTURE SCOPE

In this study, a multiband MMA comprising two square-shaped SRRs and a ring is designed and investigated for terahertz frequency. The design offers peak absorptivity of 93.18% and 96.09% at frequencies of 2.2 THz and 3.9 THz, respectively. Though the top metallic patch design is like the conventional metamaterial absorber, this proposed MMA uniquely displays three kinds of polarization characteristics in a single absorption with a frequency plot ranging from 1 THz to 4 THz. Multiple polarization sensitivity characteristics are observed in this novel MMA: polarization-sensitive, polarization-insensitive, and polarization-tunable at 1.8 THz, 2.2 THz, and 3.9 THz, respectively.

These unique polarization characteristics make the proposed MMA suitable for a variety of applications in the fields of sensing, imaging, detection, and stealth technology. The MMA applications in this study can be used as a baseline for future work in the metamaterial field. The absorbers can also be used to develop a real-life cloaking device. The electromagnetic cloaking of an object is determined by two techniques, firstly, cancelling the electric and magnetic field generated by the object, and secondly, guiding the incoming waves around the object. Similarly, the application of metamaterials in solar cells is increasing day by day due to its better absorption characteristics. The field of MM-based solar cells may provide another application opportunity.

The development of multiple polarization characteristics such as excellent sensitivity and tunability has the potential to be used in different real-time applications in the future.

REFERENCES

[1] E. Shamonina and L. Solymar, "Metamaterials: How the subject started," *Metamaterials*, vol. 1, no. 1, pp. 12–18, 2007.

[2] J. B. Pendry, "Negative Refraction Makes a Perfect Lens," *Physical Review Letters*, vol. 85, no. 18, pp. 3966–3969, 2000.

[3] R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental Verification of a Negative Index of Refraction," *Science*, vol. 292, no. 5514, pp. 77–79, 2001.

[4] M. Rahm, D. Schurig, D. A. Roberts, S. A. Cummer, D. R. Smith, and J. B. Pendry, "Design of electromagnetic cloaks and concentrators using form-invariant coordinate transformations of Maxwell's equations," *Photonics and Nanostructures - Fundamentals and Applications*, vol. 6, no. 1, pp. 87–95, 2008.

[5] R. W. Ziolkowski and C.-Y. Cheng, "Existence and design of trans-vacuum-speed metamaterials," *Physical Review E*, vol. 68, no. 2, 2003, Art. no. 026612.

[6] V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ," *Soviet Physics Uspekhi*, vol. 10, no. 4, pp. 509–514, 1968.

[7] D. S. Wilbert, M. P. Hokmabadi, J. Martinez, P. Kung, and S. M. Kim, "Terahertz metamaterials perfect absorbers for sensing and imaging," in *Proceedings of SPIE 8585, Terahertz and Ultrashort Electromagnetic Pulses for Biomedical Applications*, 2013, Art. no. 85850Y.

[8] X. Shen, T. J. Cui, J. Zhao, H. F. Ma, W. X. Jiang, and H. Li, "Polarization-independent wide-angle triple-band metamaterial absorber," *Optics Express*, vol. 19, no. 10, pp. 9401–9407, 2011.

[9] P. V. Tuong, V. D. Lam, J. W. Park, E. H. Choi, S. A. Nikitov, and Y. P. Lee, "Perfect-absorber

metamaterial based on flower-shaped structure," *Photonics and Nanostructures - Fundamentals and Applications*, vol. 11, no. 1, pp. 89–94, 2013.

[10] Y. P. Lee, P. V. Tuong, H. Y. Zheng, J. Y. Rhee, and W. H. Jang, "An application of metamaterials: perfect absorbers," *Journal of the Korean Physical Society*, vol. 60, pp. 1203–1206, 2012.

[11] O. Ayop, M. K. A. Rahim, N. A. Murad, N. A. Samsuri, F. Zubir, and H. A. Majid, "Dual-band metamaterial perfect absorber with nearly polarization-independent," *Applied Physics A*, vol. 123, no. 1, 2017, Art. no. 63.

[12] G. Duan, J. Schalch, X. Zhao, J. Zhang, R. D. Averitt, and X. Zhang, "Identifying the perfect absorption of metamaterial absorbers," *Physical Review B*, vol. 97, no. 3, pp. 4–10, 2018.

[13] Y. Zhang et al., "Study on temperature adjustable terahertz metamaterial absorber based on vanadium dioxide," *IEEE Access*, vol. 8, pp. 85154–85161, 2020.

[14] A. Mohanty, O. P. Acharya, B. Appasani, and S. K. Mohapatra, "A multi-band terahertz metamaterial absorber based on a Π and U-shaped structure," *Photonics and Nanostructures - Fundamentals and Applications*, vol. 32, pp. 74–80, 2018.

[15] Y.-L. Liao and Y. Zhao, "Ultra-narrowband dielectric metamaterial absorber with ultra-sparse nanowire grids for sensing applications," *Scientific Reports*, vol. 10, no. 1, 2020, Art. no. 1480.

[16] N. I. Landy, S. Sajuyigbe , J. J. Mock , D. R. Smith , W. J. Padilla, "A Perfect Metamaterial Absorber", *Physical Review Letters*, vol. 100, 2008, Art. no. 207402.

[17] H. Tao, N. I. Landy, C. M. Bingham, X. Zhang, R. D. Averitt, W. J. Padilla, "A metamaterial absorber for the terahertz regime: Design, fabrication and characterization," *Optics Express*, vol. 16, no. 10, pp. 7181–7188, 2008.

[18] J. Hao, J. Wang, X. Liu, W. J. Padilla, L. Zhou, and M. Qiu, "High performance optical absorber based on a plasmonic metamaterial," *Applied Physics Letter*, vol. 96, no. 25, pp. 2010–2013, 2010.

[19] T. J. Yen *et al.*, "Terahertz magnetic response from artificial materials", *Science*, vol. 303, pp. 1494–1496, 2004.

[20] S. Kalraiya, R. K. Chaudhary, R. K. Gangwar, and M. A. Abdalla, "Compact quad-band polarization independent metamaterial absorber using circular/square metallic ring resonator," *Materials Research Express*, vol. 6, no. 5, 2019, Art. no. 055812.

[21] Z.-C. Xu, R.-M. Gao, C.-F. Ding, Y.-T. Zhang, and J.-Q. Yao, "Multiband Metamaterial Absorber at Terahertz Frequencies",*Chinese Physics Letters*, vol. 31, no. 5, 2014, Art. no. 054205.

[22] B.-X. Wang, C. Tang, Q. Niu, Y. He, and R. Chen, "A broadband terahertz metamaterial absorber enabled by the simple design of a rectangular-shaped resonator with an elongated slot," *Nanoscale Advances*, vol. 1, no. 9, pp. 3621–3625, 2019.

[23] O. M. Daraei, K. Goudarzi, and M. Bemani, "A tunable ultra-broadband terahertz absorber based on two layers of graphene ribbons," *Optics & Laser Technology*, vol. 122, 2020, Art. no. 105853.

[24] A.-X. Wang *et al.*, "Six-band polarization-insensitive perfect metamaterial absorber using L-shaped resonators," *Applied Physics A*, vol. 125, no. 5, 2019, Art. no. 331.

[25] H. Wakatsuchi, D. F. Sievenpiper, and C. Christopoulos, "Designing flexible and versatile metamaterial absorbers", *IEEE Electromagnetic Compatibility Magazine*, vol. 5, no. 2, pp. 76–82, 2016.

[26] M. Nejat and N. Nozhat, "Design, Theory, and Circuit Model of Wideband, Tunable and Polarization-Insensitive Terahertz Absorber Based on Graphene," *IEEE Transactions on Nanotechnology*, vol. 18, pp. 684–690, 2019.

[27] S. Ramya and I. S. Rao, "Design of Polarization-Insensitive Dual Band Metamaterial Absorber," *Progress In Electromagnetics Research M*, vol. 50, pp. 23–31, 2016.

[28] W. Pan, X. Yu, J. Zhang, and W. Zeng, "A Broadband Terahertz Metamaterial Absorber Based on Two Circular Split Rings," *IEEE Journal of Quantum Electronics*, vol. 53, no. 1, pp. 1–6, 2017.

[29] S. C. Bakshi, D. Mitra, and L. Minz, "A Compact Design of Multiband Terahertz Metamaterial Absorber with Frequency and Polarization Tunability," *Plasmonics*, vol. 13, no. 6, pp. 1–10, 2018.

[30] B. Zhu, Y. Feng, J. Zhao, C. Huang, Z. Wang, and T. Jiang, "Polarization modulation by tunable electromagnetic metamaterial reflector/absorber," *Optics Express*, vol. 18, no. 22, pp. 23196–23203, 2010.

[31] S. Dash and A. Patnaik, "Material selection for THz antennas", *Microwave and Optical Technology Letters*, vol. 60, no. 5, pp. 1183–1187, 2018.

[32] B. Appasani, P. Prince, R. K. Ranjan, N. Gupta, and V. K. Verma, "A Simple Multi-band Metamaterial Absorber with Combined Polarization Sensitive and Polarization Insensitive Characteristics for Terahertz Applications", *Plasmonics*, vol. 14, no. 3, pp. 737–742, 2018.

[33] Y. Shan, L. Chen, C. Shi, Z. Cheng, X. Zang, B. Xu, and Y. Zhu, "Ultrathin flexible dual band

terahertz absorber", *Optics Communications*, vol. 350, no. 1, pp. 63–70, 2015.

[34] X. Li, H. Liu, Q. Sun, and N. Huang, "Ultra-broadband and polarization-insensitive wide-angle terahertz metamaterial absorber", *Photonics and Nanostructures - Fundamentals and Applications*,vol. 15, pp. 81–88, 2015.

[35] B.-X. Wang, X. Zhai, G.-Z. Wang, W.-Q. Huang, and L.-L. Wang, "A novel dual-band terahertz metamaterial absorber for a sensor application", *Journal of Applied Physics*, vol. 117, no. 1, 2015, Art. no. 014504.

[36] B.-X. Wang, G.-Z. Wang, and L.-L. Wang, "Design of a Novel Dual-Band Terahertz Metamaterial Absorber", *Plasmonics.*, vol. 11, no. 2, pp. 523–530, 2016.

[37] B.-X. Wang and G.-Z. Wang, "Novel quad-band terahertz metamaterial absorber based on single pattern U-shaped resonator," *Applied Physics Express*, vol. 10, 2017, Art. no. 034301.

[38] B.-X. Wang, "Quad-Band Terahertz Metamaterial Absorber Based on the Combining of the Dipole and Quadrupole Resonances of Two SRRs," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 23, no. 4, 2017, Art. no. 4700107.

[39] B.-X. Wang, Q. Xie, G. Dong, and W.-Q. Huang, "Design of triple-band polarization controlled terahertz metamaterial absorber", *Superlattices and Microstructures,* vol. 114, pp. 225–232, 2018.

[40] V. K. Verma *et al.*, "An Octaband Polarization Insensitive Terahertz Metamaterial Absorber Using Orthogonal Elliptical Ring Resonators", *Plasmonics*, vol. 15, no. 8, pp. 75–81, 2020.

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