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Design of Polarization-Insensitive Dual Band Metamaterial Absorber

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Abstract—A new design has been proposed for a single layer polarization-insensitive dual-band metamaterial absorber at C and X bands. The proposed structure consists of a periodic arrangement of a circular resonator embedded in a square resonator. A commercially available FR4 dielectric has been used as a substrate with metallic grounded bottom and imprints on the other side. This structure resonates at 5.5 GHz and 8.9 GHz with absorptivity of 99.8% and 99.97%, respectively. It exhibits polarization-insensitive behaviour for Transverse Electric and Transverse Magnetic polarization under oblique and normal angles of incidence. The field distributions have been studied for better understanding of the absorption mechanism. The fabricated structure has been tested, and the experimental results are similar to the simulated ones. This polarization-insensitive metamaterial absorber with its ease of design and nearly unity absorption can be used for radar applications.

1. INTRODUCTION

The emergent interest in metamaterial due to its left-handed properties [1–5] has led to its application in many potential devices, such as antenna [6, 7], filter [8], absorber [9, 10], cloaking [11, 12], etc. The research of metamaterial absorber (MMA) is definitely significant in radar applications, such as stealth technology, reduction in specific absorption rate (SAR) in mobile phones and medical devices [13, 14], etc. The absorption mechanism of the MMA is the destructive interference of the incident electromagnetic waves [15]. The unique properties of a metamaterial absorber have contributed many value added properties, such as nearly perfect absorption, ultra-thin structure and polarization independent. These advantages have led to the rapid growth of metamaterial absorbers in microwave and terahertz [16–18] frequency regimes too. Various metamaterial absorbers with different characteristics, such as single band [19, 20], dual band [21–29], triple band [30–34], quad band [35], penta-band [36] and wide band absorption, have been developed and studied.

Many researches have been performed on dual-band metamaterial absorber. The dual-band metamaterial absorber designed in 2010 by Li et al. [21] at 11.15 GHz and 16.01 GHz exhibited high absorption of 97% and 99%. Lee and Lee [22] presented MMA with complementary split ring resonators and split ring resonators operating at 2.95 GHz and 3.60 GHz with absorption of 92% and 94%, respectively. In 2013, a single square ring with slits was used to design a dual-band metamaterial absorber which was polarization insensitive [23]. The absorptivity of 96% and 99% was achieved at 10 GHz and 20 GHz, respectively. Tuong et al. [24] demonstrated a dual-band structure at 8.55 GHz and 11.78 GHz with measured absorptivity of 96% and 98% at lower and higher frequencies, respectively. Li et al. [25] varied the dielectric spacer and obtained absorption of 99.3% and 99.4%. Zhai et al. [26] used Jerusalem resonators for designing a dual-band MMA which operates at 5.95 GHz and 12.25 GHz with absorption above 90%. Li et al. [27] designed a dual-metamaterial structure with left-handed properties well suited for applications, such as antenna, filter, absorber, etc. In 2014, Ghosh et al. [28] implemented a polarization-insensitive and ultra-thin metamaterial absorber with full width half maxima of 1.15 GHz

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with 96% and 92.5% absorptivity at 9.66 GHz and 10.26 GHz, respectively. Bhattacharyya et al. [29] proposed a dual-band bandwidth enhanced MMA using two layers of dielectric material.

In this paper, a polarization-insensitive dual-band metamaterial absorber with 99.8% and 99.97% absorption at 5.5 GHz and 8.9 GHz is proposed. Nearly perfect unity absorption was achieved by fine tuning the structure dimensions. Polarization-insensitive behavior was tested under normal and oblique incidence for Transverse Magnetic (TM) and Transverse Electric (TE) modes. The proposed metamaterial absorber was fabricated, and the experimental results were compared with the simulated ones. This structure may find good use in radar applications.

2. DESIGN AND SIMULATION RESULTS OF THE STRUCTURE

Fig. 1 depicts the top layer of the proposed metamaterial absorber unit cell. The metamaterial structure is chosen such that it is simpler and easier to design. It is optimized to give negative permittivity and permeability with high absorption with less reflection leading to high absorption performance. The structure consists of a dielectric FR4 substrate of thickness 1 mm (relative permittivity $\varepsilon_r = 4.3$, dielectric loss tangent tan $\delta = 0.025$) separating the metallic imprints and metal laminated bottom ground. The top layer comprises circular and square shaped ring resonators. The dimensions were $a = 10$ mm, $b = 8$ mm, $w_1 = 0.4$ mm, $w_2 = 0.5$ mm and $r = 3.3$ mm. The copper ($\sigma = 5.8 \times 10^7$ S/m) of thickness 0.035 mm was used for both the metal layers. Using Ansys HFSS, the designed structure was simulated with periodic boundary conditions. For this periodic structure, floquet port excitation was used. When a wave is incident on the proposed metamaterial absorber, the transmission of the wave is obstructed by the copper grounded bottom, so the transmission coefficient $S_{21}(\omega)$ becomes zero. The impedance matching achieved by proper tuning of the structure leads to zero reflection. Therefore, the plane waves are completely absorbed by the metamaterial absorber. The absorptivity is given as,

$$A(\omega) = 1 - |S_{11}(\omega)|^2 - |S_{21}(\omega)|^2. \tag{1}$$

$$z(\omega) = \frac{(1 + S_{11}(\omega))}{(1 - S_{11}(\omega))}. \tag{2}$$

$A(\omega)$, $Z(\omega)$ and $S_{11}(\omega)$ denote the absorptivity, normalized input impedance and reflection coefficient, respectively, at the angular frequency ω. Initially, the metamaterial absorber with a circular resonator was designed, as shown in Fig. 2(a), and simulated. This structure resonated at 8.8 GHz and had an absorptivity of 90.1%, shown in Fig. 2(b). Fig. 3(a) depicts a square-shaped metamaterial absorber designed separately and simulated. It shows 95% absorptivity at 5.6 GHz as presented in Fig. 3(b). The proposed MMA in Fig. 1 is the combination of circular and square resonators, and the simulated absorptivity is presented in Fig. 4(a). It has been observed that this structure has a reflectivity of −27 dB and −37 dB with an increased absorption of 99.8%, 99.97% at 5.5 GHz and 8.9 GHz, respectively. The normalized impedance plot for the proposed structure calculated using Equation (2) is presented in

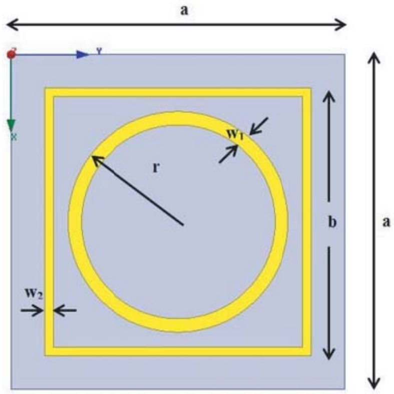
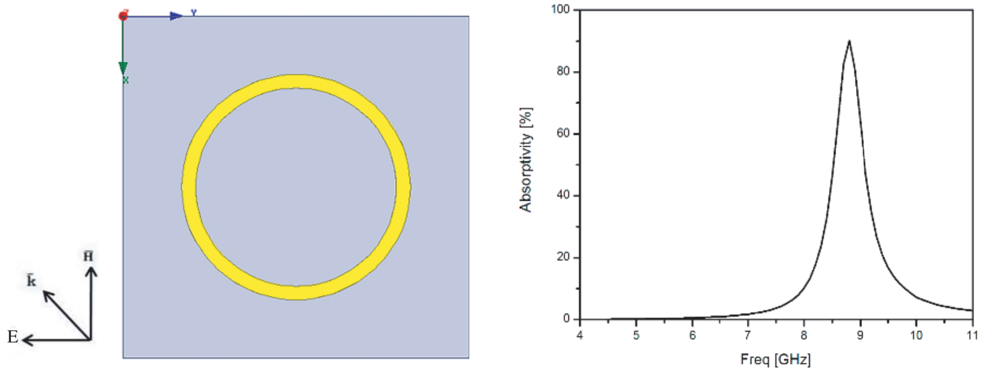
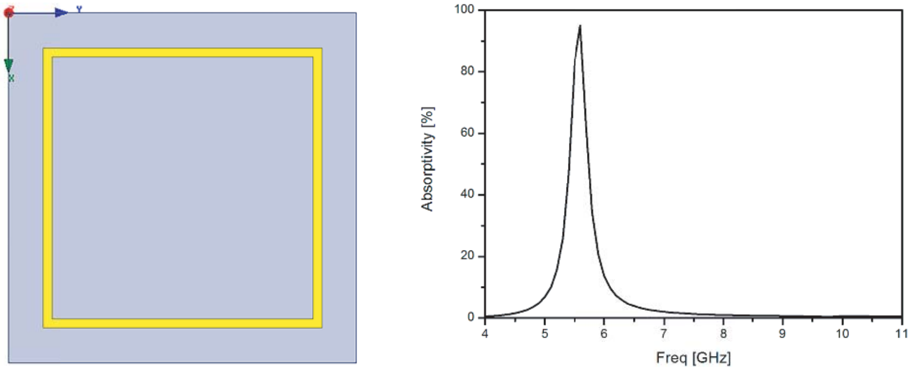


Figure 1. Top layer of the proposed MMA unit cell.



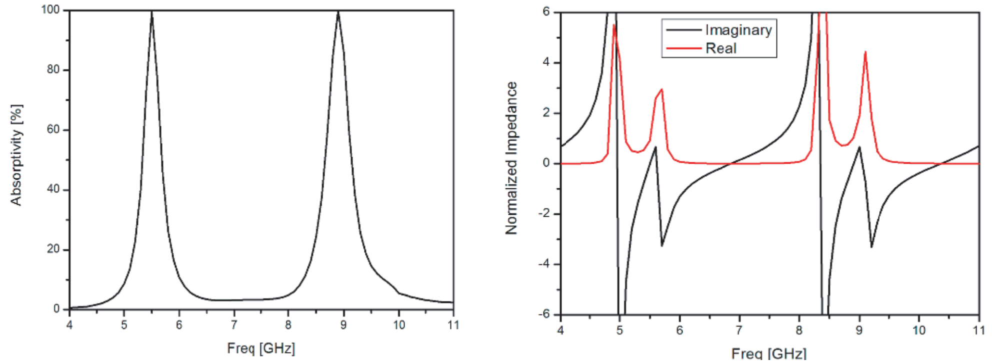
(a) (b)

Figure 2. (a) Structure with circular resonator, (b) simulated absorptivity.



(a) (b)

Figure 3. (a) Structure with square resonator, (b) simulated absorptivity.

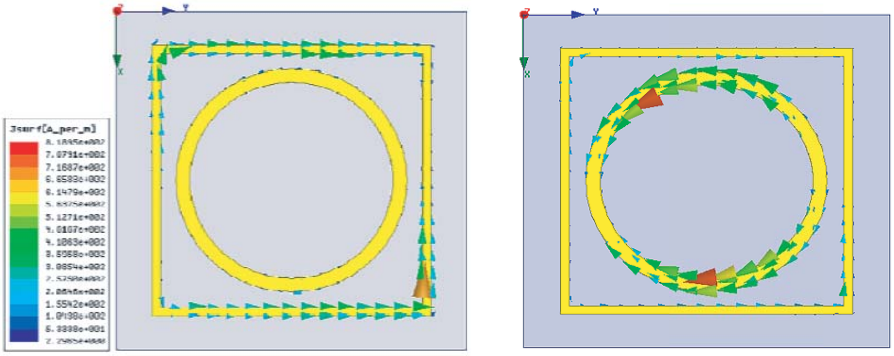


(a) (b)

Figure 4. (a) Simulated absorptivity, (b) extracted normalized impedance of the proposed MMA.

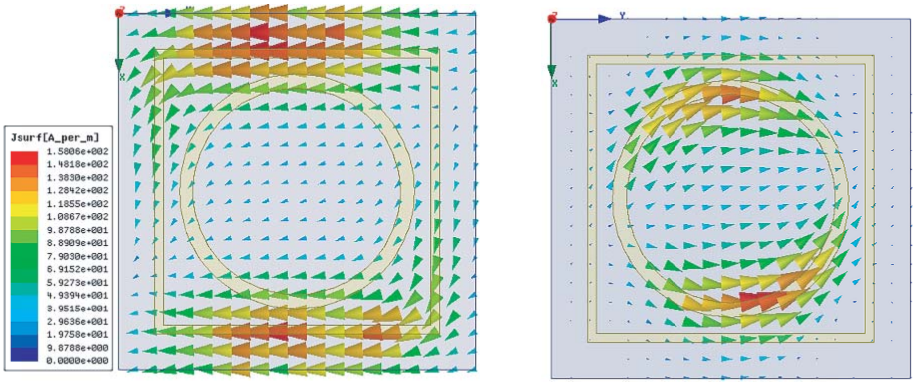
Fig. 4(b). The imaginary part of impedance becomes zero as there is no reflection, and the real part approaches unity by perfect impedance matching between the free space and the proposed structure.

Figures 5 and 6 show the distribution of surface current density in the top and bottom layers of the designed MMA at dual bands. The surface current distribution is in the anti-parallel direction to the top and bottom layers forming a circulating current loop. Much of the surface current distribution was within the outer ring, thereby contributing to absorption at 5.5 GHz as shown in Fig. 5(a) and Fig. 6(a). The surface current distributions in Fig. 5(b) and Fig. 6(b) show that the absorption at 8.9 GHz is due to the inner circular resonator. The electric field distributions at dual bands are shown in Fig. 7(a) and Fig. 7(b). The electric field is incident on the metallic top layer, and the magnetic field is perpendicular to the circulating current loop. The electric and magnetic fields become prominent at resonance frequencies, hence high absorption is achieved. These field responses are controlled by proper design optimization leading to nearly unity absorption at the dual bands.



(a) (b)

Figure 5. Surface current distributions in top layer of the proposed MMA. (a) 5.5 GHz, (b) 8.9 GHz.

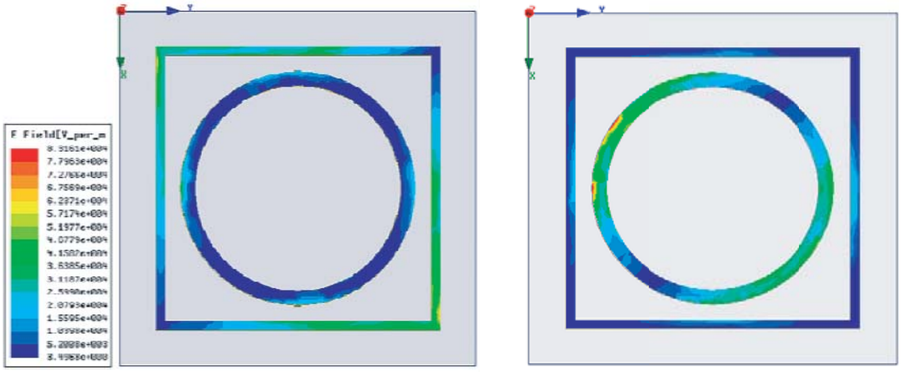


(a) (b)

Figure 6. Surface current distributions in bottom layer of the proposed MMA. (a) 5.5 GHz, (b) 8.9 GHz.

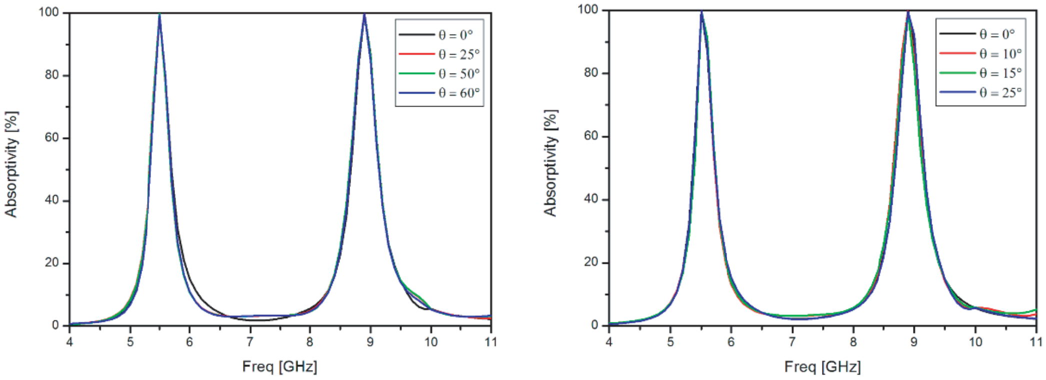
3. POLARIZATION-INSENSITIVE METAMATERIAL ABSORBER

In this section, TE and TM polarizations under varying normal and oblique angles of incidence are studied theoretically. The simulation results show that the proposed MMA at certain angles of incidence is polarization-insensitive due to the symmetrical structure. With constant electric field direction, the wave vector and magnetic field are changed to analyze the oblique incidence in TE polarization and in the reverse condition for TM polarization. The MMA is polarization-insensitive for oblique angles of incidence at 25°, 50°, 60° for TE mode and 10°, 15°, 25° for TM mode as presented in Fig. 8(a) and Fig. 8(b), respectively. Fig. 9(a) and Fig. 9(b) demonstrate the polarization-insensitive behavior of the proposed MMA for normal angles of incidence at 25°, 50° for TE mode and wide range of angles for TM mode.



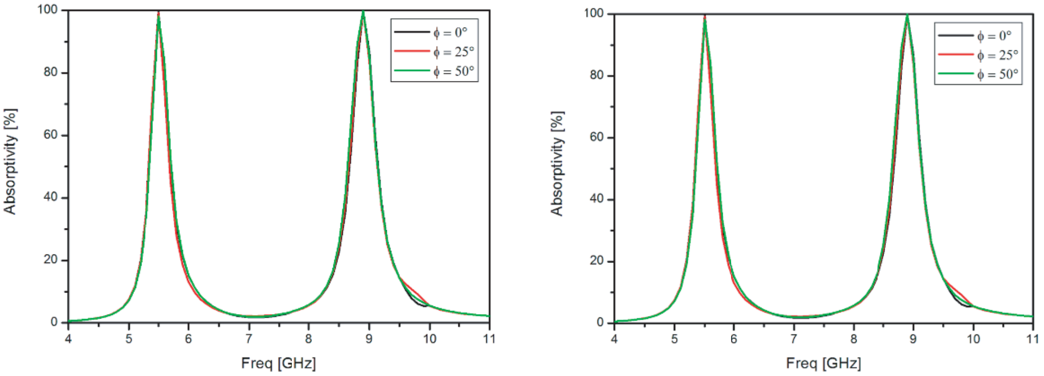
(a) (b)

Figure 7. Electric field distributions of the proposed MMA. (a) 5.5 GHz, (b) 8.9 GHz.



(a) (b)

Figure 8. Simulated absorptivity under oblique incidence for (a) TE mode, (b) TM mode.

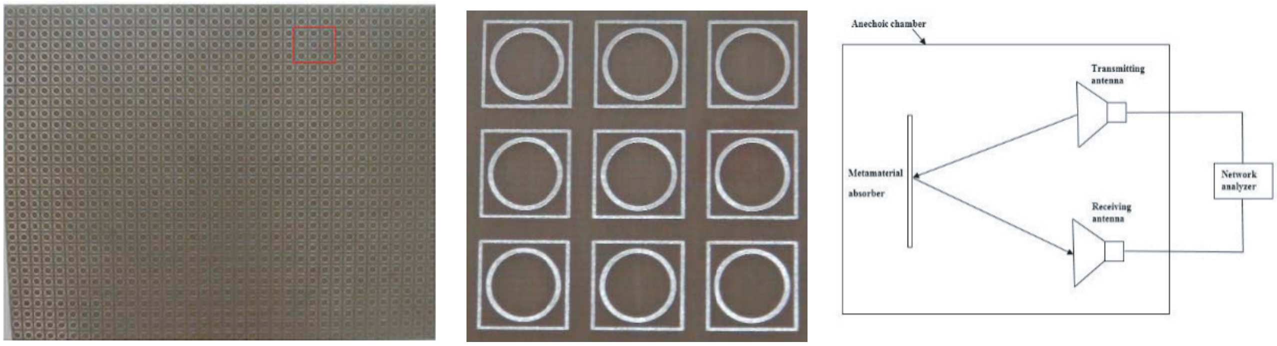


(a) (b)

Figure 9. Simulated absorptivity under normal incidence for (a) TE mode, (b) TM mode.

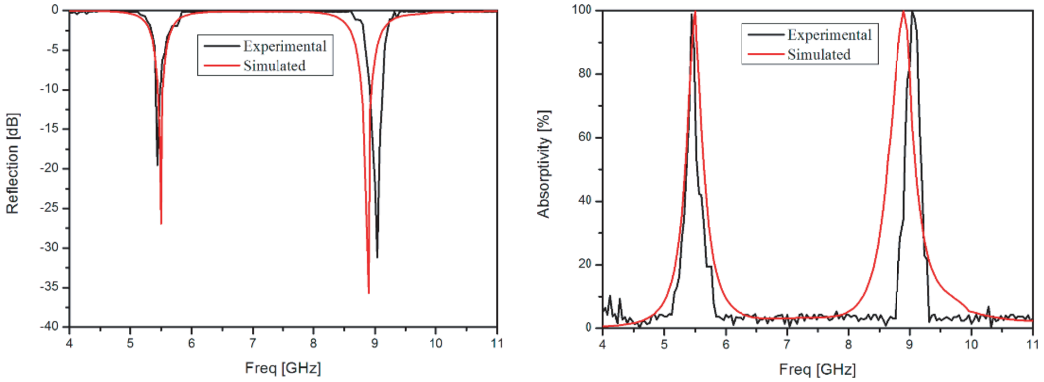
4. EXPERIMENTAL RESULTS

The proposed metamaterial absorber structure was fabricated on an FR4 dielectric substrate of thickness 1 mm through printed circuit board technology. The size of the fabricated structure was 300 mm × 360 mm, presented in Fig. 10(a). The enlarged view is shown in Fig. 10(b). The measurement setup diagram is shown in Fig. 10(c). The vector network analyzer, with the help of broadband horn antennas, was used to measure the power reflected from the fabricated structure. At first, a copper sheet with the same dimension as that of the fabricated structure was placed. The reflected power was measured and used as a reference. Then, the copper sheet was replaced by the fabricated structure, and the power reflected from the structure was measured. The actual reflection from the fabricated MMA was the difference between the reflection measured from the structure and the reference measurement.



(a) (b) (c)

Figure 10. (a) Fabricated structure, (b) enlarged view of the highlighted part in (a), (c) measurement set up diagram.



(a) (b)

Figure 11. Comparison of measured and simulated responses. (a) Reflection, (b) absorptivity.

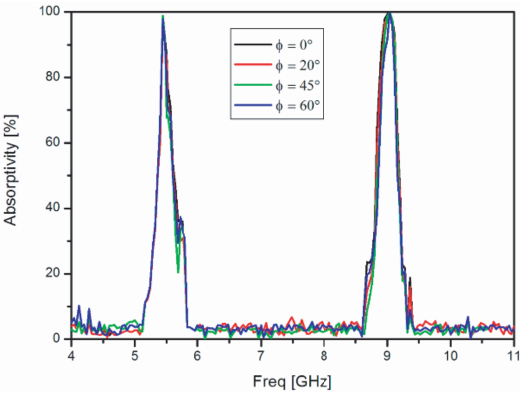


Figure 12. Measured absorptivity under normal incidence for TE mode.

The experimental result shows peaks at 5.44 GHz and 9.04 GHz with 98.88% and 99.9% absorptivity, respectively. A small deviation in the measured absorption may be due to the fabrication imperfections. The experimentally measured and simulated reflections and absorptivities are compared in Fig. 11(a) and Fig. 11(b), respectively. The TE polarization-insensitive behavior of the fabricated structure was verified for the normal angles of incidence by rotating the structure in steps of 5° and placing the antennas in static position. From Fig. 12, it is observed that the proposed structure is polarization-insensitive for 20°, 45° and 60° under normal angles of incidence, and there is a slight variation in absorptivity peaks compared to the simulated response.

The absorptivity and unit cell size of the proposed structure were compared with metamaterial absorbers whose frequency band was closer to the frequency band of the proposed MMA and are listed in Table 1. The unit cell size of the proposed structure was the same as that of the triple-band MMA [30]; however, the absorptivity obtained by the proposed MMA at 5.5 GHz was higher than that of the latter structure. The proposed MMA has a comparable unit cell size and absorption as [19] near 8.9 GHz, but it has the advantage of achieving dual bands leading to added practical use. From Table 1, it can be concluded that the proposed MMA is compact and has high absorption at 5.5 GHz and 8.9 GHz.

Table 1. Comparison among metamaterial absorbers.

Parameter	Number of bands	Unit cell size (mm)	Frequency nearer to the band of the proposed structure (GHz)	Absorptivity (%)
Ref. [30]	Triple	10	5.5	94.1
Ref. [19]	Single	36	5.48	99.99
Ref. [31]	Triple	18	5.5	96.9
Ref. [32]	Triple	18	5.22	97.1
Ref. [33]	Triple	15 × 16	5.68	95.4
Ref. [34]	Triple	18	5.65	99.98
Ref. [25]	Dual	12 × 6	9.02	99.3
Ref. [20]	Single	10	9.028	99.98
Proposed structure	Dual	10	5.5, 8.9	99.8, 99.97

5. CONCLUSION

A new design for a polarization-insensitive dual-band metamaterial absorber has been proposed. The proposed structure has two different shaped ring resonators, etched on an FR4 dielectric substrate operating at C and X bands. The inner circular and outer square resonators provide absorption of 99.97% at 8.9 GHz (X band) and 99.8% at 5.5 GHz (C band), respectively. At two distinct frequencies, the electric field and surface current density have been plotted, and their absorption mechanisms have been examined. The proposed structure at particular angles for normal and oblique incidence exhibits polarization-insensitive behavior for Transverse Electric and Transverse Magnetic modes. The designed metamaterial absorber structure has been fabricated and tested. The experimental results match with the simulated ones. Also, the measured results prove the polarization insensitivity of the proposed structure. Hence, this polarization-insensitive dual-band metamaterial absorber with nearly unity absorption may be well suitable for radar applications.

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