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ABSTRACT

In this paper, a perfect metamaterial meander line absorber is designed, fabricated, and characterized by a waveguide measurement technique. The proposed metamaterial absorber of a double metal split ring resonator has a single-band absorption response in the microwave region. The characterization and analysis technique of the absorber illustrated a development in its bandwidth value, which minimizes both reflection and transmission coefficients for different upper metal lengths. Simulation and experimental results show that the absorber has a good perfect absorption in the frequency band between 8.5 GHz and 9 GHz. Moreover, the simulation results are in good agreement with the experimental measurements, which verify that this absorber can be used for the radar cross section and any electromagnetic compatibility at the X-band region.

I. INTRODUCTION

Smith et al. showed in the initial microwave experiments that the metamaterials (MMs) are artificially active homogeneous electromagnetic structures composed of metals and dielectrics. A revision and survey of absorber characteristics is a comprehensive tool and design to ensure that the metamaterials absorbers are focused on the unique properties and benefits of the metamaterial, and extensive work has been performed on various fields such as antennas, filters, and absorbers. The microwave absorber has the most promising use of the metamaterial. The metamaterial absorber recently led to almost unity absorption of the improved bandwidth, as obtained by Ramya. These metamaterial microwave absorbers are used in large numbers to reduce the specific absorption rate on mobiles for electromagnetic wave absorption, radar cross section reduction, and electromagnetic compatibility. Different metamaterial absorbers in microwaves have been designed: terahertz and infrared (IF) frequencies with dual bands, triple bands, and multi-band absorption. The different forms of split-ring resonators used in ultra-wide-band applications are now subrogated by the electric field drove by LC resonators. Multi-layer structures were proposed for the improved absorption bandwidth but relied on polarization. The nanostructured multi-layer absorbers were suggested by Micheli et al. For the analysis of an absorbing metamaterial model, the waveguide measuring technique is used. Due to the small measurements needed and the simple measuring tool at low costs, the waveguide measuring technique is superior to the conventional methods of the measurement. The characteristics of absorption of a linear polar TE wave in the X band are investigated. The tests for single- and two-layer microwave absorbers have been examined for various coating thicknesses. Researchers have great interest in perfect absorption due to its wide range of applications in energy harvesting, sensing, and photocatalysis.

This paper is organized as follows: Sec. II gives a brief discussion on the theoretical relationship between absorptivity and effective constitutive parameters; in Sec. III, a metamaterial absorber is designed and simulated for the determination of peak absorptivity using the plane wave technique. Fabrication and the waveguide measurement results are given in Sec. IV. Comparisons between
unit cells of the model structure are provided in Sec. V. Section VI presents the conclusion.

II. DESIGN, MODELING, AND SIMULATION OF THE PROPOSED METAMATERIAL ABSORBER

A single unit cell of the absorber consists of two distinct metallic elements, as shown in Figs. 1(a) and 1(b). The program simulated a single unit cell, as shown in Fig. 1(c). The structure of the unit cell is shown in Fig. 1, which consists of a split ring resonant (SRR) double metal and grounded lower layer separated by a dielectric FR4 substratum of height $d = 0.8$ mm and dielectric relative permittivity $\varepsilon_r = 4.4$ with a loss tangent of 0.02 and a copper thickness of 0.035 mm. The remaining structure dimensions are $A_1 = 4.2$ mm, $A_2 = 12$ mm, $TT = 0.6$ mm, $G = 1$ mm, $H = 11.8$ mm, $w = 1.5$ mm, $w_1 = 0.85$ mm, $w_2 = 1.7$ mm, $L = 1.7$ mm, and $u = 8.3$ mm. The equivalent circuit model (ECM) of the metamaterial unit cell absorber is shown in Fig. 2. The structure is based on a circuit model equivalent to achieve maximum absorptivity at the X-band region.

The absorptivity $A(\omega)$ of any given material can be calculated using the following formula:

$$A(\omega) = 1 - T(\omega) - R(\omega),$$

where $R(\omega)$ and $T(\omega)$ are reflecting and transmission as frequency functions, respectively. $R(\omega)$ and $T(\omega)$ are required to be minimized simultaneously to ensure that the absorptivity $A(\omega)$ is as close as possible to the unity. The reflection and transmission are represented by the reflection coefficient $R(\omega) = |S_{11}|^2$ and the transmission coefficient $T(\omega) = |S_{21}|^2$ in terms of their scattering parameter values.

As the surface absorbs the power, the transmission coefficient $(S21)$ becomes 0. Therefore, the expression can be simplified as $A = 1 - |S11|^2$.

The transmission line models of the proposed MM absorber with the resistors are illustrated in Fig. 2. Under normal incidence, from the equivalent circuit, the absorptivity $A(\omega)$ can be obtained as

$$A(\omega) = 1 - \Gamma = 1 - \frac{|Z_{in} - Z_0|^2}{|Z_{in} + Z_0|^2},$$

where $Z_{in}$ is the input impedance of the device.

As the surface absorbs the power, the transmission coefficient $(S21)$ becomes 0. Therefore, the expression can be simplified as $A = 1 - |S11|^2$.
where $\Gamma$ is the Fresnel reflection coefficient, $Z_0$ is the characteristic impedance of air, $Z_0 = \sqrt{\mu_0/\epsilon_0} = 120\pi \equiv 377\Omega$, and $Z_m$ is the input impedance. $Y_0 = \frac{1}{Z_0}$ and $Y_m = Y_1 + Y_M$ is the characteristic air admittance and the proposed absorber input admittance, respectively. To ensure maximum absorption throughout the entire frequency range, $Z_m = Z_0$ must be satisfied [Eq. (1)]. The components of input admittance $Y_M$ and $Y_1$ can be calculated as follows:

$$Y_M = \frac{1}{R + j\omega L - \frac{1}{j\omega C} } = G_M + jB_M.$$  

The conductance $G_M$ and susceptance $B_M$ are

$$G_M = \frac{R}{R^2 + (\omega L - \frac{1}{\omega C})^2}, \quad (4a)$$

$$B_M = \frac{- (\omega L - \frac{1}{\omega C})}{R^2 + (\omega L - \frac{1}{\omega C})^2}. \quad (4b)$$

The equivalent circuit model (ECM) is described in Fig. 2 according to the transmission line theory. The base metal can be called a short transmission line, $Y_1$ is the surface admittance of the dielectric spacer. The RLC circuit network can be used as a model for the top built metal array. Metal induction of the resistance $R$ and the top built metal array. Metal induction of the resistance $R$ and metal capability $C$ is caused by the gap between the metal. However, $R$’s presence can be ignored in the THz region. In Fig. 2, the sheet admittance of the metamaterial can be regarded as $Y_M$. The input surface admittance of the dielectric spacer $Y_1$ can be written as follows:

$$Y_d = \sqrt{\frac{\epsilon_0}{\mu_0}} = Y_0 \sqrt{\frac{\epsilon_0}{\mu_0}},$$  

$$Y_1 = Y_d \coth \left[ \frac{\omega}{C_0} d \sqrt{\frac{\epsilon_0}{\mu_0}} \right], \quad (5)$$

where $Y_d$ and $\omega$ are the dielectric substrate characteristic admittance and angular frequency, respectively, and $\epsilon_0$ and $\mu_0$ are free space permittivity and permeability, respectively. To obtain $Y_M$, we can calculate $G_M$ and $B_M$ as follows:

$$G_M = Y_m - \text{Re}(Y_1) = Y_0 - \text{Re}(Y_1), \quad (6)$$

$$B_M = - \text{Im}(Y_1). \quad (7)$$

$$Y_d$$

The circuit parameters in Fig. 2 are extracted as $C = 0.26$ pF and $L = 1.2$ nH. The resistance $R$ in the circuit is the sum of the losses and surface resistance of metals. $R$ can be calculated approximately on the copper surface, $R = L/\sigma A$. Copper has the conductivity of $5.8 \times 10^7$ S/m. In addition, $Y_d$ is $5.56 \times 10^{-3}$ $\Omega$ with the length of the shorted transmission line.

Moreover, with the effective medium theory, a complex electrical permittivity can characterize MM $\epsilon(\omega) = \epsilon_1 + i\epsilon_2$ and magnetic permeability $\mu(\omega) = \mu_1 + i\mu_2$. To minimize $R(\omega)$ and $T(\omega)$ simultaneously, the absorber’s impedance, $Z_s(\omega) = \sqrt{\mu(\omega)/\epsilon(\omega)} = Z_1 + iZ_2$, should be matched to the equivalent impedance of free space $\eta_0$, which equals about $377\Omega$ to have resonant MMs, and simultaneously, the absorber’s refraction index, $n(\omega) = \sqrt{\epsilon(\omega)\mu(\omega)} = n_1+i n_2$, should have a large imaginary part.

A unit cell of the MM absorber is simulated using a commercial finite difference time domain (FDTD) solver of CST software. The simulation takes place between 7 GHz and 14 GHz. The simulated unit cell has appropriate periodic boundary conditions (PBCs). A waveguide port (port 1) is placed at a fixed distance (d = 15 mm) from the simulated structure to transmit a TEM plane wave. Another waveguide port (port 2) is placed on another side of the structure at the same distance to receive the propagating wave through the unit cell (see Fig. 3). By changing the absorber surface structure parameters, a complete double band absorber is obtained at modes 2 and 3. The length of the upper metal is varied from 8 mm to 8.6 mm. The transmission

![FIG. 3. Simulation with the boundary condition of the proposed MM absorber structure.](image)

![FIG. 4. Simulated absorptivity for different upper metal lengths u.](image)
coefficient $T(ω)$ and reflection coefficient $R(ω)$ are calculated as mentioned in formula (1) from the simulated $s_{11}$ and $s_{21}$ results, respectively.

The absorptivity is calculated from reflection and transmission coefficient results for different values of the upper metal lengths using Eq. (1), as shown in Fig. 4.

To achieve the desired wave absorption at the resonant frequency, X-band absorber design was made available for the geometric parameters as well as the resistance. Such parameters have been further defined for the spectral combination of the resonances and X-band properties. By tuning $ω_0$ of the $\varepsilon(ω)$ and $\mu(ω)$ properly to have $\varepsilon(ω) = \mu(ω)$, an impedance matching to free space could be achieved.

By changing the upper metal length of the metamaterial structure, the absorptivity has three dual-band absorber operating frequencies at three resonant modes. The three resonant modes, from

![Diagram](image1.png)

**FIG. 5.** (a) The best simulated transmission for the upper metal length at $u = 8.3$ mm. (b) The best-simulated reflection for the upper metal length at $u = 8.3$ mm.

![Diagram](image2.png)

**FIG. 6.** (a) Electric resonator (upper metal) with dimensions. (b) Cut wire (ground) with dimensions. (c) Metamaterial structure with justified dimension.
low to high frequency, are represented in modes 1, 2, and 3 for convenience. Three different resonant modes, which affect magnetic resonant coupling, are due to three different values of the upper metal lengths (8 mm, 8.3 mm, and 8.6 mm).

As shown in Fig. 4, the relation between the resonant frequency and the length of the upper metal is vice versa as expected. The resonant frequency of calculated absorption is from 8.5 GHz to 9.5 GHz as the upper metal length increased from 8 mm to 8.3 mm, respectively. Figure 4 also shows that the MM resonant frequency is decreased as the length of the upper metal \( u \) is increased at 8.6 mm.

The calculated transmission and reflection coefficient result for the upper metal length is displayed in Fig. 5. As shown in Fig. 5, the relation between the resonant frequencies at the given length (increase from 8 mm to 8.3 mm) of the upper metal is vice versa as expected. The best resonant frequency of the simulated transmission coefficient result is from 8.7 GHz, and the reflection coefficient result is 8.7 GHz. It is obvious that this absorber has a dual-band resonance at both 8.7 GHz and 9 GHz frequencies, respectively.

The optimized designed unit cell of the metamaterial absorber structure with the justified dimension is shown in Fig. 6. The program simulated a single unit cell, as shown in Fig. 6(c). A single unit cell of the absorber consists of two distinct metallic elements, as shown in Figs. 6(a) and 6(b). The upper metal length \( u \) of 8.3 mm achieves the best absorptivity at a frequency of 8.7 GHz, as shown in Fig. 7. From the simulation, it exhibits two narrow resonant frequencies of 8.7 GHz and 9 GHz with an absorptivity of 98% and 90%, respectively.

III. CHARACTERIZATION OF THE MM ABSORBER USING A WAVEGUIDE

A CST Microwave Studio software is used to simulate the proposed setup. Four unit cells of the optimized MM absorber structure are placed inside a WR 90 waveguide to cover its cross-sectional area, as shown in Fig. 8. The WR 90 waveguide has a frequency range of 8.4 GHz to 12.5 GHz. A waveguide port (port 1) is placed at the input to excite the waveguide and transmit a TE wave, as shown in Fig. 9. Another waveguide port (port 2) is placed on the other side of the waveguide to receive the propagating electromagnetic wave along the Z direction through the four-unit cells. The electric field polarization is along the X-axis, while the magnetic field polarization is along the Y-axis.
The simulated results of the absorption $A(\omega)$, reflection $R(\omega)$, and the transmission $T(\omega)$ are shown in Fig. 10. The reflection is large (greater than 0.08%) close to the lower and upper frequencies of the plot, but it has a minimum value of 100% at a frequency of 8.7 GHz. The simulated transmission $T(\omega)$ also has a low value of 0.05% at a frequency of 8.7 GHz. As both the reflection and the transmission have low values at 8.7 GHz, a good absorbance of up to 99.7% is given at this frequency.

The strength of the electric field and vectors of the electric current density, as shown in Fig. 11, can observe the magnetic and electrical resonance of the proposed MM absorber. On the XY plane of the unit cells, the normal x-polarization incidence, the electric field, the current distribution, and the electric current density are recorded for the MMs at a frequency of 8.7 GHz.

The electrical resonance is generated at a frequency of 8.7 GHz from the remaining top and bottom layers. The electric currents at the top and the bottom layers were anti-parallel. Thus, the magnetic responses are generated on the upper and lower meander line layers by the electric currents. Thermal losses dissipate the electromagnetic (EM) energy transmitted into the substrate.

IV. FABRICATION AND MEASUREMENTS

To characterize the proposed MM absorber using a waveguide technique, the structure of a four-unit cell is enough to cover the cross-sectional area of the WR 90 waveguide. Therefore, a structure, which consists of four unit cells, is fabricated using an FR-4 substrate of a dielectric constant $\varepsilon_r = 4.4$. The fabricated structure with dimensions of 14 mm $\times$ 18 mm $\times$ 0.8 mm is shown in Fig. 12.

The experimental methods used to classify the absorber structures were based on methods for measuring the spatial wave open system, i.e., measurements of reflectivity and transmission. To

FIG. 11. (a) The simulated magnitude of the electric field, (b) simulated vector surface current density, and (c) simulated vector surface current distribution.

FIG. 12. (a) The fabricated MM absorbing structure for single-band absorption. (b) The other side of the fabricated MM absorbing structure.
achieve an EM wave of normal or oblique incidence, the measuring system developed is installed by mounting a large-scale sample from the absorber to the focus of two horn antennas, which have a dielectric lens or are not centered. This method, however, uses large-scale test samples, and a part of the energy that cannot be detected by the two horn antennas may be spread to other directions.

The waveguide closed system technology is used to test the structure absorption. It only requires a small sample and a simple measurement. The absorber structure test is of the same width as the waveguide’s internal opening. The trial sample is located at the entrance port of the standard WR90 waveguide. A portable vector network analyzer (VNA) is used to measure the scattering parameters of the waveguide, as shown in Fig. 13.

The absorptivity of the test sample is calculated from the measured scattering parameters in the frequency range of 8 GHz to 12 GHz. Compared to the results shown in Fig. 14, measured absorptivity is present. There is a good agreement between measured data and simulated tests. The proposed absorbing structure has single-band resonance absorption at 11 GHz. The absorptivity at the resonant frequency can reach 99.7%.

V. COMPARISON BETWEEN FOUR UNIT CELLS OF THE MODEL STRUCTURE

To demonstrate the model’s efficiency shown in Fig. 1, the paper model was compared. Figure 15 shows four configurations, three of which [(b)–(d)] have been published and will be used to compare the suggested design in Fig. 15(a). Table I displays the results of the comparison between the suggested model (a) and the previously studied models [(b)–(d)] in terms of absorptivity and resonant frequency. For sample 1, the safest structure is a dual-band absorption peak at 8.5 GHz with 99.98% absorptivity and 9 GHz with a magnitude of 85.4%.

A sketch of the suggested sample b is displayed in Fig. 15(b). The simulation value results in Table I show that the value of absorption is 89.4%, which covers the 10.6 GHz range. The absorption value of sample 2 decreases the magnitude.

As shown in Fig. 15(c), the resulting absorption value is much higher than that of sample b. The simulation results show that the absorption value of sample 3 is 87.3%, which covers the 10.3 GHz range.
Thus, the line at the center is neglected in sample d, as shown in Fig. 15(d). The results show that the absorption value is 83.5% at 10.3 GHz, which is limited by 3% than that of sample 3.

VI. CONCLUSION

The design of a single-band metamaterial split ring absorber surface printed on the FR-4 substrate was implemented after studying the effect of etching the metamaterial unit cells. The characterization and analysis technique of the absorber satisfies the improvement in the bandwidth value for different dielectric thicknesses. The absorption band was an X-band that was enhanced from 8 GHz to 12 GHz, and it exhibited a relatively large absorption bandwidth.

The waveguide measurement technique is superior to the conventional measurement methods due to the small-scale test samples required, the simple measurement device, and its low cost. An acceptable consistency between the fabricated and simulated results has been achieved, which makes the proposed surface suitable for radar application and electromagnetic compatibility.

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