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DESIGN AND PERFORMANCE SIMULATION OF STRUCTURED MICROWAVE ABSORBER BASED ON CONDUCTIVE ABS 3D PRINTING FILAMENT

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ABSTRACT

Electromagnetic absorbing materials with broadband, lightweight, wide-angle, and polarization-insensitive characteristics attracts extensive research interest recently, due to rapid advancement in radar detection techniques and communication devices. Three-dimensional printing is being employed to realize cost-effective structured electromagnetic absorbers that has lately become a common practice of improving radar stealth performance and shielding effectiveness. Structured absorbers permit realization of desired absorption characteristics by careful design of their geometrical structures. In this study, a two-layer structured microwave absorber using conductive ABS polymer is simulated. COMSOL Multiphysics environment is used to investigate the absorption characteristics of the designed structure. Under normal incidence, simulation results revealed at least 90% of absorption from 7.2 GHz to 18.0 GHz for both Transverse Electric (TE) and Transverse Magnetic (TM) polarizations. Oblique incidence results for TE polarization indicate that the absorption rate is more than 90% in the whole range of 7.2–18 GHz frequency band up to 45^0 while the absorption rate is more than 80% for 60^0 incident waves. The absorption rate is more than 90% in the 7.2-18 GHz range for oblique incidences of up to 30^0 only for TM polarization, but greater than 70% at 45^0 incident angles. Additionally, the designed absorber is independent of the polarization of the incident wave. As a result of the exhibited favourable absorption characteristics, the studied absorber provides great potentials for its experimentation and practicability using the low-cost 3D printing manufacturing process.

Keywords: 3D Printing, Conductive ABS, Microwave Absorber, Oblique, Structured.

INTRODUCTION

In recent years, technological advancements in communication devices and radar detection techniques have increasingly brought about electromagnetic interference (EMI) and radiation problems, which incur the urgent need for radical electromagnetic interference shielding devices for military and civilian applications. As devices designed to effectively absorb incident electromagnetic radiation by transforming it into ohmic heat or other forms of energy, electromagnetic (EM) wave absorbers are often used for shielding (Ahmad et al., 2019). The operating frequencies of EM absorbers previously demonstrated have covered the microwave band (Al-zoubi & Naseem, 2017; H. Chen et al., 2018; M. Chen et al., 2012; Choi & Kim, 2015), through Terahertz band (Tao et al., 2008; Vora et al., 2018; Wen et al., 2009), to the infrared and visible light band (Hu et al., 2009; Pan et al., 2019) of EM wave spectrum.

Numerous reports on the development of microwave absorbing materials that aim to achieve lower reflection loss, smaller thickness, and wider effective absorption bandwidth (Lai et al., 2020) have been put forward over the years. Nowadays, several polymeric nanocomposite absorbers prepared by adding one or more forms of absorbing agents to the polymer matrix have been reported (Ahmad et al., 2020; Qing et al., 2010; Zhu et al., 2011). Moreover, nanocomposite-based absorbers have proven to be an effective material to improve the electromagnetic waves absorption characteristics by designing the composition and microstructures of the composite (Liu et al., 2018). Also, recent research indicated that structural EM wave absorbers have significantly developed modern stealth materials in their ability to adjust the macrostructure of absorbers, which play a vital role in regulating the impedance match of EM wave absorbers (Abdullahi & Ali, 2019; Choi & Kim, 2015; Jiang et al., 2018; Luo et al., 2019).

However, lightweight, wide effective bandwidth, wide-angle, polarization-insensitive, and cost-effective microwave absorbers are not only highly demanded in practical applications, but very challenging to realize as well. Therefore, new microwave absorbing materials with the essential features to arrest the EMI and radiation issues are appealing in the field of electromagnetics. Three-dimensional (3D) printing technology has attracted massive attention due to its many advantages like near-complete design freedom, flexibility, design complexity, cost efficiency, and high sustainability (Guo et al., 2019). This has inspired researchers in the microwave field to explore 3D printing for the manufacturing of components like antennas, waveguides, and absorbers (Kjelgard et al., 2018). Accordingly, the high dielectric constant property of conductive Acrylonitrile Butadiene Styrene (ABS) is utilized to design a metamaterial-inspired structured microwave absorber (SMA) using COMSOL Multiphysics. Consequently, the study offers great potentials for its experimentation and practicability using the low-cost 3D printing manufacturing process.

MATERIALS AND METHOD

For validation purposes, a 3D printed microwave absorber which was numerically and experimentally realized (Ren & Yin, 2018) using Computer Simulation Technology (CST) Microwave Studio solver, was repeated on the COMSOL

Multiphysics solver used in this work. Results from the CST Microwave Studio and the COMSOL Multiphysics solvers are presented in Figure 1.

The optimized geometric structure of a single unit cell of the proposed broadband SMA is shown in Figure 2. It consists of two layers of conductive ABS 3D printing polymer from Torwell technologies (Torwell Technologies, 2020) with a copper plate ground plane. The surface layer is cross-shaped, and the bottom layer is considered as a conventional single slab absorber. The geometric dimensions of the SMA unit cell are optimized to ensure minimized reflectivity in the working frequency band. The thickness of the copper plate ground plane is designed to be greater than its skin depth for the microwave frequency range, to prevent transmission of radiation.

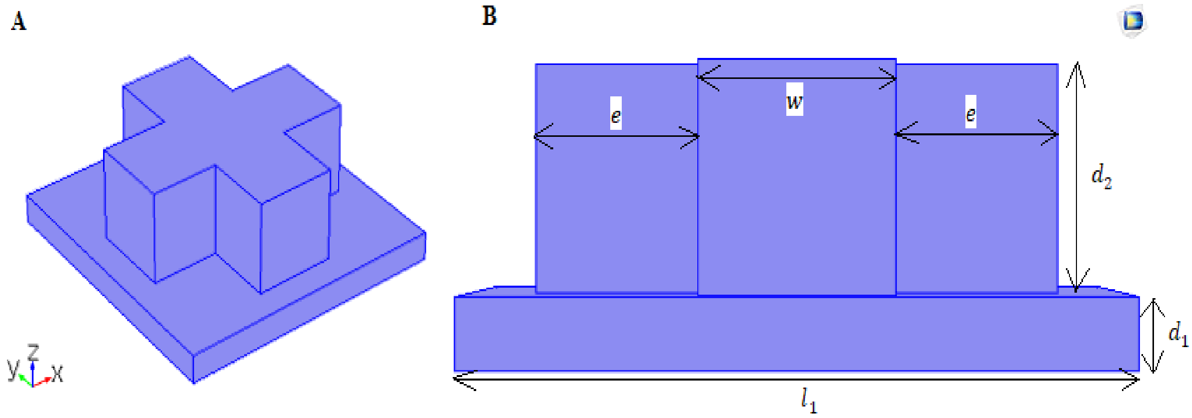

Figure 2: Designed Unit Cell Structure of the Proposed Structured Microwave Absorber: (a) model of the periodic unit (b) model size. $l_1 = 15.0mm, w = 4.4mm, e = 3.8mm,$ $d_1 = 1.3mm, d_2 = 4.2mm$.

To investigate the absorption properties of the proposed SMA, numerical simulations and optimization have been carried out by using the finite element method (FEM) based COMSOL Multiphysics solver. The electromagnetic parameters of the conductive ABS polymer measured by Ren & Yin, (2018) are imported into the simulation software to define the frequency-dependent material properties using an interpolation tool. Perfect magnetic conductor (PMC) and perfect electric conductor (PEC) boundary conditions which set tangential fields to 0 (Luo et al., 2019) are respectively applied along x and y axes to mimic an infinite periodic structure of the proposed SMA. A periodic port is used to supply incident plane-polarized electromagnetic waves along the z-axis plane. Impedance boundary condition (IBC) which treats any material behind the boundary as being infinitely large is chosen for the ground plane. Physics-controlled meshing is used in the simulation and maximum mesh element size was set at one-tenth of the minimum wavelength ($\frac{1}{10}\lambda_{min}$) of the input wave.

The output of the simulation software is the scattering parameters (S —parameters). In general, electromagnetic absorption behaviour of a structure can be calculated by using equation (1) (Abdulkarim et al., 2020) where the frequency-dependent parameters $A(\omega)$, $\mathrm{R}(\omega)$, and $\mathrm{T}(\omega)$ represent the absorption, reflectance, and transmittance in order.

$$A(\omega) = 1 - |\mathrm{R}(\omega)| - |\mathrm{T}(\omega)| \quad (1)$$

Due to the ground plane in the designed structure, T(ω) can be neglected. Therefore, equation (1) reduces to equation (2).

$$A(\omega) = 1 - |\mathrm{R}(\omega)| \quad (2)$$

Using the scattering parameter (S_{11}) from the simulations, the absorption can be calculated using equation (3).

$$A(\omega) = 1 - |S_{11}|^2 \quad (3)$$

RESULTS AND DISCUSSIONS

Simulation result of the 3D-printed low-cost dielectric-resonator-based ultra-broadband microwave absorber using carbon-loaded ABS polymer (Ren & Yin, 2018) is represented in Figure 1 together with the simulated result from the repeated microwave absorber using COMSOL Multiphysics. The two simulation results are in excellent agreement in both shape and peaks as could be seen in Figure 1. This is a confirmation of the precision, reliability, and accuracy of the COMSOL Multiphysics numerical solver used in the present work, thus relieving us of prompt experimental work for the validation of the subsequent simulation results.

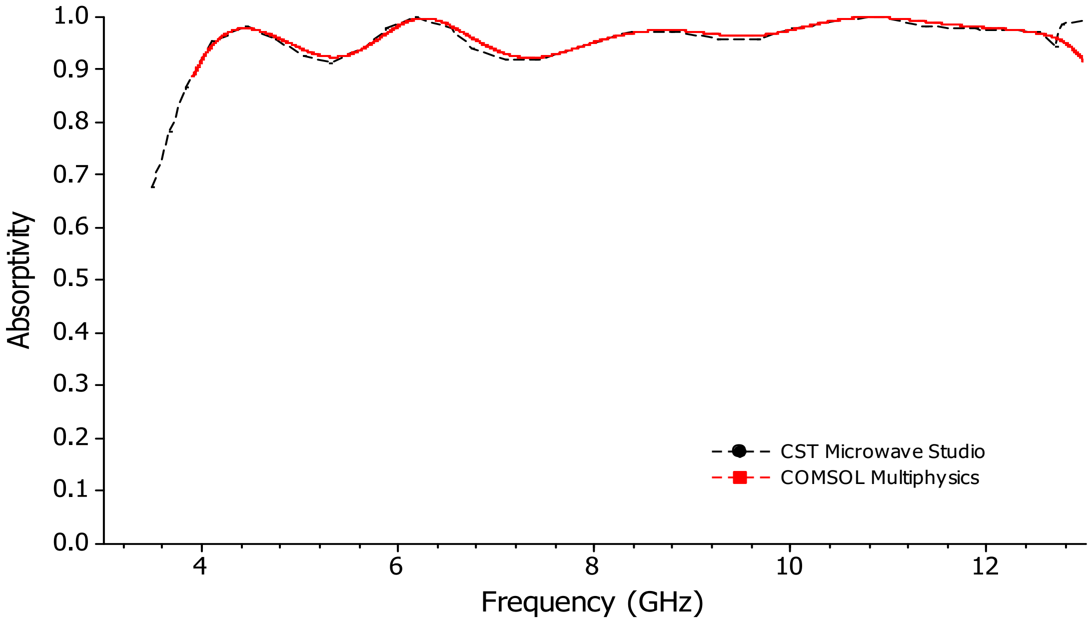

Figure 1: Simulated Absorptivity Plots for COMSOL Multiphysics Software Validation

Based on the complex relative permittivity and permeability of the conductive ABS measured by Ren & Yin, (2018), the absorptivity of the two-layer SMA was simulated and calculated from the equation of absorption strength given in Equation (1), using the COMSOL Multiphysics' RF module based on finite element method. As a result, the frequency dependence of the simulated absorptivity of the SMA in the frequency range of 6–18 GHz at normal incidence is shown in Figure 3. It can be seen that the two-layer SMA design presented a more than 90% microwave absorption in the 7.2 -18 GHz range for both TE and TM wave modes. Thus, the proposed SMA demonstrated broadband absorption behaviour at normal incidence. Compared with the cylindrical-shaped resonator-based microwave absorber studied by Ren & Yin, (2018) realized from the same conductive ABS as the current study, the proposed cross-shaped SMA demonstrates wider effective bandwidth of 10.8 GHz (7.2-18 GHz) at normal incidence and thinner thickness of 5.5 mm only. The corresponding values obtained by Ren & Yin, (2018) are 8.1 GHz (3.9-12 GHz) and 9.37 mm respectively. The lattice constant size of 23.7mm obtained by Ren & Yin, (2018) is comparable to wavelength of interacting frequencies high than 12 GHz, hence limiting the absorption bandwidth to 4-12 GHz only due to absorption instability. The 15mm lattice constant size obtained in the present design, is myopic to frequencies of interests (8-18 GHz) due to its subwavelength size which leads to absorption stability and the design consequently behaves as a metamaterial.

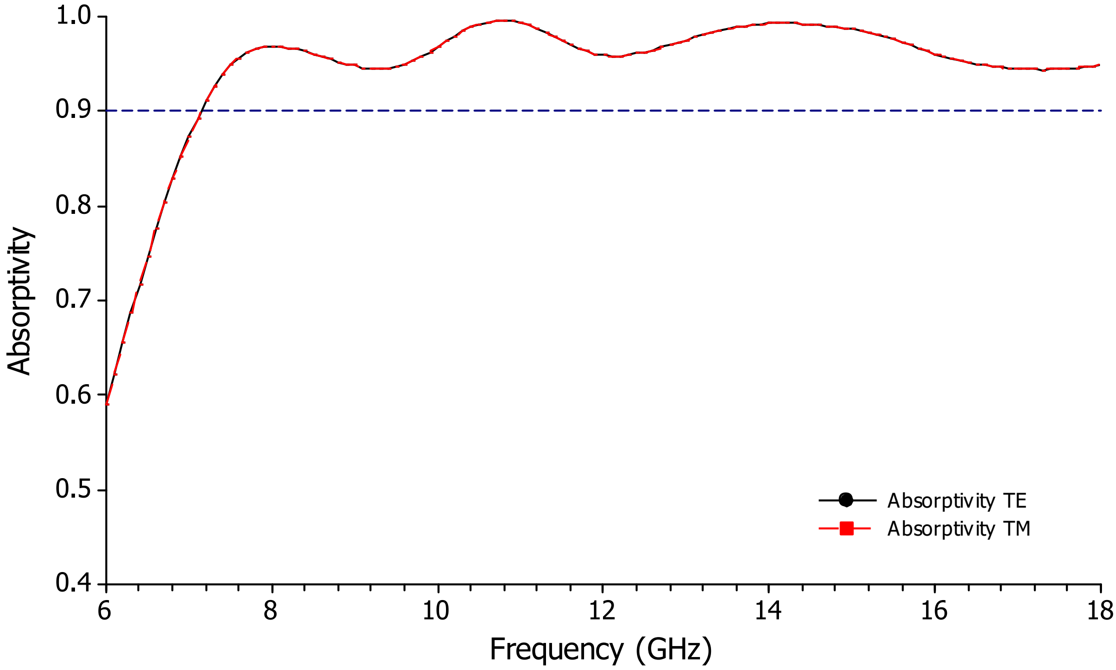

Figure 3: Simulated Absorptivity Plots of the Structure at Normal Incidence for TE and TM Polarizations.

In actual practice, the incident electromagnetic wave encounters the absorber structures obliquely. Hence, the angle of incidence acceptance of the model SMA was investigated and results for both transverse electric (TE) and transverse magnetic (TM) polarization conditions are presented in Figures 4 and 5 respectively. The results indicate that, for TE polarization, the absorption rate is more than 90% in the whole range of 7.2–18 GHz frequency band for normal incidence and oblique incidences up to 45^0. However, the absorption rate is more than 80% for 60^0 incident waves.

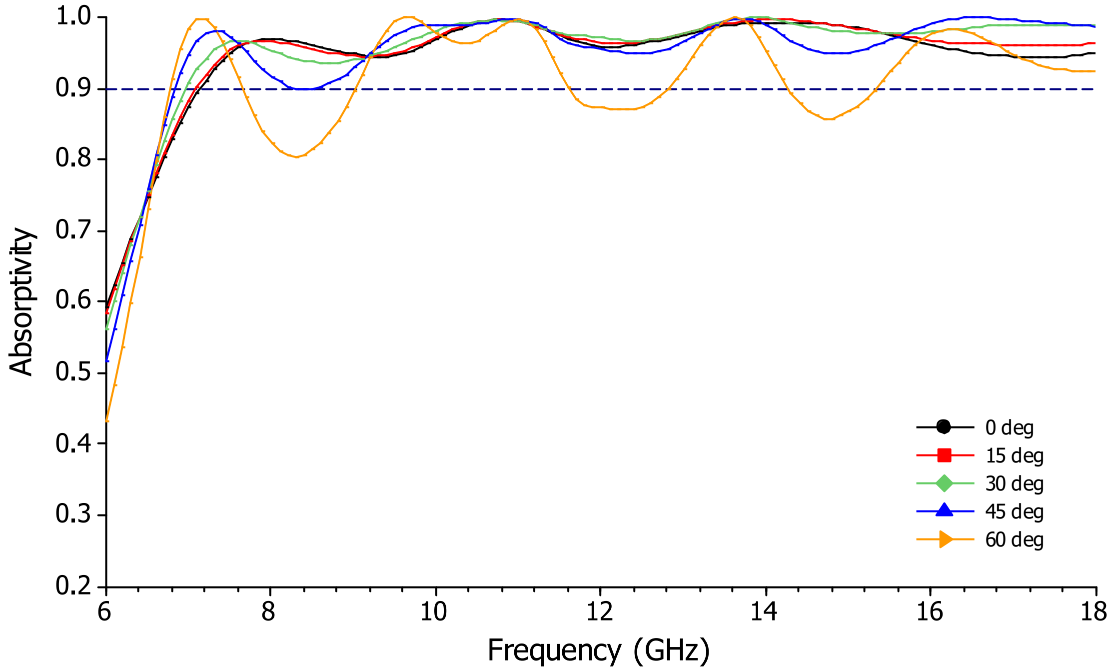

Figure 4: Simulated Absorptivity of the Structure at Normal and Oblique Incidence for TE Polarized Wave

In contrast to the TE polarization, when the EM wave propagates in TM polarization, the absorption rate is more than 90% in the 7.2-18 GHz range for normal incidence and oblique incidences of up to 30^0 only, while the absorption rate is more than

80% in the 10-18 GHz range, greater than 70% in the 7.2-18 GHz range at 45^0 incident angles. Therefore, we can see that in both the TE and TM polarizations under oblique incidences, the absorptivity remains at a high level and is higher than 90% in most of the frequency bands of interest.

Simulation results of the absorption characteristic for the proposed SMA structure at different polarization angles are revealed in Figure 6. At first look, it is observed that both shape and peaks of the curves are overlapped which indicated that the designed absorber is independent of the polarization of the incident wave. It is thus proper to state that the designed structure exhibited a wide-angle and polarization-insensitive property which is attributed to the symmetrical shape of the designed structure.

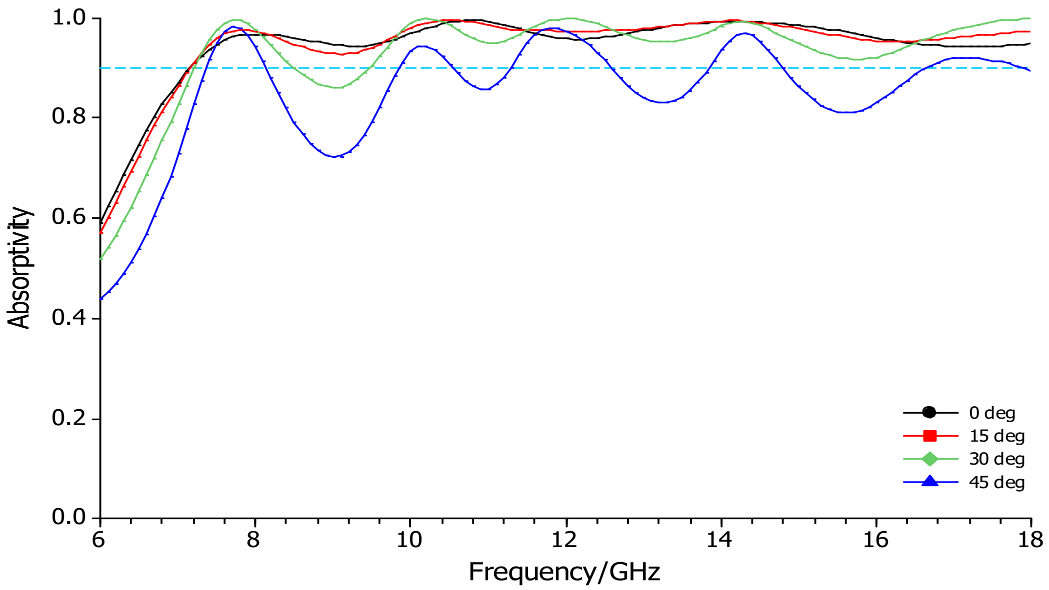

Figure 5: Simulated Absorptivity of the Structure at Normal and Oblique Incidence for TM Polarized Wave

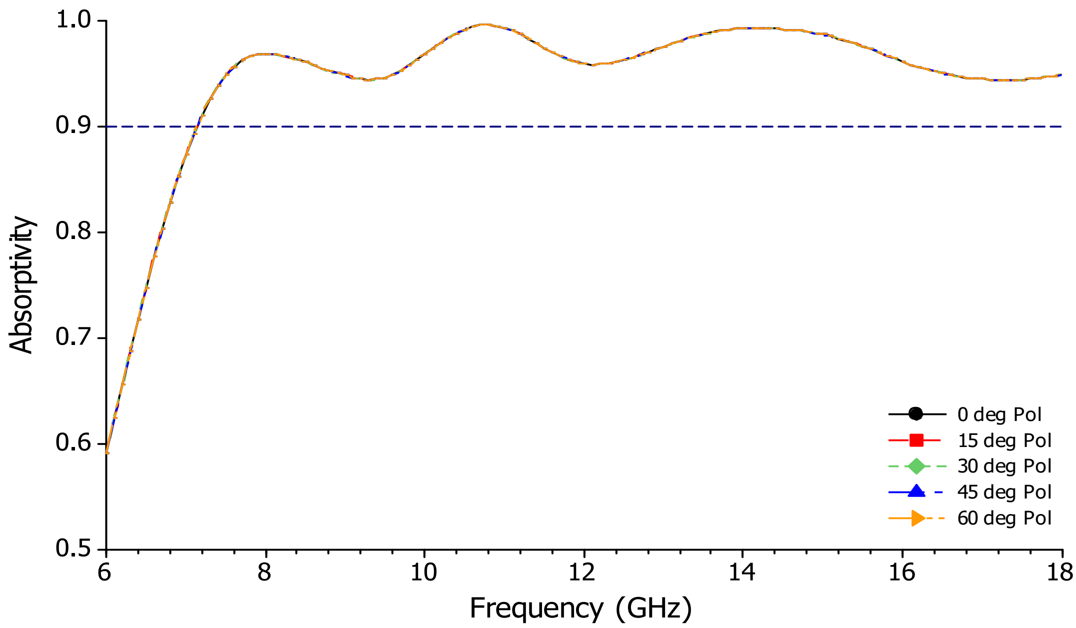

Figure 6: Simulated Absorptivity Plots at Different Polarization Angles for TE wave

To explore the physical absorption mechanism of the proposed SMA, current density and power loss density were simulated at three absorption peaks occurring at 8.0, 10.8, and 14.2 GHz frequencies when the incident angle is 0^0, and results are revealed in Figures 7 and 8 respectively. As depicted in Figure 7, the current density patterns at these frequencies represent the absorption peaks which are similar to power loss density patterns as can be seen in Figure 8. Noticeably, the power loss distribution coincides well with the current density distribution, indicating that the current density plays a prominent role in microwave absorption which is mainly caused by ohmic losses.

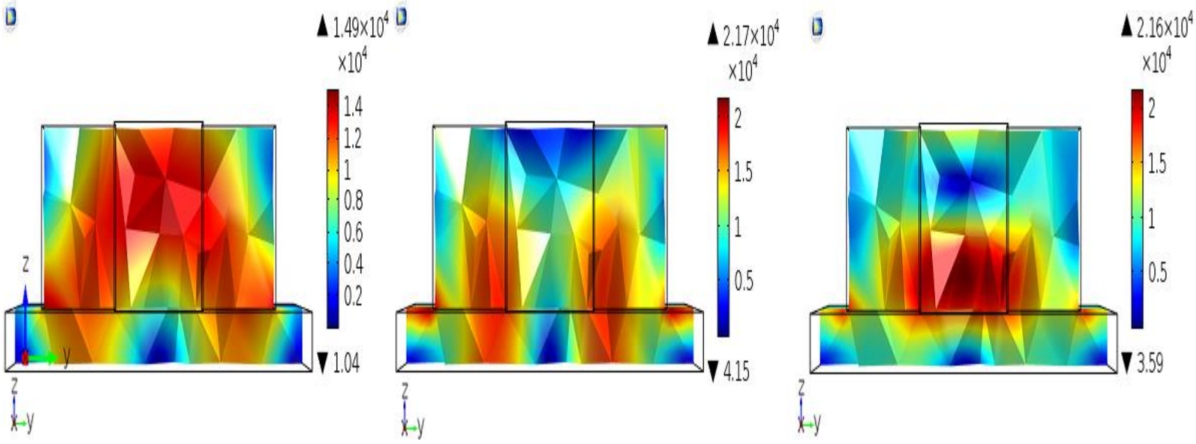

Figure 7: Simulated Current Density Plots at 8.0 GHz, 10.8 GHz, and 14.2 GHz absorption peaks respectively

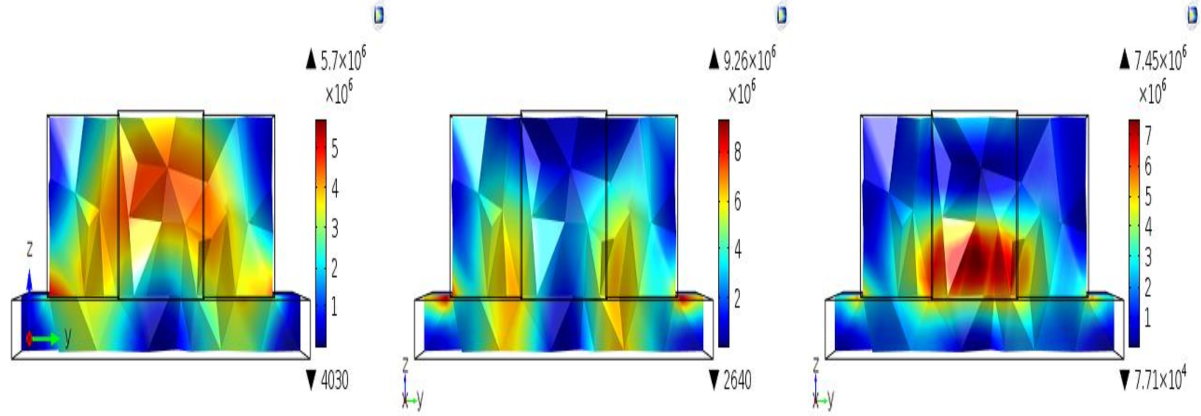

Figure 8: Simulated Power Loss Density Plots at 8.0 GHz, 10.8 GHz, and 14.2 GHz absorption peaks respectively

CONCLUSION

A two-layer structured thin broadband microwave absorber exhibiting more than 90% of absorption in the whole band of 7.2 GHz to 18 GHz was designed, simulated and studied. The proposed design consists of a cross-shape resonator mounted on the bottom layer conventional absorber. Simulation results for the oblique incidence proved that the absorptivity remains at a high level and is higher than 90% for almost the entire band of interest and insensitive to polarization angle changes. A study of the absorption mechanism indicated that it is mainly caused by ohmic losses. Finally, the simulation study makes way for experimentation and practical applications using the low-cost 3D printing manufacturing process.

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