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Development of Single-layered, Wide-angle, Polarisation-insensitive Metamaterial Absorber

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ABSTRACT

The simultaneous achievement of multiband absorption, polarisation-insensitive, and angularly stable absorber is a difficult job. Therefore, in this article, an efficient single-layered absorber is designed, critically analysed, fabricated, and experimentally validated. The proposed model incorporates eight sectors loaded a circle inside the square. The four discrete absorption peaks are observed at 4.4 GHz, 6.0 GHz, 14.1 GHz, and 16.0 GHz manifesting absorption intensities of 94%, 84%, 82%, and 92%, respectively. Parametric studies have been also exercised to investigate the influence of discrete geometrical design variables on the proposed absorber. The proposed structure is symmetrical in geometry, consequence in polarisation-independent behaviour. The absorption mechanism is also explained by analysing the surface current, electric field, and magnetic field distributions. Besides, the complex electromagnetic parameters are extracted to realise the absorption phenomenon. Additionally, to validate the simulated results, an optimal sample is fabricated and the measured response is well-matched with simulated ones.

Keywords: Absorber; Metamaterial; Multiband; Polarisation-independent

1. INTRODUCTION

The postulation of perfect metamaterial absorber (MMA) has been initiated by Landy[1], *et al.*. Since, then this topic has been universally exploited by physicists and engineers, owing to their defence and civil applications[2-3]. Metamaterials (MM) are artificial or synthetic structures that possess unique properties such as negative permittivity (ε), permeability (μ) and refractive index (n), etc.[4]. The unique and useful properties of MM are offered by the shape, size, and arrangements of the unit cell, rather than the composition of the material[5]. Conventional absorbers have larger thickness resultant in bulky, expensive, and narrow bandwidth leads to restricting nowadays, which are replaced by MM based absorbers. Different microwave absorbing structures are accessible in the literature on account of the targeted frequency regime[6-7]. Researchers have proposed numerous absorbing structures operating in a single band[8], dual-band[9], and multiband applications[10-12]. The broadband and multiband characteristics of the absorbers can be obtained, by stacking more than one layer, which leads to enhance complexity in the fabrication process and cost as well. Recent researchers are also an emphasis on polarisation insensitivity of the absorber. The lumped resistors have been utilised to obtain the polarisation-insensitive characteristics[13]. Nevertheless, concomitantly achievement of the single layer, lower thickness, and polarisation insensitivity with a cost-effective absorber is still a challenging aspect among researchers. Researchers have proposed an insensitive absorber by employed diode for single and broadband applications[14]. The fabrication of such a prototype becomes difficult due to the use of active elements. A single-layered, wideband, and polarisation-insensitive absorber has been proposed by Lee[15], *et al.*. The thickness of the substrate was 2.4 mm, which restricts the practical application of the absorber. Moreover, chip resistors are also utilised in the proposed structure, leads to high cost and complexity. Nevertheless, concomitantly achievement of the single layer, lower thickness, and polarisation insensitivity with a cost-effective absorber is a difficult job. In this paper, a multiband, single-layered, and wide-angle polarisation-insensitive absorber is demonstrated. To understand the absorption mechanism, the surface current (SC), the magnetic field (H), and electric field (E) distributions are investigated. The optimised structure is fabricated and measured by the free-space measurement technique.

2. ABSORBER UNIT CELL DESIGN

The proposed structure unit cell is composed of a metallic patch patterned on the upper surface of FR4 substrate with 1.6 mm thickness. The bottom surface of the FR4 substrate is perfectly metal laminated. The metal employed on both sides of the substrate formed of copper (conductivity, σ = 5.8 × 107 S/m) of 0.035 mm thickness. The proposed unit cell comprises eight sectors loaded a circle inside the square as manifested in Fig. 1. Table 1 illustrates the optimised geometrical design

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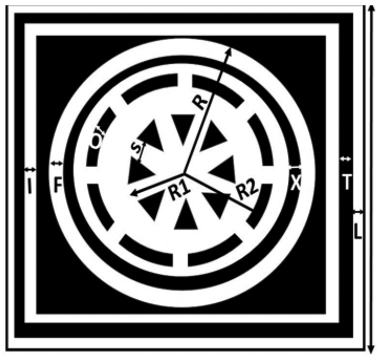

Figure 1. Front view of the absorber unit cell.

variables of the proposed structure. The structure has been designed, optimised, simulated, and analysed using the computer simulation technology (CST) microwave studio.

Table 1. Geometrical design variables of the absorber unit cell

Parameter	Dimension (mm)	Parameter	Dimension (mm)
P	10	I	0.3
L	0.15	R	4.3
T	0.3	R1	2.4
O	0.3	R2	3.2
S	0.9	F	0.3
X	0.3	-	-

3. SIMULATED RESULTS AND CRITICAL ANALYSIS

The simulated reflection coefficient (RC)-frequency plots of the proposed structure are investigated and demonstrated in Fig. 2 The four resonant peaks of -25.9 dB, -18.9 dB, -16.1 dB, and -21.3 dB are noticed at 4.4 GHz, 6.0 GHz, 14.1 GHz, and 16.0 GHz, respectively. The significant result acquired from the RC graph is absorption characteristics, which are illustrated in Fig. 3. It has been observed that at resonant frequencies, the maximum absorption has been achieved in the range of 2 to 18 GHz. As the bottom surface of the structure is perfectly metal laminated, resultant in no transmission. It can be concluded from Fig. 3, that at the resonance the maximum absorption has been achieved. The maximum absorption is observed of 94% and 92% at 4.4 GHz and 16.0 GHz, respectively.

The absorption frequencies depend upon the geometric parameters of the absorber, as the change in dimensions leads to a corresponding change in absorption response. Parametric studies are performed to discover the influence of the distinct geometrical design variables on the absorption. The first study is performed on the gap between the sectors which is denoted by the 'S'. With the decrease in the gap between the sectors, the value of capacitance also decreases, hence the higher resonating frequency-shifted towards the left. It has been observed in Fig. 4(a) that the optimal value of 'S' is 0.9 mm. There is no difference is observed in lower frequency with change in 'S' parameter because it is majorly due to the excitation of the outer square and outer circle. With the further increase in the value of 'S', the four resonating peaks are observed with upwards shifting in the graph. The next study is performed on substrate thickness 'h' and illustrated in Fig. 4(b). It has been perceived that as the thickness of the substrate increases, the resonating

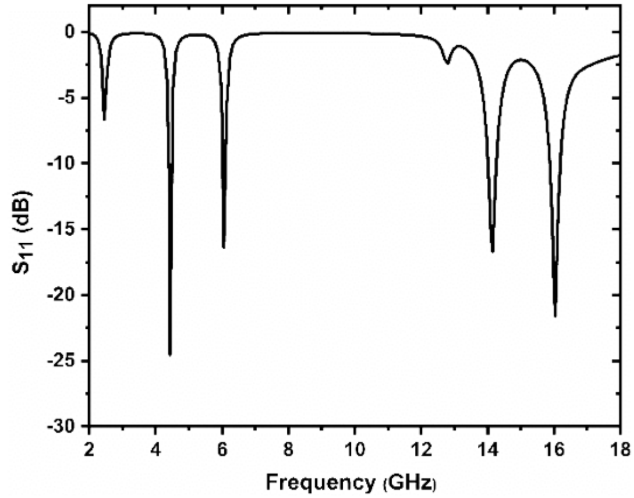

Figure 2. Simulated RC spectra of the proposed absorber in the range of 2 to 18 GHz.

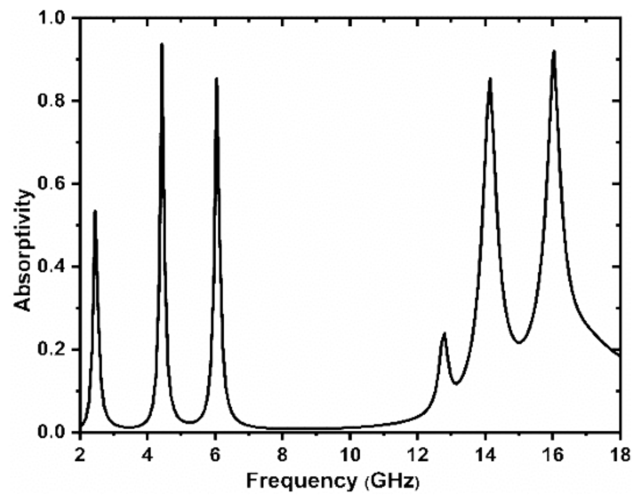

Figure 3. Simulated absorption characteristics of the proposed absorber.

frequency-shifted towards the left. The optimal value of the 'h' is 1.6 mm. As the value of thickness approaches 2.0 mm, the higher absorption frequency diminished. Further, the study is performed on the substrate permittivity as illustrated in Fig. 4(c). The proposed absorber is realised using an FR4 substrate with relative permittivity 'ε_r' of 4.2.

Foremost, simulated RC plots of the absorber with different angles of incidence under transverse electric (TE) and transverse magnetic (TM) polarisations are studied and illuminated in Figs. 5(a) and 5(b), respectively. For TE polarisation a slight variation is observed in lower frequency with an increase of incident angle as portrayed in Fig. 5(a). In a higher frequency band, the structure shows different behaviour for a distinct angle of incidence. A similar effect is observed for TM polarisation as shown in Fig. 5(b). The structure is studied under different polarisation angles in the range of 0^o to 60^o. It is analysed from Fig. 5(c) that the structure exhibit polarisation-insensitive characteristics as the absorber is a fourfold symmetric structure.

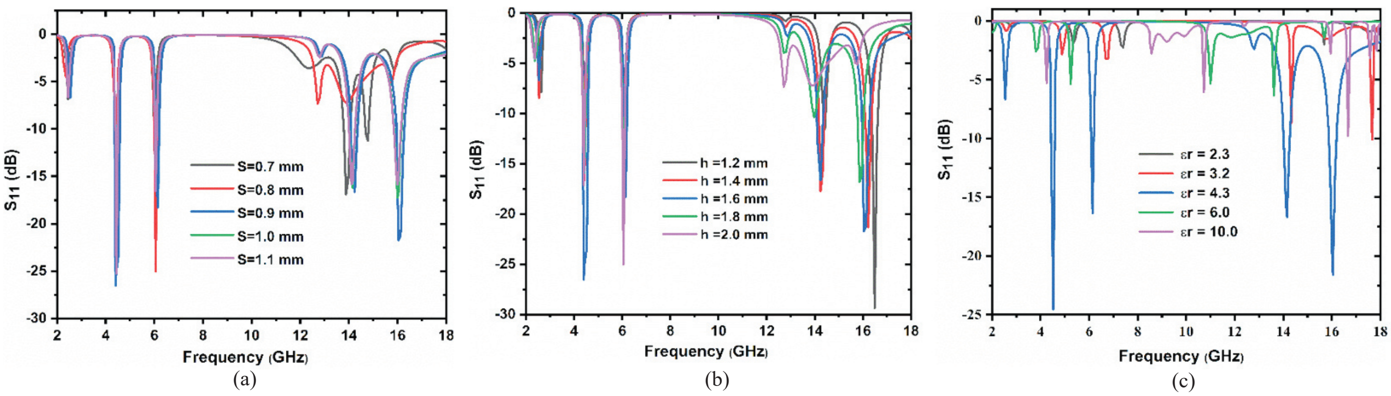

Figure 4. The effect of variation of geometrical design variables (a) 'S', (b) 'h', and (c) 'ε_r'.

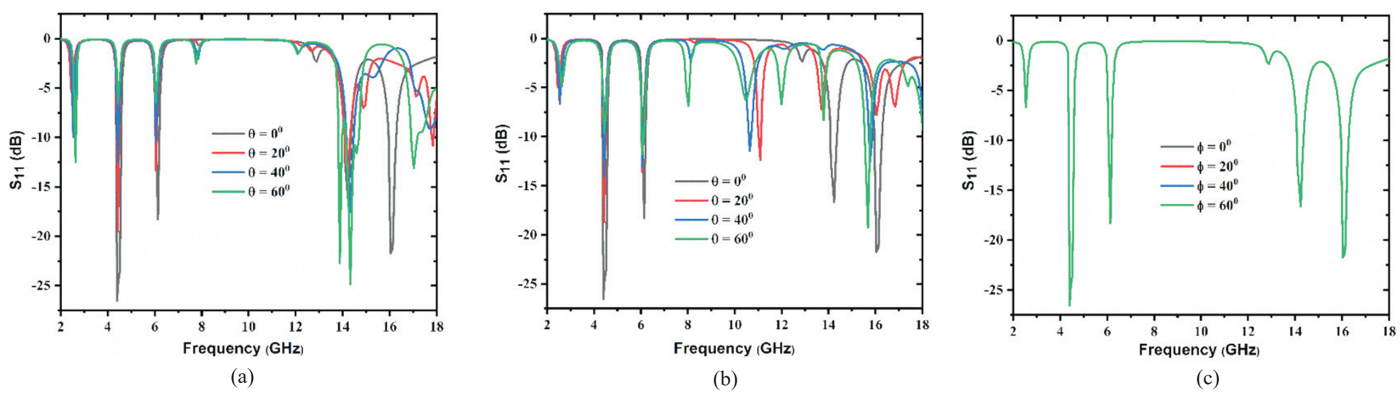

Figure 5. Simulated RC (a) different angle of incidence for TE polarisation, (b) for TM polarisation (c) different polarisation angles under normal incidence.

To have a comprehensible picture of absorption behaviour and to understand the absorption mechanism, we have represented SC, E, and H field distributions of the proposed structure. Figures. 6(a)-6(d) are manifested in the surface current (SC) distributions at 4.4 GHz, 6.0 GHz, 14.1 GHz, and 16.0 GHz discretely. It is observed that over the lower frequencies (i.e., at 4.4 GHz and 6.0 GHz) absorption is predominantly because of the square and circle portion of the structure. Similarly, at the higher frequencies (i.e., at 14.1GHz and 16.0 GHz) the eight sectors are also energetic along with other parts, with a strong current. E field distributions at the resonating frequencies are illustrated in Figs. 7(a)-7(d). It is well being matched with SC distributions. E-field is concentrated on the outer square and the outer circle portion in lower frequencies. While at higher frequencies, the major E-field is also concentrated on the sectors of the proposed structure. Ergo, a strong magnetic resonance is observed because SC generates circulating loops, resultant in high absorption achieved at the resonant frequencies[16]. Figures. 8(a)-8(d) represent the H-field distribution at the resonating frequencies, which are well-matched with surface current and E-field distributions.

4. FABRICATION AND MEASUREMENT OF ABSORBER

To validate the simulated results, a prototype of size 200×200 mm^2 has been developed using a standard printed circuit board (PCB) technology as shown in Fig. 9(a).

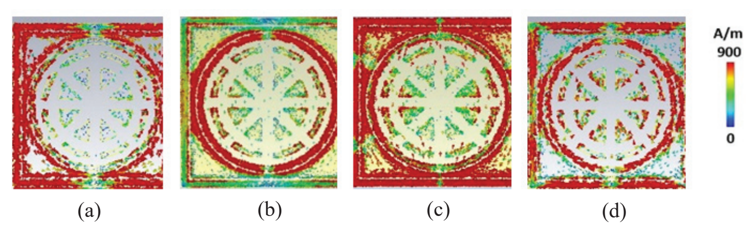

Figure 6. SC Distributions at (a) 4.4GHz, (b) 6.0 GHz, (c) 14.1GHz, and (d) 16.0 GHz.

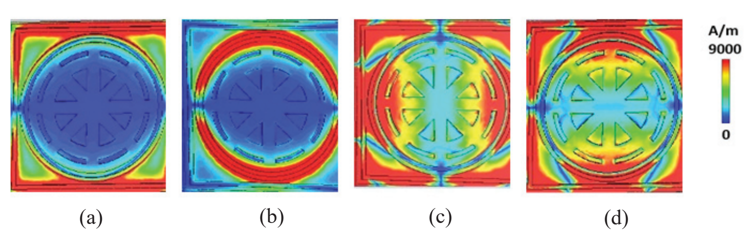

Figure 7. E-field distributions of the structure at (a) 4.4 GHz, (b) 6.0 GHz, (c) 14.1 GHz, and (d) 16.0 GHz.

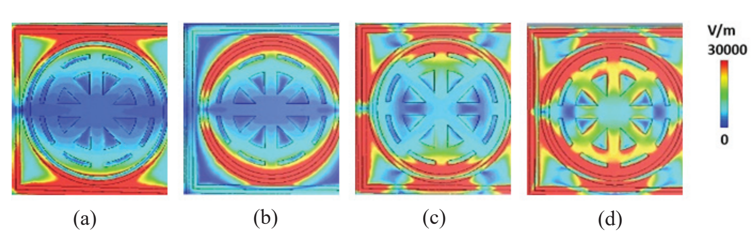

Figure 8. H-field distributions of the structure at (a) 4.4GHz, (b) 6.0 GHz, (c) 14.1 GHz, and (d) 16.0 GHz.

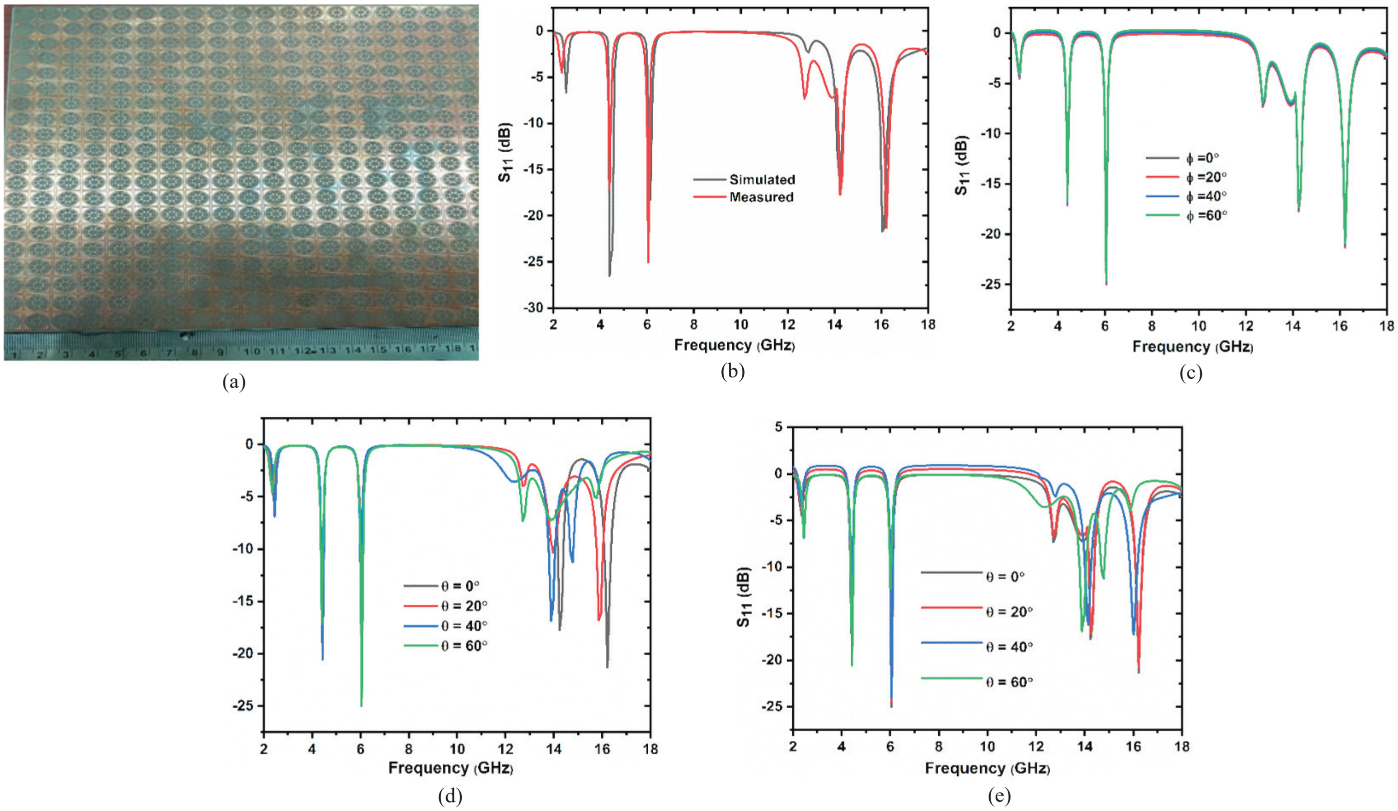

Figure 9. Measured characteristics (a) fabricated sample, (b) normal incidence, (c) different polarisation angles, (d) different angles of incidence for TE, and (e) TM.

A non-destructive free space measurement setup has been employed to measure the frequency-dependent RC properties of the fabricated sample. The measurement has been performed in an anechoic chamber consist of a Keysight vector network analyser (VNA) 35063A and broadband horn antennas. The descriptive details of a free space microwave measurement setup are provided by Panwar & Lee[17]. The simulated and measured RC characteristics under normal incidence are shown in Fig. 9(b). A quite good agreement is noticed between simulated and measured results, except slight discrepancies which might be due to fabrication uncertainties.

The polarisation insensitive response is also investigated experimentally and illustrated in Fig. 9(c), which illustrates the same RC response with variation in polarisation angle 'θ' till 60°. It has been observed in Fig. 9(c) that the prototype exhibits polarisation-insensitive behaviour in the range of 2 to 18 GHz. The measured RC response of the proposed fabricated sample with a distinct incidence angle under TE and TM are portrayed in Figs. 9(d) and 9(e), respectively. The measured results show the variation in higher frequencies under TE and TM polarisations. More or less identical results are procured in lower frequencies under TE and TM polarisations.

The complex electromagnetic (EM) properties are extracted from scattering parameters using the approach provided in by Kim and Lee[15]. The frequency response of the EM properties in terms of permittivity, permeability, and normalised impedance is reported in Figs. 10(a)-10(c), respectively. The values of real and imaginary permittivity and permeability concerning the resonant frequencies are summarised in Table 2. The negative values are responsible for maximum absorption and also indicate the nature of MMA. It is observed that at the peak frequencies the normalised impedance value of the structure is almost equal to unity, which satisfies the condition of impedance matching.

Table 2. EM properties at resonance frequencies

Frequency (GHz)	ε'	ε"	μ'	μ"
4.4	0.55	-7.4	2.4	-24.6
6.0	0.26	-4.0	5.2	-23.5
14.1	1.0	-4.3	0.9	-4.1
16.0	0.9	-3.0	1.0	-4.5

5. ANALYSIS OF DATA

The proposed 1.6 mm thick microwave absorbing structure possesses four discrete absorption peaks observed at 4.4 GHz, 6.0 GHz, 14.1 GHz, and 16.0 GHz manifesting absorption intensities of 94%, 84%, 82%, and 92%, respectively. A comparison of the proposed work with other reported structures is presented in Table 3. The comparison is made in terms of thickness (t) of the structure, complexity, and the number of covering bands. A multi-layered, square geometry along with resistors has been utilised to obtain polarisation-insensitive characteristics[13]. FR4 substrate has been used in the absorber, which exhibits an absorption bandwidth of 13.26 GHz. The reflection dip was observed at 11.0 GHz, with an RC of -18.8 dB. The overall thickness of the substrate was 4.6 mm. The diodes-loaded square loop was designed to achieve a polarisation-insensitive absorber [14]. The FR4 substrate has been utilised to obtain the absorption at 3.71 GHz with an RC of -30.08dB. The overall thickness of the structure was 8.0

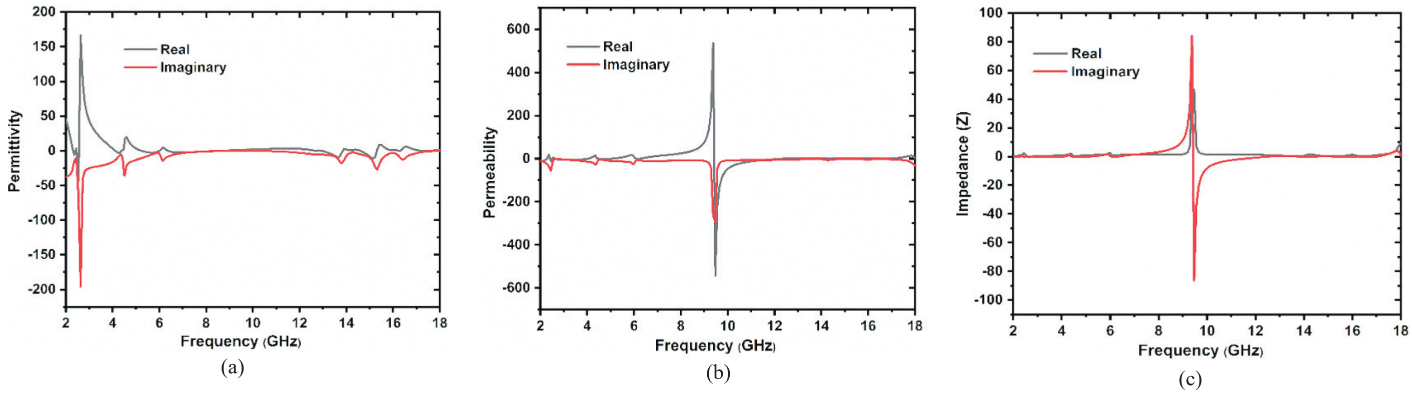

Figure 10. Complex EM properties (a) dielectric permittivity, (b) dielectric permeability, and (c) normalised impedance.

Table 3. Comparative analysis of the proposed absorber with other relevant reported works

References	Structure complexity	T (mm)	Polarisation insensitive	BW
[13]	Complex due to resistors	3	Yes	Single-band
[14]	Complex due to diodes	1	Yes	Single-band
[15]	Complex due to resistors	2.4	Yes	Broadband
[16]	Simplicity	2	No	Broadband
[18]	Complex due to the vias and multi-layered	10.1	No	Single-band
[19]	Complex due to resistors	3	Yes	Wideband
Proposed work	Single layered	1.6	Yes	Multiband

mm. A polarisation-insensitive single-layered absorber was realised using a trumpet-shaped resonator[15]. Moreover, chip resistors have been utilised in the structure. The authors used an FR4 substrate of 2.4 mm thickness to achieve 8.3 GHz absorption bandwidth ranging from 8.6 to 16.9 GHz. A 2.0 mm thick, momo-layer hybrid absorber has been designed to achieve broadband absorption characteristics[16].The structure shows a minimum RC of -29.0 dB at 12.2 GHz. The multi-layered absorber exhibits an absorption bandwidth of 0.5 GHz in the range of 0.6 GHz to 1.1 GHz[18]. The authors used two dimensional MM with active elements to achieve the maximum absorption. The whole thickness of the structure was 10.1 mm and it also shows polarisation-sensitive behaviour. A polarisation-insensitive, thin, and wideband MM absorber was investigated analytically and experimentally[19]. The dual octagonal rings loaded resistors were printed on an FR4 dielectric substrate. The maximum absorption bandwidth of 9.25 GHz was observed in the frequency range from 7.93 to 17.18 GHz with a substrate thickness of 3.0 mm. The analysis carried out in Table 3 reflects that the obtained results for the present work are in strong agreement with the other reported works. The polarisation insensitivity, angular stability, multiband absorption response, and compactness are a few key features of the present absorber configuration.

6. CONCLUSIONS

In summary, a multiband and single-layered absorber comprised of eight sectors loaded circles inside the square is successfully designed, critically analysed, and experimentally validated. The material properties of the proposed model are extracted to procure enlighten into the absorption phenomenon. Besides, the structure is polarisation insensitive and the structure is also investigated for angular stability. The absorption mechanism of the structure is analysed and explicated with the aid of SC, E-field, and H- field. The measured results possess a good matching with simulated ones. The proposed structure can be utilised for various practical applications, like stealth technology and electromagnetic interference (EMI) suppression, etc.

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In the current study, he has provided the technical and scientific inputs for the analysis of data and contributed to writing and editing the paper.

Dr Rajesh Khanna is a Professor of Electronics and Communication Engineering at the Thapar Institute of Engineering and Technology, Patiala. His current interests are in Wireless Communication and Antennas and he has guided several research projects in which useful algorithms for wireless communication have been developed and implemented. Presently his research work is focused on the design and development of antennas for various applications and Cognitive Radios. He has widely published over sixty peer-reviewed publications. He has completed projects worth 1.8 Crores.
In the present work, he has guided the overall aim and objectives of the study.