ISSN : 2350-0743

www.ijramr.com

International Journal of Recent Advances in Multidisciplinary Research
Vol. 04, Issue 11, pp.2952-2958, November, 2017

RESEARCH ARTICLE

EXPERIMENTAL ANALYSIS BASED ON OPTICAL MODEL AND ELECTROMAGNETIC PROPERTIES OF MULTILAYER ABSORBERS

[1,2,3]Samuel M. Leal da Silva, [1]Newton Adriano S. Gomes, [4]Simone de S. Pinto, [1]Alberto José O. Faro and [1,4]Mirabel C. Rezende

[1]Instituto Tecnológico de Aeronáutica, ITA, Praça Mal. do Ar Eduardo Gomes, 50, 12228-904 - São José dos Campos-SP, Brazil
[2]Comando de Comunicações e Guerra Eletrônica do Exército, Estrada Parque do Contorno, Rodovia DF001, km 05 - Setor Taquari - Lago Norte, 71559-902 – Brasília-DF, Brazil
[3]Instituto Superior de Educação de Brasília, Asa Sul - SGAS Quadra 613/614 70.200-730 – Brasília – DF, Brazil
[4]Instituto de Ciência e Tecnologia, ICT/UNIFESP, Talim, 330, 12231-280 - São José dos Campos-SP, Brazil

ARTICLE INFO

Article History:
Received 21st August, 2017
Received in revised form
06th September, 2017
Accepted 03rd October, 2017
Published online 11th November, 2017

Keywords:

Multilayer absorbing materials,
Radar absorbing materials,
Electromagnetic properties.

ABSTRACT

This research aims to contribute with the design optimization of multilayer absorber material applicable in stealth technologies. This study involves a pre-analysis of the electromagnetic properties of five individual plates (absorbing layers), considering the reflection and transmission coefficients. From these characteristics was established the best combinations of the individual layers in sets of three layers. For this, five plates based on styrene-butadiene rubber (SBR) matrix loaded with carbon black (2-50 phr) were processed. Electrical conductivity, electric permittivity, and the reflection and transmission coefficients at NRL Arch of the five plates were measured. The results were correlated to obtain the best impedance matching of the sets of three layers looking for the lowest reflectivity. The proposed experimental data correlation was compared to computational simulations based on the model of Small reflections in stratified medium. Besides this, all possible arrangements of three layers were experimentally evaluated by NRL Arch in the range of 8 – 11 GHz. The top five arrays with three layers are shown. The experimental results present a good fit with the performed simulations. The good adjustment between the experimental measurements and theoretical predictions allow us to state a pre-analysis route to support the processing the multilayer microwave absorbers.

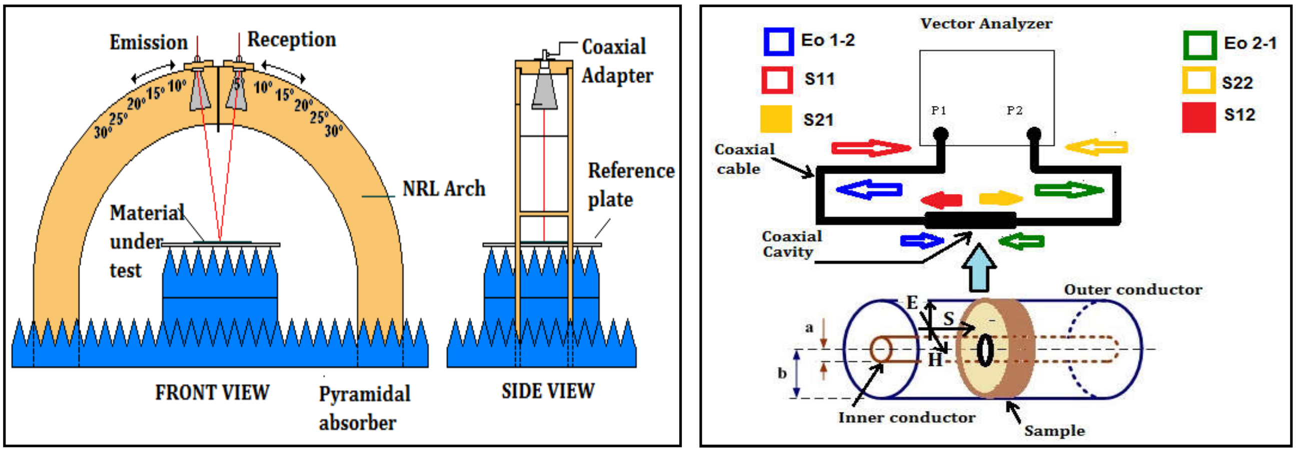
INTRODUCTION

Whether in Electromagnetic Compatibility (EMC) area or in projects of Radar Cross Section Reduction (RCSR) of combat platforms, the shield or the reduction of electromagnetic scattering have been a challenge for research centers and industry. The shielding of electromagnetic noise and the reduction of electromagnetic scattering may be achieved by using RAM (Radar Absorbing Materials) Nohara *et al*. (2002), Silva (2004). This class of materials is classified into dielectric, magnetic or hybrid absorbers. Generally, RAM are composed of a polymeric matrix loaded other materials (absorbing centers) that interact with electromagnetic radiation in the microwave band. In this case, the polymeric matrix presents little or no interaction with the microwaves. On the other hand, the absorbing centers may be magnetic materials like ferrites, carbonyl iron or any metallic particles, in the case of magnetic RAM. In the case of dielectric RAM, the absorbing centers can be carbon black, carbon fiber, carbon nanotubes, graphene foils, silicon carbide or Intrinsically Conducting Polymers (ICPs), for example Nohara *et al* (2002), Silva (2004). The narrow band RAM concept attends more specifically EMC purposes, when the frequency range of spurious signals radiated by equipment, for example, is known. In the case of reduction of electromagnetic radiation spread by a target, for example, a combat platform, it is necessary a broadband RAM, because the opponent radars may be operating in different frequency bands, Silva (2004). Soon, as the widest range of frequencies is attenuated by RAM, more efficient is the signal attenuation on target. One of possibilities of obtaining broadband RAM is by the arrangement of different layers of materials, each one with different formulations and thicknesses, forming a multilayer material. When there are many formulations of individual layers, the choice of the best layers and the more adequate arrangement of them for obtaining a multilayer RAM is a complex task, due to the great number of possibilities of arrangements. The chosen and the arrangement of the different layers depend on electric and magnetic properties of each layer that provide transmission and reflection coefficients compatible to reach the impedance

****Corresponding author:*** [1,2,3]**Samuel M. Leal da Silva**
[1]Instituto Tecnológico de Aeronáutica, ITA, Praça Mal. do Ar Eduardo Gomes, 50, 12228-904 - São José dos Campos-SP, Brazil
[2]Centro de Instrução de Guerra Eletrônica, Estrada Parque do Contorno, Rodovia DF001, km 05 - Setor Taquari - Lago Norte, 71559-902 – Brasília-DF, Brazil
[3]Centro Tecnológico de Armas, Av. das Américas, 28705, Guaratiba, 23020-470 - Rio de Janeiro – RJ, Brazil

matching and, consequently, the microwave attenuation. These materials may be analyzed to obtain the coefficients or even their properties through free space techniques, coaxial cavities, Jarvis (1990) and NRL (Naval Research Laboratory) Arch (all of them work with transversal electric and magnetic waves - TEM). The NRL Arch (Figure 1(a)) is a method of scalar measurements of the reflection coefficient based on emission, scattering and reception characterized by TEM modes. The emission and reception occur almost on a normal angle with the plane of sample, Bartley (2014).

Figure 1(b) illustrates the measurement technique in a coaxial cavity with the TEM mode. In this case, however, it is possible to measure amplitude and phase of the four reflection and transmission coefficients, which are briefly described as S_{ij} (i=1,2; j=1,2) scattering parameters Hock (2003), Micheli *et al* (2012). From these data, it is possible to calculate the electric permittivity and the magnetic permeability, Jarvis (1990), Bartley (2014). In all cases mentioned, it can be interpreted the arrangement as a transmission line with the concentrated or distributed parameters according to the thickness relation of the sample and the wavelength of incident radiation.



(a) (b)

Figure 1. TEM methods: (a) NRL Arch[1] and (b) coaxial cavity

Qin *et al* (2012) reported the importance of several kinds of carbon loads on the absorber design, particularly highlighting the graphene and carbon nanotubes (CNT). Obviously, these materials have received great attention due to their characteristics and properties that have allowed their use in electronic systems design with great performance. However, these nanofillers are not easy to obtain and more expensive. Micheli *et al* (2012) modeled, processed and measured multilayer absorbers composed by an epoxy resin matrix and CNT as filler material, overlaid by an epoxy resin layer. These authors measured the electromagnetic properties of the samples at 6, 12 and 18 GHz. Afterwards; they feed an optimization algorithm based on particulate conduction paths. Despite the great contribution of this work, the authors considered only the electronic conduction mechanism for the losses, neglecting other interactions between the radiation and the material. Although the tested frequencies are within the microwave range, characterizing basically similar interactions, it is possible that overlay effects can be occurred resulting in variations on the reflection coefficient, not detected around 6 GHz, in accordance to the measurements performed. Then, the purpose of this paper is to present the microwave attenuation results of multilayer RAM based on a cheaper load, i.e., carbon black, dispersed in SBR rubber matrix showing an approximate and simple analysis criteria to stablish the more adequate arrangement of multilayers, considering for this the electromagnetic properties of each layer in the microwave frequency band of 8 - 11 GHz.

Theoretical foundations

Except for those cases of the radiated emission in what the noise generator subsystem is too close the victim subsystem, it may be considered the situation of plane incident wave *E(x)* Balanis (2005), Pozar (2005), as in Equation 1.

$$E(x) = E_0^+ e^{-\gamma x}, \qquad (1)$$

where: γ is the propagation constant of a medium and x the propagation direction.

The intrinsic impedance (Z_i) of each layer can be defined from the angular frequency (ω), the complex magnetic permeability (μ), the electrical conductivity (σ) and the complex electric permittivity (ε):

$$Z_i = \sqrt{\frac{j\omega\sigma_T + \omega^2\varepsilon'}{\sigma_T^2 + \omega^2\varepsilon'^2}} \qquad (2)$$

The permeability and permittivity can be defined respectively as:

$$\mu = \mu_r \mu_0 , \qquad (3)$$

and

$$\varepsilon = \varepsilon_r \varepsilon_0 , \qquad (4)$$

being: μ_0 the permeability of vacuum, μ_r the relative permeability, ε_0 the permittivity of vacuum and ε_r the relative permittivity.

The complex electric permittivity of a material is composed by imaginary part (ε'') and real part (ε'). This permittivity is defined as:

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad (5)$$

In such case, the total electrical conductivity (σ_T) will be composed by a static component (σ) and a dynamic component ($\omega\varepsilon_0\varepsilon_r''$) Krauss (1999):

$$\sigma_T = \sigma + \omega\varepsilon_0\varepsilon_r'' \qquad (6)$$

Applying Equations (3) and (4) into (2) and after considering Equations (5) and (6), we can obtain the normalized impedance (Z_{i0}). For a situation in which the material is non-magnetic (μ_r = 1), Z_{i0} depend only on the total conductivity (σ_T), the relative electric permittivity (real component) and the angular frequency, resulting:

$$Z_{i0} = \sqrt{\frac{\omega^2\varepsilon_0^2\varepsilon_r' + j\omega\varepsilon_0\sigma_T}{\sigma_T^2 + \omega^2\varepsilon_0^2\varepsilon_r'^2}} \qquad (7)$$

It results of impedance matching between two any mediums (Z_{n+1} and Z_n), a reflection coefficient, represented generically by Balanis (2005), Pozar (2005):

$$\Gamma_n = \frac{z_{n+1} - Z_n}{Z_{n+1} + Z_n}, n = 0,1,2,3... \qquad (8)$$

$$|\Gamma_n|^2 = \left|\frac{Z_{n+1} - Z_n}{Z_{n+1} + Z_n}\right|^2 \qquad (9)$$

Considering the concept of the reflection coefficient (Γ), for the energy conservation it is necessary that this coefficient relates to the transmission coefficient (T) and the energy absorbed (A) by the medium:

$$\Gamma = 1 - (T + A) \qquad (10)$$

MATERIALS AND METHODS

This study used a commercial rubber matrix (Styrene-Butadiene Rubber - SBR), and a conductive carbon black (CB) from Degussa, type Printex XE-2B. Five samples of SBR loaded with carbon black in the form of square sheets (250 mm x 250 mm x 3 mm) were prepared. The preparation used a roll mill and the sheets were vulcanized in a hot press at 180 °C with 200 bar of pressure**.** The code of the samples (layers) and the CB concentration in the SBR matrix are shown in Table 1. The multilayer absorbers were constructed by stacking of three layers from the five individual layers processed. From these five layers it was tested twenty aleatory combinations.

Table 1. SBR/carbon black samples

Layer Code	Carbon black concentration (phr)
CB1	4
CB2	6
CB3	10
CB4	50
CB5	2

Each individual layer was characterized with respect to the static electrical conductivity (four-point-aligned method) by using an equipment of Keithley. The electric permittivity of each layer was obtained from "S" parameters measurements in the range of 8 to 11 GHz. These measurements were achieved in coaxial cavity of 3 mm diameter (as shown in Figure 1(b)) connected to a vector network analyzer 8510C from Agilent, using the software 85071 of Agilent, based on the Nicolson-Ross-Weir method, Agilent (2014), Singh *et al.* (2010). This method uses amplitude and phase of the "S_{ij}" parameters to calculate the electric permittivity. Teflon was used as reference material in the complex permittivity parameters measurements. The reflection and transmission coefficients of each individual layer were also characterized using the NRL Arch (Figure 1(a)), in the frequency range of 8 – 11 GHz. An aluminum plate was used as reference reflector material in these measurements. From the analysis of the measurements of static conductivity, electric permittivity in coaxial cavity and the reflection and transmission coefficients (both in NRL Arch) structures with three layers were proposed. This correlation with the proposition of multilayer RAM, is named in this study as 'criterion of analysis'. Parallel to the experimental work, i.e., to the analysis criteria, a Matlab code, previously developed and tested by the authors, Silva *et al* (2009), was used to compare the results obtained with the proposed analysis criteria presented in this work. The used Matlab code was based on the "Theory of small reflections", Balanis (2005). This code allows simulating all possible arrangements of three layers from the five individual layers prepared and their reflection coefficients. For this, it is used the coefficients of each of the five layers prepared. From the results the code highlights the top five arrangements of three layers that result the smallest reflection coefficients, but it does not show the absolute value of the reflection coefficients.

RESULTS AND DISCUSSION

Table 2 shows the electrical conductivity values measured for the five SBR/CB layers (described in Table 1) and Figure 2(a,b) present the complex parameters of the electric permittivity. It is also important to point out that the studied materials behave as non-magnetic materials. Therefore, they present magnetic permeability approximately the same of vacuum, as cited in the literature, Balanis (2005), Pozar (2005).

Table 2. Electrical conductivity of layers

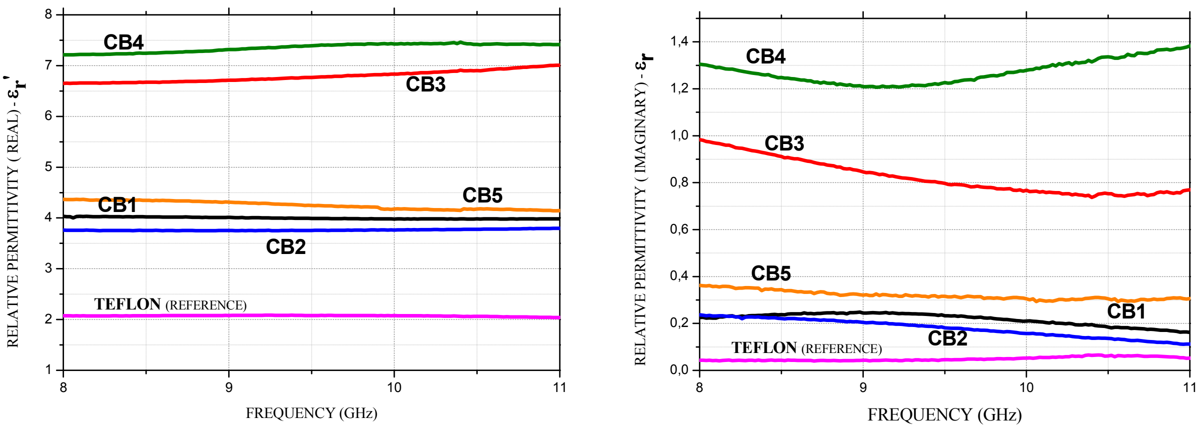
Samples	Electrical Conductivity (S/m)
CB1 (4 phr)	2.8×10^{-1}
CB2 (6 phr)	3.0×10^{-8}
CB3 (10 phr)	1.7×10^{-1}
CB4 (50 phr)	4.7×10^{-1}
CB5 (2 phr)	4.5×10^{-7}

Table 2 shows that the static conductivity values are directly related to the carbon black concentration used in the formulations. These results show that above 10 phr CB content, the material shows an accentuated increase of the conductivity with value in the same magnitude of the 50 phr sample. This behavior indicates that the percolation limit was achieved from 10 phr. The observed conductivity for the CB1 suggests that this sample is heterogeneous or occurred error in this measure. Besides the increment of the conductivity with the CB content increases, it was observed that the CB4 (50 phr) becomes more rigid losing the resilience property characteristic of rubbers. This aspect indicates the saturation of the SBR matrix from 50 phr of CB. Considering the properties presented in Table 2 and Figure 2 for the five samples it is verified that the CB2 and CB5 samples are more resistive showing a behavior more purely dielectric. In this case, $\omega\varepsilon' >> \sigma_T$. Then, Equation 7 may be reduced to obtaining normalized impedance as follow (Equation 11):

$$Z_{i0}^{I} \cong \sqrt{\frac{1}{\varepsilon_r'}} \qquad (11)$$

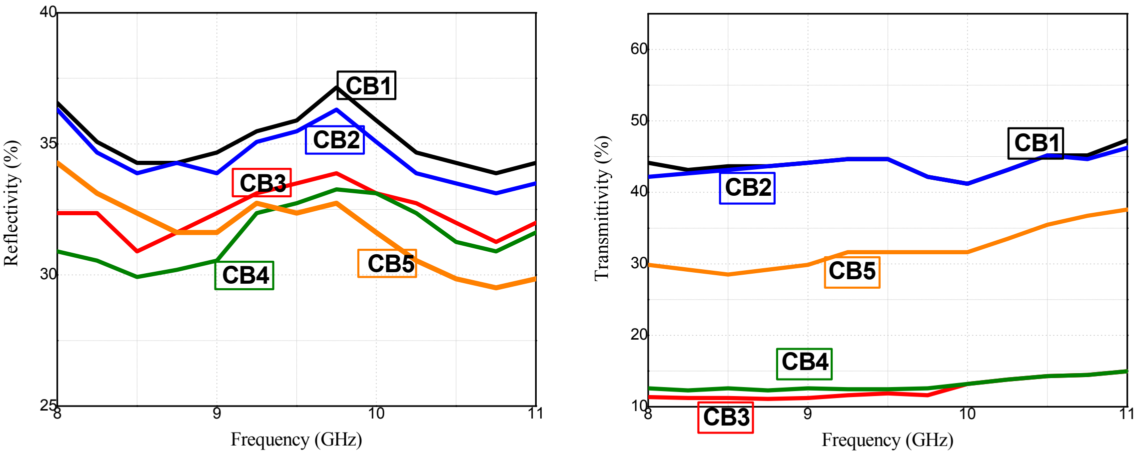
The reflectivity and transmissivity measurements of the samples (plate shape) in NRL Arch are shown in Figure 3(a,b). The absorption of each sample was obtained from Equation 10 as shown in Figure 4.

conductivity, CB5 presented losses (according to Figure 4) around 10 - 20% higher than CB2. CB3 and CB4 samples present the highest values of losses, around 55% of absorption in the frequency range of 8 – 11 GHz. The samples CB3 and CB4 are capable to conduct currents, even though with limitations, justified by values of conductivity presented, which are on the same order of magnitude and too close. It is necessary to remember that good conductors present σ > ωε and good dielectric materials show ωε > σ, Krauss (1999), Silva *et al* (2009). In this study, the materials (quasi-conductors) present conductor and dielectric characteristics with σ ~ ωε. The losses in dielectrics and quasi-conductors can exist from current of displacement (resonances and polarizations) or current of displacement and current of conduction (Ohmic effect), respectively. According to the results of conductivity and permittivity, CB3 and CB4 generated losses from these two latter types of currents,



(a) **(b)**

Figure 2. Real (a) and imaginary (b) values of permittivity of the layers



(a) **(b)**

Figure 3. Reflectivity (a) and transmissivity (b) measurements of individual layers

Thus, it may be verified that the normalized impedance of CB2 and CB5 depends on the real permittivity what characterize that these samples as lossless materials. It also may be noticed in Table 2 that these samples presented the lowest conductivity values what is a characteristic of dielectric materials, with CB5 showing a static conductivity one order of magnitude greater than the CB2 sample. However, even though CB2 and CB5 have shown similar values of permittivity and low static because σ ~ ωε. On the other hand, for the CB2 and CB5 we consider losses just from currents of displacement. In all cases, it is possible to observe (Figure 2(a)) that real permittivity is almost constant in the frequency range (8 – 11GHz), indicating absence of resonances and existence of losses from polarization only, Singh *et al* (2010), Kong *et al* (2010). It may be noticed that comparing CB1, CB3 and CB4, we can affirm that CB1 presents the lowest values of imaginary permittivity that results in low losses by dynamic effect of the current. In the case of this subgroup of samples, CB1 also presented the highest amplitudes of transmitted signal (Figure (3b)) and the lowest losses. It may be verified in Figure 2 that the results of permittivity of CB1 are too close to that presented by the samples CB2 and CB5, which are samples with characteristic of good dielectric material (Table 2 and Figure 2). The measurements of transmission and reflection (Figure 3) revealed a behavior of CB1 and CB2 very close, even though the differences of static conductivity of these samples. In summary, the dynamic conductivity measurements indicate a similar behavior among the samples CB1, CB2 and CB5. On the other hand, the static conductivity measures show an approximate behavior for CB1, CB3 and CB4.

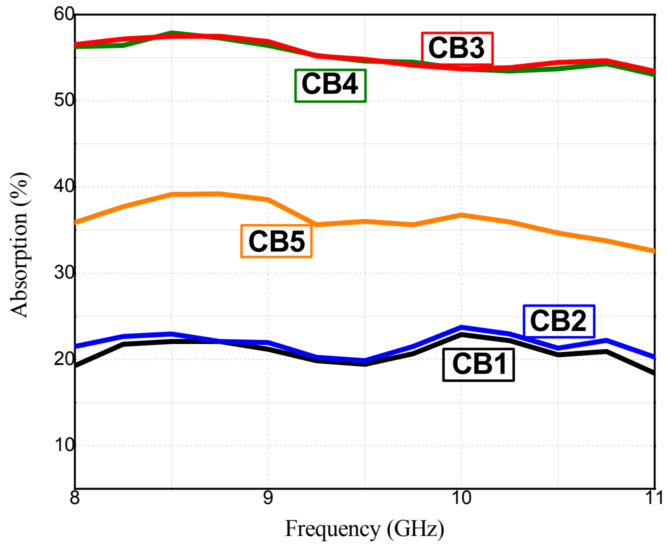


Figure 4. Microwave absorption of individual layers

Even though, the results of transmission and reflection measurements demonstrated an approximate behavior among the component of the subgroups: {CB3, CB4} and {CB2, CB1}. Already the CB5-sample presented intermediate values of transmission coefficient and losses, when compared with the two subgroups mentioned. A reason for the observed behaviors for {CB2, CB1} and {CB5} is due to the fact that there is a strong presence of mechanisms of reflection and transmission in the case of the first set of samples, as can be seen in Figure 3 where it can be seen reflection coefficients around 35% and transmission between 40 and 45% for CB1 and CB2, respectively. According to Equation 10, there is an evident interference of these mechanisms of interaction in the first subgroup, while for {CB5} there is an equilibrium between all mechanisms of interaction, as shown in Figure 3 in which it is possible verify 30 - 35% of transmission and 30 - 37% of reflection. Another reason is due to the measures of permittivity were performed in coaxial cavities. This technique of measurement allows obtaining signals that interacted with all transversal section of the sample. So, the technique of cavity is a volumetric measurement that allows calculating the electric permittivity, transmission and reflection coefficients. While the static conductivity measurements are punctual and less representative even considering an average of measurements. Like this, the technique of cavity confers greater relevance in relation to the static conductivity measures when the best ordering of the layers in the multilayer RAM processing is required.

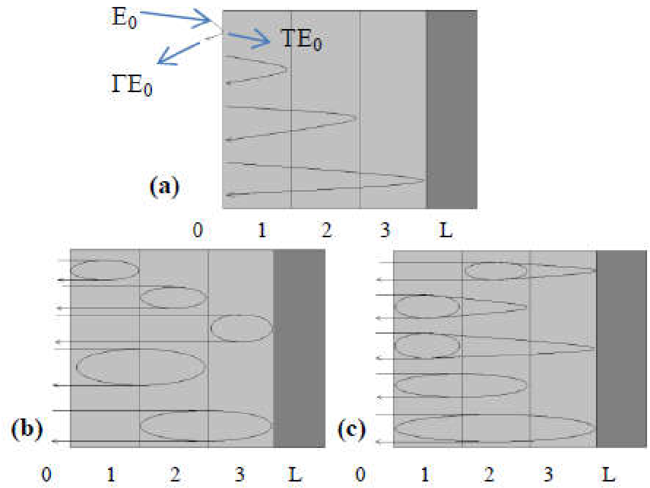


Figure 5. Possible interactions (reflections and transmissions) of the wave with the interfaces of the mediums (air, three layers and a conductor plane (L). One (a), two (b) and three (c) interfaces, Silva *et al* (2010)

Figure 5 shows possible interactions (reflections and transmissions) of the wave with interfaces of the mediums (air, three layers and a conductor plane). The interface with the air layer (first interface or input layer) should have a higher transmission that enables interactions between the wave and the absorbing centers in matrix of RAM. The first interface illustrated in Figure 5(a) (proposed in the literature, Silva *et al* (2009) as total reflection coefficient) occurs at all interfaces, including that one of the ellipsis. Then, it is expected that the layers of CB1, CB2 and CB5 must contribute to the best absorption when used in the first positions, i. e., as input layers. On the other hand, the internal layers should have greater losses and low reflection coefficients permitting the occurrence of interactions between the wave and the material structure. When this condition is attended the interactions promote the conversion of wave energy into heat Balanis (2005). In this context, the CB3 and CB4 should be used in inner positions. These statements are based on the reported values of imaginary permittivity (Figure 2(b)) and conductivity (Table 2) of the CB3 and CB4 samples. Equation 8 shows that lower reflection coefficient results in better impedance matching between air and the layers.

Based on this criterion of analysis, this work purposes the follow sequences: CB5-CB3-CB4, CB5-CB4-CB3, CB2-CB3-CB4, CB2-CB4-CB3, CB1-CB3-CB4 and CB1- CB3-CB4, expecting to obtain the lowest reflection coefficients in the frequency band of interest (8 – 11 GHz). After to propose the mentioned criterion to construct the multilayer absorber, based on experimental values of coefficients, it was used the Matlab code, Silva *et al* (2009), based on Small Reflection Theory, Balanis (2005), to determine the reflection coefficients of the multilayer samples. The code presented by Silva *et al*.(2009) complements that one proposed by Balanis (2005) and represents the summation of all reflection and transmission coefficients, including the second reflection (direction of inner of material) and the third reflection (after the second and in direction of the medium "0") represented by ellipsis at Figure 5(b,c). From the five plates, the code was developed according to Equation 12 to simulate the reflection coefficient of the multilayer with three layers. As stated before, this code shows the five smallest reflection coefficients of tri-layer arrangements. It is intended to present the sets of layers with the smallest reflection coefficients, but without the commitment to furnish the absolute value of the coefficients. This code aims to improve the proposal presented by Balanis (2005) to evaluate the reflection coefficients of multilayers. The coefficient properties and thickness (in this case all layers presented 3 mm) of each layer were introduced in Equation 12. In Figure 6 we have the response of the code. It is possible to see many curves of reflectivity corresponding to the different possibilities of three layers arrangements, based on Equation 12 that represents the situations designed in Figure 5.

$$\begin{aligned}
\Gamma = {} & \Gamma_1 + T_{10}T_{01}\Gamma_2 e^{-2\gamma_1 x_1} + T_{10}T_{01}T_{12}T_{21}\Gamma_3 e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} + \\
& T_{10}T_{01}T_{12}T_{21}T_{13}T_{31}\Gamma_L e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} e^{-2\gamma_3 x_3} + \\
& T_{10}T_{01}\Gamma_2(-\Gamma_1)\Gamma_2 e^{-2\gamma_1 x_1} e^{-2\gamma_1 x_1} + \\
& T_{10}T_{01}T_{12}T_{21}(-\Gamma_1)\Gamma_2\Gamma_3 e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} e^{-2\gamma_1 x_1} + \\
& T_{10}T_{01}T_{12}T_{21}(-\Gamma_2)\Gamma_3\Gamma_3 e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} e^{-2\gamma_2 x_2} + \\
& T_{10}T_{01}T_{12}T_{21}\Gamma_3(-\Gamma_3)\Gamma_L e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} e^{-2\gamma_3 x_3} + \\
& T_{10}T_{01}T_{12}T_{21}T_{23}T_{32}\Gamma_L(-\Gamma_2)\Gamma_3 e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} e^{-2\gamma_3 x_3} e^{-2\gamma_2 x_2} + \\
& T_{10}T_{01}T_{12}T_{21}T_{23}T_{32}\Gamma_L(-\Gamma_1)(\Gamma_2) e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} e^{-2\gamma_3 x_3} e^{-2\gamma_1 x_1} + \\
& T_{10}T_{01}T_{12}T_{21}T_{12}T_{21}\Gamma_3(-\Gamma_1)\Gamma_3 e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} + \\
& T_{10}T_{01}T_{12}T_{21}T_{23}T_{32}T_{23}T_{32}\Gamma_L(-\Gamma_2)\Gamma_L e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} e^{-2\gamma_3 x_3} e^{-2\gamma_2 x_2} e^{-2\gamma_3 x_3} + \\
& T_{10}T_{01}T_{12}T_{21}T_{23}T_{32}T_{12}T_{21}\Gamma_L(-\Gamma_1)\Gamma_3 e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} e^{-2\gamma_3 x_3} e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} + \\
& T_{10}T_{01}T_{12}T_{21}T_{23}T_{32}T_{12}T_{21}\Gamma_L(-\Gamma_1)\Gamma_L e^{-2\gamma_1 x_1} e^{-2\gamma_2 x_2} e^{-2\gamma_3 x_3} e^{-2\gamma_2 x_2} e^{-2\gamma_3 x_3} e^{-2\gamma_1 x_1}
\end{aligned} \tag{12}$$

The Matlab code indicates the five arrangements (upper right side of Figure 6) of three layers that present the lowest reflection coefficient in a determinate band (in this case, between 8.75 and 8.77 GHz). The choice of this frequency band is due to the fact of a special interest in the frequency of 8.76 GHz, correspondent to radar under study by the team of researchers.

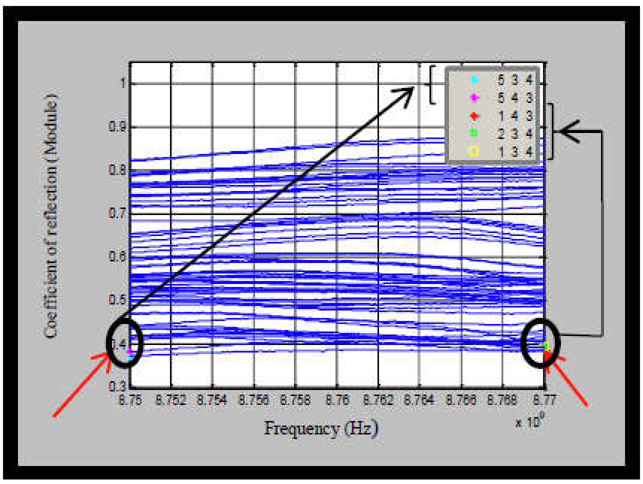


Figure 6. Reflection coefficient obtained with the Matlab code around 8.76 GHz

In all propositions resulted from the code in Matlab, the first layer is composed by layers of the group {CB1, CB2, CB5} and the inner layers are formed by layers of the group {CB3, CB4}. Thus, the considerations proposed in this study are consistent with the response of the theoretical model simulated by computational tool generated in Matlab. This result allows to state that the route of analysis proposed in this work can be used to obtain multilayer absorbers with good approximation, allowing the experimental work even without the prediction software to support. Experimental reflectivity measurements of approximately twenty arrangements of tri-layer samples, including those determined by the proposed method of analysis and supported by the theoretical model, were performed in the NRL Arch in the frequency range of 8 to 11 GHz. These measurements were carried out to check the response of the layer sequences and the five best results (lower reflectivity) are reported in Figure 7. For this, an aluminum plate (reflector material) was used as reference material in the NRL Arch and the reflectivity was 0 dB in the range of 8 - 11 GHz.

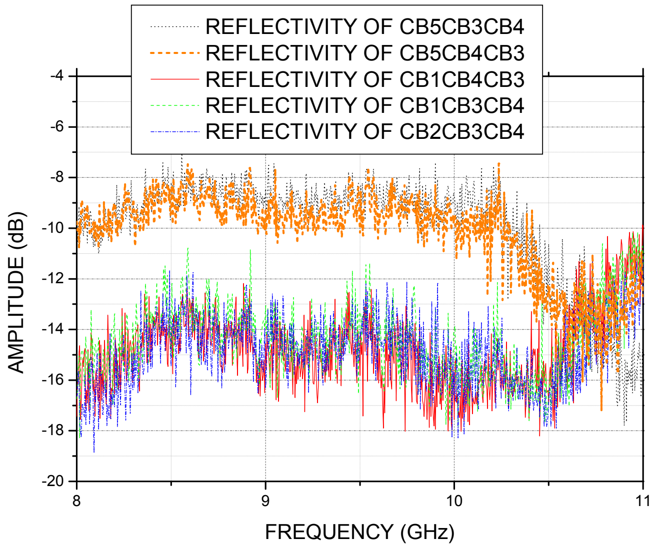


Figure 7. Reflectivity curves in the NRL Arch of the multilayer RAM

Considering the frequency region around 8.76 GHz, it was found that the multilayer sample named CB5CB4CB3 and CB5CB3CB4 reflected the signals around 9 dB and the CB1CB4CB3, CB1CB3CB4 and CB2CB3CB4 reflected 15 dB below the reference. Although the response of the theoretical model presents any differences from the experiment results in relation to the sequence of more effective layers, it may be considered that there is good coherence between the proposed method (criteria of analysis) and the response of code to define the layers and their ordering in the multilayer RAM processing.

Conclusion

Materials based on SBR and carbon black were processed so that it could get its electromagnetic properties. The electrical conductivity and the reflection and transmission coefficients were used as parameters for analysis and prediction of the behavior of materials in the range of 8.0 to 11.0 GHz (mainly in the frequency of 8.76 GHz). The data obtained in the materials characterization were introduced in a computer code, based on theoretical model proposed in a previous work. In this way it was simulated the reflection coefficients of absorbers with three layers. The analysis of the properties and the reflection and transmission coefficients allowed proposing a criterion for the experimental data which enables to propose the best compositions of layers and their ordering to obtain a multilayer absorber. The criteria provided samples that were measured in NRL Arch. The comparison of experimental results with that one resulted from a Matlab code shows a very good agreement for tri-layer compositions. These results allow concluding that it is possible to establish a practical, fast and approximate criterion to support the multilayer absorbing materials based on the properties of individual layer. The establishment of this analysis takes a great importance as far as it becomes an alternative for the multilayer absorber construction. Even without a supporting computational tool, it may offer the possibility, still in the laboratorial characterization step, to perform the first tests only based on the characterization of the individual layers.

Acknowledgments

This work was supported by CAPES/PVNS and CNPq (Proc.: 303287/2013-6 and 150211/2014-7).

REFERENCES

Agilent. 85071E - Materials Measurement Software. <www. agilent.com/find/materials>. Accessed: 2014.

Akhterov, M. V. 2010. Microwave Absorption in Nanostructures (Thesis). California: University of California, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.368.3225&rep=rep1&type=pdf.

Balanis: C. 2005. Advanced Engineering Electromagnetic, (Wiley, New York). pp. 200-220.

Bartley, P. and S. Begley, 2014. Materials Measurements. <http://151.100.120.244/personale/frezza/biblioteca/dispense/MisureMateriali.pdf>. Accessed: 2014.

Hock, K. M. 2003. Impedance Matching for the Multiplayer Medium Toward a Design Methodology, IEEE Transactions on Microwave Theory Techniques; 51:908-914. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1191747.

Jarvis, J. B. 1990. Transmission/Reflection and Short-Circuit Line Permittivity Measurements, U.S. Department of Commerce, National Institute of Standard and Technology.

Kong, I., S. H. Ahmada, M. H. Abdullah, D. Hui, A. N. Yusoff, D. Puryanti: 2010. Magnetic and Microwave Absorbing Properties of Magnetite- thermoplastic Natural Rubber Nanocomposites. *Journal of Magnetism and Magnetic Materials*, 322, 3401-3409. DOI: org/10.1016/j.jmmm.2010.06.036.

Kraus. J. D. 1999. Electromagnetics, (McGraw-Hill, Boston), 5ed, 187-189.

Micheli, D., C. Apollo, R. Pastore, M. Marchetti: 2012. Modeling of Radar Absorbing Materials Using Winning Particle Optimization Applied on Electrically Conductive Nanostructured Composite Material, *International Journal of Material Science – IJMSCI*, 2. 31-38.

Nohara, E. L., M. A. S. Miacci, M. C. Rezende, I. M. Martin: 2002. Comparison of Reflectivity Measure Techniques – RCS and NRL Arch – in Evaluation of Microwave Absorbers. In: Proceedings of the Congresso Brasileiro de Engenharia e Ciência dos Materiais - CBECIMAT, Natal; Brasil.

Pozar, D. M. 2005. Microwave Engineering. (John Wiley, 3rd ed.,). pp. 174-180.

Qin, F. C. A. Brosseau: 2012. A Review and Analysis of Microwave Absorption in Polymer Composites Filled with Carbonaceous Particles. *J. Appl. Phys*., 111, 111:061301. DOI: org/10.1063/1.3688435.

Silva, S. M. L. 2004. Methodology of Radar Cross Section Reduction of Combat Platform [Dissertation]. São José dos Campos: Technological Institute of Aeronautics.

Silva, S. M. L., M. C. Rezende, A. J. O. Faro, 2009. Modelagem Numérica de Pequenas Reflexões para Obtenção de Estruturas Multicamadas Compostas por Folhas de Material Absorvedor de Microondas. XII Encontro de Modelagem Computacional (EMC. Rio de Janeiro; Brazil.).

Singh, C., S. B. Naranga, I. S. Hudiaraa, K. C. J. Rajub, K. Sudheendran. 2010: Microwave and Electrical Properties of Co-Zr Substituted Ba-Sr Ferrite. *Journal of Ceramic Processing Research*, 11, 692-697.

****