

ELECTROMAGNETIC PROPERTIES OF A MAGNETO-DIELECTRIC COMPOSED THROUGH AN ALGORITHM BASED ON THE NICOLSON-ROSS-WEIR METHOD

Propiedades electromagnéticas de un compuesto magneto dieléctrico a través de un algoritmo basado en el método Nicolson-Ross-Weir

Gabriel Peña Rodríguez¹, Rodrigo Vera Barrera², David Leonardo Mancipe³, Luis Ángel Lara González⁴,
¹Universidad Francisco de Paula Santander, Centro de Investigación en Materiales Cerámicos, Colombia.

²⁻³Universidad Pedagógica y Tecnológica de Colombia, Grupo de Investigación GINTEL, Colombia.

⁴Universidad Pedagógica y Tecnológica de Colombia, Grupo de Investigación GEAM, Colombia.

Email: ¹gabrielpr@ufps.edu.co, ²vera.barrera.rodrigo@gmail.com, ³david.mancipe@uptc.edu.co,
⁴luisangel.lara@uptc.edu.co

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Abstract

The present work implements the Nicolson-Ross-Weir (NRW) method to find the permittivity and permeability through an algorithm in Matlab® of a magneto- dielectric composed material made of polyester resin and magnetite powders randomly dispersed and oriented vertically and horizontally in the polymeric matrix. The measured data come from the simulation of the S parameters in ADS® between 150 kHz and 4GHz, on a microstrip type transmission line. The algorithm allowed to verify that the best response in high frequency of the magneto - dielectric composed where the vertically oriented particles, present the highest relative permittivity obtaining $E_r= 5.5$ for 30% wt concentration and $E_r= 4.5$ concentration of 20% wt, with an absorption coefficient which increases in function of frequency and the concentration of magnetite in the functional filler.

Key words: *composed materials, dielectric properties, electrical properties, ferromagnetic, magnetic properties, polymer, magnetite.*

Resumen

El presente trabajo implementa el método Nicolson-Ross-Weir (NRW) para encontrar la permitividad y permeabilidad mediante un algoritmo en Matlab® de un material magneto dieléctrico compuesto fabricado a base de resina de poliéster y polvos de magnetita dispersos al azar y orientados de forma vertical y horizontal en la matriz polimérica. Los datos medidos provienen de la simulación de los parámetros S en ADS® entre 150 KHz y 4GHz, sobre una línea de transmisión de tipo microcinta, el algoritmo permitió verificar que la mejor respuesta en alta frecuencia del compuesto magneto dieléctrico se presenta cuando las partículas están orientadas verticalmente, con permitividades relativas altas obteniendo $E_r= 5.5$ para la concentración del 30% y $E_r= 4.5$ para la concentración de 20% en porcentaje en peso, con un coeficiente de absorción, el cual aumenta en función de la frecuencia y la concentración de magnetita en el relleno funcional.

Palabras clave: *materiales compuestos, propiedades dieléctricas, propiedades eléctricas, ferromagnético, propiedades magnéticas, polímeros, magnetita.*

1. INTRODUCTION

Based on the characteristics of a metamaterial allows us to identify the area of application where it will have the greatest impact on science and industry [1]. Magneto-dielectric (MD) materials are a branch of metamaterials and the objective of their study is designing negative or positive permeability with a value determined [2]. The elaboration of a MD material consists of mixing one or more raw materials to get improved properties which are not obtained individually from original materials but from the orientation, proportion and geometry of the metamaterials used in the construction and their interaction with the electromagnetic waves [3], these materials are presented permeability (U) and permittivity (E) larger than one since in their manufacture are polarized in the presence of electromagnetic fields [4]. The extraction of the parameters E y U have gained much more interest within the scientific community because of the need to characterize them.

At the same time, electromagnetic pollution (EM) has grown considerably as the telecommunications industry and the marketing of several radiofrequency devices have advanced, which can create electromagnetic pollution with some effects on human activity [5]. For this reason, it is important to design electronic devices that offer better radiofrequency performance and guarantee high absorption power in order to reduce the electromagnetic radiation presents in telecommunications devices [6].

Magneto - dielectric materials composed by filled with iron oxides become attractive for the design of this type of radio frequency devices based on the absorption properties, low molecular weight, its abundance and low cost [7].

Several methods based on the measurement of the reflection and transmission coefficients as a sample of the material have been proposed in the literature [8] among these is the Nicolson-Ross-Weir (NRW) technique [9] extraction of dielectric parameters where a method is presented to determine the permittivity and permeability

in the frequency domain of a material sample by measuring the dispersion parameters S_{11} and S_{12} . This method reveals an issue to do the phase periodicity of the wave propagation factor P which results in infinite solutions for permittivity E and permeability U . However, this is solved by choosing solutions that comply with a reflection coefficient $|r| \leq 1$ [9]. In [10] It is proposed to solve this ambiguity in the phase, choosing a branch of solutions that correspond to one value of two or more measured frequencies. In spite of these methods require knowledge of the material and having to select a family of answers. So [11] it seems to be the most attractive solution because it is enough to measure the different phase among the previous points and use the information of the phase delay in the previously measured points.

In this paper, we design a method to predict the permittivity and permeability behavior of a magneto – dielectric composed material from the NRW technique, by analyzing the S parameters extracted with a Rohde & Schwarz ZVB8 Networks Vector Network Analyzer [12] Based on this technique, an algorithm was implemented in Matlab® software, through which the results extracted from the simulation of a transmission line in ADS® whose relative permittivity E_r is known in advance and which matches the value thrown by the Matlab® algorithm. Once the functionality of the algorithm has been validated, the permittivity and permeability of a microstrip type magneto – dielectric substrate made from P115A polyester resin and magnetic powders whose concentration varies between 10, 20 and 30% weight percentage, with particle size between 25 - 45 microns is extracted. Additionally, the magnetite particles were randomly distributed and vertically and horizontally aligned in the polymeric matrix by applying a constant 300 mT magnetic field, during the curing process [13].

2. NICOLSON-ROSS-WEIR EXTRACTION TECHNIQUE

The Nicholson-Ross-Weir extraction technique is based on measuring reflection and transmission on an isotropic material without losses under specific frequency conditions with permittivity or dielectric constant E_r and

permeability μ_r [12].

The phase propagation factor P of electromagnetic waves through the substrate can be determined from the measured scattering parameters and the impedance in the transmission line [11] as seen in eq. (1):

$$P = e^{\gamma d} = \frac{1 - S_{11} + S_{21}}{2S_{21}} + \frac{2S_{11}}{\left(z - \frac{1}{z}\right)S_{21}} \quad (1)$$

Where γ and d are the propagation constant and the length of the sample respectively. Eq. (2) presents the impedance of the transmission line z [14]:

$$z = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{((1 - S_{11})^2 - S_{21}^2)}} \quad (2)$$

The difficulty with the extraction technique is that P presents a periodicity of the wave propagating through the material which causes eq. (1) to have infinite solutions because $e^{\gamma d} = e^{\alpha d} e^{j(\beta d + 2\pi m)}$ where α γ β are the constants of attenuation and propagation respectively and m is any integer. The solution presented by [11] consists in measuring the phase difference between the previously measured points, instead of calculating the phase at a particular point. The phase propagation factor, eq. (1), can be rewritten as presented in eq. (3):

$$\ln(e^{\gamma d}) = \ln(|e^{\gamma d}|) + j \arg(e^{\gamma d}) \quad (3)$$

For a point set in frequency $w_0, w_1 \dots w_n$ of the measured reflection and transmission coefficients, a propagation constant $Y_0, Y_1 \dots Y_n$ and a phase factor argument. The argument $\phi_0, \phi_1 \dots \phi_n$ at a specific point is expressed in eq. (4):

$$\phi_N = \phi_0 + \sum_{i=1}^N \arg\left(\frac{e^{\gamma_i d}}{e^{\gamma_{i-1} d}}\right) \quad (4)$$

Where ϕ_0 is the phase value at the first measured point. The propagation constant $\gamma = j\omega\sqrt{\mu_0\epsilon_0}\sqrt{n^2 - (\omega_c/\omega)^2}$ is replaced in eq. (3) where $n^2 = \epsilon_r \mu_r$ and knowing the fact that the angular cutoff frequency in a quasi-TEM line $\omega_c \rightarrow 0$ and using eq. (4), is obtained eq. (5) of the effective parameters [14].

$$\epsilon_r \mu_r = \left(\frac{1}{kd} \left[-j \ln(|e^{\gamma d}|) + \phi_0 + \sum_{i=1}^N \arg\left(\frac{e^{\gamma_i d}}{e^{\gamma_{i-1} d}}\right) \right] \right)^2 \quad (5)$$

Where k is a parameter known as the wave number. To find the relative dielectric constant E_r and permeability μ_r , the effective wave impedance expression is used as shown in eq. (6) and eq. (7) [14].

$$E_r = \left(\frac{\frac{1}{kd} \left[-j \ln(|e^{\gamma d}|) + \phi_0 + \sum_{i=1}^N \arg\left(\frac{e^{\gamma_i d}}{e^{\gamma_{i-1} d}}\right) \right]}{z} \right) \quad (6)$$

$$\mu_r = z \left(\frac{1}{kd} \left[-j \ln(|e^{\gamma d}|) + \phi_0 + \sum_{i=1}^N \arg\left(\frac{e^{\gamma_i d}}{e^{\gamma_{i-1} d}}\right) \right] \right) \quad (7)$$

Where z corresponds to eq. (2).

In a transmission line the phase velocity is $vp = c/\sqrt{\epsilon_{eff}}$ and it is in relation to wavelength λ [15], which converts the dielectric constant into a design parameter to be controlled.

3. EXPERIMENTAL METHODOLOGY

3.1. Manufacture of the magnetodielectric material

The manufacturing process of the microstrip began by weighing 50 grams of resin at room temperature (17°C). The concentration by weight of magnetite in the polymeric matrix was defined in weight percentages of 10%, 20% and 30%, as reported by Ngo [16] and Husain [17]. Taking into account these parameters, 5, 10 and 20 grams of magnetite were weighed with a 325 sieve size which varies between 25-45 microns. Then, the filler material was added to the resin by stirring the mixture for 5 minutes at a frequency of 100 rpm using a DLAB OS20-S stirrer.

Acrylic molds of 7 cm wide, 7 cm long, with a thickness of 1.72 mm, covered with a release agent, were used. A 0.94 mm thick copper sheet was placed on its base and once the mixture was homogenized, 1% catalyst (SuperCat S-960®) was added depending on the volume of resin, mixing for approximately 1 minute, after which the mixture was poured into the acrylic molds, filling them to the top, once this process was completed, a second

copper sheet was placed on the surface with the same dimensions as the base in a sandwich type configuration.

In order to guarantee the adhesion of the sheets with the polyester resin loaded with magnetite powder and the homogeneity in the dimensions of the compounds, an acrylic press was used during the curing process Fig. 1a. Once the mixture was pressed, the magnetite particles in the filler were aligned by using ferrite magnets with a constant magnetic field of 300mT. The samples were prepared in three configurations, randomly scattered particles, without field effect, horizontally aligned Fig. 1b, and vertically aligned with the magnetic field lines Fig. 1c, [10]. All composite samples were cured at room temperature for 24 hours.

Once the material was cured and the process of stripping the microstrips was completed, the transmission lines were prepared, for which a 4 mm thick portion of copper was isolated from the samples. A total of 9 samples were immersed in ferric chloride in a concentration of 40 vol%.

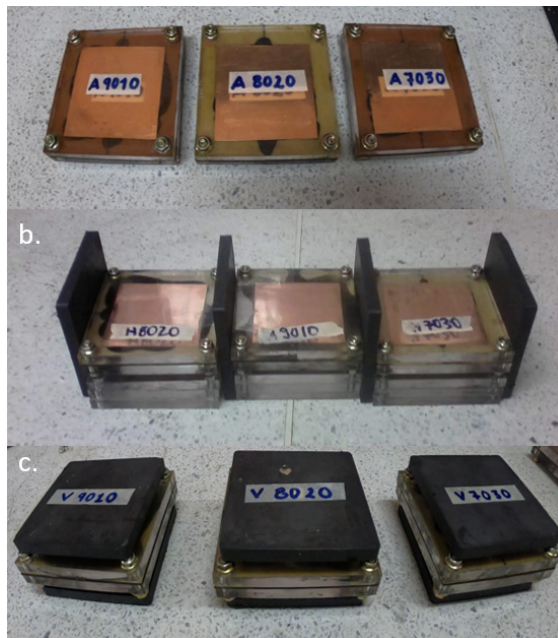


Figure 1. Curing samples composed of 10, 20, and 30% magnetite (a) without magnetic field, (b) in the presence of a horizontal fixed magnetic field and (c) a vertical fixed magnetic field produced by two permanent magnets.

After the chemical reaction, microstrip type circuits were obtained on which SMA type connectors were soldered on each of the circuit terminals in order to configure the transmission line as shown in Figure 2.

3.2. Extraction of S parameters

In order to analyze each one of the 9 elaborated microstrips, a complete factorial design of 32 were prepared, which was built with two factors and three levels per factor, matrix alignment (Mi) and percentage in weight of Wti filling.

The levels of each factor are shown in Table 1. The high frequency behavior and response of the magneto-dielectric composed was carried out by using a vector network analyzer from Rohde & Schwarz ZVB8 Networks. The VNA equipment was calibrated in a frequency range of 150 kHz to 4 GHz [18] in order to measure each of the samples, obtaining the S dispersion parameters.

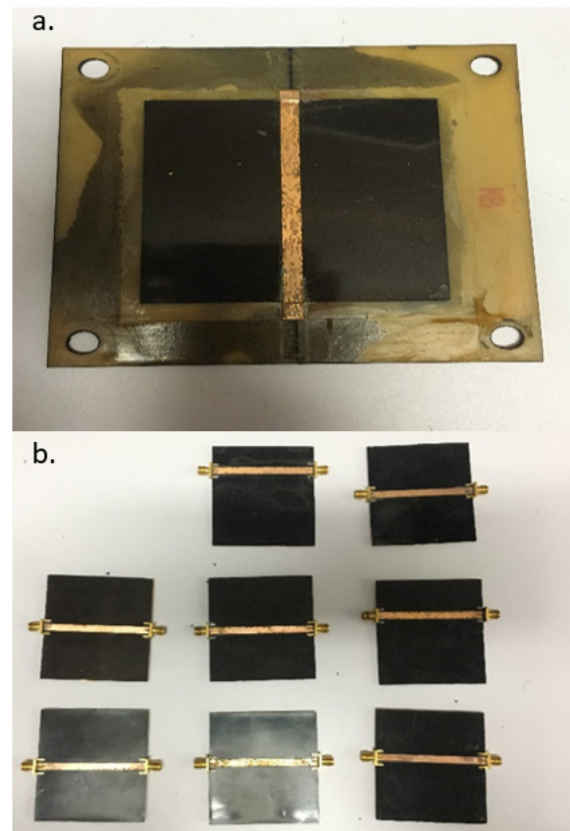


Figure 2. Microstrip type circuit setup.

Table 1. Factor levels included within the factorial design of 3^2 .

Levels	Under	Medium	High
Alignment (Mi)	Random (M1)	Vertical (M2)	Horizontal (M3)
% of filling (Wti)	10	20	30

3.3. Numerical extraction of E_r

In Figure 3, the ADS® simulation scheme is illustrated, used to extract the dispersion parameters, where a transmission line length $L=70$ mm with a relative dielectric constant equal to 3 is simulated. The 402 measured points of magnitude and phase against frequency of S_{11} y S_{21} are exported to Matlab® for the calculation of E_r .

Eq. (6) was implemented in Matlab®, where the information is entered into the algorithm by means of a vector containing the data extracted from the simulation of the transmission line dispersion parameters analyzed in ADS®, eq. 8 represents the extraction vector for the calculation of permittivity E_r in Matlab®. (8)

$$E_r(i) = c / (w(i) * L * -\log(\text{abs } p(i)) + \text{phi}0 + \text{sum_phi}) / z(i) \quad (8)$$

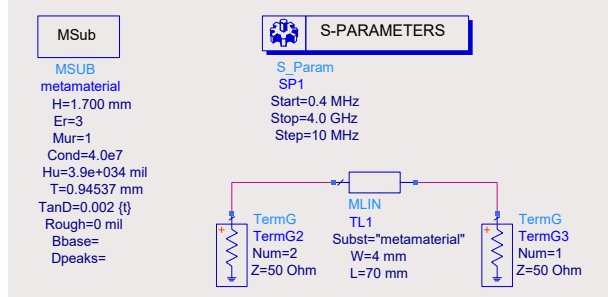


Figure 3. Simulation of a transmission line in ADS® with constant $E_r=3$.

Where, c corresponds to the speed of light, w represents the angular frequency of the measured point, in this case, L is the length of the sample, p is the phase propagation factor calculated from eq. (1), $\text{phi}0$ represents the first phase of P calculated, the variable sum_phi is the

accumulated value of the phase in a point N and the previous phase values and finally z is the transmission line impedance eq.(2). In order to solve the fact that the periodic response of P can result in infinite solutions for E_r , if the value of $\text{phi}0$ is negative the algorithm takes a value between 0 and 360 degrees.

The variable sum_phi is calculated by a basic accumulation algorithm in which the division between the $P(i)$ y $P(i-1)$, the value of the angle of that operation is extracted and the result is stored in the variable

Figure 4 illustrates the flowchart of the implemented algorithm. Figure 5 shows the permittivity calculated from the data extracted from the simulation (Figure 3). A line can be seen almost constant over 3 which coincides with the expected value of the simulation and indicates that the NRW method of parameter extraction implemented has good accuracy.

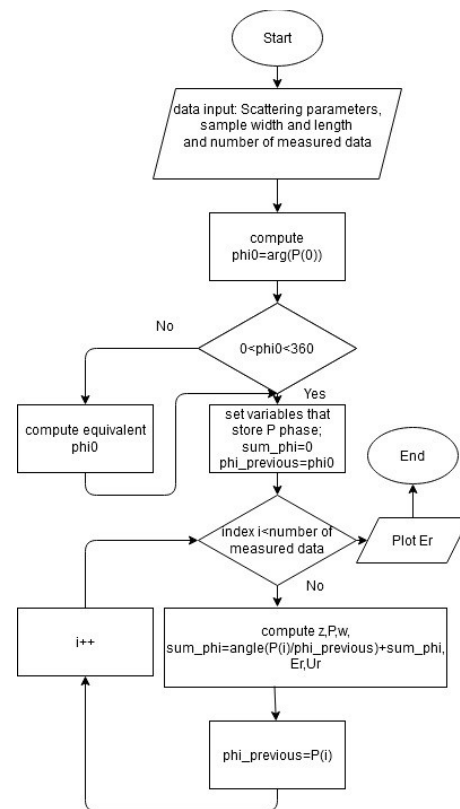


Figure 4. Flowchart of Matlab® algorithm for calculating permittivity.

As shown in the Figure 6, the phase propagation factor P has a periodic character; however, the algorithm was able to extract the dielectric constant.

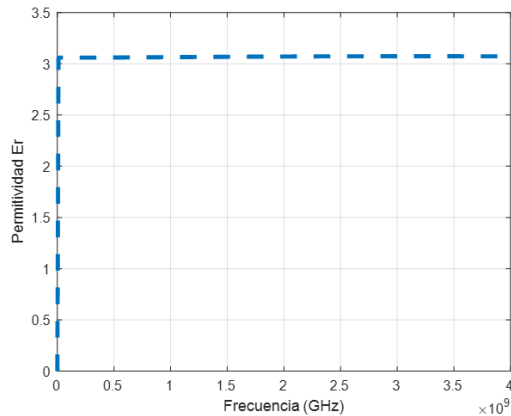


Figure 5. Permittivity $\epsilon_r=3$ Calculated with Matlab®.

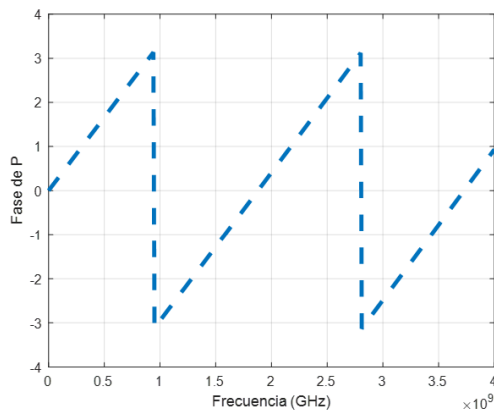


Figure 6. Phase graph of the phase propagation factor P .

4. EXPERIMENTAL RESULTS

4.1. Microstructural analysis

The first variable of interest defined in the experimental design of the present research is the alignment of the magnetite particles in the polymeric matrix, which was achieved by the application of a constant magnetic field of 300 mT, during the curing and cross-linking process of the polyester resin.

Three specific configurations were established for each material, randomly scattered particles, particles horizontally aligned to the magnetic field, and particles

vertically aligned to the magnetic field. The micrographic analysis using a Carl Zeiss EVO 10 scanning electron microscope is shown in Figure 7.

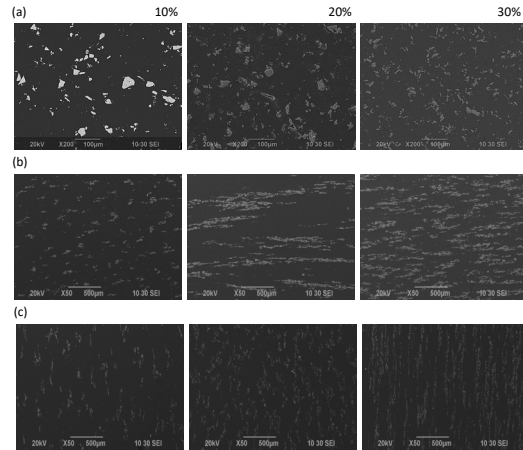


Figure 7. Distribution of magnetite particles in the polymeric matrix, a. randomly dispersed, b. horizontally aligned, and c. vertically aligned, in concentrations of 10, 20 and 30 % of magnetite.

In Figure 7, it is evident that by increasing the concentration of magnetite within the polymeric matrix, the filler particles adjust better to the field lines. At the same time, it is perceived that in low concentrations with 10% magnetite, the particles are presented in insufficient quantity which do not allow a complete adjustment of the magnetic field line, creating vacant spaces where the own resistivity of the polymer can increase, creating different conductive zones within the composed material.

4.2. Obtaining dielectric properties

The best morphological configuration of the filler against the field lines is given by mixing 70% polyester resin and 30% magnetite with a particle size below 45 μm , sieve 325, the images presented coincide with the observations made in previous works by Jolly [19] and Varga [20].

4.3. Obtaining dielectric properties

Figures 8 and 9 show the dielectric and relative permeability constants obtained by applying the algorithm designed in Matlab®, taking into account the orientation and concentration of the magnetite particles

in the polymer matrix, are characterized in a frequency range between 150 kHz and 4 GHz.

In the Figure 8 (a) for composite material with randomly dispersed particles, a dependence is observed between the frequency and E_r , which decreases at the end of the frequency band. The relative permittivity E_r of the samples containing less magnetite Fe_3O_4 in the functional filling of the substrate is around $E_r=2$. However, the value of this property increases significantly as the concentration of magnetite increases.

Figure 8 (b) represents the behavior of the composed material with particles aligned horizontally and in the direction of the transmission line. In this sense, the composed material behaves as an ordinary dielectric since no significant changes are seen when increasing the percentage of magnetite in the filler [21].

The vertically oriented particles, Figure 8 (c) illustrates the highest relative permittivity obtaining $E_r= 5.5$.for 30% concentration and $E_r= 4.5$ for the concentration of 20% of the magnetite content in the polymer matrix in the range of 2.5 to 4GHz. It increases to respect to the other configurations can be given by the dipole polarization of the magnetite at increasing frequency, which can be favored by the alignment of the particles vertically in the polymer matrix, allowing the transfer of electrons between the iron ions Fe_{2+} and Fe_{3+} present in the magnetite [12].

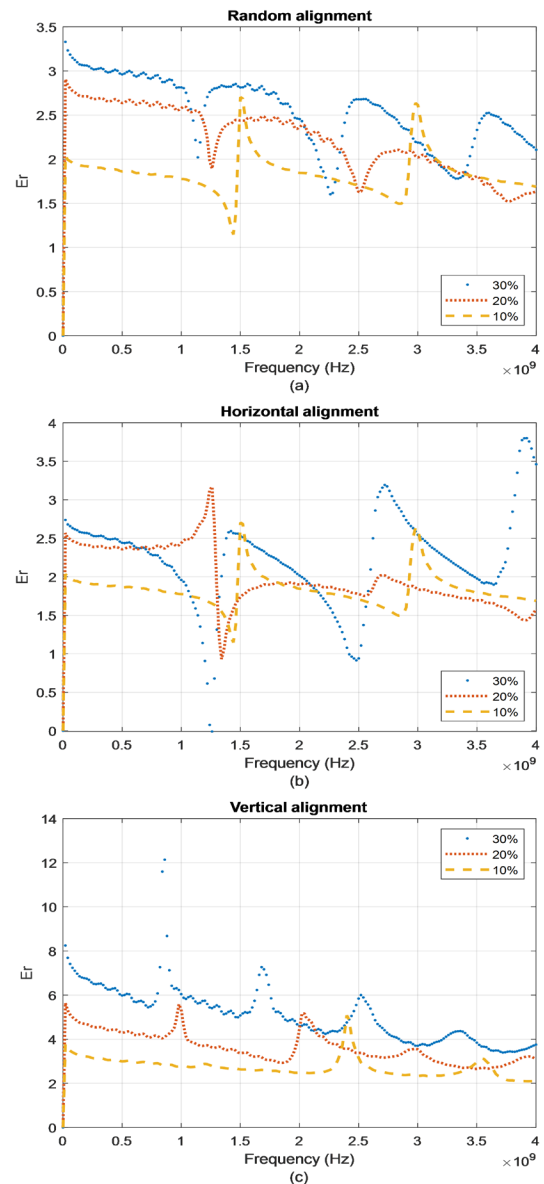


Figure 8. Relative permittivity of the nine samples organized by orientation; (a) random, (b) horizontal and (c) vertical.

Figure 9 shows the relative permeability. It can be seen that with lower concentrations of magnetite in the polymer matrix, the U_r is close to one by the dielectric property of the resin and grows as the concentration increases.

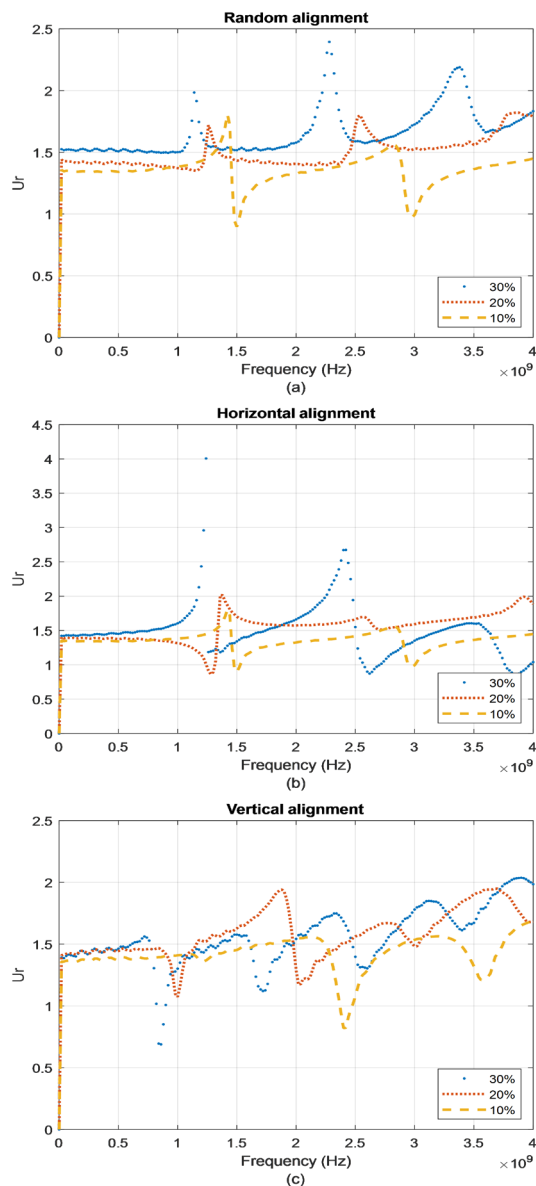


Figure 9. Relative permeability of the nine samples organized by orientation; (a) random, (b) horizontal and (c) vertical.

By the other side, Figure 10 illustrates the electrical conductivity calculated by the expression $\sigma(S/m)=2\pi f\epsilon_0 \epsilon''_r$. [21].

The vertically aligned magnetite particles with a concentration of 30% magnetite in Figure 8(c) shows an increase in conductivity as the frequency increases, which

coincides with the drop in relative permittivity shown in Figure 8(c), in turn the horizontal alignment contributes to the magnetic loss, making the dielectric effect of the polymer stronger.

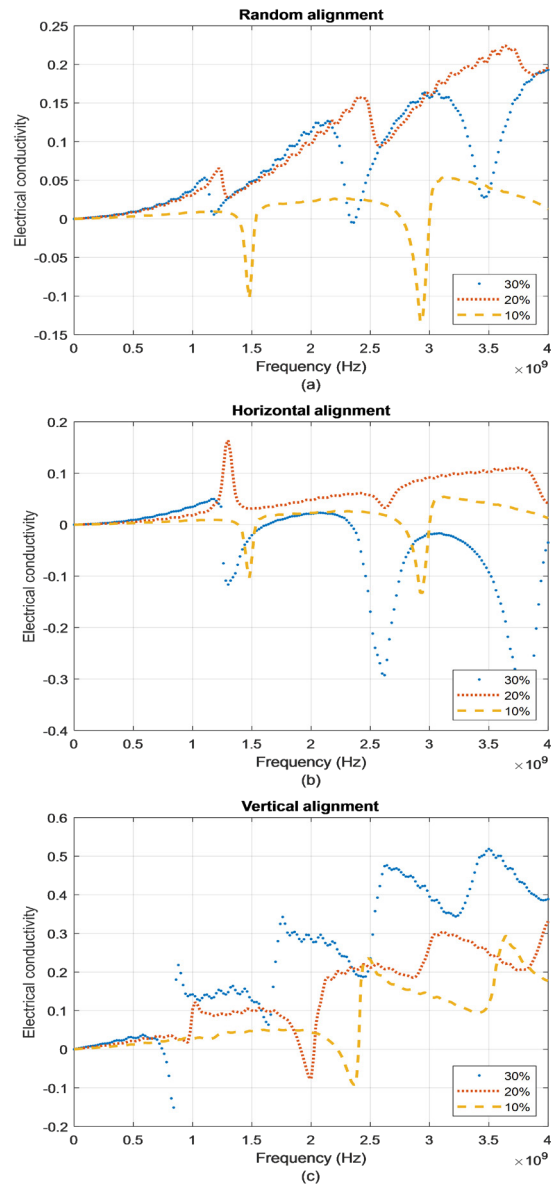


Figure 10. Conductivity σ of the nine samples organized by orientation; (a) random, (b) horizontal and (c) vertical.

This variation is particularly due to the natural resonance of magnetite, which can be attributed to exchange resonances, which coincides with Aharoni et al [22].

By the way, Figure 11 shows the absorption coefficient of the compound calculated by $A = 1 - |S_{11}|^2 - |S_{22}|^2$. The value of A increases as the concentration of magnetite in the composite increases.

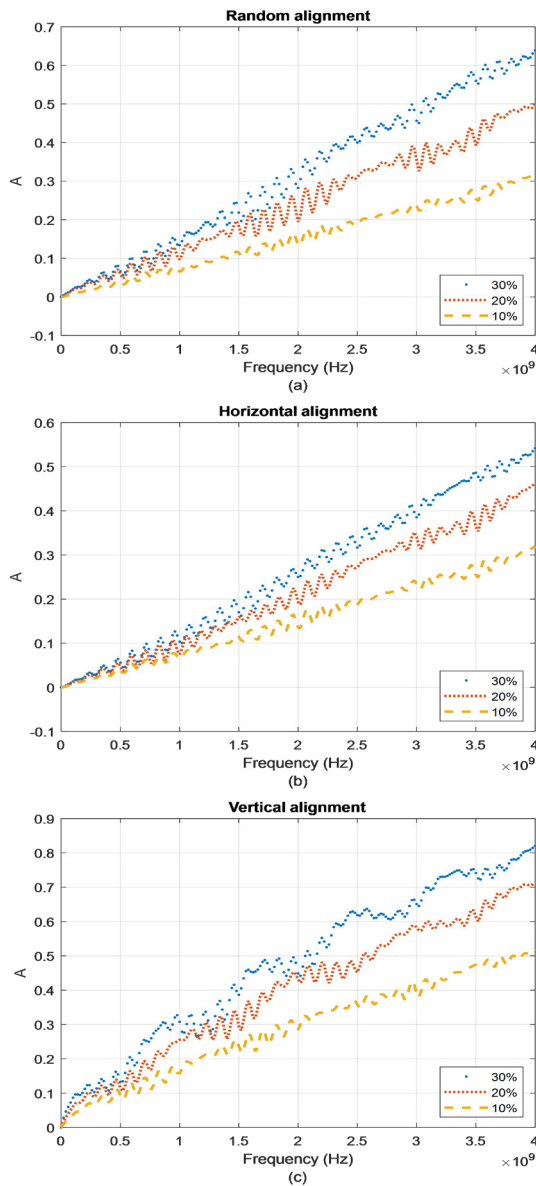


Figure 11. Absorption coefficient A of the nine samples organized by orientation: (a) random, (b) horizontal and (c) vertical.

Table 2 presents the relative permittivity and permeability values which confirm that the best performing samples

were those with Fe_2O_4 were oriented vertically.

Table 2. Permittivity and relative permeability of the composite material.

	Er (1.5Ghz)	Er (3Ghz)	Ur (1.5Ghz)	Ur (3Ghz)
M7030A	2.8	2.2	1.5	1.7
M8020A	2.4	2.1	1.4	1.5
M9010A	2.7	2.6	0.9	1
M7030V	5.7	3.7	1.6	1.8
M8020V	3.4	3.5	1.6	1.5
M9010V	2.6	2.3	1.5	1.5
M7030H	2.5	2.5	1.3	1.4
M8020H	2.7	1.8	1.7	1.6
M9010H	1.7	2.6	0.9	1

4. CONCLUSIONS

It was designed and validated an algorithm in Matlab® which allowed to extract the dielectric properties of a dielectric microstrip type composed material made from polyester resin and magnetite powders randomly dispersed and aligned horizontally and vertically by a constant magnetic field of 300 mT.

Nine mixtures of the dielectric magnet material were elaborated with magnetite concentrations of 10.20 and 30% weight percentage by means of dispersion in the polymeric matrix. The conductivity and absorption coefficient of the compounds increased as a function of the frequency and concentration of magnetite in the filler with high values for the 20 and 30% magnetite mixtures.

The alignment and concentration of the magnetite particles in the functional filler directly influence the dielectric behavior of the compound, where the best configuration is given for material with vertically aligned particles in the polymer matrix with a concentration of 30% weight percentage.

A designed magneto-dielectric material can be characterized at high frequency by measuring the scattering parameters and entering the data into the algorithm. The method of extracting NRW dielectric

parameters proved to be easy to implement and of high accuracy.

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