Progress In Electromagnetics Research Letters, Vol. 39, 63–72, 2013

EXPERIMENTAL VERIFICATION OF A TRIPLE BAND THIN RADAR ABSORBER METAMATERIAL FOR OBLIQUE INCIDENCE APPLICATIONS

Mahmoud A. Abdalla*

Electromagnetic Fields Group, Electronic Engineering Department, MTC University, Cairo, Egypt

Abstract—This paper presents the theory, design, and experimental investigation of an ultra thin (6% λ_0) and triple band metamaterial radar absorber. The theoretical design of the reported absorber is investigated. The absorber performance was validated using the electromagnetic simulations and confirmed by experimental measurements for different incidence angles. The results confirm that the proposed metamaterial absorber can demonstrate triple bands with better than -15 dB reflection coefficient for all incident angles.

1. INTRODUCTION

Radar absorber materials (RAMs) are generally coating materials that coat an object to reduce the backscattered power from the object which can be employed in many military and civilian applications. The challenge in the RAM design aims to improve their performance in terms of the absorption level, operation bandwidth, in addition to the enhancement of the physical limitations of its thickness and conformability. The simplest RAM type is the Dallenbach layer which consists of a single lossy and magnetically loaded dielectric slab whose intrinsic impedance is similar to that of free space in front of a ground plane. This absorber is narrow bandwidth and thick [1]. Another common type is known as Salisbury screen which is constructed using a single resistive sheet mounted at a quarter-wavelength distance above a metal backing plane [2]. Salisbury RAM is mainly narrow band and thick especially at lower frequencies. Jaumann absorber is a multi-layered structure [3] which has wider bandwidth but it requires thicker structures. Several attempts have been done for realizing thin RAM,

Received 22 February 2013, Accepted 28 March 2013, Scheduled 12 April 2013
* Corresponding author: Mahmoud A. Abdalla (maaabdalla@ieee.org).

reducing the conventional quarter wavelength thickness criterion, using various complex materials and structures [4–7].

Recently, artificial effective media named as metamaterials have been introduced. Metamaterials can be realized using an ordered array scatters satisfying a sufficient long wavelength condition at RF/microwave frequencies. Studies explained that electromagnetic wave propagation in these materials has many unique properties so that metamaterials can exhibit unique properties in many RF/microwave, and RAM development. Metamaterials were employed to introduce an ultra thin absorber whose thickness is one tenth or one fifth free-space wavelengths. This has been realized by closely placing a metamaterial surface above a perfect conducting plate [8–11]. Example for metamaterial RAMs includes the use of an artificial magnetic conductor (AMC) surface loaded with $377\,\Omega$ resistors in order to remove the $\lambda/4$ thickness requirement of the Salisbury screen. Another example is resonant metamaterial absorber whose impedance matches to that of free space and possess a large imaginary part of refraction index simultaneously so that it achieves a large resonant dissipation. Moreover, resonant metamaterial absorber has the advantage of its ability to be scaled from microwave to terahertz bands [12]. As a result in the increase demand in multi-band wireless applications, multi-band radar absorber is one objective for designing microwave radar absorber. Examples of these attempts different prototypes of dual band absorber were discussed in [13–16]. However, up to our knowledge, no triple band microwave radar absorber for oblique incident applications has been reported.

In this paper, we introduce an ultra thin and triple band microwave radar absorber for oblique incident applications. The reported absorber was designed using a resonant split ring resonator (SRR) absorber. The resonance was achieved based on the multiple resonances concept that was suggested for dual band absorber [17]. The theoretical analysis, simulation and experimental measurements of the proposed radar absorbing material were introduced. The proposed structures have the advantage of thin structure, high absorption of incident electromagnetic waves, a reasonable operation bandwidth, in addition to be applicable for different incidence angles.

2. THEORY

As mentioned above, the basic principle operation of RAM is based on matching the interface impedance of the RAM layer (Z_{in}) to the free space impedance (Z_0). The reflection coefficient at the interface of the RAM layer can be written in terms of the input admittance (Y_{in}) and the free space admittance (Y_0) as

$$\Gamma = \frac{Y_{in} - Y_0}{Y_{in} + Y_0} \tag{1}$$

This can be explained easily in the case of the thin capacitive loaded RAM absorber using transmission line concepts as shown in Fig. 1(a). From circuit point of view, a plane wave incident normally upon a grounded layer is equivalent to a short circuited capacitive loaded lossy transmission line. The capacitive load admittance can be expressed as

$$Y_C = j\omega C \tag{2}$$

In the case of designing thin RAM layer whose thickness is less than quarter wavelength, the transmission line can be considered as an inductive load since its admittance Y_L is

$$Y_L = -jY_{od}Co\tan(\beta d) = -j\frac{1}{\omega L} \tag{3}$$

where β is the propagation constant and Y_{od} the characteristic admittance of the dielectric spacer. Thus, at the resonant frequency, the transmission line impedance can match the free space one and hence, it yields zero reflection for normal incident plane waves at resonant frequency. Give, R_S is the lossy loaded resistance, the input admittance Y in can be expressed as

$$Y_{in} = Y_L + Y_C + \frac{1}{R_S} \tag{4}$$

By realizing the resonant LC circuit using resonant metamaterial absorber and the employed substrate in a lossy layer, the equivalent circuit criterion for the reduced thickness absorber, which is shown in Fig. 1(a) can be fulfilled.

One of the common metamaterial absorbers is split ring resonators (SRRs) [12]. The topology of the SRR particle is shown in Fig. 1(b). The split rings structure acts as a resonant structure due to the effect of the induced capacitance and the structure inductance. The opposite direction of the split rings is to concentrate the electric field between the two rings and hence produce a large capacitance in the small gap region between the rings and hence reducing the resonant frequency of the SRR.

For normal incidence upon the SRR unit cell, i.e., the incident electromagnetic wave direction is in k direction as indicated in Fig. 1(b). Also, assuming the electric field component direction of the incident wave is along the gap in the split ring resonator. Hence, capacitance is induced between the rings. The total capacitance (C_o)

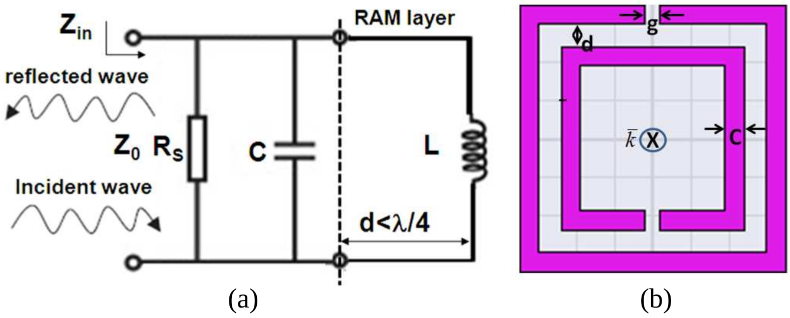

Figure 1. (a) An equivalent circuit of a thin capacitive loaded RAM. (b) Topology of the SRR particle pointing out direction of propagation (k).

between the rings expressed in terms of the per unit length capacitance between the rings (C_{pl}) and average perimeter (L_r) as [18]

$$C_0 = L_r C_{pl} \tag{5}$$

Such capacitance can work together with the inductive load introduced by the thin substrate to result in the resonance of the incident radar wave. Therefore, if the SRR particle is printed over a lossy substrate, this can satisfy the thin radar absorber equivalent circuit model shown in Fig. 1(a). Thus, we can claim that the use of periodic array of SRR over a thin substrate acts as a metamaterial radar absorber.

3. DESIGN AND SIMULATED RESULTS

By emphasizing the reflection coefficient in (1), it is obvious if the capacitive circuit contains different capacitive elements, the input admittance Y_{in} can be designed so that multiple zero reflection can be satisfied. This can be done by manipulating the different capacitive elements to introduce multi band absorber. In our work, this concept was employed by using different SRR units so that their multi resonance and the coupling between them will result in multi band absorber. We called it asymmetric SRR metamaterial RAM which can resonate at different frequencies. By proper manipulating of these capacitance values, the operational frequency can be designed to be within the desired X band.

For triple band metamaterial absorber purpose, we have suggested the modification of the unit cell to combine 2×2 rectangular SRRs with different dimensions. The whole circuit is printed over a lossy

FR4 substrate with relative dielectric constant $\varepsilon_r = 4.4$, a dielectric loss tangent, $\tan\delta = 0.02$, and thickness, $h = 1.6$ mm. A schematic for a 2×2 sample of a periodic asymmetric SRR radar absorber is illustrated in Fig. 2. In the figure, for each employed SRR unit, the periodic distance in both planar directions is 5 mm. The inner ring square lengths are (0.6 mm, 0.8 mm, 1.6 mm, and 2.1 mm). The two ring separations (d) are (0.45 mm, 0.25 mm, 0.2 mm, and 0.45 mm). The two ring gaps (g) are (0.2 mm, 0.3 mm, 0.2 mm, and 0.2 mm).

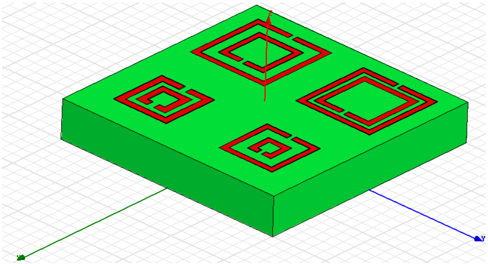

Figure 2. A 2×2 sample of a periodic asymmetric SRR radar absorber.

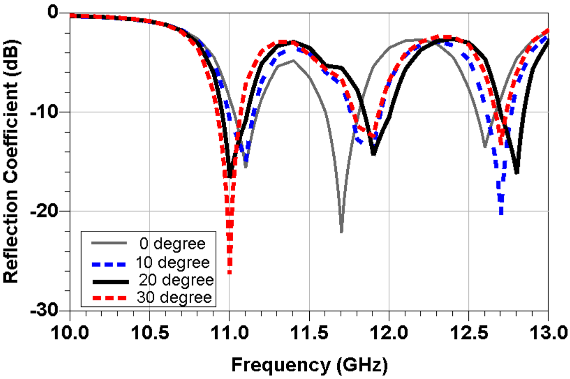

Figure 3. Simulated reflection coefficient for asymmetric metamaterial absorber for different oblique incidence angles.

The simulated reflection coefficient for an incident electromagnetic wave with different incidence angles on the proposed asymmetric absorber is shown in Fig. 3 and has been calculated employing the full wave electromagnetic simulator (Ansoft-HFSS). Periodic boundary conditions were imposed on the unit cell. The simulated reflection coefficient demonstrates main triple bands for electromagnetic wave absorption. The first band was designed to be centered at 11.1 GHz, the second band at 11.8 GHz, and the third one at 12.65 GHz. The three bands satisfy minimum reflection coefficient better than −10 dB. Almost identical behavior has been observed for all cases of incidence angles studied.

Approximate values for these resonant frequencies can be verified by extracting the TL inductance from (3) and SRR capacitance from (5) and substituting in (4) for minimum admittance at resonance in (3). For example, the smallest SRR particle demonstrates minimum admittance at 11.95 GHz. However, exact resonant frequencies calculation requires considering the coupling effects between the four particles in both X and Y directions.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

A prototype for the proposed metamaterial absorber was fabricated. Next, the reflection coefficient of the incident electromagnetic wave was measured. The measurement setup is shown in Fig. 4. The measurement setting can be summarized as follow; the prototype RAM is placed on wooden support, two horn antennas have been chosen as Tx and Rx antennas. Taking into account the largest horns dimension ($D = 9$ cm) and the upper limit of the frequency band (13 GHz, $\lambda = 2.3$ cm), the far-field distance can be estimated as RFF $= 2D^2/\lambda = 70$ cm). Accordingly, the separation between each horn and the reported radar absorber was set ($R_{\text{meas}} = 0.8$ m).

The refection coefficient of the incident electromagnetic wave was extracted through the measured scattering parameter (S_{21}) in two different steps. First step is measuring the reflection from the RAM ground surface and the second step is the reflection from radar absorber face. The difference between the measured results represents the normalized reflection coefficient from the metamaterial RAM. This

Figure 4. The measurement setting.

can be explained in details for the case of normal incidence as will be illustrated in Fig. 5. In the figure, the measured S_{21} from the ground surface is approximately constant around -24 dB which can account for the free space propagation loss.

Then, measured S_{21} of the reported RAM shows triple bands at 10.7 GHz, 11.8 GHz, and 12.45 GHz with magnitude at resonance frequencies less than -40 dB. The difference between the two previous cases is the normalized reflection coefficient which also is shown in Fig. 5. In Fig. 5, we notice that the normalized reflection coefficient at the triple resonating frequencies can fulfill almost -20 dB. Therefore, we can claim that the measured results agree, to a good extend, with the simulated ones in Fig. 3. However, a small shift in resonance frequency can be observed in the measurement results. This can account for the unpredicted imperfect in the fabrication process of the printed PCB RAM layer. Also, these results confirm that the aforementioned theoretical calculation of the smallest SRR particle resonance frequency can predict the absorber performance, approximately.

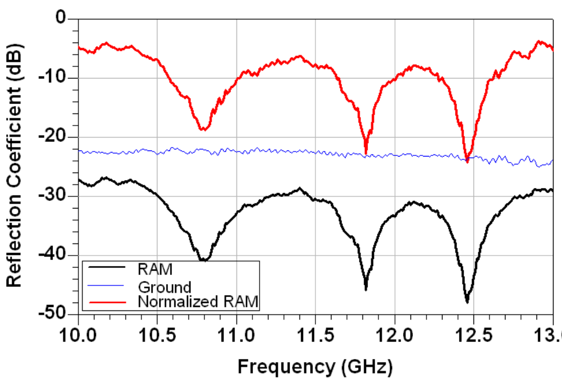

Figure 5. The measured reflection coefficient from ground surface, radar absorber surface, and normalized reflection coefficient.

In order to test the manufactured radar absorber prototype for oblique electromagnetic wave incidence, the reflection coefficient of the reported RAM is measured for different electromagnetic wave incidence angles and compared to the normal incidence case. The measured normalized reflection coefficients for $\theta_{\rm inc} = 0^\circ$, 10°, 20°, and 30° are shown in Fig. 6. In the figure, it is obvious that the designed triple band is guaranteed for all incidence angles without any frequency shift. Also, the proposed RAM satisfies better than -15 dB reflection coefficient at all resonant frequencies in all measured cases.

Comparing the simulated results (in Fig. 3) to the experimental ones (in Fig. 6), we can observe that both results confirm the triple band performance of the proposed radar absorber. A detailed comparison between the simulated and measured results is summarized as shown in Table 1. It is worth to mention that the absorber band was defined as the one that has reflection coefficient less than −10 dB. From the tabulated date, we can observe the good agreement between the measured and simulated results. However, there is some frequency shifts between cut off frequencies of the triple bands. This difference

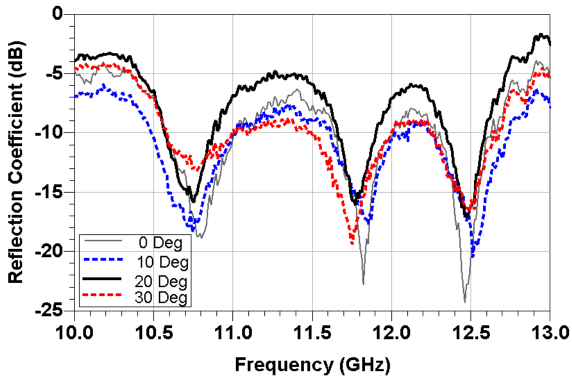

Figure 6. The measured (normalized) reflection coefficient of asymmetric SRR radar absorber for different oblique incidence angles.

Table 1. A comparison between the simulated and measured radar absorption bandss.

Studied Case	Simulated Results		
	1st Band (GHz)	2nd Band (GHz)	3rd Band (GHz)
0 Deg.	11–11.2	11.6–11.8	12.55–12.65
10 Deg.	11–11.15	11.75–11.95	12.6–12.75
20 Deg.	10.8–11.15	11.8–12	12.7–12.85
30 Deg.	10.9–11.1	11.75–11.95	12.65–12.75
Studied Case	Measured Results		
	1st Band (GHz)	2nd Band (GHz)	3rd Band (GHz)
0 Deg.	10.6–11	11.6–12	12.3–12.7
10 Deg.	10.5–11	11.6–12	12.3–12.75
20 Deg.	10.6–10.9	11.7–11.9	12.4–12.6
30 Deg.	10.6–11	11.55–12	12.3–12.7

between these cut off frequencies ranges from 0 GHz in best conditions and does not exceed ±0.5 GHz at worst cases. This can be explained due to the ideal conditions assumed in the simulations compared to the real measurement conditions.

5. CONCLUSIONS

A thin (6% λ_0 at mid frequency) metamaterial radar absorber material with triple bands has been presented. The metamaterial absorber was designed based on the multiple resonance concepts using asymmetric SRR configuration. The theoretical analysis of the proposed metamaterial thin absorber has been discussed, and its performance was validated using full wave simulation. Finally, its performance is confirmed by experimental measurements. Both results confirm that the proposed asymmetric SRR metamaterial absorber can achieve triple band of operation and demonstrates close to −20 dB reflection coefficient for all bands and for all oblique incidence angles. Thus, the results demonstrate that the proposed structures have the advantage of compactness, high absorption of incident electromagnetic waves, and a reasonable operation bandwidth.

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