Progress In Electromagnetics Research B, Vol. 33, 277–289, 2011

CHARACTERIZATION OF MAGNETICALLY LOADED MICROWAVE ABSORBERS

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Abstract—This work presents new method, retrieved results and validation for complex and frequency dependent permittivity and permeability parameter extraction of two composite, homogeneous and isotropic magnetically loaded microwave absorbers. Permittivities and permeabilities are extracted from free space transmission measurements for frequencies from 22 up to 140 GHz. For validation of the results reflection measurements (samples with and without metal backing) are performed and are compared with simulations that use extracted models. The proposed new method solves some shortcomings of the popular methods: extracts both permittivity and permeability only from transmission parameter measurements, gives good results even with noisy data, does not need initial guesses of unknown model parameters.

1. INTRODUCTION

Absorbing materials are in use for different purposes: in anechoic chambers, for electromagnetic shielding, in antenna design, for calibration targets of radiometers, etc. It is very important to characterize them in terms of frequency dependent complex permittivities and permeabilities for a broad frequency range. We use Eccosorb absorbing materials of Emerson and Cuming company in calibration target design. Permittivities and permeabilities of these materials are characterized by manufacturer [1] up to frequency of 18 GHz but we need to know these values at much higher frequencies. Some examples of extracted permittivity values for mentioned absorbers are given in [2, 3] but only for frequencies above

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Received 11 July 2011, Accepted 28 July 2011, Scheduled 4 August 2011

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100 GHz where permeability is equal 1 is assumed. Goal of our work is to extract frequency dependent permitivitties and permeabilities of Eccosorb absorbers for low as well as high microwave frequencies.

When electromagnetic wave interacts with material sample of the finite thickness, reflected and transmitted signals (scattering parameters) can be registered. Magnitude and phase of the reflected and transmitted signals depend on materials characteristics — permittivity (ε) and permeability (μ). It means that permittivity and permeability of certain material can be extracted from scattering parameters (S_{11} and S_{21}). Scattering parameters can be measured in different ways. Also, different methods for permittivity and permeability extractions exist.

For scattering parameters measurements coaxial line, rectangular and cylindrical waveguide measurements are widely used measurement techniques due to their simplicity [4, 5]. In these methods, material sample is placed inside of section of the waveguide or coaxial line and scattering parameters are measured with vector network analyzer. Major problem in waveguide measurements is possible existence of air gaps between the sample and walls of the waveguide. Sample that will be put in the waveguide must be very precisely machined. Also, waveguide measurements are not suitable for high frequencies because waveguide dimensions as well as examined sample dimensions become very small. Free space measurement is non invasive broadband technique for transmission and reflection parameters measurements and is suitable for measurements in microwave frequencies. Scattering parameters are measured of the sample that is plane parallel. Measurement setup consists of two identical antennas that operate in certain frequency range and vector network analyzer. For measurements, corrugated horn antennas can be used. Antennas are aligned and one of them transmits signal while the other antenna works as receiver. Material sample is placed between two antennas so sent signal passes through material and is registered by the other antenna. On that way free space transmission coefficient is measured. For reflection measurements, one antenna is connected to the vector network analyzer via directional coupler. The antenna is sending signal and also measures reflection from the sample that is in front of the antenna.

There are different approaches regarding to permittivity and permeability extractions from scattering parameters. The Nicholson Ross Weir (NRW) derivation is an analytical method that calculates permittivity and permeability from measured S_{11} and S_{21} parameters. Dependence of scattering parameters from material properties is derived considering multiple reflections of the wave incident upon the air-sample interfaces when the sample is in free space or inside of waveguide [4,5]. The problem arises when S_{11} and S_{21} are noisy. NRW derivation does not give correct results because it calculates permittivity and permeability from S_{11} and S_{21} for each frequency point. If data is noisy, then calculated values of ε and μ will be 'noisy'.

Taking various linear combinations of scattering parameters it is possible to calculate unknown permittivity and permeability [4,6]. One of the numerical methods for both permittivity and permeability determination is based on nonlinear least square optimization technique and is described in details in [6]. Complex permittivities and permeabilities are represented as a sum of resonance and relaxation terms. Measured scattering parameters are fitted with simulations in the nonlinear least square sense and unknown free parameters from permittivity and permeability models are extracted. Important thing is to have good initial guesses of the unknown parameters contained in permittivity and permeability models in order of optimization to converge to the correct solution. Initial guesses should be within 10 to 20 percent of the true values [6]. It is very difficult to use mentioned method if we do not have any a priori knowledge of material that we examine.

This paper presents method that extracts both permittivity and permeability of two composite absorbing material in the microwave frequency range. The proposed method solves some shortcomings of the popular methods: needs only transmission measurements (both amplitude and phase), gives good results even with noisy data, does not need initial guesses of unknown parameters of permittivity and permeability models. For the first time, extracted permittivity and permeability values of Eccosorb [1] CR110, CR114 and CRS117 samples up to frequency of 140 GHz will be presented.

2. PARAMETER EXTRACTION METHOD

2.1. Models for Permittivity and Permeability

Complex dielectric permittivity and complex magnetic permeability characterize materials' behavior in the presence of electromagnetic field. Polarization response of the matter to an electromagnetic excitation cannot precede the cause, so models which represent permittivity and permeability must satisfy Kramers-Kronig relation [6]. Kramers-Kronig relation is mathematical property that connects real and imaginary part of response functions (in our case permittivity or permeability). Models that satisfy causality constrain given by Kramers-Kronig relation are Debye relaxation model (1) for permittivity representation and Lorenzian resonant model (2), for permeability representation.

$$\varepsilon(f) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\frac{f}{f_r}} \tag{1}$$

In Equation (1), ε_s is the static dielectric permittivity; ε_∞ is permittivity at infinite frequency; f_r is relaxation frequency.

$$\mu(f) = 1 + \frac{\mu_s - 1}{\left(1 + j\frac{f}{f_r}\right)^2} \tag{2}$$

In Equation (2), μ_s is static permeability and f_r is resonant frequency.

There are also modified Debye relaxation models that include asymmetrical and damping factors [8]. These models are Cole-Cole (3), Cole-Davidson (4) and Havriliak-Negami (5).

$$\varepsilon(f) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\left(\frac{f}{f_r}\right)^{1-\alpha}} \tag{3}$$

$$\varepsilon(f) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{\left(1 + j\left(\frac{f}{f_r}\right)\right)^{\beta}} \tag{4}$$

$$\varepsilon(f) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{\left(1 + j\left(\frac{f}{f_r}\right)^{1-\alpha}\right)^{\beta}} \tag{5}$$

Parameters α and β in (3)–(5) are empirical parameters and their values are between 0 and 1. α is a damping factor and describes the degree of flatness or the relaxation region. β is an asymmetric factor and describes relaxation properties asymmetric around relaxation frequency.

Similar to modifications of Debye model, (6) and (7) represent modification of Lorenzian model [8].

$$\mu(f) = 1 + \frac{\mu_s - 1}{1 + j\gamma\frac{f}{f_r} - \left(\frac{f}{f_r}\right)^2} \tag{6}$$

$$\mu(f) = 1 + \frac{\mu_s - 1}{\left(1 + j\gamma\frac{f}{f_r} - \left(\frac{f}{f_r}\right)^2\right)^{k}} \tag{7}$$

In (6) and (7), γ factor is an empirical constant and represents damping factor of a resonance type. k is also empirical constant which values are between 0 and 1. It is asymmetrical factor of a resonance type.

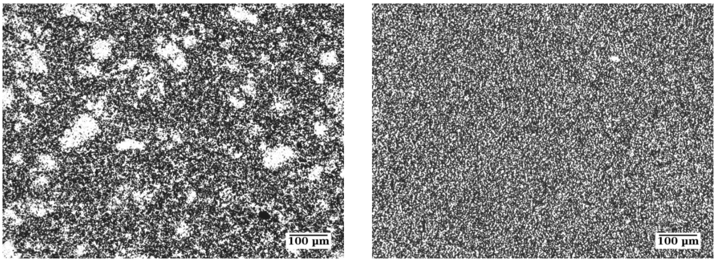
In our work, we will model dielectric permittivities of the samples with Debye relaxation model (1) and complex permeability with Lorenzian resonant model (2) and we will 'tune' permeability models by involving empirical factors k and γ. Both permittivity and permeability models can consist of multiple relaxation and resonance frequencies which depends on composition of examined material. Since examined samples are two composite (low loss epoxy and magnetic filler) and according to [7,9] it is expected to have one dielectric and one magnetic dispersion area in the frequency range from 22 to 140 GHz. From that reason, in our expressions for frequency dependent permittivities and permeabilities we use single pole models.

2.2. Measurement of Scattering Parameters

There are uncertainties in the scattering parameters measurements and they have some frequency dependence with higher frequencies having larger uncertainties. More sensitive to measurement uncertainties is S_{11} parameter [4–6]. For that reason we use free space transmission S_{21} parameter for permittivity and permeability model retrieval, and free space reflection S_{11} (sample with and without metal backing) parameter for extracted permittivity and permeability models validation. Materials that we examined are Eccosorb [1] CR110, CR114 and CRS117, 2.00 mm thick, plane parallel circular samples. In the CR materials, the particles of the magnetic filler are embedded in a castable epoxy resin, which forms a rigid material once it is cured. The CRS materials are based on a Silicone rubber which remains flexible after it has been cured. A higher product number indicates a higher filling factor of the magnetic loading and a higher absorption. CR and CRS materials (with the same product number) should have similar properties in terms of complex and frequency dependent permittivities and permeabilities.

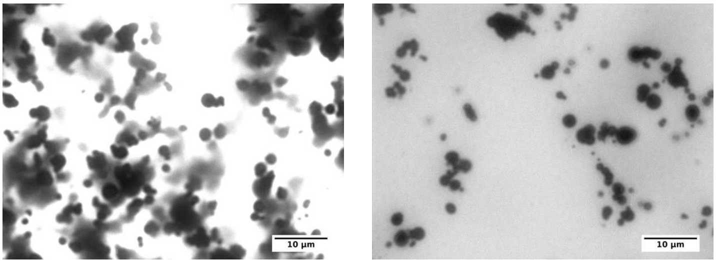
Figures 1 and 2 show microscopic photographs of CR110 and CR114. Figure 1 shows the different densities of the two materials, which had been polished to approximately 20 micrometers thick slabs for these images. The left-hand side of the Figure 2 shows the same CR110 sample at a higher magnification while right-hand side of the Figure 2 shows dispersed particles of CR114.

Our measurements and parameter extractions are performed for frequencies from 22 to 140 GHz. Antennas that we used are corrugated horn antennas which provide a better approximation of free space propagation at the aperture than rectangular antennas. Free space measurements below 22 GHz were not feasible because of the limited



(a) (b)

Figure 1. Microscopic views of (a) CR110 and (b) CR114 samples. The same magnification is used for both photographs.



(a) (b)

Figure 2. Microscopic views of (a) CR110 and (b) CR114 samples. The left photograph represents CR110 20 micrometers thick sample while the right photograph represents dispersed CR114 particles.

diameter of the samples. Instead of placing material sample between two aligned antennas, we do transmission measurements by placing sample on the aperture of one of the antennas. Calibration for S_{21} measurements is done with a 'through' measurement (8).

$$S_{21cal} = \frac{S_{21meas}}{S_{21through}} \tag{8}$$

In (8), S_{21cal} is calibrated signal; S_{21meas} is transmission parameter measured through material sample; $S_{21through}$ is through measurement.

Reflection measurements are done by placing material sample at the aperture of the antenna. The measurements are then repeated with a metal backing placed directly behind the sample. Antenna is connected to the vector network analyzer through directional coupler. For calibration purposes we measure the reference signal (metal plate is on the aperture of the antenna, 100 percent reflection) and the signal when low reflectivity pyramidal foam absorber ($S_{11foam} < -50\,\mathrm{dB}$) is in front of the antenna's aperture (to calibrate directivity). Calibration of the measured reflection parameter is given with (9).

$$S_{11cal} = \frac{S_{11meas} - S_{11foam}}{S_{11alu} - S_{11foam}} \tag{9}$$

In (9), S_{11cal} is calibrated signal; S_{11meas} is measured reflection parameter of the sample; S_{11foam} is measured reflection when foam absorber is on the top of antenna's aperture; S_{11alu} is reference reflection measurement, when metal is on the aperture of the antenna.

2.3. Procedure for Parameters Extraction

We do not have any information about epoxy and magnetic inclusions properties. Our assumptions about material samples that we examined are: they are two component composite materials (this is given by manufacturer, samples are mixtures of dielectric matrix and magnetic particles), inclusions are smaller than wavelength, material is isotropic and homogeneous at macroscopic scale. Epoxy is low loss dielectric material, while magnetic inclusions have magnetic and also dielectric properties. With previous assumptions and according to [9], if magnetic dispersion of inclusions is of resonance Lorenzian type then dispersion law for the composite will be Lorenzian as well. Analogous to that, dielectric dispersion of the composite can be modeled with relaxation Debye model.

At high frequencies ($> 70\,\mathrm{GHz}$) there are no magnetic losses because magnetization is not possible since applied field is very fast and magnetic domains cannot follow the field. Permeability is equal 1. It means that material samples exhibit only dielectric losses. We modeled dielectric losses with simple Debye model (1). Next step is to fit measured transmission parameter, with simulated S_{21}, both amplitude and phase. Fitting is based on minimization of the differences (in both amplitude and phase) between simulated and measured transmission data. Model of free space propagation is required to relate the material properties (permittivity and permeability) to the transmission (reflection) parameters. For that purpose we use routine based on Fresnel equations. There are three unknowns in Debye model for permittivity calculation, ε_s, ε_∞ and f_r. Static permittivity, ε_s is calculated for all samples by measuring capacitance of the sample at very low frequency. We measure the samples capacitance in a calibrated capacity bridge operating between 10 Hz and 20 kHz. Capacitance measurement works good if wavelength is much longer then the sample thickness. It is satisfied in our case because capacitance measurements are performed at 1 kHz frequency and samples thicknesses are 2 mm. One problem in capacitance measurements are fringing fields. To eliminate that, we measure capacitance of the sample C and then capacitance of the capacitor with air instead of material sample C_{air}. Static permittivity ε_s is expressed with (10).

$$\varepsilon_s = \frac{C}{C_{air}} \tag{10}$$

C is measured capacitance of the material sample and C_{air} is capacitance between parallel capacitor plates which are separated for a distance equal to the thickness of the material sample, but instead of material there is air.

We include measured ε_s into permittivity Debye model. The next step is to do measured and simulated data fitting at high frequencies ($\mu = 1$), both amplitude and phase, and to extract two other unknown parameters of Debye model, f_r and ε_∞. Once we have full Debye dielectric permittivity model, we can extract permeability.

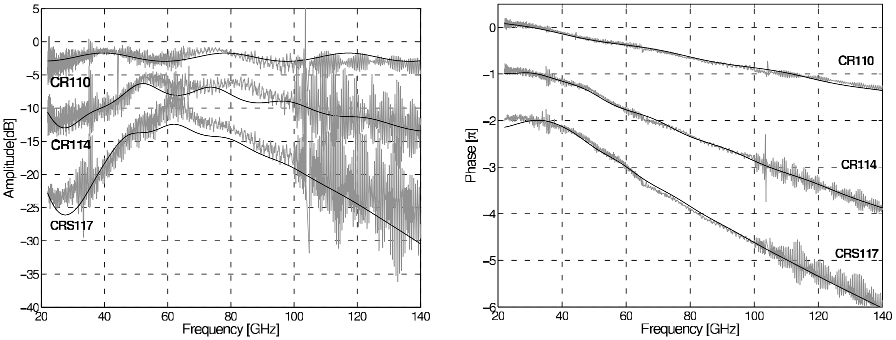
Starting guess is that permeability of the CR110 sample satisfies Debye relaxation model (same like permittivity in (1)). The reason is CR110 is the sample with the smallest amount of magnetic inclusions so permeability behavior should change from resonance to relaxation. Permeability models of CR114 and CRS117 samples are presumed to be of Lorenzian type (2). With these guesses, we do fitting of measurements and simulations at frequencies where permeability is different than 1, while for permittivity we use a model extracted in the previous step (from fitting with high frequency data). From fitting, we obtain free parameters of presumed permeability models.

3. RESULTS

3.1. Simulated and Measured Reflections

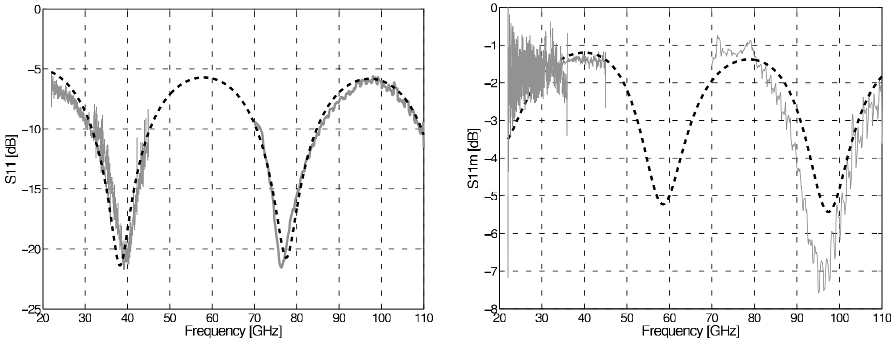
Figure 3 represents measured and fitted amplitude and phase of examined Eccosorb samples. A phase offset of one π (Figure 3(a)) has been applied between phases of different samples for clarity.

To validate extracted models for both permittivity and permeability, we compared simulated reflection parameters (samples with and without metal backing) with measurements. Comparisons are presented in the Figures 4 to 6 and good agreement between measurements and simulations is achieved. Reflection measurements are performed in Ka, U and W band. There are some inconsistencies in measurements in different frequency bands. That could come from the fact that we used different corrugated horn antennas for different frequency bands.



(a) (b)

Figure 3. (a) Measured and fitted transmission parameter amplitudes and (b) phases of CR110, CR114 and CRS117 samples.



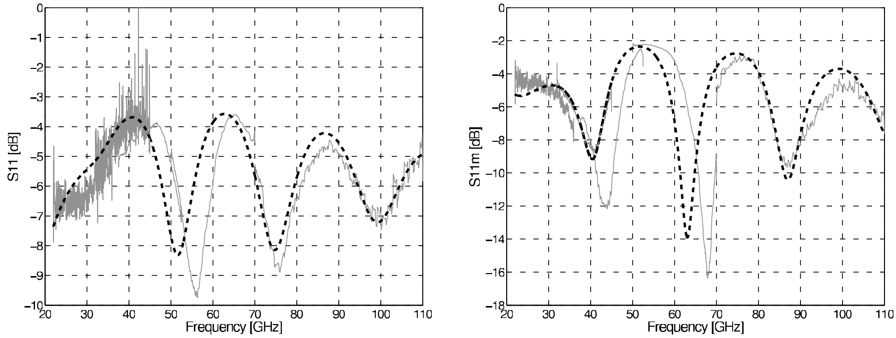
(a) (b)

Figure 4. Measured and simulated reflection coefficient of CR110 (a) without metal backing and (b) with metal backing. Dashed black line represents simulations and gray full line measurements.

Another possible source for the inconsistency in measurements can be caused by the presence of the air gaps between samples and metal backing. Small air gaps exist because some of the examined samples are not completely flat, but are bended.

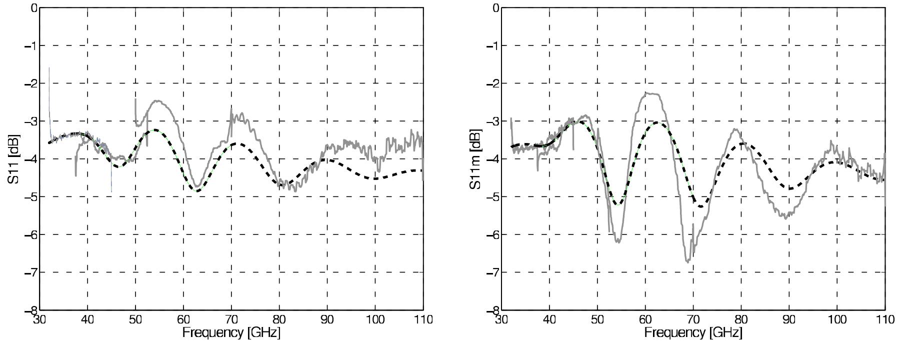
3.2. Extracted Permittivities and Permeabilities of Eccosorb Samples

By looking in amplitude behavior of transmission measurements (Figure 3) we can say that if permittivities and permeabilities are



(a) (b)

Figure 5. Measured and simulated reflection coefficient of CR114 (a) without metal backing and (b) with metal backing. Dashed black line represents simulations and gray full line measurements.

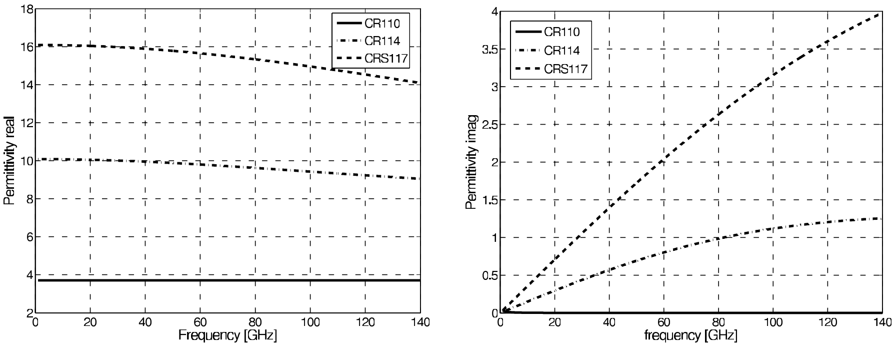


(a) (b)

Figure 6. Measured and simulated reflection coefficient of CRS117 (a) without metal backing and (b) with metal backing. Dashed black line represents simulations and gray full line measurements.

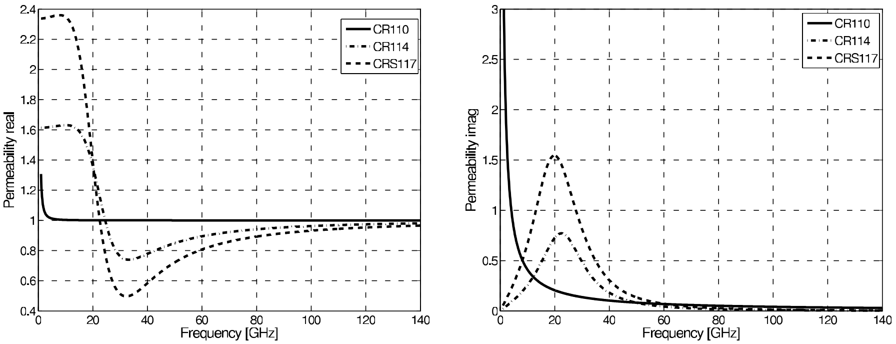
not frequency dependent, transmission coefficient would decrease with increasing frequency. The fact that measured transmission coefficient decreases in some frequency range and increase in the other, says about frequency dependent material parameters.

Figures 7 and 8 represent extracted frequency dependent real and imaginary part of permittivities and permeabilities of examined samples. As we mentioned, CR110 sample is low loss material with very small amount of magnetic particles that can produce losses. Because of the small concentration of magnetic particles, magnetic



(a) (b)

Figure 7. Real and imaginary parts of retrieved permittivity of Eccosorb samples. Data below 22 GHz is an extrapolation of the fit and can differ from the true material characteristics.



(a) (b)

Figure 8. Real and imaginary parts of retrieved permeability of Eccosorb samples. The same comment about data below 22 GHz in the Figure 7 is also valid here.

loss mechanism is transformed from resonance to relaxation (which is seen in the Figure 8, right graph, imaginary part of permeability). Both CR114 and CRS117 materials show Debye relaxation model for permittivity and Lorenzian model for permeability. The difference is that CRS117 material contains more magnetic inclusions compared to CR114 and because of that shows the highest value of imaginary part of permeability.

Permeability of magnetic materials (in the range from 0 up to GHz frequencies) can contain one or multiple dispersion areas [10, 11].

Below 22 GHz we could not perform free space measurements and for that reason we do not have sufficient data to extend the fit in this frequency range. Also, we do not have any information about chemical structure of materials that we examined. Because of mentioned reasons, we cannot be sure in correctness of the reconstructed model for permeability behavior for frequencies below 22 GHz. It is similar situation regarding dielectric losses. According to [7] dielectric dispersion area can exist at low frequencies. For these reasons, retrieved permittivity and permeability data should be used in the frequency range from 22 to 140 GHz, i.e., in the frequency range at which we performed fitting procedure. Nevertheless, Figures 7 and 8 also show the extrapolated frequency range down to 0 Hz to reveal the general shape of the fitted resonances.

4. CONCLUSION

In this paper, we described a method for frequency dependent permittivity and permeability parameters extraction of magnetically loaded absorbing materials from free space transmission measurements. Our approach can be applied to noisy data and did not need any parameter to be known in advance. Starting assumption was based on the fact that material was two composite (dielectric matrix and magnetic particles). According to [9] about models that represent composite materials, dielectric property of our samples was modeled with simple Debye relaxation model, while complex permeability was modeled with Lorenzian resonant model. Important thing was that we restored first permittivity models of the samples by fitting at high frequencies where permeability is constant and equal 1. After that step we did fitting at low frequencies to extract permeability model.

Proposed method is also suitable for permittivity extraction in dielectric materials in situations when we do not have any a priori information about material except that material is two composite, homogeneous and isotropic. Also, for the first time we presented extracted complex and frequency dependent values of permittivities and permeabilities of Eccosorb absorbing materials (CRS117, CR110 and CR114) in the frequency range from 22 to 140 GHz. Since below 22 GHz we did not perform scattering parameters measurements and fitting, we can not say if the extracted models are also valid in that region. Future work will include investigation of permittivity and permeability frequency dependence at low frequencies (from 0 up to 22 GHz) and between 150–650 GHz.

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