A Simple Technique to Analysis of Microwave Absorbers using Frequency Selective Surfaces

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***Abstract*—This work aims to analyze the variation of some parameters in the design of microwave absorbers using FSS. The methodology consists of a combination of two techniques: the equivalent circuit method, which provides the transmission and reflection characteristics of the individual structures for a plane wave with normal incidence, and the scattering matrix technique, which provides the result of two FSS cascaded, a conductive FSS and a resistive FSS, getting absorption properties in the projected range. Simulated results are presented and comparison with results obtained with commercial software are made.**

***Keywords*— Simple Technique, Analysis, Microwave Absorbers, Frequency Selective Surfaces**

I. INTRODUCTION

Considering the fact that the use of wireless communication systems has grown too fast, investigations concerning absorbers of electromagnetic waves has called closest attention of researchers [1] - [3]. It is applicable from indoor system to military applications. Paralleling with this growth, some extremely relevant investigations through Frequency Selective Surfaces (FSS) allows its filter property to be applicable in several systems, for example: wireless security, military applications, and telecommunications [4] - [6].

A conventional FSS can be placed in the walls of a building for wireless security, providing isolation and reducing interference between adjacent vicinities. However, when used as a band-stop filter a conventional FSS may give rise to heavy reflections from its surface resulting in additional multipath, delay spread, and signal degradation [7]. To avoid this problem, a resistive FSS can be combined with a conventional FSS in cascade. Thus, instead of reflecting the electromagnetic signals, the structure will absorb them, avoiding the problems mentioned.

Therefore, the main goal of this paper concerns to propose a simple technique to analyze microwaves absorbers using FSS, initially analyzing the variation of some parameters in the design of microwave absorbers using FSS about studying the behavior of microwave absorbers. Thus, the methodology consists basically in combining two simple numerical techniques: the equivalent circuit method and the scattering matrix. The equivalent circuit method provides characteristics of transmission from the structures to a plane wave and it requires an extremely limited computing resource comparing with another methods. Furthermore, the scattering matrix will be used to cascade the FSS conductive and the FSS resistive achieving absorption characteristics in the band designed.

To conclude, a mathematical development through the Equivalent Circuit Method of a FSS modeling with cross-dipole geometry and a resistive FSS will be presented, as well as the cascading between the two structures. Besides, improvements and also the next steps will be discussed in the conclusion.

II. EQUIVALENT CIRCUIT METHOD

The development of equivalent circuits for representation of periodic structures (FSS) starts from an endless circuit arrangement of parallel conductive strips, developed by Marcuvitz [8]. He equated the circuit parameters, however the first to apply the concept FSS was Anderson [9]. After this, several researchers have applied the equivalent circuit method to analysis ofFSS [10] - [12].

In this paper, two different FSS must be considered, as shown in Fig. 1: the resistive FSS and the conventional FSS. First, we will show the development of the conventional FSS and then we will show the development of the resistive FSS.

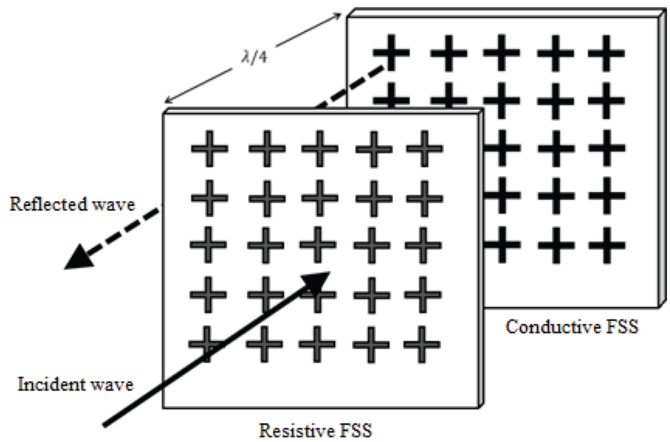

Fig. 1. The cascade structure

A. Conventional FSS Analysis

In Fig. 2, the physical parameters of a periodic array of crossed dipole are the periodicity p, the spacing gap g, and the length of the dipole l. When p is much lower than the wavelength λ the equivalent impedance is a simple inductance or capacitance that depends on whether the electric field of the incident wave is parallel or perpendicular to the conductive strips [8].

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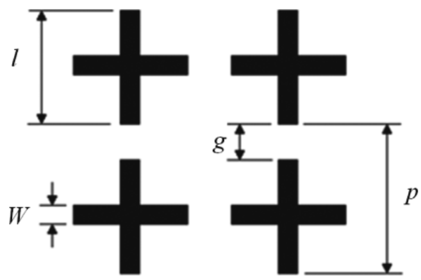

Fig. 2. Periodic array of crossed dipoles and its physical parameters.

The shape of the cross dipole allows to separate their conductive strips in perpendicular and parallel strips to the electric field, as shown in Fig. 3. The parallel strips to the electric field correspond to an inductive element and the perpendicular strips to the electric field correspond to a capacitive element that respectively correspond to the inductive and capacitive impedances as shown in Fig. 4.

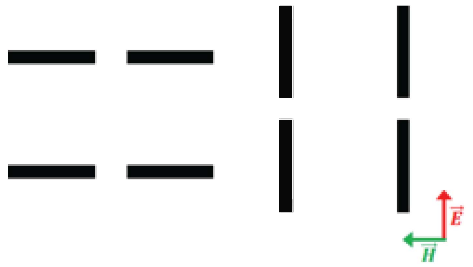

Fig. 3. Conducting strips of crossed dipole separated.

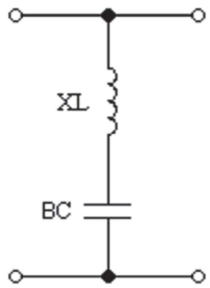

Fig. 4. Equivalent circuit proposed for the cross dipole.

For a better model of the frequency response of the structure, Munk in [13] recommends the insertion of a capacitor in parallel with the branch LC as shown in Fig. 5. Thus, by graphical analysis of the frequency response, the capacitor C2 does not influence the resonant frequency, but will help to better model the bandwidth. The equivalent circuit for the proposed for the crossed dipole is composed by an inductive reactance based on the strip width w, a capacitive susceptance derived from the spacing p - l, and another capacitive susceptance derived from the gap g.

According [11] the inductive reactance and the capacitive susceptance are reduced by a factor l/p due to the strips not be continuous. However, in this study, instead of using this factor is used the Munk's theory described in [13] for non-continuous periodic structures. According to the theory developed by Marcuvitz a parallel electric field at finite conducting strips equivalent to an inductor, Munk says that when these strips are finite they have an associated capacitor.

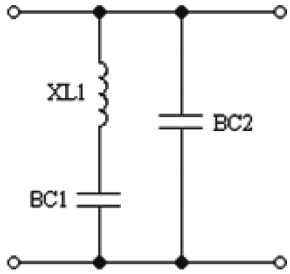

Fig. 5. The new equivalent circuit proposed for the cross dipole.

The value of the inductive reactance is calculated as:

$$X_L = 1.3\, F(p, w, \lambda, \phi) \tag{1}$$

Where the function $F(p, w, \lambda, \phi)$ is the function developed by Marcuvitz [8] for parallel strips. The susceptance B_{C1} is calculated as:

$$B_{C1} = 0.17 \varepsilon_{eff} B_{Cg} \tag{2}$$

where:

$$B_{Cg} = 4F(p, g, \lambda, \theta) \tag{3}$$

The capacitive susceptance B_{C2} is responsible for asymmetric configuration of the curves of S_{11} and S_{21}, in other words, the behavior of the curve before and after the resonance frequency. B_{C2} is formed by the sum of B_{Cp-w} and B_{Cg}:

$$B_{C2} = 0{,}12 \varepsilon_{eff} (B_{Cp-w} + B_{Cg}) \tag{4}$$

$$B_{Cp-w} = 4F(p, p-w, \lambda, \theta) \tag{5}$$

The admittance is calculated as:

$$Y = \frac{1}{X_L - \frac{1}{B_{C1}}} - \frac{1}{\frac{1}{B_{C2}}} \tag{6}$$

The transmission coefficient is given by:

$$\sigma = \frac{1}{1 + 0{,}25 Y^2} \tag{7}$$

All reactive elements are normalized by the air impedance.

The reflection coefficient is given by:

$$\Gamma = \sqrt{1 - \sigma^2} \tag{8}$$

An important detail that should be observed in the modeling of FSS structures to equivalent circuits is the question of the dielectric substrate height on the dielectric constant. It is known that the dielectric height allows to vary the resonant frequency of the filter. If using the effective dielectric constant of the material it will not provide the changes that occur due to variation of the dielectric height. Therefore, its value must be changed by time. According to [14], the equivalent formula for the dielectric constant is given by:

$$\varepsilon_{eff} = \varepsilon_r + (\varepsilon_r - 1)\left[\frac{-1}{exp^N(x)}\right] \tag{9}$$

where,

$$x = \frac{10h}{p} \tag{10}$$

and h corresponds to the height of the substrate, p is the periodicity of the cells, and N is an exponential factor which takes into account the geometry of the unity cell. This parameter varies with the different types of geometries FSS. In the case of a cross dipole array a proper value is 1.8.

B. Resistive FSS Analysis

A different composition is used for the resistive structure. In general, a surface resistance R_S is added in modeling structures. In [15] has been proposed for modeling the FSS lossy line from the same equations presented in [8]. For the TM mode, we have:

$$Z = (R - jX_C)sec\theta \tag{11}$$

$$\left(\frac{X_C}{Z}\right)^{-1} = \frac{4p}{\lambda}\left[\ln \sec\psi + \frac{Qsen^4\psi}{1+Qcos^4\psi} + \left(\frac{p}{4\lambda}\right)^2 (1-3\cos^2\psi)^2 sen^4\psi\right] \tag{12}$$

Where X_C is the capacitive reactance. For the TE mode, we have:

$$Z = (R + jX_L)cos\theta \tag{13}$$

$$\left(\frac{X_L}{Z}\right) = \frac{p}{\lambda}\left[\ln \csc\psi + \frac{Qcos^4\psi}{1+Qsin^4\psi} + \left(\frac{p}{4\lambda}\right)^2 (1-3\sin^2\psi)^2 cos^4\psi\right] \tag{14}$$

where,

$$Q = \frac{1}{\sqrt{1-\left(\frac{p}{\lambda}\right)^2}} - 1 \tag{15}$$

$$R = \left(\frac{p}{w}\right) R_s \tag{16}$$

$$\psi = \frac{\pi w}{2p} \tag{17}$$

The reflection coefficient is given by:

$$\Gamma = \frac{-Z_0}{Z_0 + 2Z} \tag{18}$$

The transmission coefficient is given by:

$$\sigma = \frac{-Z_0}{Z_0 + 2Z} \tag{19}$$

Overall, the impedance is formed by the equivalent reactance between the inductive and capacitive components, depending on the equivalent circuit, and a resistance R added.

III. Scattering Matrix Technique

In this paper a conventional FSS is cascaded with a resistive FSS so as to obtain absorption characteristics. The interaction between these structures can be calculated using the scattering matrix that allows the analysis of N cascaded structures, as shown in Fig. 6. For this cascaded surface its location is referred to as $Z = d_1 + d_2 + ... + d_{n-1}$. Transmission and reflection coefficients of each *nth* surface is given by σ_n and Γ_n.

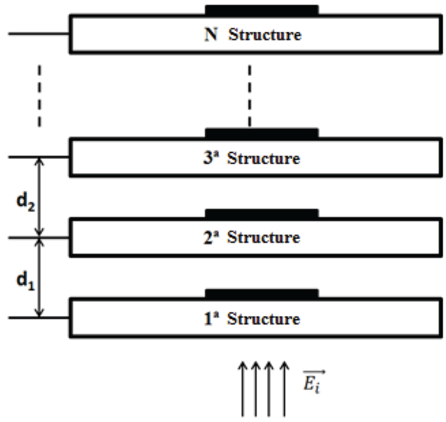

Fig. 6. A cascading of *N* FSS.

To obtain more accurate results, the matrix would have to be of infinite order. However, we will use the one mode interaction. This means that, instead of using the main lobe (main beam) and the side lobes (grating lobes), we will only use the main lobe. The side lobes correspond to the sum of the double Fourier series used in periodic structures, called Floquet theorem for harmonic spaces. Using the one mode iteration, the final result for the transmission and reflection coefficients for the cascaded structure, i.e., the total transmission and reflection coefficients after the cascade of the FSS are:

$$\sigma_T = A - (BC/D) \tag{19}$$

$$\Gamma_T = -(C/D) \tag{20}$$

The terms (A, B, C, D) are calculated by the following steps. First step, for each FSS, we must obtain a scattering matrix $\bar{\bar{S}}_n$ of 2×2 order, as:

$$\bar{\bar{S}}_n = \begin{bmatrix} \sigma_n\left(1 - \frac{\Gamma_n^2}{\sigma_n}\right) & \frac{\Gamma_n}{\sigma_n} e^{j2kl_n} \\ -\frac{\Gamma_n}{\sigma_n} e^{-j2kl_n} & \frac{1}{\sigma_n} \end{bmatrix} \tag{21}$$

So, the terms A, B, C, and D are given as:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \bar{\bar{S}}_n \bar{\bar{S}}_{n-1} \dots \bar{\bar{S}}_3 \bar{\bar{S}}_2 \bar{\bar{S}}_1 \tag{22}$$

IV. Results

First, the cascaded FSS was simulated using the Ansoft HFSS changing the distance between them. The following distance values (d) have been chosen: 4mm, 8mm, 10mm, 14mm and 18mm. Fig. 7 shows the behavior of the transmission and reflection coefficients when changing the spacing between the resistive FSS and conductive FSS. In this configuration, the sheet resistivity used is 50 Ω/sq. The result of the simulation by commercial software to R_S = 50 Ω/sq and d = 10 mm is equal to performing in [7].

In the designed frequency range and using a resistive FSS with R_S = 50 Ω/sq, the lowest attenuation of the reflection coefficient is at a distance of 10 mm, about -12.5 dB. However, when the surface resistance is changed to 100 Ω/sq, as shown in Fig. 8, the distance that allows the lowest attenuation is 4 mm, about -9.32 dB. It can also be analyzed that the curves of the reflection coefficients are quite different when varying sheet resistivity of 50 Ω/sq to 100 Ω/sq.

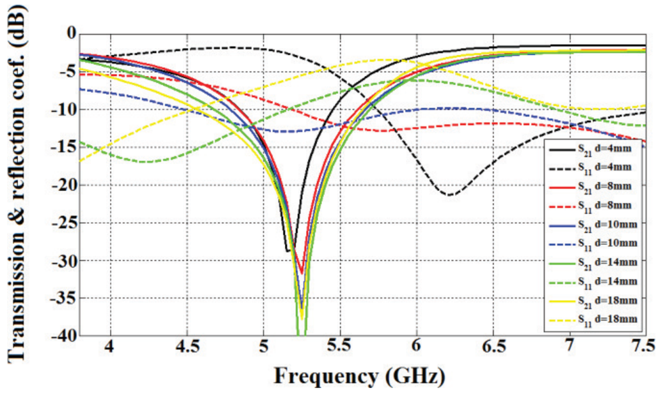

Fig. 7. Variation of the distance between the cascaded FSS to R_S = 50 Ω/sq.

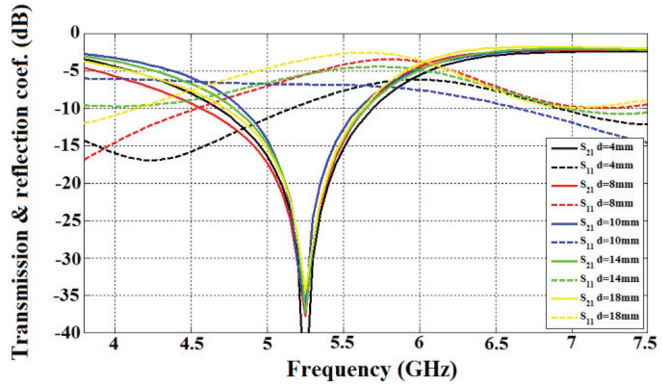

Fig. 8. Variation of the distance between the cascaded FSS to R_S = 100 Ω/sq.

Transmission coefficients showed little variation compared the variations of the reflection coefficients. The resonant frequency was about 5.25 GHz and 5.37 GHz. The quarter wavelength at the resonant frequency is approximately 14 mm. Analyzing the results, it can be concluded that the distance can be reduced to achieve a low attenuation by the suitable choice of the sheet resistivity.

There was a disagreement between the values simulated by the technique of scattering matrix, Fig. 9 and Fig. 10, and simulated by comercial software, Fig 7 and Fig. 8. This deviations between results from these two techniques may be due to inadequate computing the non-uniformity of the resistive factor in the code whose non-uniformity is shown in the curves of the reflection coefficients of the simulation of commercial software. In Figure 9, the lower attenuation of the reflection coefficient is achieved at a distance of 14 mm, about -24.94 dB, however the observation made in the comercial software simulation (Fig.7 and Fig. 8) about the correct distance to provide a minimum attenuation is also observed the scattering matrix technique. The reflection coefficient increases again after the lower attenuation (in d = 14mm) as can be shown in distance of 18 mm in Fig. 9 and Fig. 10, for R_S = 50 Ω/sq and 100 Ω/sq, respectively. In Figure 10 (R_S = 100 Ω/sq) the lowest attenuation is -10.32 dB, and occurs at the same distance of 14 mm in Fig. 9 (R_S= 50 Ω/sq).

After analyzing the change of distance in cascaded structure, the second study analyzed the variation of the sheet resistivity. First, the cascaded structure was simulated using a commercial software simulation and then simulated using scattering matrix technique. The values of sheet resistivity (R_S) commercially available are 10 Ω/sq, 25 Ω/sq, 50 Ω/sq, 100 Ω/sq and 250 Ω/sq and can be manufactured using NiP (Nickel Phosphorous) resistive alloy. Fig. 11 shows the behavior when increasing the sheet resistivity of the resistive FSS within of cascaded structure. In this configuration, the distance used is 10 mm.

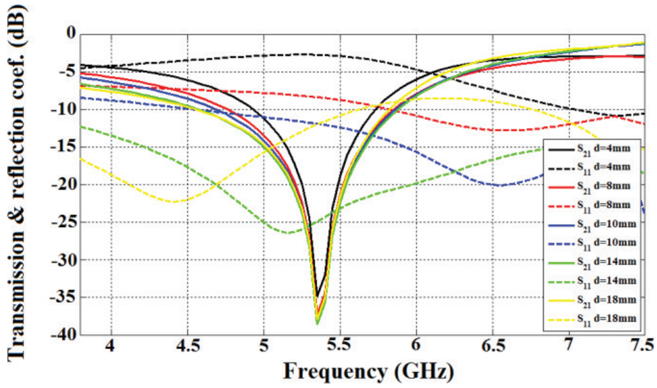

Fig. 9. Variation of the distance between the cascaded FSS to R_S = 50 Ω/sq using scattering matrix technique.

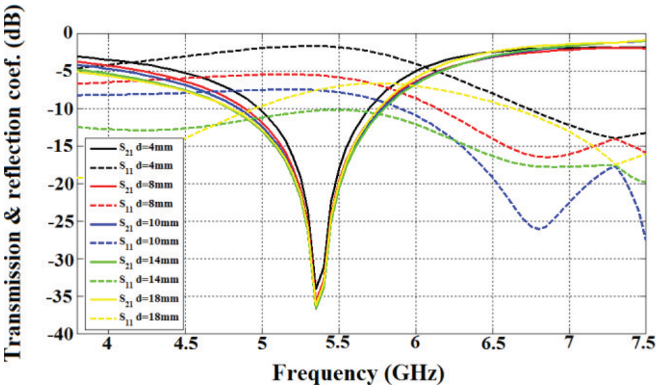

Fig. 10. Variation of the distance between the cascaded FSS to R_S = 100 Ω/sq using scattering matrix technique.

As the sheet resistivity increases the resonant frequency of the transmission coefficient does not change and remained at 5.25 GHz. The bandwidth using a sheet resistivity R_S = 10 Ω/sq corresponding to 1.15 GHz. When the sheet resistivity varies for 25 Ω/sq there is a reduction of 8.7% in bandwidth, corresponding to 1.05 GHz. When the sheet resistivity of 25 Ω/sq is replaced for 50 Ω/sq there is a reduction of 16.2% in bandwidth, corresponding to 0.88 GHz. Replacing 50 Ω/sq to 100 Ω/sq, the reduction is 14.77% corresponding to a bandwidth of 0.75 GHz and 100 Ω/sq to 250 Ω/sq, a reduction of 13.33% bandwidth, or 0.65 GHz.

For R_S= 10 and 25 Ω/sq, the lowest attenuation of reflection coefficient is not presented in the frequency of resonance designed. The reflection coefficient for R_S = 50 Ω/sq shows attenuation closer to design specifications than the others sheets resistivity and is below -10 dB, the 100 and 250 Ω/sq are above -10 dB. For design purposes, could be used both a R_S = 25 Ω/sq as a 50 Ω/sq due the fact that both have values below -10 dB at the resonance frequency. However using R_S = 25 Ω/sq the resonant frequencies of the reflection coefficient is outside of the projected range, in other words, may interfere with other frequencies. Therefore, a project to determine the desired reflection is necessary because even varying the sheet resistivity, there is no guarantee that the less attenuation is located in the projected range.

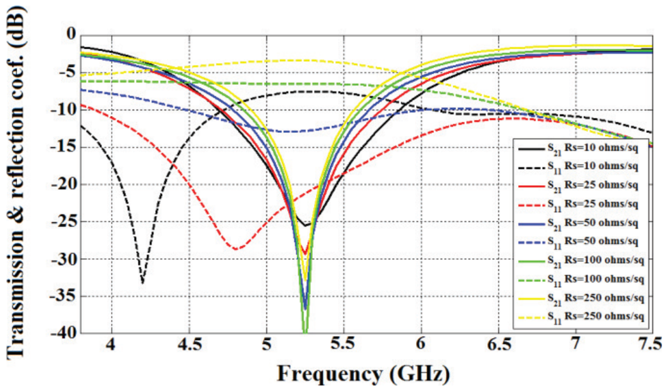

Fig. 11. Variation of the sheet resistivity (R_S) in the cascaded structure.

Fig. 12 shows the simulation using the Equivalent Circuit Method and the Scattering Matrix Technique.

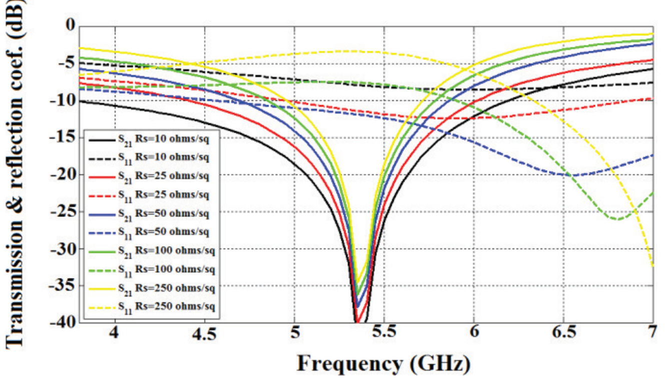

Fig. 12. Variation of the sheet resistivity (R_S) in the cascaded structure using scattering matrix technique.

There was a difference in the standard curves of reflection coefficients when compared with curves simulated in HFSS. However, is observed that in both results, as it increases the sheet resistivity, the attenuation tends to a minimum value. After this minimum value, the attenuation decreases.

V. Conclusions

In this work, we analyzed two important parameters in the microwave absorbers design integrated with FSS, the distance between cascaded structures and the resistivity sheet. The study of both is essential when analyzing the behavior of microwave absorbers. The change of distance between the cascaded structures allows to show that the less attenuation of the reflection coefficient tends to an optimal distance. The reflection coefficient decreases as the spacing is increased between the FSS. The change of distance allows converge to a minimum, as can be shown in the simulations using commercial software. The behavior in simulation is similar, however as it is a method of approximation, the lower attenuation of the reflection coefficient is expressed in different distances.

An analysis in terms of bandwidth for the transmission factor in the simulation of the variation in sheet resistivity was performed. The increase in sheet resistance resulted in a reduction in bandwidth. There was no significant change in the resonant frequency. Analyzing the reflection coefficient is observed that the variation of sheet resistivity does not make sure that the less attenuation is located in the desired range. Thus, it takes a project to determine the desired reflection.

The parameters of distance and sheet resistivity in cascaded structure are important in the analysis of transmission and reflection coefficients. The technique presented allows to analyze the cascade behavior between the resistive FSS and a conventional FSS characterized as a microwave absorber.

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