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Review Article

High Radio Frequencies interaction of Composite Materials using Rectangular Waveguide

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Abstract: The main goal of this paper is studying the composite material behavior under microwave which they used in antennas reflectors. For that, a transmission line method based on X- band WR90 rectangular waveguide is used. The Bi-anisotropic electrical properties are defined as tensors in finite element model. The fibers of the single layer composite are oriented in different directions. The S-parameters (S11 and S12) are calculated using COMSOL Multiyphysics, the S-parameters and currents density behavior show that they very affected by the orientations of the fibers which mean must be considered in any design of RF equipments, more the fibers are parallel with the electrical field more the reflection coefficient get higher.

Keywords: Microwave, Bi-anisotropic, Carbon Fiber Composite, Rectangular Waveguide, X-band, Fiber Orientation, S-parameters

1. Introduction

Due to their desirable mechanical properties such as light weight, high strength and resistance to corrosion, composite materials have been widely used in many manufacturing industries for many years, such as aerospace, automotive, marine and defense. A composite material is formed by combining two or more materials such that the reinforcing and matrix parts of these materials with different properties do not mix with each other, thereby forming a composite material with heterogeneous electrical and mechanical properties. Reinforcing materials can be fibers such as carbon, glass, ceramic and aramid or particles. In addition, matrix types include polymers, cements and plastics.

Precisely, during the design of telecommunication systems such as antenna reflectors as shown in figurer 1 a), b) ,c) [8], printed substrate antennas as shown in Figure 1) d), [2], the electrical properties of the materials used in the manufacture of these systems or even perform numerical simulations, especially electrical permittivity, magnetic permeability and electrical conductivity must be considered by knowing their effect on the absorption, transmissions and reflections characteristics such as S-parameters[1-10]. In several years, Fibers Reinforced Polymer (FRP) became more interesting and indispensable in the field of manufacturing of radio frequencies telecommunication systems and radio absorption material (RAM) due of its ability to withstand external conditions , besides his special electrical properties, although the electrical properties of FRP are Bi-anisotropic ,which they could be represented as tensors to describe the heterogeneous nature and the fibers orientation effect on the their electromagnetic behavior when exposed under microwaves [9-18].

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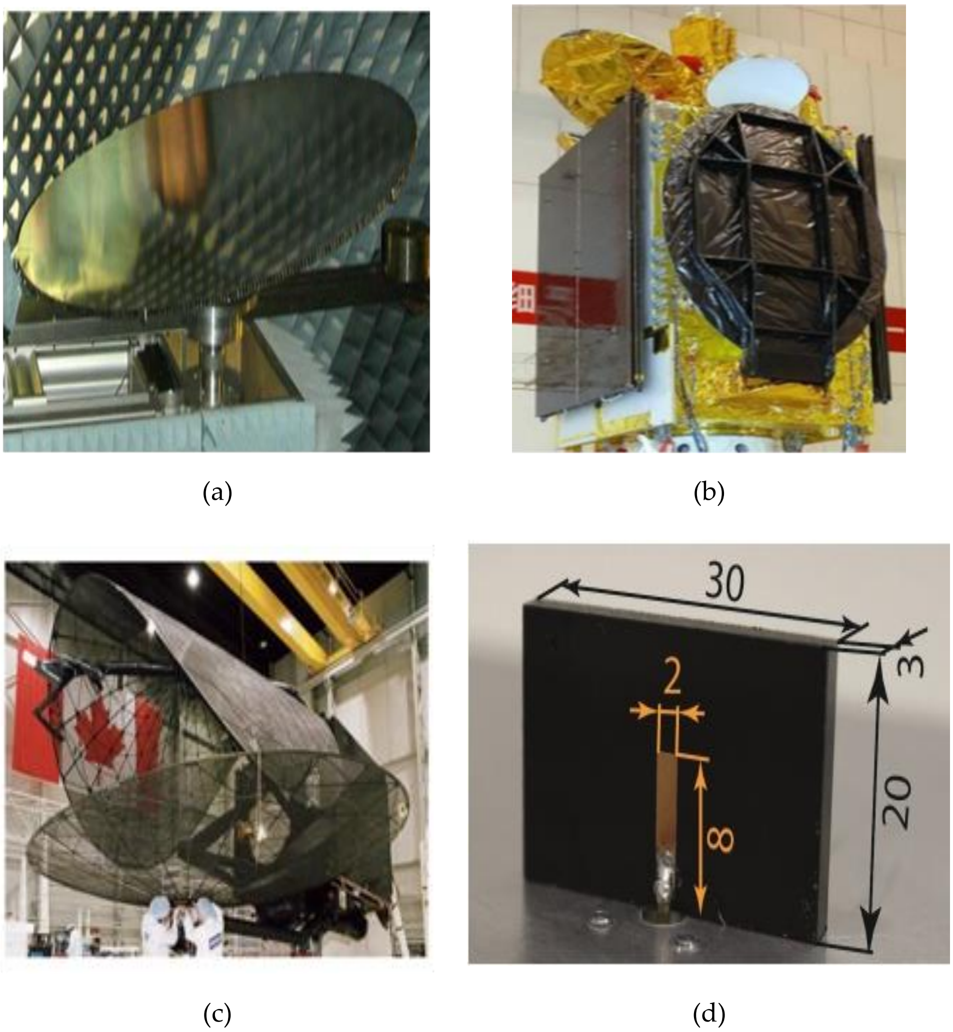

Figure 1. Antennas reflectors made from composite laminate; (a) Created by GmbH [8]; (b)Thin-shell deployable reflector [25];(c) DFH-4 Alcomsat-1 reflector; (d) patch antenna with composite substrate [2].

These last one are related to several parameters such as volume fraction and fibers orientations inside the FRP, fibers orientation could be very effective when it comes to the S-parameters because its decide the behavior of the FRP under microwaves. For this purpose this paper is made to study the fibers orientations effect of one single layer of FRP under microwaves in the three principal directions of the electrical properties. In addition the fibers orientation are changed [12, 19], for that a transmission line method based on X-band WR90 (22.1 mm x 6.9 mm) rectangular waveguide is used, the working frequency is 10 GHz, the cutoff frequency for TE10 is 6.9 GHz, the Bi-anisotropic electrical properties are defined as tensors in finite element model, the fibers of the single layer composite are oriented in different directions, the S-parameters (S11 and S12) are calculated using COMSOL Multyphysics, the S-parameters and currents density behavior show that they very affected by the orientations of the fibers which mean must be considered in any design of RF components.

2. Mathematical Modeling

2.1. Electromagnetic equations of rectangular wave guide

By using the electromagnetic equation of the electrical and magnetic fields, the general equations of unidirectional microwaves depending only on the electrical and magnetic field in term of the magnetic and the electrical field in z direction are given by the following equations:

$$\vec{E}_x = \frac{-j}{k_\rho^2}\left(k_z \frac{\partial \vec{E}_z}{\partial x} + \omega\mu \frac{\partial \vec{H}_z}{\partial y} \right) \tag{1}$$

$$\vec{E}_y = \frac{j}{k_\rho^2}\left(-k_z \frac{\partial \vec{E}_z}{\partial y} + \omega\mu \frac{\partial \vec{H}_z}{\partial x} \right) \tag{2}$$

$$\vec{H}_x = \frac{j}{k_\rho^2}\left(\omega\varepsilon \frac{\partial \vec{E}_z}{\partial y} - k_z \frac{\partial \vec{H}_z}{\partial x} \right) \tag{3}$$

$$\vec{H}_y = \frac{-j}{k_\rho^2}\left(\omega\varepsilon \frac{\partial \vec{E}_z}{\partial x} + k_z \frac{\partial \vec{H}_z}{\partial y} \right) \tag{4}$$

Where: $\vec{E}$ and $\vec{H}$ are the electric and the magnetic field respectively, ε and μ are the electrical permittivity and the magnetic permeability, k_ρ, k_ρ and k_z are the wave number and the propagation constant which they related to the phase constant β as shown in the following equation:

$$k_\rho^2 = \beta^2 - k_z^2 \tag{5}$$

After applying the transverse electric mode in rectangular waveguide TE_{mn} where the electric field in the wave propagation is $\vec{E}_z = 0$ and the magnetic field is propagated as $\vec{H}_z = H_0(x,y)e^{-jk_z z}$, the equations 1 to 4 are becomes:

$$E_x = H_0 \frac{j\omega\mu}{k_\rho^{2(m,n)}} \frac{n\pi}{b} \cos\left(\frac{m\pi}{a}x\right) \sin\left(\frac{n\pi}{b}y\right) e^{-jk_z^{m,n}z} \tag{6}$$

$$E_y = -H_0 \frac{j\omega\mu}{k_\rho^{2(m,n)}} \frac{m\pi}{a} \sin\left(\frac{m\pi}{a}x\right) \cos\left(\frac{n\pi}{b}y\right) e^{-jk_z^{m,n}z} \tag{7}$$

$$H_x = H_0 \frac{j\gamma_{m,n}}{k_\rho^{2(m,n)}} \frac{m\pi}{a} \sin\left(\frac{m\pi}{a}x\right) \cos\left(\frac{n\pi}{b}y\right) e^{-jk_z^{m,n}z} \tag{8}$$

$$H_y = H_0 \frac{j\gamma_{m,n}}{k_\rho^{2(m,n)}} \frac{n\pi}{b} \cos\left(\frac{m\pi}{a}x\right) \sin\left(\frac{n\pi}{b}y\right) e^{-jk_z^{m,n}z} \tag{9}$$

$$H_Z = H_0 \cos\left(\frac{m\pi}{a}x\right) \cos\left(\frac{n\pi}{b}y\right) e^{-jk_z^{m,n}z} \tag{10}$$

where m and n are the transverse electric mode number, a and b are the length and the height of the rectangular waveguide respectively in meter, $\mu = \mu_r \mu_0$ is the magnetic permeability (μ_0 =$4\pi 10^{-7}$ (H/m) magnetic permeability of vacuum).

These equations allow us to recognize the behavior of the electrical and the magnetic field inside the rectangular waveguide.

2.2. Bi-Anisotropic electrical properties of FRP

The simulated sample is a FRP which has anisotropic properties such as electrical conductivity tensor and electrical permittivity as shown in Figure 2 below.

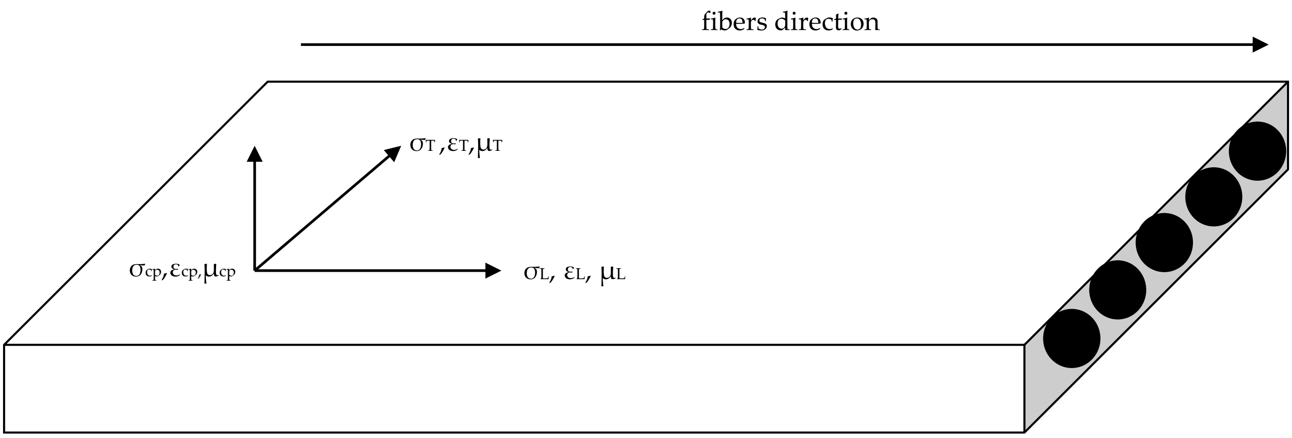

Figure 2. Bi-Anisotropic Electrical properties of CFRP.

The basics bi-anisotropic electrical properties or CFRP tensors are given by [10-12]:

$$\sigma = \begin{bmatrix} \sigma_L & 0 & 0 \\ 0 & \sigma_T & 0 \\ 0 & 0 & \sigma_{cp} \end{bmatrix} \tag{10}$$

$$\varepsilon = \begin{bmatrix} \varepsilon_L & 0 & 0 \\ 0 & \varepsilon_T & 0 \\ 0 & 0 & \varepsilon_{cp} \end{bmatrix} \tag{11}$$

$$\mu = \begin{bmatrix} \mu_L & 0 & 0 \\ 0 & \mu_T & 0 \\ 0 & 0 & \mu_{cp} \end{bmatrix} \tag{12}$$

Where: $\sigma_L, \varepsilon_L, \mu_L; \sigma_T, \varepsilon_T, \mu_T$ and $\sigma_{cp}, \varepsilon_{cp}, \mu_{cp}$ are the electrical conductivity, the electrical permittivity and the magnetic permeability of the RFP in the longitudinal direction, transverse direction and the thickness direction respectively.

The complex permittivity in each direction of FRP is given by:

$$\varepsilon_r = \varepsilon_r^{'} + j\varepsilon_r^{''} \tag{13}$$

where $\varepsilon_r^{'}$ and $\varepsilon_r^{''}$ are the dielectric constant and the dielectric loss factor which is given as:

$$\varepsilon_r^{''} = \frac{\sigma_{eff}}{\omega\varepsilon_0} \tag{14}$$

with σ_{eff} is the effective conductivity which could be depends on the fibers direction and the thickness conductivity (where the microwaves cross through), ε_0 is the dielectric permittivity in vacuum ($\varepsilon_0 = 8.85\times10^{-12} F/m$), ω is the pulsation with $\omega = 2\pi f$, f is the frequency in Hz.

The complex magnetic relative permeability in each direction of FRP is given by:

$$\mu_r = \mu_r^{'} + j\mu_r^{''} \tag{15}$$

Where $\mu_r^{'}$ and $\mu_r^{''}$ are the real and the imaginary parts of magnetic permeability.

According to Christopher L. Holloway et al the tensors components of conductivity and permittivity could be calculated using the following equations[1]:

$$\varepsilon_x = \frac{\varepsilon_m\varepsilon_f}{(1-g)\varepsilon_f + g\varepsilon_m} \tag{16}$$

$$\mu_x = \frac{\mu_m\mu_f}{(1-g)\mu_f + g\mu_m} \tag{17}$$

$$\varepsilon_y = \varepsilon_z = (1-g)\varepsilon_m + g\varepsilon_f \tag{18}$$

$$\mu_y = \mu_z = (1-g)\mu_m + g\mu_f \tag{19}$$

Where ε_m, μ_m, ε_f and μ_f are the matrix permittivity and permeability, and the fibers permittivity and permeability respectively, g is the relative volume of space occupied by the fiber in the period cell by a distance x' (fibers fill factor in FRP) which given by:

$$g = \frac{2\sqrt{Dx^{'} - x^{'2}}}{p}$$

Where D, p are the fiber diameter, and the pitch between fiber to another, respectively.

To take into account the fibers orientations as shown in Figure 3 the electrical properties are related to the fiber's directions:

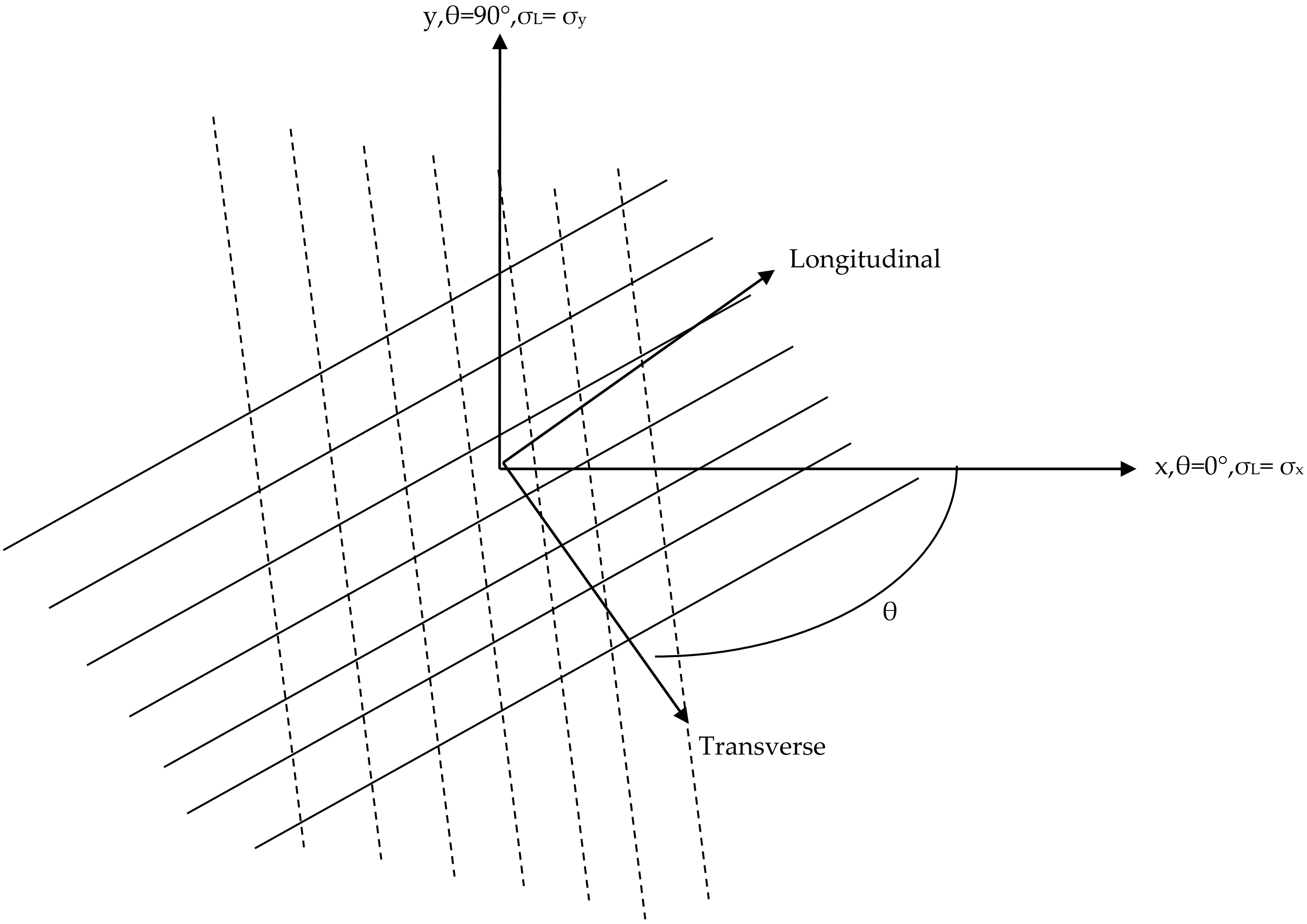

Figure 3. Fiber's orientation according to rotated coordination system.

The orientations of fibers can be very affected on the transmission and reflection parameters due to the rotated of the principal axis (x,y) of the electrical conductivity known as longitudinal and transverse axis.

The new conductivity tensors and permittivity tensor taken into account the fibers orientation angle θ at longitudinal and transverse axis are given by the following equations[21-23]:

$$\sigma = \begin{bmatrix} \sigma_L \cos^2(\theta) + \sigma_T \sin^2(\theta) & \frac{\sigma_L - \sigma_T}{2}\sin(2\theta) & 0 \\ \frac{\sigma_L - \sigma_T}{2}\sin(2\theta) & \sigma_L \sin^2(\theta) + \sigma_T \cos^2(\theta) & 0 \\ 0 & 0 & \sigma_{cp} \end{bmatrix} \tag{20}$$

$$\varepsilon = \begin{bmatrix} \varepsilon_L \cos^2(\theta) + \varepsilon_T \sin^2(\theta) & \frac{\varepsilon_L - \varepsilon_T}{2}\sin(2\theta) & 0 \\ \frac{\varepsilon_L - \varepsilon_T}{2}\sin(2\theta) & \varepsilon_L \sin^2(\theta) + \varepsilon_T \cos^2(\theta) & 0 \\ 0 & 0 & \varepsilon_{cp} \end{bmatrix} \tag{21}$$

$$\mu = \begin{bmatrix} \mu_L \cos^2(\theta) + \mu_T \sin^2(\theta) & \frac{\mu_L - \mu_T}{2}\sin(2\theta) & 0 \\ \frac{\mu_L - \mu_T}{2}\sin(2\theta) & \mu_L \sin^2(\theta) + \mu_T \cos^2(\theta) & 0 \\ 0 & 0 & \mu_{cp} \end{bmatrix} \tag{22}$$

These electrical properties tensors are symmetrical type compared with the previous axial electrical properties (at 0°). In addition these tensors show the effect and interference on the effective conductivity and permittivity when the CFRP is rotating from longitudinal to transverse direction.

2.3. S-parameters Model

To study all the above, a finite element model is used by COMSOL Multiyphysics, the sample is FRP put it in the model of WR90 X-band waveguide (22.86 mm x 10.16 mm) as shown in Figure 4 bellow with TE_{10} mode (m=1, n=0), the FRP is introduced as bi-anisotropic material with biaxial electrical properties taken into consideration the orientations angle, the thickness of one layer of CFRP is taken as 0.125mm.

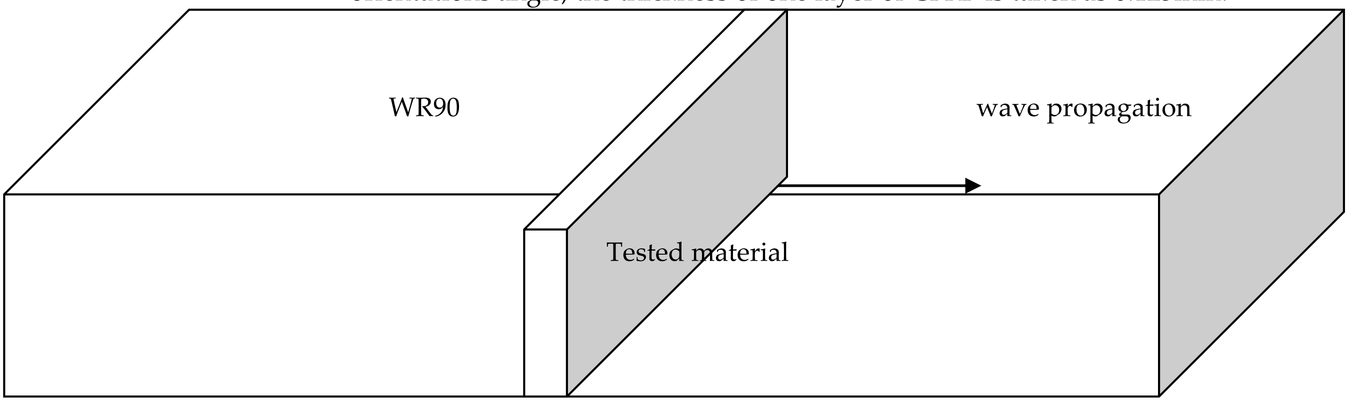

Figure 4. Description model CFRP inside rectangular waveguide.

The cutoff frequency of the WR90 X-band is 6.56 GHz, the working frequency is 10 GHz, the given principal axis electrical properties in the model are in the Table 1.

The propagation constant on the air and the propagation constant inside the FRP sample are given by the following equations [2]:

$$\gamma_0 = j\frac{2\pi}{\lambda_0}\sqrt{1-\left(\frac{\lambda_0}{\lambda_c}\right)^2} \tag{23}$$

$$\gamma_c = j\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_{reff}^{'} - j\frac{\sigma_{eff}}{\varepsilon_0\omega} - \left(\frac{\lambda_0}{\lambda_c}\right)^2} \tag{24}$$

Where λ_0 and λ_c are the wavelength in vacuum which depend on the working frequency, and cutoff wavelength depend on the cutoff frequency, ε'_{reff} is the effective electric permittivity.

The equation (25) clearly shows that the propagations constant of FRP is affected by the electrical properties such as the electrical conductivity and the electrical permittivity.

The reflection coefficient according to the propagation constants is given by the following equation [2]:

$$\Gamma = \frac{\gamma_0 - \gamma_c}{\gamma_0 + \gamma_c} \tag{25}$$

Thus, the S- parameters S11 and S21 based on the reflection and transmission coefficients combined with propagation constant can be written as follows[2]:

$$S_{11} = \frac{\left(1 - e^{-2\gamma_c t}\right)\Gamma}{1 - \Gamma^2 e^{-2\gamma_c t}} \tag{26}$$

$$S_{21} = \frac{\left(1 - \Gamma^2\right)e^{-\gamma_c t}}{1 - \Gamma^2 e^{-2\gamma_c t}} \tag{27}$$

Where *t* is sample thickness.

3. Results and Discussions

To study the effect of the fiber's orientation, the conductivity tensor on the principal axis is shown in the table below with the effective electrical permittivity:

Table 1. Principal axis electrical properties of CFRP.

Electrical conductivity (S/m)	Electrical permittivity and magnetic permeability
σ_L=10^4 to 10^5	ε_f=1; μ_f=1
σ_T=10 to 100	ε_m=2.5+1.5j ; μ_m=1
σ_{cp}= 10 to 100	D=7um ; x'=D/2 ; p=D+x'

Figure 5 shows the current density in FRP sample with different fiber orientation (0°, 45° and 90°).

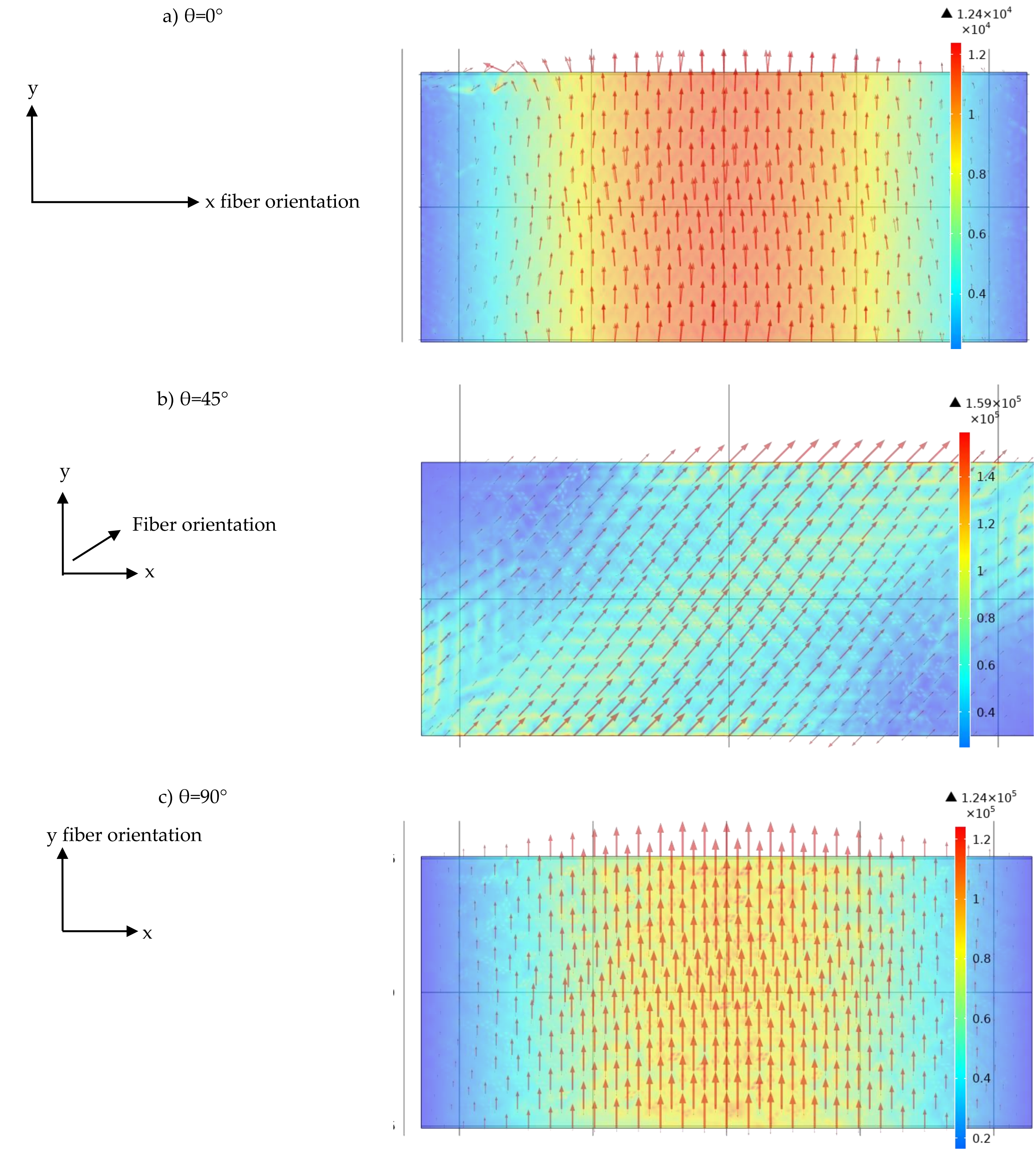

Figure 5. Current density behavior in CFRP.

At 0° the current density is lower than 45° and 90° due to the fibres orientation perpendicular to the electrical field. In addition, the current density direction is following the vertical direction even though that electrical conductivity in the horizontal is bigger than in the vertical direction (σ_x>> σ_L), that means that the current density direction is forced to take the lower conductivity direction due to the displacement current which follow the electrical field direction as shown in Figure 6a, indeed the induced currents by the magnetic field this important remarque support this argument in [22] for the field of radio frequency (high frequencies) as well as in low frequencies.

a) θ=0°

b) θ=45°

c) θ=90°

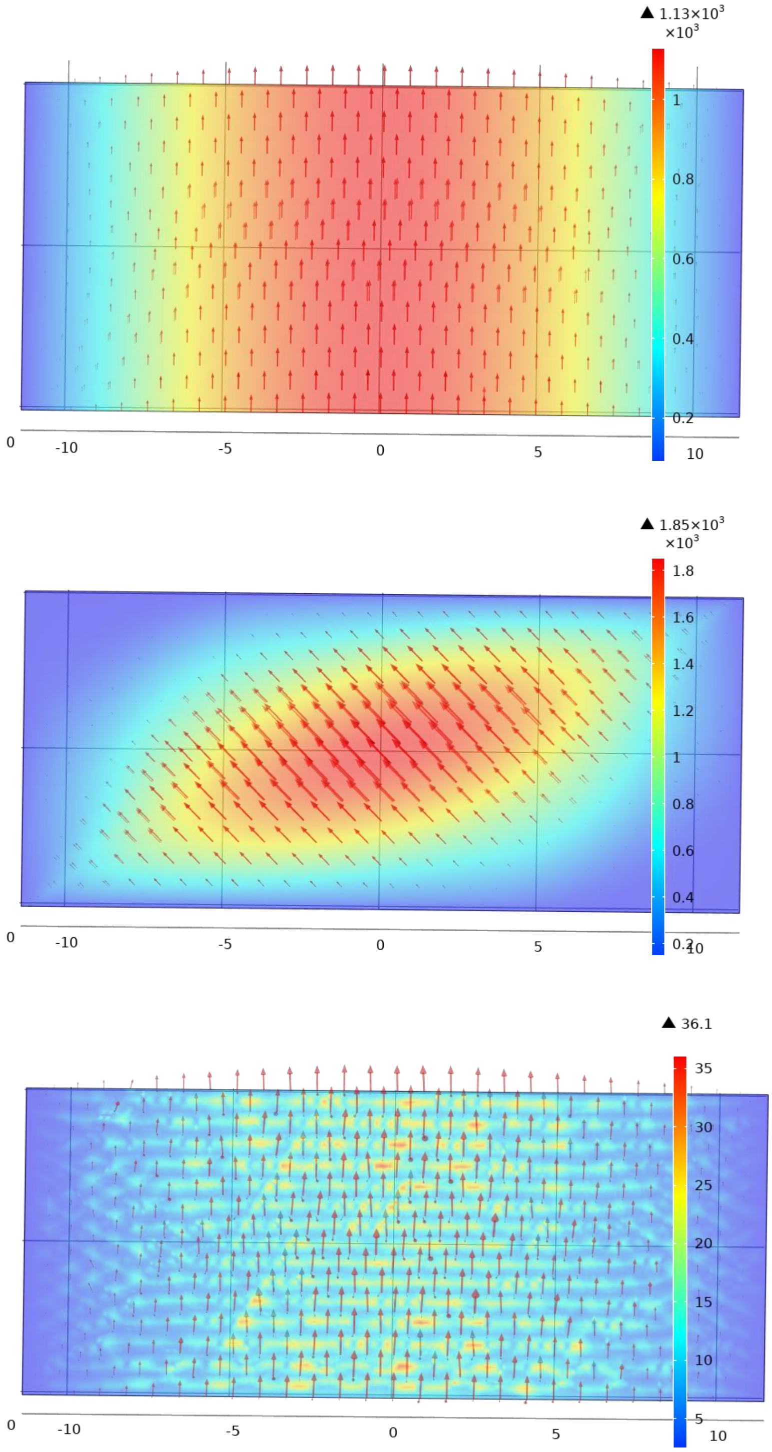

Figure 6. Electrical field behavior in CFRP.

Nevertheless, in Figure 5b and Figure 6b the fibers are oriented in 45°, the electrical field is almost perpendicular to the current density but in opposed oblique direction, in this case the electrical field and the current density are the resultant of two principal which they take y and x direction, in addition the opposed oblique direction due to the high conductivity direction in the oblique way which is very effect if compared with the conductivity in x and y directions.

When the fibers are oriented in 90° which are parallel to the electrical field as shown in Figure 5c and Figure 6c, the current density and the electrical field are taken the natural way in y direction due to the highest value of the electrical conductivity in this direction where $\sigma_y = \sigma_L$ and $\sigma_x = \sigma_T$ with $\sigma_y >> \sigma_T$.

This previous analysis we found that the fibers orientation is highly affected on the behavior of the current density and the electrical field, as result the refection and transmission properties are changed according to the fibers orientation as shown in Figure 7) and Figure 8) which represent the S-parameters magnitude and S-parameters phase in term of oriented fibers in CFRP, meanwhile the CFRP more reflected.

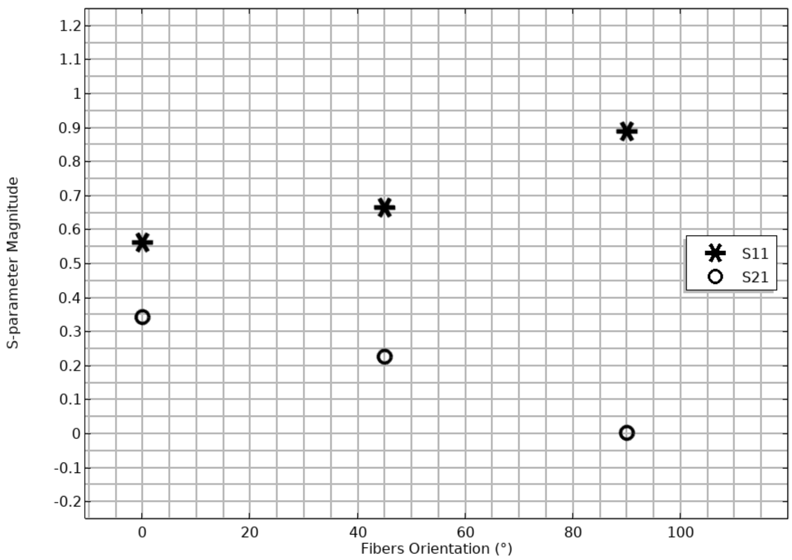

Figure 7. Fibers orientation effect on S-parameters.

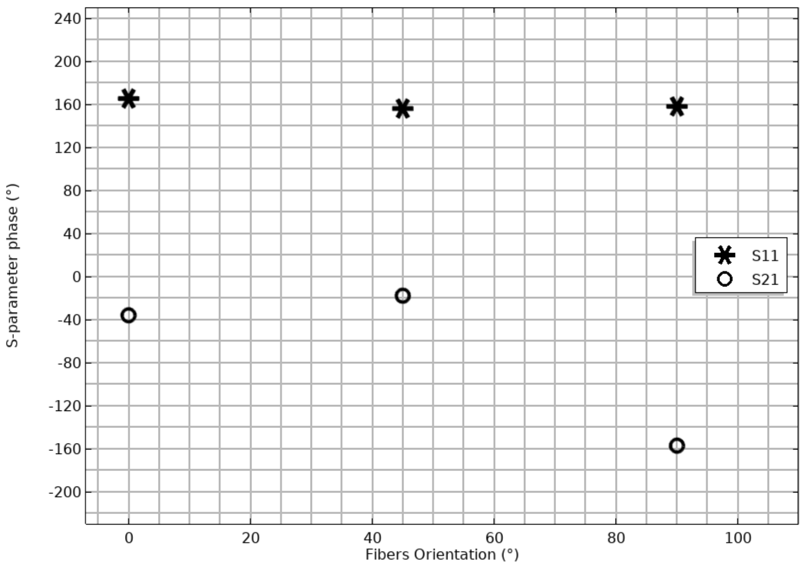

Figure 8. Fibers orientation effect on S-parameters phase.

When the fibers become parallel with the electrical field polarization, the transmission phase is affected as well as with fiber orientation.

4. Conclusion

A FEM is used to study the anisotropic unidirectional FRP behavior under microwaves in X band, the study is consisted to analyze the simulation results with different angles of carbon fibers.

The reflection coefficient and transmission coefficient are related to fiber orientation angle, more the fiber angle parallel with the electrical field more the reflection coefficient get higher, the CFRP can be used for reflectors with contion that the fibers must be parallel to the electrical field.

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