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# DESIGN AND SIMULATION OF CROSS-BLOCK STRUCTURED RADAR ABSORBING METAMATERIAL BASED ON CARBONYL IRON POWDER COMPOSITE

**M. B. Abdullahi[1,*] and M. H. Ali[2]**
[1,] DEPARTMENT OF PHYSICS, USMANU DANFODIYO UNIVERSITY SOKOTO, SOKOTO STATE, NIGERIA.
[2,] DEPARTMENT OF PHYSICS, BAYERO UNIVERSITY KANO, KANO STATE, NIGERIA.
***E-mail addresses:*** [1] *abdullahi.bello@udusok.edu.ng,* [2] *mutariali@gmail.com*

**ABSTRACT**
***This paper reports the design and simulation of a three layered cross-block structured radar absorbing metamaterial (RAMM). The effective electromagnetic parameters of the designed structure are highly dependent on its geometric dimensions, subsequently behaving as a metamaterial. COMSOL Multiphysics simulation software was used to analyze the frequency dependent absorption response of the designed RAMM. The input impedance of multilayered absorber and strong fluctuation theory equations are used to theoretically verify the absorption response of the RAMM. The simulated result showed that the reflectivity of the RAMM is below -10dB from 4.2 – 18.0 GHz frequency band with absorber thickness of 4.2mm. The calculated reflectivity result is in close agreement with the simulated result, thus confirming the validity of the design. The operational bandwidth to thickness ratio of this RAMM was found to be 13.029 making it better than the recently reported one with a value of 9.745 and thus contributing significantly in overcoming the contradicting demand of broadband and thin thickness.***

***Keywords:*** *Bandwidth, COMSOL Multiphysics, Metamaterial, Radar Absorbing Metamaterial, Reflectivity.*

## 1. INTRODUCTION

Validation of three decades old theoretical prediction of negative index of refraction [1] through its experimental demonstration, initiated a new area of research known as metamaterials. Metamaterials are artificially designed structures capable of demonstrating fascinating and unique properties that are not found in naturally occurring materials such as perfect lensing [2–3], invisibility cloaking [4], negative index of refraction [5–8] and perfect absorption [9]. Interests in metamaterials originate from their available use in virtually any band of the electromagnetic spectrum and their ability to achieve almost any desired response [10]. Since the inspiration by Landy *et al* [11] in the last decade, metamaterial absorbers research witnessed rapid transitional development from the single band, fixed polarization and normal incidence to multiband, broadband, polarization insensitive and wide angle of incidence nowadays [12].

Metamaterial absorbers (MMA) operate in a specific narrow frequency band which limits their application in broadband requirement [13]. MMA that include magnetic microwave absorbing materials (MMWAMs) as substrates, obviously improved the narrow band characteristic of the MMAs [14–15] primarily due to its large value of permeability [16]. MMWAMS demonstrates light weight and thin thickness in the frequency regime of 2-18 GHz [17–20], the most exploited band in radio frequency due to its wide application in radar and other vital communication devices [21]. As thin as 1mm thickness, they can absorb more than 85% of the incident electromagnetic wave over the 8–18 GHz range [22–23]. However, the bandwidth for 90% absorption is limited to a few GHz as the absorption in 2–8 GHz is very weak, hence obtaining a wide bandwidth response without compromising thickness is a great challenge [24–26].

Previously, inclusion of magnetic substrates in the design of MMA has been widely adopted. A composite

* Corresponding author, tel: +234 – 706 – 817 – 9649

X-band radar absorbing structure of 2.93 mm thickness that absorbed more than 90% of incident wave was proposed [27]. A new type of thin and broadband three layers structure metamaterial absorbers [28] that achieved in excess of 12 GHz absorption bandwidth with reflectivity below −10 dB in the 2–18 GHz frequency range at a thickness of 1.8mm was reported. Likewise, a three-layered metamaterial absorber [29] intended for broadband radar absorption was fabricated by means of selective laser sintering 3D printing technology and optimized results indicated reflectivity below −10 dB in the frequency range from 8 GHz to 18 GHz at 2.89mm thickness. A composite absorbent consisting of carbonyl iron powder and nylon [30]was used to modeled a metamaterial absorber of 4.7 mm optimized thickness which results in a reflection loss below -10 dB from 4 to 18 GHz range.

Although the MMA with magnetic inclusion exhibits broadband absorption characteristics [29– 30], it is still required to improve broadband absorption at decreased thickness. In this work, a flaked carbonyl iron powder magnetic microwave absorbing material was structured and its geometric dimensions optimized. This fine tunes its absorption properties hence giving it metamaterial concept and characteristics leading to a competitive operational bandwidth to thickness ratio value.

## 2. THEORY

Generally, the reflectivity of an absorber R, backed by perfect electrical conductor (PEC) ground plate can be written as [30]

$$R = 20log\left|\frac{Z_{in}^{0} - 1}{Z_{in}^{0} + 1}\right| \qquad (1)$$

where R is reflectance and $Z_{in}^0$ is surface layer input impedance.

The governing equation of a multilayered absorber based on transmission line method which is required to evaluate the reflectivity of the model absorber is presented as [30]

$$Z_{in}i = Z_i\frac{Z_{in}(i+1) + Z_i\ \tanh\gamma_i d_i}{Z_i\ + Z_{in}(i+1)\tanh\gamma_i d_i} \qquad (2)$$

where $Z_{in}i$ = Input impedance, $d_i$ = Layer thickness, $Z_i$ = Characteristic impedance, $\gamma_i$ = Propagation constant, $i$ = layer number and $Z_{in}4 = 0$. $Z_i = \sqrt{\frac{\mu_{r,i}}{\varepsilon_{r,i}}}$ and $\gamma_i = j2\pi f\frac{\sqrt{\varepsilon_{r,i}\mu_{r,i}}}{c}$.

Effective electromagnetic parameters of structured layers can be obtained using equation (3), which is based on strong fluctuation theory of honeycomb-structured surfaces [31].

$$\varepsilon_{eff} = \frac{1}{2}\Big[(1-2g)(1-\varepsilon_r) + \sqrt{(1-2g)^2(1-\varepsilon_r)^2 + 4\varepsilon_r}\ \Big] \qquad (3)$$

Here, $\varepsilon_{eff}$ is the effective permittivity, $g$ is the volume ratio of the solid part in a layer, and $\varepsilon_r$ is the permittivity of the solid. Effective permeability $\mu_{eff}$ can be obtained by replacing $\varepsilon_r$ with $\mu_r$ in equation 3. The operational bandwidth to thickness ratio that was used to describe the performance of the absorber is given by [32]

$$\frac{\text{Bandwith}}{\text{Thicknes}} = \frac{\lambda_{fmin} - \lambda_{fmax}}{h} \qquad (4)$$

where $\lambda_{fmin}$ and $\lambda_{fmax}$ are the wavelengths at $f_{min}$and $f_{max}$ respectively and $h$ is the thickness of the absorber.

## 3. DESIGN AND SIMULATION

The three dimensional optimized geometric structure of a single unit cell of the proposed radar absorbing metamaterial (RAMM) is shown in Figure 1. It consists of three layers of flaked carbonyl iron powder materials with a copper plate ground plane. The surface layer is cross shaped, the middle layer is block shape structured and the bottom layer is considered as a conventional single slab absorber. The thickness of the bottom copper metallic plate (0.036mm) is designed to be greater than the skin depth of the copper under the studied frequency intervals (2-18 GHz), so that it does not transmit any radiation. Finite element method (FEM) based on Comsol Multiphysics simulation package is used for numerical modeling of the proposed radar absorbing metamaterial.

The metamaterial absorber design in this work is for radar applications, therefore the frequency range of 2-18GHz is considered. The electromagnetic parameters of the flaked carbonyl iron powder as measured by [28] are imported into the simulation software to define the frequency dependent material properties using interpolation tool. The boundary conditions along x- and y-axis are chosen to be perfect magnetic conductor (PMC) and perfect electric conductor (PEC) in order, where port is used to input plane polarized electromagnetic wave along z-axis. These boundary conditions as cited in [33] are used to mimic the infinite periodic structure that ensures symmetry along x- and y-axis and the wave strikes perpendicularly onto the infinite radar absorbing metamaterial along z-axis.

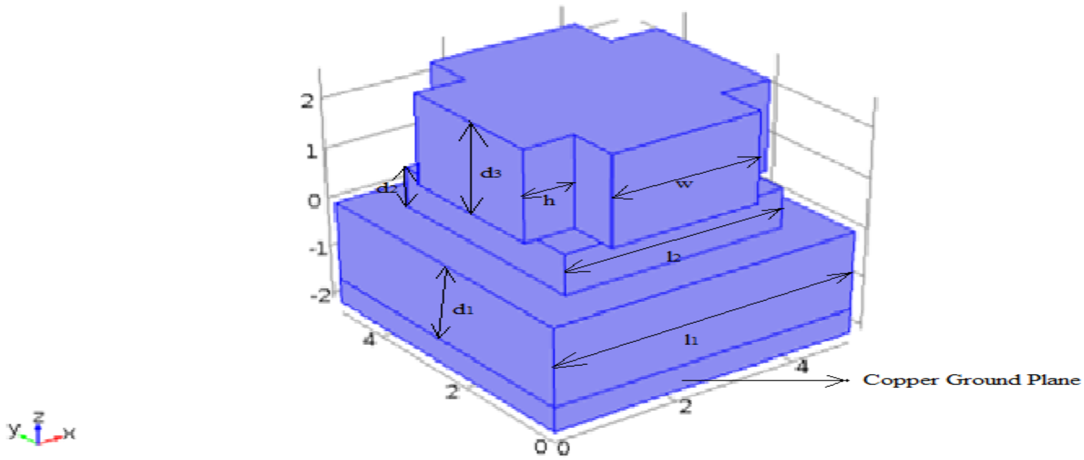



*Figure 1: Designed Unit Cell Structure of the Proposed Radar Absorbing Metamaterial.*
Geometric dimensions are: $l_1 = 5.0m$, $l_2 = 3.6mm$, $w = 2.4mm$, $h = 0.8mm$, $d_1 = 1.6mm$, $d_2 = 0.8mm$, $d_3 = 1.8mm$ and $ground\ plane\ thickness = 0.036mm$.

Physics controlled tetrahedral meshing is used in the simulation and impedance boundary condition (IBC) is selected to represent ground plane condition while the output of the simulation software is the scattering parameters (S-parameters).
In order to validate the COMSOL Multiphysics software used in this work, a metamaterial absorber which was numerically and experimentally realized by Zhou et al [29] using finite integration technique (FIT) based commercial program CST Microwave Studio, has been replicated on the COMSOL Multiphysics solver. The optimized unit cell geometric dimensions of the absorber as reported are $l_1 = 5.0m$, $l_2 = 3.96mm$, $l_3 = 2.34mm$, $d_1 = 0.84mm$, $d_2 = 0.88mm$, $d_3 = 1.17mm$, $ground\ plane\ thickness = 0.036mm$. Their model absorber demonstrates reflectivity below -10dB from 8-18 GHz at 2.89mm.
The reflectivity of the absorber was theoretically evaluated using equations 2 and 3. The calculated reflectivity is then compared with the simulated reflectivity in order to validate the performance of the designed RAMM.

## 4. RESULTS AND DISCUSSIONS

Simulation results of the radar absorbing metamaterial proposed by Zhou *et al*, is represented in Figure 2. Figure 3 depicts the simulated result of the replicated metamaterial absorber reported by Zhou *et al* using COMSOL Multiphysics.

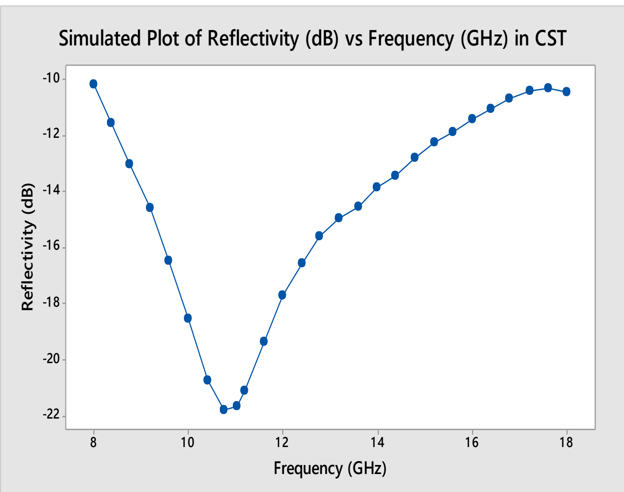



*Figure 2: Simulation result using CST by Zhou, et. al [29]*

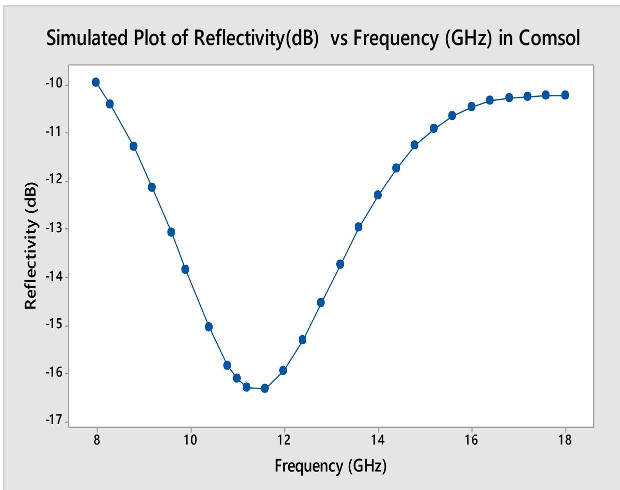



*Figure 3: Simulation Results using COMSOL Multiphysics*

The simulation results for both methods (FIT based solver by Zhou *et al* and FEM based solver used in this work) achieved matching results of below -10dB reflectivity throughout the 8-18 GHz frequency range as could be seen from Figures 2 and 3, which is a confirmation of the precision and accuracy of COMSOL Multiphysics numerical solver used in the present work. The similarity of the reflectivity curves further confirms the accuracy of our simulation software despite slight deviations in the reflectivity peaks.

Parametric studies with respect to the dimensions of the structure are carried out to achieve optimal result for the model RAMM. The magnitude of the reflectivity as a function of the side lengths (w and h) of cross-shaped layer and the layers thickness (parameter $d_i$) are separately presented in Figures 4 and 5 respectively. The parameters combination with optimum absorption characteristics are used in modeling the RAMM.

The reflectivity results from the simulations and theoretical calculations are shown in Figures 6 and 7. These results are compared in Figure 8. It is observed that, the simulated result of the designed RAMM has reflectivity below -10dB ranging between 4.2 – 18.0 GHz. This means the absorption of the incident radar wave is 90% or greater within 4.2 – 18.0 GHz intervals. It is operational bandwidth is therefore 13.8 GHz with thickness of 4.2mm. The operational bandwidth to thickness ratio performance of the proposed RAMM is 13.029. The proposed RAMM thickness, bandwidth and operational bandwidth to thickness ratio indicated an outstanding performance towards overcoming the challenging task of having broadband and thin thickness absorber, compared to the currently published structures of its kind [27–30], [32], [34–36]. The below -10dB reflectivity bandwidth of 13.8 GHz for the designed RAMM is wider than the 10 GHz bandwidth obtained in [29], 13.2 GHz in [30] and 3.5 GHz in [32]. Others are 10 GHz [34], 3.13 GHz [35] and 3.18 GHz [36]. Likewise, the referenced absorbers' operational bandwidth to thickness ratio of 7.204 [29], 9.745 [30] and 6.43 [32] are smaller than that of the modeled RAMM value of 13.029. The designed RAMM thus outclassed these broadband absorbers because the larger the ratio, the better the performance of the absorber [32].

For the calculated result, reflectivity below -10dB takes place from 3.1 to 18.0 GHz. Comparatively there is favorable agreement between the simulated and the calculated results. The results tend to be consistent in both shape and peaks, though there is deviation in respect of the working bandwidth (13.8 GHz for the simulated and 14.9 GHz for the calculated). This could be attributed to the fact that, the middle and surface layers are not in full accord with honeycomb-structure employed in the theoretical assessment of the RAMM as their volume ratio is slightly greater than 50% [29].

Figure 9 shows the power loss density of the three-layered absorber at the frequency of 4 GHz and Figure 10 revealed that of 12 GHz in simulation.

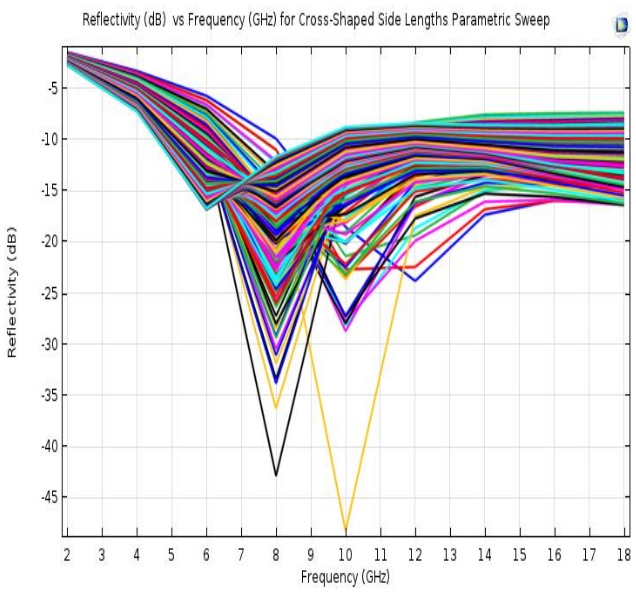



*Figure 4: Cross-Shaped layer side lengths parametric sweep results*

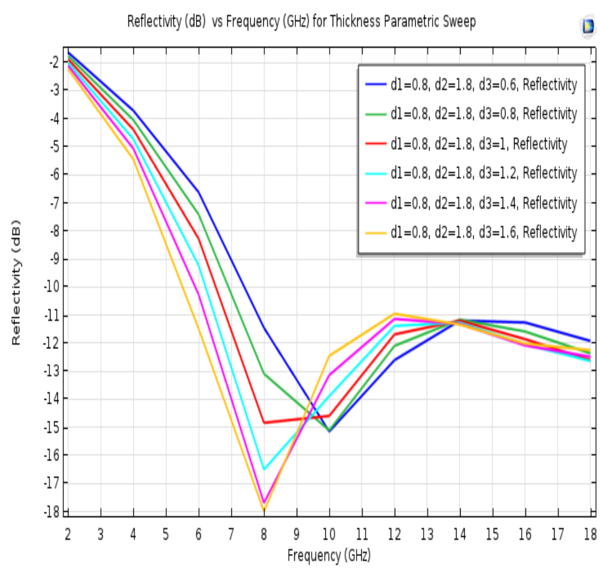



*Figure 5: Layers thickness parametric sweep for RAMM*

It can be seen clearly that the main loss at 4 GHz frequency of the incident wave occurred around the central area of the bottom layer, which simply corresponded to the surface layer as it is in alignment with the position of the cross-shaped surface layer. This contradicts the typical evenly horizontal loss in conventional slab [29] making the structure behaving in an unconventional manner hence becoming a metamaterial. It is therefore a convincing fact that the surface and middle layers provided appropriate impedance matching conditions where the full-wave energy of 2-8GHz frequency regime was consumed mainly in the bottom layer.

Meanwhile, the main loss at 12GHz happened at the central position of the cross-shaped surface layer structure as revealed in Figure 10. According to [37]; absorption characteristics of magnetic absorbing materials such as the carbonyl iron flakes used in this work, is weak in the 2-8 GHz frequency range even though they can absorb more than 85% of the incident electromagnetic wave over 8-18 GHz range.

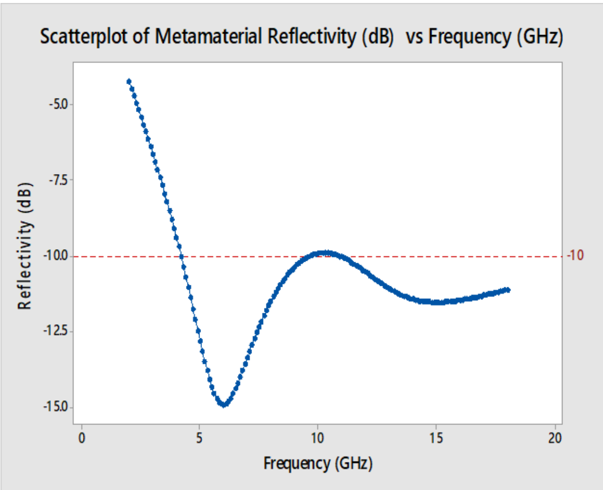



*Figure 6: Reflectivity result obtained from the RAMM simulation on COMSOL Multiphysics*

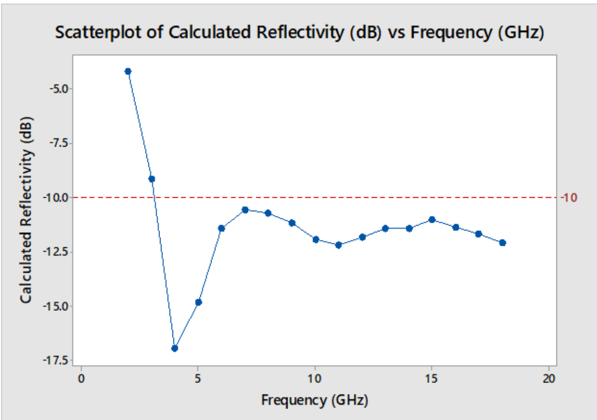



*Figure 7: Calculated reflectivity result of the designed RAMM*

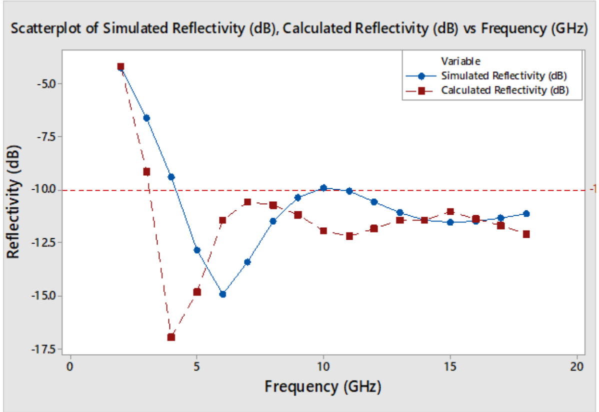



*Figure 8: Simulation and Calculation results of the designed RAMM*

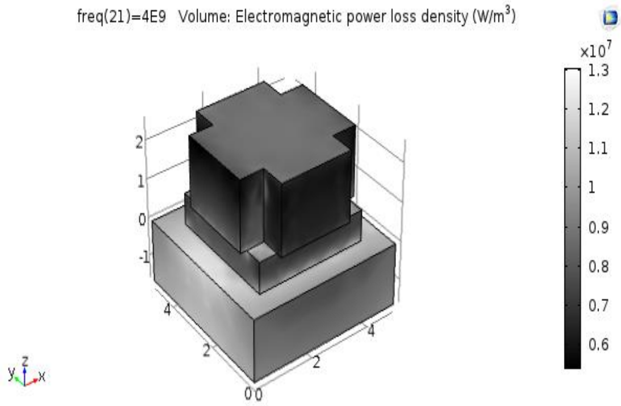



*Figure 9: Electromagnetic Power Loss Density of the RAMM at 4 GHz*

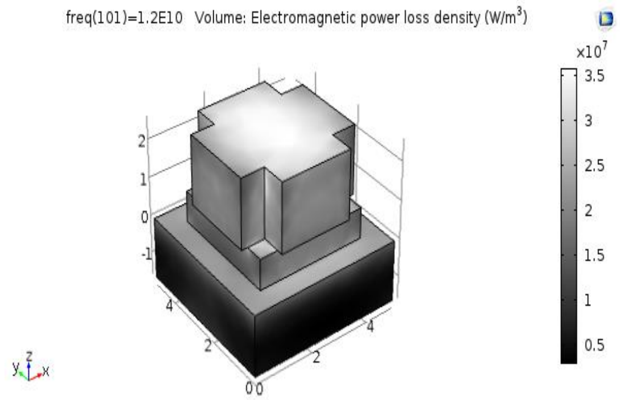
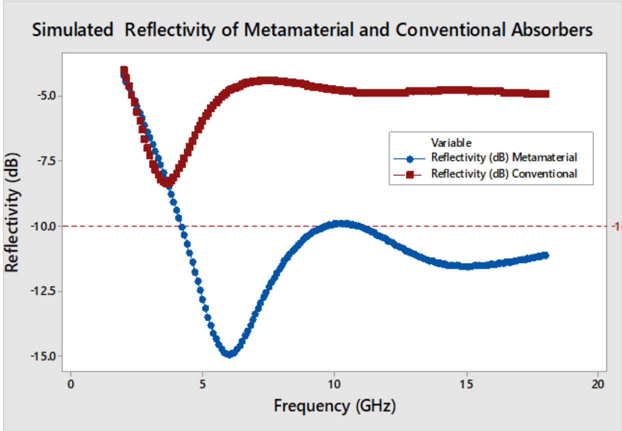



*Figure 10: Electromagnetic Power Loss Density of the RAMM at 12 GHz*

This is however improved by the structural design of the modeled RAMM which guides the 2-8 GHz frequencies to the bottom layer for effective absorptions while the 8-18 GHz frequencies are efficiently absorbed at the surface layer. Therefore, it is reasonable to infer that the absorption band of metamaterial at low frequencies and that of magnetic microwave absorbing materials at high frequencies are both inherited by the designed metamaterial absorber as clearly indicated by the electromagnetic power loss density results.

* Corresponding author, tel: +234 – 706 – 817 – 9649

Figure 11 provided the plots of simulated reflectivity of metamaterial and conventional absorbers made from the same material and thickness for performance comparison. From the figure, the designed metamaterial absorber clearly surpassed the conventional one as none of the entire 2-18 GHz frequency range reaches -10 dB reflectivity bench marks for good absorption characteristics.




## 5. CONCLUSION

A new broadband radar absorbing metamaterial was developed in COMSOL Multiphysics environment. The designed RAMM demonstrates good absorption features with reflectivity below -10dB (>90% absorption) from 4.2GHz to 18GHz in the radar frequency band having a total thickness of 4.2mm only. Moreover, the proposed RAMM has relatively wider operational bandwidth compared to the currently published structures discussed, with a competitive value of 13.029 for the operational bandwidth to thickness ratio. The absorption bandwidth below -10dB is 14.9GHz for the calculated and 13.8GHz for the simulated and the closely resemble shapes and peaks of the simulated and calculated results further confirm the validity of the designed structure. The developed RAMM has potentials to be used for multiple electromagnetic applications like stealth technology and wireless communication.

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