A Low Profile Quadruple-Band Polarization Insensitive Metamaterial Absorber

Ting Wu[*], Yan-Ming Ma, Juan Chen, and Li-Li Wang

Abstract—In this paper, a quadruple-band metamaterial polarization-insensitive absorber with low profile is proposed. The proposed unit cell is composed of three conformal modified rings with square patches at corners. $10 * 10$ periodic unit cells constitute the proposed metamaterial absorber. The absorber offers low profile, and overall dimensions are $100\,\text{mm} * 100\,\text{mm}$. The surface current distribution and equivalent circuit model are presented to explain the mechanism. The proposed structure is fabricated, and experiments are carried out to validate the design principle. The simulated and measured results show that the proposed structure exhibites four absorption peaks of 98.87%, 95.11%, 93.97%, and 99.99% under normal incidence at 8.16–8.29 GHz, 10.275–10.38 GHz, 14.255–14.38 GHz, and 15.465–15.7 GHz which cover X- and Ku-bands, respectively. The designed structure is exactly symmetrical which makes it insensitive to polarization angle variations. Furthermore, the four operating bands of the absorber can be adjusted independently which makes the design suitable for absorbing electromagnetic energy and reducing the radar cross-section (RCS) of target.

1. INTRODUCTION

Metamaterials have gained a great deal of interest in the science community due to their unconventional electric and magnetic features [1]. Thanks to these peculiar characteristics which are hardly found in nature, many researches have been done on the metamaterial cloaking [2], perfect lens [3, 4], absorbers [5, 6], etc. [7]. Over the past several years, electromagnetic (EM) metamaterials (MMs) with perfect absorption have attracted great attention from scientists in many research fields [8]. In [9], Landy et al. have proposed a thin metamaterial absorber (MMA), in which electric and magnetic resonance makes the absorber possess matched impedance to eliminate the reflection and strongly absorb the incident wave. Since then, many MMAs have been proposed and demonstrated for the communities of both physics and material science and have found increasingly wide utilization in many fields including photodetectors [10], energy harvesting [11], and solar cells [12].

The rapid development of metamaterial opened a new possibility to design and improve the performance of an absorber. Various single band, dual-band, multi-band, wideband, polarization-insensitive and wide-angle absorbers have been reported [13–17]. Single-/dual-/triple band metamaterial absorbers based on cut wire and square ring are discussed at microwave frequencies [18]. Several researchers have studied the design of MM unit cells with polarization and incidence angle-insensitivity. Polarization-independent MM absorbers can be realized through a symmetric unit cell [19, 20]. Incidence angle-insensitivity can be achieved by novel geometries of unit cells, such as four-fold rotational symmetric electric resonator with a cross-printed bottom [21], subwavelength unit cell in a multilayer [20], and circular sector [22]. Ultrathin- and multiple band absorbers are presented in [23, 24]. A conformal metamaterial absorber for curved surface as well as flat surface application is presented in [25]. In [26], a polarization insensitive metamaterial absorber by using compact unit cells with

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triple-band operation is presented. Then, the authors have done a lot of work in multi-frequency and wide-angle absorber [27–30]. All of them are of great importance. As can be seen from the literature surveyed, it is difficult to get all the characteristics, such as ultrathin, polarization insensitive, conformal, multiband, and wide angular stability, in a simple structure.

In this paper, a quadruple-band metamaterial absorber is proposed for X- and Ku-band applications. The proposed absorber consists of 10*10 periodic unit cells which is composed of three conformal modified rings with square patches at corners. The structure is fabricated, and experiments are carried out to validate the design principle. The simulated and measured results show that S_{11} of the proposed absorber is 1.6% (8.16–8.29 GHz) centered at 8.23 GHz, 1.1% (10.275–10.38 GHz) centered at 10.33 GHz, 1.0% (14.255–14.38 GHz) centered at 14.325 GHz, and 1.6% (15.465–15.7 GHz) centered at 15.58 GHz. Meanwhile, the proposed structure is insensitive for the transverse magnetic/transverse electric field polarization of incident waves and also the angle of incidence. Moreover, the four operating bands of the proposed absorber can be adjusted independently which provides a great freedom for design. Detailed geometry configuration and experimental results of the proposed absorber are demonstrated in the following parts. The paper is divided in four parts. In Section 2, we discuss the design and absorption mechanism of the proposed absorber. Then, the fabrication and measured results are given in Section 3. At last, the conclusion is given in Section 4.

2. STRUCTURE DESIGN AND ABSORPTION MECHANISM

2.1. Geometry and Simulation of the Proposed Absorber

Figure 1 shows the unit cell of the proposed quadruple-band metamaterial absorber. The top view of the proposed structure which consists of three conformal modified rings with square patches at corners and a rectangle strip at sides on the substrate is given in Figure 1(a). From Figure 1(b), we can see that the metamaterial absorber is designed on an FR4 epoxy substrate with thickness $H_1 = 0.8$ mm, relative permittivity $\varepsilon_r = 4.4$, and loss tangent 0.02. The back side of the substrate has zero transmitted power due to the printed full copper lamination. The overall size is $0.022\lambda_0$, $0.028\lambda_0$, $0.038\lambda_0$, and $0.042\lambda_0$ at 8.23 GHz, 10.33 GHz, 14.325, and 15.58 GHz, respectively, where λ_0 is the free space wavelength. Obviously, the proposed absorber offers low profile which is suitable for different curved surface applications unlike planar absorbers. Furthermore, the designed structure is exactly symmetrical which makes it insensitive for the transverse magnetic/transverse electric field polarization of incident waves and also the angle of incidence.

To understand the design processes more clearly, the contribution of individual element is shown in Figure 2. Five structures with different elements are simulated to make it more intuitive. It can be clearly seen that the first band is due to the third conformal ring. The middle conformal modified
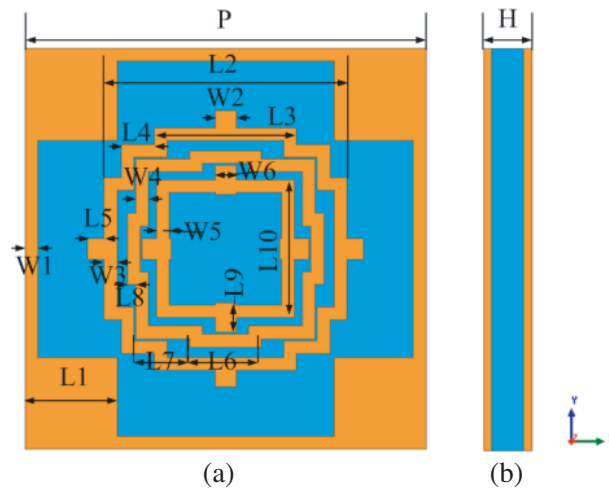

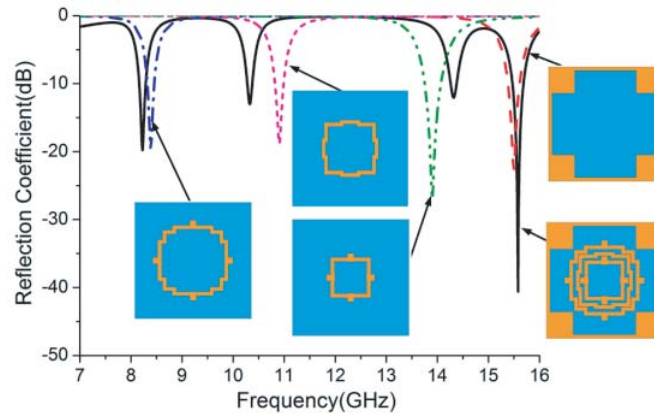**Figure 1.** Unit cell of proposed absorber. (a) Top view. (b) Side view.

Figure 2. Simulated reflection coefficient of the different structures.

ring is responsible for the second band. The inner conformal modified ring is responsible for the third band while the square patches at corners are for the fourth band. By combining the four structures and carefully adjusting the elements, the proposed metamaterial absorber can work in four frequency bands as shown in Figure 2. The numerical analysis and geometry refinement of the proposed antenna are performed by using ANSYS HFSS 13.0 simulation software.

2.2. Theoretical Analysis of the Absorption Mechanism

As described above, the back side of the substrate has full copper lamination which leads to zero transmitted power. Thus, absorbance $(A(\omega))$ can be evaluated from Eq. (1) where $|S_{11}(\omega)|^2$ is the reflected power, and $|S_{21}(\omega)|^2$ is the transmitted power.

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

Figure 3 shows the equivalent circuit of the proposed conformal absorber. Taking L_1 and C_1 for example, L_1 is the effective inductance offered by a cross-spanner like structure while C_1 is the capacitance offered by the gaps between the adjacent unit cells and capacitance due to mutual coupling, so do the other elements. Also, copper lamination at the bottom plane provides a short circuit. From the equivalent circuit, the input impedance Z_{in} can be evaluated by Eq. (2). Z_d is the impedance offered by the dielectric of thickness 0.8 mm. Z_{FSS} is the total impedance offered by metallic surface at top, Z_0 the characteristic impedance, β the propagation constant, t_d the height of dielectric layer, and ω the
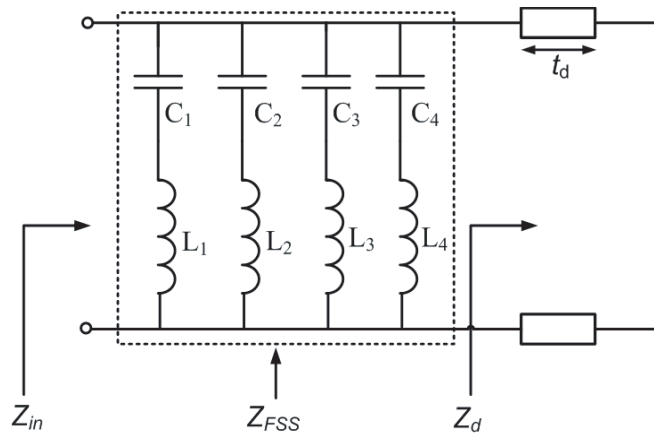

Figure 3. Equivalent circuit model of proposed absorber.

angular frequency.

$$Z_{\text{in}} = Z_{FSS} \left\| \left(j\omega L_1 + \frac{1}{j\omega C_1}\right) \right\| \left(j\omega L_2 + \frac{1}{j\omega C_2}\right) \left\| \left(j\omega L_3 + \frac{1}{j\omega C_3}\right) \right\| \left(j\omega L_4 + \frac{1}{j\omega C_4}\right) \left\| \frac{Z_0}{\sqrt{\varepsilon_r}} \tan\left(\beta t_d\right) \quad (2)$$

When the top FSS reactance has the same value (equal magnitude but opposite in sign) as the reactance of the stacked dielectric substrate, the parallel circuit resonates. Then the overall input impedance Z_{in} becomes purely real, and while it matches free space impedance Z_0, the reflection becomes zero and gives rise to near-unity absorption.

Some parameters have great influence on the performance of the proposed structure. Therefore, parametric analyses have been carried out for a suitable selection of absorption frequencies by varying the physical dimension of vital geometrical parameters. In the following discussion, we change one parameter with the other parameters unchanged. By this way, we can study the influence of different parameters. Moreover, the four operating bands of the proposed metamaterial absorber can be adjusted independently. Only one frequency band will be affected if one parameter is changed. This property makes it very easy for us to adjust the structure.

The simulated reflection coefficient against the frequency of the proposed metamaterial absorber with different values of L_1 is shown in Figure 4. It can be clearly seen that by increasing the length of L_1, the highest operating band decreases while the other three bands remain nearly unchanged. So an appropriate value $L_1 = 2.2$ mm is chosen. The influences of L_4 and L_5 on the proposed structure are shown in Figure 5 and Figure 6, respectively, and both affect the lowest operating band. We can see that with the increase of L_4 and L_5, the lowest operating band decreases while the other three operating
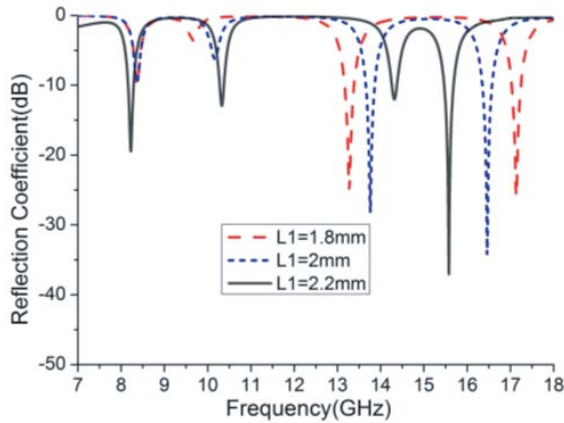

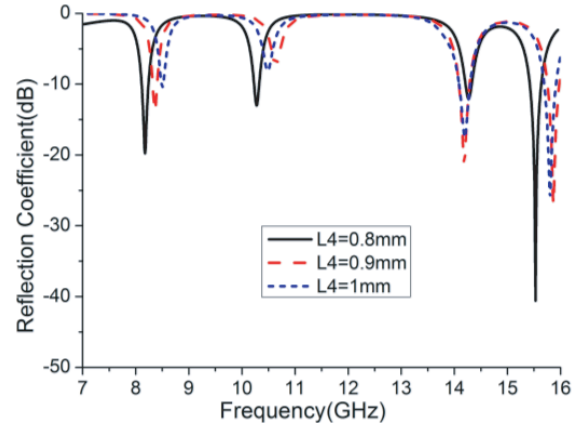**Figure 4.** Simulated S_{11} of different values of L_1.

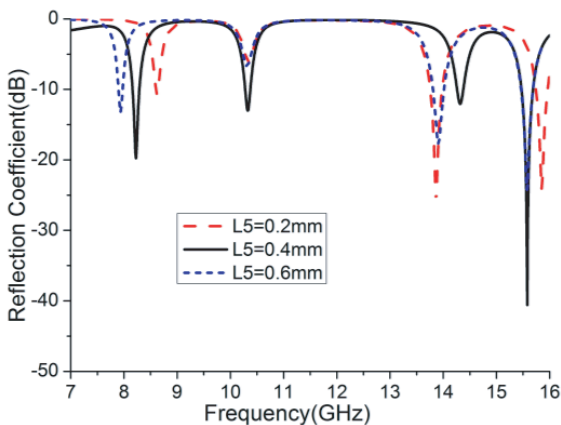

Figure 5. Simulated S_{11} of different values of L_4.

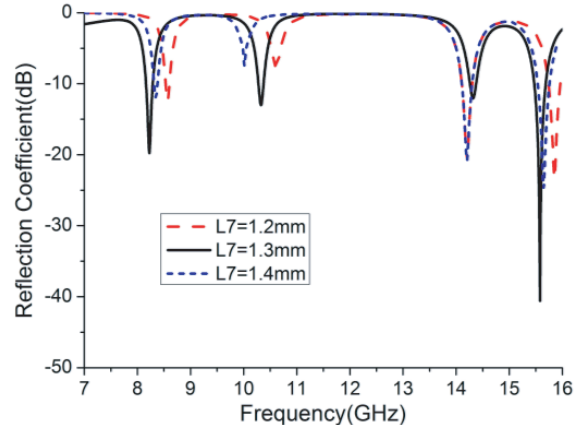**Figure 6.** Simulated S_{11} of different values of L_5.

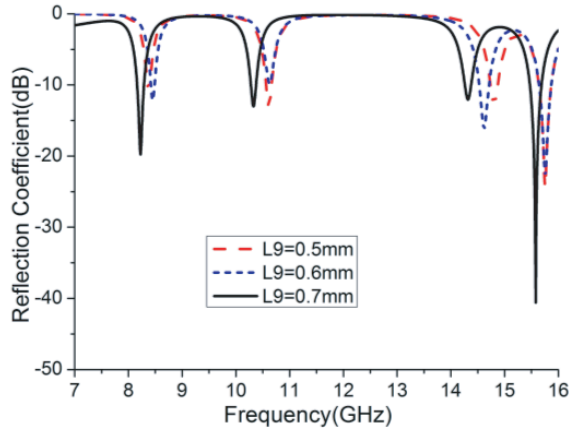**Figure 7.** Simulated S_{11} of different values of L_7.

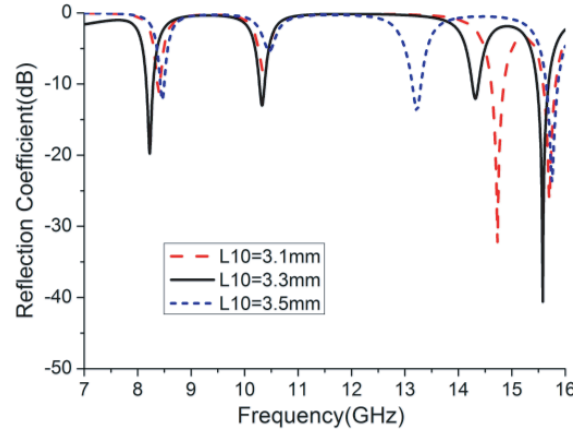**Figure 8.** Simulated S_{11} of different values of L_9.

Figure 9. Simulated S_{11} of different values of L_{10}.

bands remain unchanged. As shown in Figure 7, the variation of L_7 has little influence on the other operating bands and mainly affects the second band. With the increase of L_7 the second operating band decreases. Figure 8 and Figure 9 show the influences of L_9 and L_{10} on the proposed absorber. It can be observed that with the increase of L_9 and L_{10}, the third operating band decreases.

As stated above, the four operating bands of the proposed structure can be adjusted independently which means that the coupling is small. By carefully adjusting the dimensions according to the laws above, the proposed structure can exhibit four absorption peaks under normal incidence at 8.16–8.29 GHz, 10.275–10.38 GHz, 14.255–14.38 GHz, and 15.465–15.7 GHz which cover X- and Ku-bands. Furthermore, this concept can be applied in designing absorbers for multi-band applications. The final optimized dimensions are listed in Table 1.

Table 1. Parameters for the proposed absorber (unit: mm).

P	H	L_1	L_2	L_3	L_4
9.6	0.8	2.2	5.8	3.4	0.8
L_5	L_6	L_7	L_8	L_9	L_{10}
0.4	1.7	1.3	0.2	0.7	3.3
W_1	W_2	W_3	W_4	W_5	W_6
0.3	0.5	0.3	0.3	0.3	0.5

In order to show the absorption mechanism better, the surface current densities of proposed structure at 8.23 GHz, 10.33 GHz, 14.325 GHz, and 15.58 GHz are given in Figure 10. We can see that current is concentrated on the second conformal ring with modified corners at 8.23 GHz while at 10.33 GHz, it is mainly present on the third conformal modified ring. Current is concentrated on the inner conformal rings with modified corners at 14.325. At 15.58 GHz, the current is concentrated on the square patches at corners. As stated above, we can see that the four operating bands are affected and adjusted by the four structures independently which verify our design.

3. FABRICATION AND MEASUREMENT RESULTS

To validate the design, the proposed metamaterial absorber is fabricated using standard printed circuit board technology. The fabricated structure is shown in Figure 11(a). We can see that the proposed absorber consists of $10 * 10$ periodic unit cells. The absorber is fabricated on a $100\,\text{mm} * 100\,\text{mm}$ FR4 substrate with a thickness of $0.8\,\text{mm}$. An AV3672B vector network analyzer (VNA) is used to
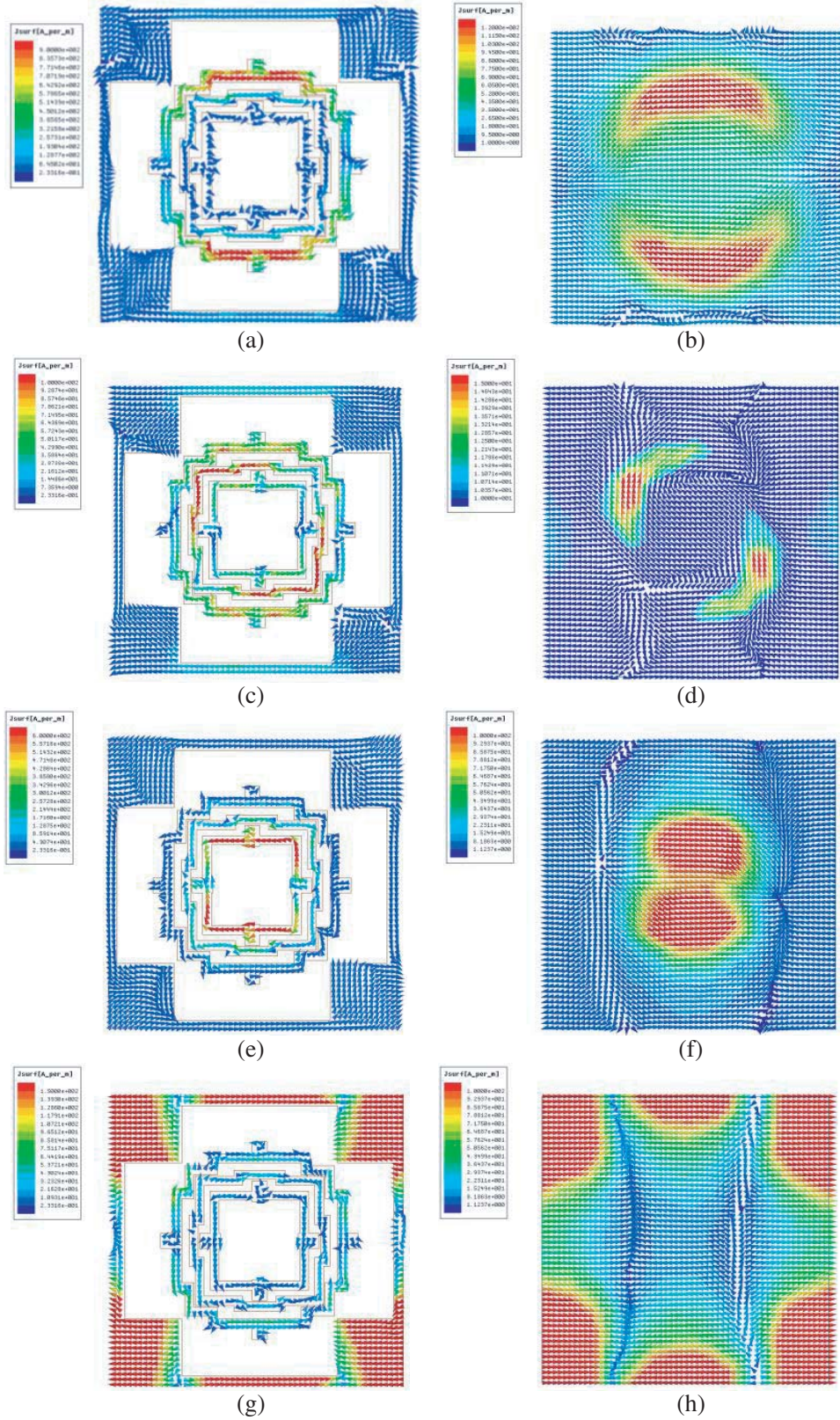
Figure 10. Surface current density of proposed metamaterial absorber. (a) Top at 8.23 GHz. (b) Bottom at 8.23 GHz. (c) Top at 10.33 GHz. (d) Bottom at 13.33 GHz. (e) Top at 14.325 GHz. (f) Bottom at 14.325 GHz. (g) Top at 15.58 GHz. (h) Bottom at 15.58 GHz.
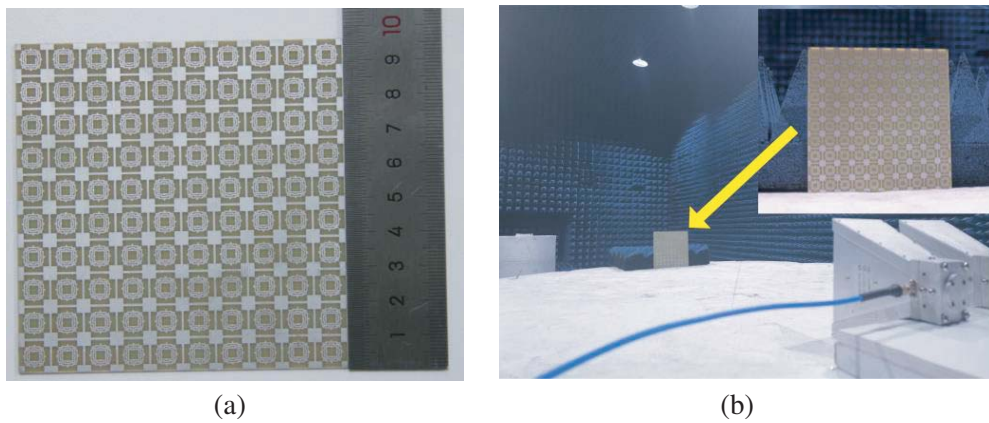
(a)   (b)

Figure 11. (a) Photograph of the prototype absorber. (b) Measurement setup for absorber measurement.

(a)   (b)
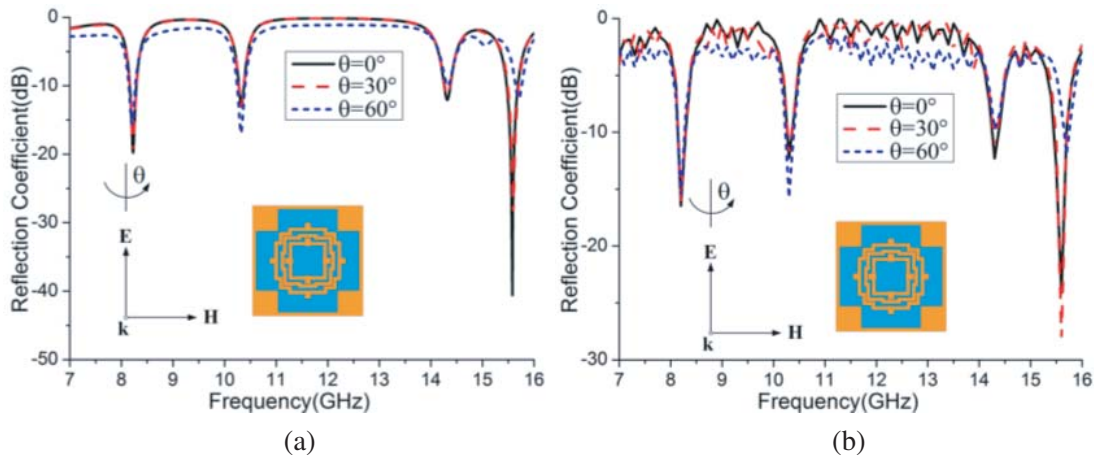
Figure 12. Reflection coefficient of proposed metamaterial absorber for different TE polarization angles. (a) Simulated. (b) Measured.

measure the reflection coefficient in free space. To measure the performance of the proposed absorber, a copper sheet is placed initially, and reflected power is measured under normal incidence. Then, the copper sheet is replaced with the proposed absorber, and again the power reflected from its surface is measured. Figure 11(b) is a photograph of the microwave anechoic chamber where the proposed absorber is measured.

The proposed structure is symmetric which inherently makes it insensitive to polarization angle variations. The four operating bands are obtained by four individual elements. As stated above, the four operating bands of the proposed structure can be adjusted independently which means that the coupling is small. Furthermore, the proposed absorber offers wide angular stability with reflection coefficient better than -10 dB under oblique incidence for TE and TM polarized waves up to $60°$. The simulated and measured results of input reflection coefficient of the proposed absorber for various angles of incidence are shown in Figure 12 for TE polarized wave and Figure 13 for TM polarized wave. It is observed that the proposed absorber offers wide angular stability up to $60°$ for both TE polarization and TM polarization with input reflection coefficient better than -10 dB. Figure 14 shows the simulated and measured input reflection coefficient profiles of the proposed structure for various polarization angles. We can see that there is no deterioration in absorber performance as it offers four-fold symmetry which makes it insensitive towards polarization.

Figure 15 shows the simulated and measured reflection coefficients against the frequency of the
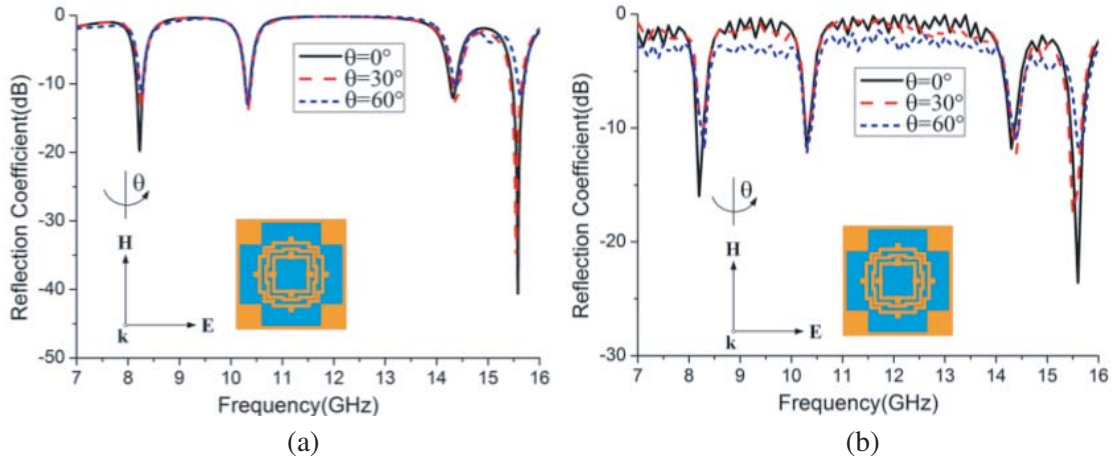
Figure 13. Reflection coefficient of proposed metamaterial absorber for different TM polarization angles. (a) Simulated. (b) Measured.
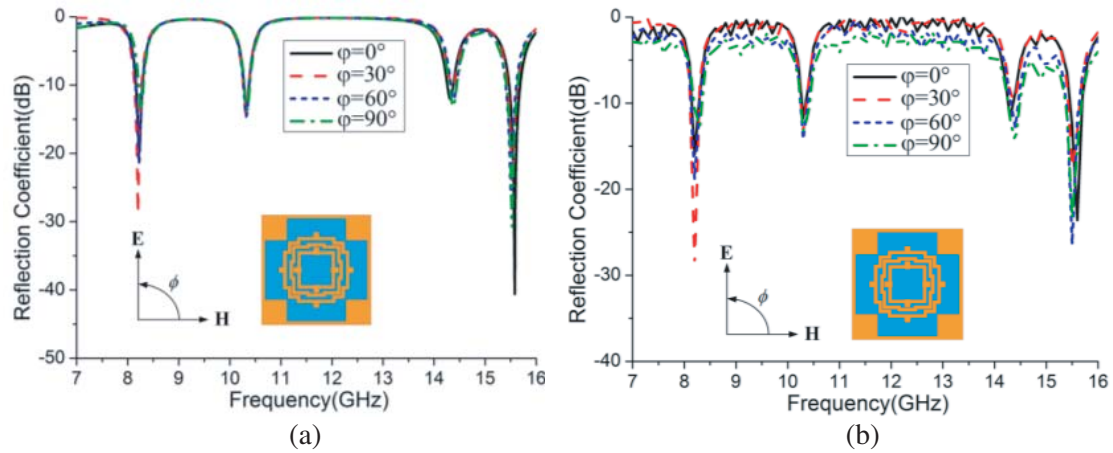

Figure 14. Reflection coefficient of proposed metamaterial absorber for polarization angles (φ) ranging from 0–90°. (a) Simulated. (b) Measured.
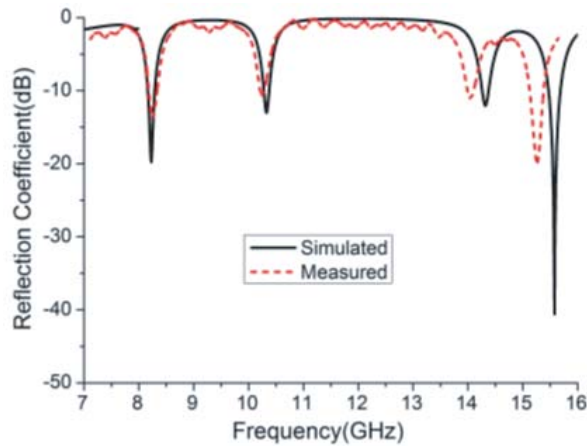

Figure 15. Simulated and Measured reflection coefficient of proposed absorber under normal incidence.

proposed absorber under normal incidence. It can be observed that the reflection coefficients are 1.6% (8.16–8.29 GHz) centered at 8.23 GHz, 1.1% (10.275–10.38 GHz) centered at 10.33 GHz, 1.0% (14.255–14.38 GHz) centered at 14.325 GHz, and 1.6% (15.465–15.7 GHz) centered at 15.58 GHz. Good agreement between the simulated and measured results can be observed. The discrepancy between the simulated and measured results can be mostly attributed to the tolerance in the manufacturing process. Also the finite size effect and tolerances are inherent in fabrications and measurements.

4. CONCLUSION

A quadruple-band metamaterial absorber for X- and Ku-band applications is proposed in this paper. The unit cell is composed of three conformal modified rings with square patches at corners and rectangle strip at sides on the substrate. The proposed absorber is consists of $10 * 10$ periodic unit cells. The results show that the proposed structure can exhibit four absorption peaks under normal incidence at 8.16–8.29 GHz, 10.275–10.38 GHz, 14.255–14.38 GHz, and 15.465–15.7 GHz. The absorber is insensitive for the transverse magnetic/transverse electric field polarization of incident waves and also the angle of incidence. For better understand the design processes, the contribution of individual element is studied, and the surface current density is given. Various design parameters have also been optimized for selecting the suitable band of operation and desired application. The simulated and measured results demonstrate that the proposed structure is feasible for use as a metamaterial absorber. Moreover, the operating bands of the proposed structure can be adjusted independently which manifests its suitability for applications.

ACKNOWLEDGMENT

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