An ultra-thin quad-band metamaterial inspired absorber using symmetric bent-arrow shaped resonator for sensing and imaging in defense applications

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Abstract

In this paper, a novel compact quad-band polarization insensitive metamaterial absorber has been proposed to be employable in the microwave frequency regime. The unit-cell geometry comprises of four symmetric bent-arrow shaped resonators, where each arrow has been bounded by an open ring. The resultant structure is further surrounded by a closed ring to obtain an extra resonance band. Full-wave simulation with normal incidence depicts quad-band operation with absorption peaks at 3.24 GHz (S-band), 6.55 GHz (C-band), 15.22 GHz (Ku-Band), 15.94 GHz (Ku-band) and absorptivity levels of 99.57%, 99.94%, 96.10%, 98.65% correspondingly. It also shows full width half maximum (FWHM) bandwidth of 100 MHz, 200 MHz and 1210 MHz in the first, second and third bands respectively. Furthermore, the proposed structure is based on four-fold symmetry therefore exhibits polarization-insensitive behaviour unlike conventional absorbers. The structure is fabricated on 1 mm FR4 Glass Epoxy substrate equivalent to 0.0108λ₀ hence, can be used as absorber coating for planar surfaces. The designed absorber has been fabricated and experimental results were in good agreement with the simulated responses enabling its wide application in various technologies like stealth technology, radar cross section reduction, anechoic chambers, electromagnetic interference/electromagnetic compatibility, and radio frequency identification.

1. Introduction

Electromagnetic metamaterials (MTMs) can be defined as artificially engineered and effectively homogeneous electromagnetic structures that exhibit properties those are hard to be found in nature. The unnatural responses of metamaterial in subwavelength scale have attracted many researchers all over the world due to its capability of exhibiting negative refractive index [1]. It has numerous applications such as antennas [2], cloaking [3], super lens [4], and absorbers [5]. Out of these applications, metamaterial absorbers have diverse potential applications in stealth technology, radar cross section reduction, anechoic chambers, electromagnetic interference/electromagnetic compatibility, and radio frequency identification. Before the advent of metamaterial, absorbers were designed using Salisbury screen [6–8] which were thick and bulky thus were difficult to use in some applications.

Typically, a metamaterial absorber comprises of perennial arrangement of unit cells, where each unit cell consists of metallic surface etched over a thin layer of grounded substrate. These structures are capable of achieving near unity absorption by tailoring their electromagnetic parameters such as effective permittivity and permeability. Landy et al first demonstrated an absorber consisting of electric ring resonator (ERR) and cut wire [9] in 2008. In the above work, it has been demonstrated that electric and magnetic fields were excited at a particular frequency which can be tuned separately by varying the dimensions of the ERR and cut wire...
respectively. After this, some wideband absorbers were also reported using: metallic patches placed diagonally [10], metallic incurved square loop loaded with lumped resistors [11].

When absorbers are placed at a location, they could be oriented at any position and, hence it is highly desirable that microwave absorbers should remain independent of polarization angle. Some of the wideband absorbers are sensitive to polarization which limit their application, as any change in orientation will result in variation of absorbance results [12]. It may be noted that multiband metamaterial absorber has various potential applications therefore multiband absorbers have become very popular in recent years [13–17]. Bhattacharya et al proposed a triple-band absorber using two square loop structure but compactness of structure was compromised due to the extraneous placement of square ring resonators [13]. Consequently, some triple band microwave absorbers have been investigated using tetra-triangle resonators [14], and electric field driven LC resonators [15]. Bhattacharya et al suggested a technique to achieve polarization insensitivity, that whole combination of unit cells act like a single symmetric unit cell while individual cells may or may not be symmetric [13, 15]. The most common way is to make unit cell four-fold symmetric which can be achieved by implementing symmetrical shapes like circle, squares etc in the unit cell design [16, 17].

Sharma et al [18] have also investigated a triple band microwave absorber consisting of two modified closed loop resonators (CLR’s) but the reported structures require substrate thickness to be greater than 1 mm which increases the overall electrical thickness of the absorber. Polarization insensitive quad-band ultrathin metamaterial absorbers can also be found in literature [19, 20]. In [20], a quad band metamaterial microwave absorber was proposed using closed ring resonator, enclosing square patches. It may be noted that proposed design requires large unit cell size, that in turn blights the compactness of the structure. It is important to note that electrical size of these absorbers can further be improved while making them more compact and suitable for potential practical applications. Recently some notable work on perfect metamaterial multiband absorbers [21, 22] and broadband absorbers [23, 24] have been reported on the same concept.

In this paper an electrically compact, quad-band, ultrathin and polarization insensitive structure has been presented. The proposed structure exhibits absorption characteristics in S-band, C-band and Ku-band. Proposed structure has an electrical size of $0.108 \lambda_0 \times 0.108 \lambda_0$ and an electrical thickness of $0.0108 \lambda_0$. The optimization of the structure is carried out in such a way to ensure that proposed absorber remains compact and four-fold symmetric. The electromagnetic field distributions and the surface current plots at the absorption peaks have been illustrated to analyse the absorption behaviour of the proposed absorber. The designed structure has been studied for different angles of polarization under normal incidence. The structure has been fabricated using metal etching technique and the same has been tested in free space. The novelty of the proposed absorber corresponds to its quad band performance with excellent polarization insensitive behaviour and less electrical size and thickness. In addition, this absorber exhibits wide incident angle TE and TM polarization.

The paper is organised as follows—section 2, demonstrates the geometry, evolution of the proposed absorber and polarization insensitive performance. It also explains the metamaterial behaviour of the proposed unit cell. Section 3, includes the absorption curves with respect to different dimensions involved in the proposed unit cell. Section 4, describes the study of electric and magnetic fields to analyse the different bands. Section 5, presents experiment results and validation corresponding to simulated one and comparison of the suggested work with recently published multiband absorbers. Finally section 6, concludes the article, featuring its findings and future scope of the work.

2. Design and analysis of the absorber

2.1. Geometric layout of the proposed absorber

The geometrical composition of the proposed quad-band absorber unit cell structure is shown in figure 1. This structure comprises of a top metallic patch printed on a grounded dielectric substrate. Commercially available FR4 substrate has been used as dielectric with relative permittivity ($\varepsilon_r$) of 4.2, dielectric loss tangent ($\tan \delta$) of 0.02 and thickness of 1 mm. Copper film was used for both the top and bottom layers with thickness of 0.035 mm. The top metallic layer of investigated structure is a combination of four anti clockwise rotating arrows and an outer ring which is the outermost part of the unit cell. Each arrow is partially enclosed by a plus shaped resonator leaving the arrow head uncovered.

The physical parameters of the unit cell were selected such that, the impedance of the metamaterial approaches near equal to the free space impedance at operating frequency which results in maximum absorption. Absorption coefficient for any structure can be calculated by (1).

$$A(f) = 1 - |S_{11}(f)|^2 - |S_{21}(f)|^2$$  \hspace{1cm} (1)

Where $|S_{11}(f)|^2$ and $|S_{21}(f)|^2$ are the reflected and transmitted power respectively.
As background of the designed structure is metal hence the transmittivity will be zero i.e. $|S_{21}| = 0$. Thus (1) has been reduced to $A(f) = 1 - |S_{11}(f)|^2$ which means optimal value of absorptivity requires smaller value of reflectivity. Typically this reflectivity is having components in the $x$ and $y$ directions corresponding to the Co-polarized and Cross-polarized EM waves \[25–27\]. Thus

$$|S_{11}(f)|^2 = |S_{11}(f)_{xx}|^2 + |S_{11}(f)_{xy}|^2 \quad (2)$$

### 2.2. Design methodology and evolution of the proposed absorber

Keeping in view the conditions of homogeneity, metamaterial unit cell size ($a$) should be much smaller than quarter of the guided wavelength i.e. $a \ll \lambda_g/4$ \[28\], we set the initial dimensions of the unit cell as per the $\lambda_0/10 \times \lambda_0/10$ in order to work in the preliminary 3 GHz bands. Where $\lambda_0$ is the corresponding wavelength analogous to the lowest frequency of operation.

This section portrays the design procedure of the suggested absorber. To discuss this, the proposed structure has been organized into different arrangements, these arrangements are referred as Structure-A, Structure-B, Structure-C, and Structure-D correspondingly as shown in figure 2. Structure-A presents a simple square shaped ring on a substrate of $10 \times 10$ mm$^2$. Structure-B is a combination of four square shaped open ring rotated at 90°. Structure-C is a combination of Structure-A and Structure-B. Structure-D is composition of four bent arrows, each arrow is located at different positions from 90° out of phase with each other.

Figure 3 shows the progressive absorbance results corresponding to the different structure compositions discussed above. Figure 3(a) includes the absorptivity plots of Structure-A, Structure-B and Structure-C. Structure-A receives one absorption peak at 3.24 GHz only with peak absorbance of 99% while Structure-B observes two absorption peaks at 6.68 GHz and 13.81 GHz with peak absorptivity of 99.92% and 71.33% respectively. Then these two structures are combined to form Structure-C and it exhibits three good absorption peaks at 3.21 GHz, 6.84 GHz and 14.75 GHz with peak absorptivity of 98.47%, 96.76% and 91.65% respectively. It can be inspected that first band is slightly reduced with no deterioration in absorbance level. Second and third band is shifted to higher side due to capacitive coupling among Structure-A and Structure-B.

Further Structure-D is simulated and corresponding results are displayed in figure 3(b). Structure-D shows an absorption peak at 16.06 GHz with peak absorptivity of 81.46%. The results of the proposed absorber is shown by combining the Structure-C and Structure-D together. It could be clearly observed from the simulated response that there are four strong absorption frequencies at 3.24, 6.55, 15.22 and 15.94 GHz with absorption rates of 99.57%, 99.94%, 96.10% and 98.65% respectively. It is evident from the results that first absorption peak is due to the outer ring (outermost part), while second peak is due to arrow head and covered part of arrows. This study tells that third peak derives from the coupling between the outermost ring and the covered part of arrows and, fourth peak is due to the arrows tail. These will be further confirmed in the later sections with the help of parametric studies, electric field distributions and current density investigations. The unit cell structure was simulated in Ansys HFSS using periodic boundary conditions.

![Figure 1. Geometrical configuration of the proposed absorber unit cell. (All dimensions are in mm): $a = 10$, $t = 0.2$, $P_1 = 0.6$, $P_2 = 0.3$, $l_1 = 3.3$, $l_2 = 3.2$, $S_1 = 0.8$, $S_2 = 0.6$, $S_3 = 2.06$, $S_4 = 1.99$, $S_5 = 2.80$, $S_6 = 2.67$.](image-url)
2.3. Investigations under normal and oblique incidence

The proposed absorber unit cell is designed such that absorbance behaviour must remain unchanged with respect to their azimuthal angle ($\phi$). As discussed in the literature this could be carried out by fourfold symmetric structure. In order to verify the same, the proposed absorber has been analysed for different angles of polarization ($\phi$) from $0^\circ$ to $90^\circ$ in the step size of $15^\circ$.

Figure 4 confirms that suggested absorber exhibits polarization insensitive behaviour excellently throughout all the four bands. Further it is important to investigate the nature of the absorber with respect to their oblique incidence.

Figures 5(a) and (b) illustrates the simulated absorption rates as a function of frequency at various incident angles for TE and TM polarizations. With the incident angle ranging widely from $0^\circ$ to $45^\circ$, the four absorptivity peaks are almost at the same operating bands with good absorption rates. In both TE and TM at $45^\circ$, an additional peak starts to appear near 10 GHz frequency.

2.4. Validation of proposed unit cell as metamaterial

Metamaterial has proven to be quite useful for miniaturization in microwave structures as discussed in the literature. It is, therefore, essential to validate the metamaterial behaviour of the proposed unit-cell. To do this, proposed unit-cell has been characterized using two-port analysis and imposing suitable boundary conditions. The S parameters are then extracted from the unit cell and permittivity and permeability can be retrieved consequently as following the procedure in [29]. Figures 6(a) and (b) expresses the retrieved real and imaginary part of the permittivity and permeability respectively.

It can be seen, after carefully observing the figure that at all resonant peaks, real part of permittivity and permeability closes to zero at 3.24 GHz, 6.35 GHz and 15.94 GHz while simultaneously negative at 15.22 GHz. This satisfies the condition for zero reflectance, hence high absorption occurs at these frequencies [30]. The value of effective permittivity and permeability at all peaks are showcased in table 1.
Figure 4. Simulated absorption curves of the proposed absorber by varying azimuthal angles ($\phi$).

Figure 5. Simulated absorption rates at various incident angles for: (a) TE polarization, (b) TM polarization.

Figure 6. Extracted permittivity and permeability characteristics for the proposed unit cell, (a) Real part, (b) Imaginary Part.
3. Parametric analysis

It is important to study the resonance behaviour with the help of parametric analysis. It was already mentioned during the evolution of the structure, that first band is originated due to outer ring only and is independent from the other dimensions. Therefore, in this study we have included the design parameters which is responsible for exciting second, third and fourth band. During the optimization process, it has been conferred that second, third and fourth band can be originated and controlled by modulating the parameters of the arrow. An absorber with compact structure has the advantage of small size, but makes it difficult to adjust the resonance frequency points due to the unavoidable couplings between the different parts of the structure. This investigation involves the dimensions associated with the arrows as in following section.

3.1. Length and width of the arrow tail

The absorbance results have been first analysed with respect to the width of the arrow tail (S₂) as shown in figure 7(a). The value of S₂ has been varied from 0.4 mm to 0.8 mm with the step size of 0.1 mm. It can be observed that third and fourth peaks both has shifted towards higher side while increasing this value and has been fixed to S₂ = 0.6 mm. After this, length of the arrow tail (S₅) was modulated as shown in figure 7(b). It can be observed that this dimension is significantly responsible for driving the fourth peak. S₅ is moderated from 2.2 mm to 3 mm in the step size of 0.2 mm, out of them 2.8 mm is chosen as the optimum one. It was inspected that third and fourth peaks shifted towards left side as we were increasing this length. Since, third band is due to the coupling among outer ring and covered part of the arrows, therefore third band is slightly affected. Hence, by carefully optimizing both of the parameters, third and fourth peaks were obtained with good absorption rates.

3.2. Length and width of the arrow head

Length of the arrow head plays an eminent role to drive the second band and third band. Figure 8(a) shows the variation in absorption coefficient while varying the dimension l₁. It could be clearly seen that it affects the response of second, third and fourth band. Therefore, optimization of this parameter is very important in designing the proposed absorber.

It also, confirms the claim (mentioned in section 2.2) that second peak is due to the coupling among arrow head and covered part of the arrows. This dimension is also associated indirectly with the third and fourth band as coupling has been affected by altering this dimension. Length l₁ of arrow head is varied from 2.9 mm to 3.4 mm to obtain the three bands with high absorption peak and is obtained at l₁ = 3.3 mm.

Figure 8(b) illustrates the absorptivity response when arrow head width (S₁) is varied from 0.4 mm to 0.8 mm. The second band is independent from this dimension as can be monitored. Fine tuning of this dimension helps to couple the fields, better among arrow head and covered part of the arrows, as a result of this, absorption peaks for third and fourth bands have improved as can be noted from figure 8(b).

4. Absorption mechanism

To get a better insight of physical mechanism of absorption, in the proposed absorber, the electric field and surface current distribution have been examined for the four peak absorption frequencies under the normal incidence. In the absorption mechanism, Resonator-A is considered as outer ring , Resonator-B is considered as arrows while Resonator-C is considered as the covered part of arrows.

4.1. Study of electric fields distribution

Figure 9 shows the electric field plots at all four simulated peaks 3.24 GHz, 6.55 GHz, 15.22 GHz, 15.94 GHz considering uniform magnitudes. It can be seen that maximum concentration of electric field at 3.24 GHz frequency is on Resonator-A and some concentration on the arms of Resonator-C therefore this confirms the
statement offered during the evolution of the absorber that first peak is due to the outer ring however this ring associates with the other bands as well.

Further electric field distribution at 6.55 GHz is plotted which observes a strong concentration exists in Resonator-C and moderate concentration at Resonator-A. These both resonators (Resonator-A and Resonator-C) are also responsible for obtaining third-band at 15.22 GHz frequency. This can be verified by plotting the electric fields at 15.22 GHz as shown in figure 9(c). It can be inspected that there is considerable electric coupling among Resonator-A and Resonator-C and therefore this absorption peak is due to the contribution of both the resonators. Figure 9(d) illustrates the electric fields at 15.94 GHz. It can be studied, that this band is the outcome of contribution of all the resonators (Resonator-A, Resonator-B and Resonator-C). It can be stated, that these bent arrows help to originate another mode while Resonator-A and Resonator-C are liable for enhancing the absorptivity.

4.2. Study of surface current density

Electric field excitation was depicted in the last section. In order to show the magnetic excitation, surface current density at the top and bottom portion at different resonant peaks have been plotted in figure 10. It has been clearly seen that maximum current is concentrated on (i) outer ring of the proposed absorber at 3.24 GHz, (ii) boundaries of the arrows and outer ring at 6.55 GHz, (iii) bent arrows and boundaries of the arrows, in figure 10(c) (iv) all elements of the proposed absorber in figure 10(d). It is important to note that, simultaneous excitation of electric and magnetic fields at resonant frequencies offer high absorption of electromagnetic waves.
The results shown in figure 10 supports the electric field results as was shown in figure 9. Moreover, the direction of the currents at all absorption peaks are anti-parallel, with respect to top and bottom surface of the absorber. Thus, it is forming a circular loop which affirms the magnetic excitation of the absorber at all the frequencies. Therefore, it can be concluded that electric and magnetic fields are simultaneously excited at all the absorption peaks i.e. 3.24 GHz, 6.55 GHz, 15.22 GHz, and 15.94 GHz.

4.3. Study of input impedance

It is important to ensure the minimum reflections from the surface of the absorbers and consequently maximum absorptions at the given bands [10]. To get the same, input impedance of the absorber should be perfectly matched with the impedance of the free space. Therefore, normalized input impedance of the proposed absorber has been determined with the help of following relation [31]:

$$Z(\omega) = \left[ \frac{(1 + S_{11}(\omega))^2 - S_{21}^2(\omega)}{(1 - S_{11}(\omega))^2 - S_{21}^2(\omega)} \right]^{1/2}$$

In the given equation (3) transmission coefficient $|S_{21}(\omega)| = 0$, due to metallic backing. Therefore, this quantity ($Z$) approximately depends on $S_{11}(\omega)$. The real and imaginary part of this impedance should be nearly unity and zero respectively at all absorption peaks, to achieve the perfect matching. Table 2, reveals the same at
all four peaks, as real part of the impedance is close to unity while reactance part is close to zero, which leads to high absorption rate at these frequencies.

5. Experimental results and validation

In order to validate all the inferences, proposed absorber has been fabricated on a FR4 Glass Epoxy substrate of thickness 1 mm and dielectric with relative permittivity ($\varepsilon_r$) of 4.2, dielectric loss tangent ($\tan\delta$) of 0.02. To do this, 30 unit-cells of proposed structure was accommodated on a 1 Feet $\times$ 1 Feet substrate as depicted in figure 11. It also, shows the zoomed view of the single fabricated unit-cell and the back view of the absorber sheet. Proposed absorber has been tested under free space by the method as explained in the [13, 15, 17]. The measurement was carried out using 10 MHz – 26.5 GHz Agilent PNA N8522A, and two UWB horn antennas working over 1 GHz – 18 GHz. To perform the measurement, a vector network analyzer was calibrated over the range of 3 GHz to 18 GHz as absorption was claimed between that range. Copper sheet of identical size and thickness is used to quantify the reflection coefficient considering free space losses. After that, the absorber prototype is placed at the same position and measured the reflection coefficient again. The difference between former and latter will give us the information of reflection coefficient and consequently absorptivity has been obtained. Figure 12 portrays the comparison among simulated and measured results, carried using the setup as explained above. It has been observed, that proposed absorber is following the simulated results with good agreement. Measured results depict peak absorptivity of 96.29%, 86.59% and 93.62% at 3.46 GHz, 6.43 GHz and 16.03 GHz respectively. It also delivers measured Full Width Half Maximum (FWHM) bandwidth of 168 MHz (3.375–3.543 GHz), 300 MHz (6.3–6.6 GHz) and 1425 MHz (14.7–16.125 GHz) correspondingly in
the first, second and third bands. Minor shifts in the frequency of absorption and magnitude of absorbance is noted which may be due to the fabrication tolerance, and permittivity tolerance. Significant noise could be monitored in experimental results because measurements were carried out in free space and not in anechoic chambers. Therefore, unwanted radiations from the surrounding area might have affected the reflection coefficients and consequently the absorbance results.

Figure 10. Surface current density distributions at the top and bottom surface of the proposed structure at: (a) 3.24 GHz, (b) 6.55 GHz, (c) 15.22 GHz, (d) 15.94 GHz.
Further in order to investigate the polarization insensitive behaviour of the proposed work, prototype has been placed with utmost care, at different angles in the xy plane. Copper sheet of identical dimensions (back side of the prototype) has been placed at different angles to minimize the free space losses from the environment.

Similar procedure was then followed as in case of absorption measurement and reflection coefficients are taken at different angles such as $\phi = 15^\circ$, $30^\circ$, $45^\circ$ etc figure 13 shows the absorption results depicts polarization insensitive behaviour under normal incidence. It can be observed that proposed absorber has the capability to have same absorption coefficient, while rotated in the xy plane. There are, negligible shifts in the absorption frequency, which could be, due to the inaccuracies in the placement of the sample under test.

**Figure 11.** Photograph of the fabricated absorber sheet used for the experimental verification.

**Figure 12.** Simulated and experimental absorbance of the proposed absorber.

| Absorption frequency (GHz) | Real part of normalized input impedance Re (Z) | Imaginary part of normalized input impedance Im (Z) |
|---------------------------|-----------------------------------------------|--------------------------------------------------|
| 3.24                      | 1.1334                                       | −0.0392                                          |
| 6.55                      | 0.9537                                       | −0.0087                                          |
| 15.22                     | 0.9488                                       | −0.3898                                          |
| 15.94                     | 0.9823                                       | −0.2262                                          |

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It is very important to study the polarization behaviour under oblique incidence. Hence, we established a setup by drawing an arc of ±45° on the floor and kept two horn antennas at the same angle as presented in the setup given in figure 14(a). Absorber sheet was placed at φ = 0° in this case and to mitigate the measurement errors. Copper sheets were again placed at different horn antenna angles (incident angles) before obtaining the reflection coefficients. It is evident that the proposed absorber is symmetric in the xy plane therefore oblique incidence was measured under TE polarization only. Figure 14(b) shows absorptivity responses with respect to variation in the incident angles. We have used the θ = 0° result, as taken in the φ = 0° case, since waves incident normally to the absorber interface. Further, two horn antennas were placed at 15°, 30° and 45° consecutively and results were obtained as shown in figure 14(b). It can be observed that, one spurious band is emerging near 10 GHz at 30° and 45° as was detected in the simulated results. The reason for achieving this band may be origination of another mode, when wave incident obliquely after certain angles. All absorption frequencies were intact at different incidence angles and followed the simulated results well, in agreement. The angle is being marked carefully on the floor and kept the horn antennas at 1 meter distance in this case. Hence, it can be said that the proposed absorber performs wide incident angle absorption.
| Parameters => | Lowest absorption frequency (GHz) | Unit cell size (mm$^2$) | Electrical size of the unit cell | Thickness (in terms of $\lambda_0$) | No. of bands | Polarization insensitive |
|----------------|----------------------------------|------------------------|-------------------------------|----------------------------------|--------------|------------------------|
| References     |                                  |                        |                               |                                  |              |                        |
| [14]           | 3.07                             | 18 × 18                | 0.184 $\lambda_0$ × 0.184 $\lambda_0$ | 0.0149                           | 3            | Yes                    |
| [15]           | 4.828                            | 18 × 18                | 0.289 $\lambda_0$ × 0.289 $\lambda_0$ | 0.0161                           | 3            | Yes                    |
| [16]           | 5.50                             | 10 × 10                | 0.183 $\lambda_0$ × 0.183 $\lambda_0$ | 0.0183                           | 3            | Yes                    |
| [17]           | 5.76                             | 17 × 17                | 0.326 $\lambda_0$ × 0.326 $\lambda_0$ | 0.019                            | 4            | Yes                    |
| [18]           | 3.18                             | 15 × 15                | 0.159 $\lambda_0$ × 0.159 $\lambda_0$ | 0.0163                           | 3            | Yes                    |
| [19]           | 4.11                             | 15 × 15                | 0.205 $\lambda_0$ × 0.205 $\lambda_0$ | 0.013                            | 4            | Yes                    |
| [20]           | 4.34                             | 20 × 20                | 0.289 $\lambda_0$ × 0.289 $\lambda_0$ | 0.011                            | 4            | Yes                    |
| Proposed Work  | 3.24                             | 10 × 10                | 0.108 $\lambda_0$ × 0.108 $\lambda_0$ | 0.0108                           | 4            | Yes                    |
Next, proposed work is compared with few of the relevant work available in the literature. Table 3, compiles the notable work done in the previous years, specifically on ultrathin polarization insensitive absorbers. Unit cell size and thickness of different absorbers are depicted in terms of $\lambda_0$, where $\lambda_0$ represents the free space wavelength as per the smallest frequency given in 2nd column. Table 3, shows that the proposed antenna displays lowest electrical size and thickness, simultaneously. In addition, it exhibits multiband properties with all the bands exhibiting polarization insensitive and wide incident angle behaviour.

6. Conclusion

In this article a novel compact, ultra-thin, polarisation insensitive, quad-band metamaterial absorber has been designed, characterized and tested. Proposed structure exhibits peak absorption at 3.24 GHz, 6.55 GHz, 15.22 GHz and 15.94 GHz. The investigated structure has been studied for various polarization angles under normal and oblique incidence. Simulated and experimental results were in good agreement and reaffirms polarisation insensitive nature of proposed structure. Electric field, and surface current distribution have also been studied to get a better insight of absorption mechanism. Compared to previous structures, proposed structure shows much better electrical thickness of 0.0108 $\lambda_0$. Material parameters were extracted and plotted to prove the metamaterial behaviour of the proposed absorber. Experimental results show that it offers reasonable amount of FWHM bandwidth in the first and second band while, wideband behaviour in Ku- band. Thus, proposed absorber can be potentially employed in various defence applications particularly, in sensing and imaging.

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