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Characterization of Magnetic Sheet Materials Using Waveguide Terminated by Multilayered Structure and Finite Difference Time Domain Method

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Abstract- in this work, a non-destructive technique for simultaneously EM-properties determination of planar radar absorbing materials is presented. The technique is based on using waveguide radiating into multilayered structure to produce the needed independent reflection coefficients necessary to extract the unknown EM-properties at X-band of microwave frequency range. The measurement geometry consists of rectangular waveguide with finite flange placed against a combination of the sample under test and a known material layer backed by a PEC to increase measurement accuracy. To account for finite flange, the geometry is numerically modeled via Finite Difference Time Domain (FDTD) method yielding theoretical values for reflection coefficients which is imposed on the measured ones to obtain both complex pemittivty ε_r and permeability μ_r by inverse problem. Measurement results of ε_r and μ_r for several samples of radar absorbing materials are presented. The proposed technique is promising for non-destructive simultaneous multiparameter measurements and other applications such as thickness evaluation of lossy layered media.

Keywords- *Multilayer medium, FDTD, EM properties, complex permittivity and permeability, Rectangular waveguide, Radar absorbing material, X-band Frequency*

I. Introduction

The *in situ* of EM- properties and/or thickness of radar absorbing materials measurement over a wide range of frequencies is extremely challenging. Thus, a non-destructive, fast, and accurate technique is desirable for monitoring its thickness or EM-properties of these materials. The penetration ability of microwaves inside a layered dielectric medium and their sensitivity to the boundary between two dissimilar layers make them quite suitable for this type of measurement [1][2].

Researchers have developed several methods for characterizing the electromagnetic properties of materials. Each method is suitable for some specific applications and has its own advantages and drawbacks. As non-destructive testing tools, the open-ended waveguide probe is widely used for lossy materials characterization among them [3]-[5]. This is due to its lessening of some restrictions on sample preparation and openness in structure make it able to be readily used for this type of measurement. Also, waveguide is more suitable once the testing is going to be performed for characterization of high absorption materials, due to high level radiation of power from its aperture. For reflection only probes such as open-ended rectangular waveguide, since two complex quantities are to be extracted (ε_r and μ_r) an experimental procedure is required in which two-independent reflection coefficients are measured using this technique. To achieve this purpose, three methods have been proposed via changing frequency, or changing thickness or changing part of the sample namely called frequency-varying method, thickness-varying method and sample-varying method respectively. Although frequency-varying method [6][7] simplifies measurement process, but the main problem with using this method is that the choice of frequency deviation *(Δf)* should be selected as small as possible such that the reflection coefficient is changed enough to be distinguished by Automatic Network Analyzer (ANA). Also, thickness-varying method proves to be a viable, accurate method in a laboratory environment, where unknown material samples can be fabricated as needed [8]. However, for *in situ* measurements, sample-varying method becomes a more suitable option than the thickness-varying method. Many researchers has examined and investigated this technique for layered medium characterization and theoretical formulations of the probe input admittance have been developed under the assumption that the probe has infinite in extend flange [9]-[14]. For high-loss materials, researches have shown that in order to obtain approximate results in the measurement, the flange dimension must be chosen larger than or equal to 1-2 wavelength in the media [11]-[16]. In order to include the effect of probe finite flange on measurement, numerical analysis can be applied to model problem geometry since it is quite difficult, in this case, to use analytical procedure. A variety of electromagnetic phenomena and complex geometries have been simulated numerically using FDTD method because of its flexibility, and versatility [17]-[19]. But to the best of author's knowledge no appreciable work is available in the open literature where FDTD is used to evaluate both complex permittivity and permeability except [20]-[23] where FDTD is used to determine complex permittivity only.

In this paper, multilayered structure technique with open-ended waveguide is proposed, as shown in Fig. 1, to perform simultaneously multiparameter (EM-properties) determination of radar absorbing materials. The proposed technique is based on the fact that for simultaneous multiparameter measurement using reflection only probe, if there are *n* unknowns to be determined, we need at least an independent measurements of reflection coefficient to be able to solve even one of them. Both complex permittivity and permeability of sheet (planar) radar absorbing materials are to be extracted from two independent reflection coefficients measurement achieved by using structure with two layers as shown in Fig. 2. The material under test sample is to be tested first with known thickness (single layer), then to test again a combination of this sample followed by another one with known permittivity, permeability and thickness (two layers), backed by a perfect conductor (PEC) forming a multilayered structure sample. FDTD method is applied for the geometry of the problem to numerically calculate the probe aperture admittance or its equivalent reflection coefficient. The obtained results of ε_r and μ_r for selected radar absorbing material samples by inverse problem using FDTD modeling and measurements are to be verified by comparing with the reference data to demonstrate the feasibility of the proposed technique.

II. FDTD MODELING OF THE PROBLEM

The geometry of the proposed technique is shown in Fig. 1. It can be considered as a system consisting of waveguide probe radiating into *N* layers of lossy materials backed by metal. The multilayer structure problem is encountered in many practical applications. For example, in modern military technology or in electromagnetic shielding, it is required to reduce reflections of electromagnetic waves of the RF and microwave frequency ranges from metal surfaces. This problem may be solved by placing a layer (or layers) of composite radar absorbing materials. Since the aim of this paper is to determine two complex quantities (ε_r and μ_r), we limit ourselves, without loss of generality, to two layers problem as shown in Fig. 2. As shown in Fig. 2, an open-ended rectangular waveguide with finite flange is placed on the top of two layers of materials. The upper layer is the material under test (MUT) with unknown parameters ε_{r1} and μ_{r1} and known thickness d_1 followed by a layer of known EM-properties material ε_{r2}, μ_{r2} and thickness d_2. backed by perfect conductor. The waveguide used in the measurement is with dimensions (*a* and *b*) chosen such that only the dominant TE_{10} mode propagates at X-band of microwave frequency range. The energy radiated from the probe penetrates through different layers and reflected back into the aperture. The material properties and thicknesses information are carried by reflection coefficient Γ_o.

In this paper FDTD method is used to formulate the problem under consideration and calculate reflection coefficient. The geometry of the problem shown in Fig.2 consists of an internal region and an external region. The internal region is the interior of rectangular waveguide probe while the external region is the multilayer material (material under test and known properties material) backed by PEC. For rectangular waveguide probe, by using FDTD modeling, the electromagnetic fields distribution can be calculated inside the waveguide and the material under test at different physical conditions and then the reflection coefficients. Both material regions can be considered as lossy materials or a combination of lossy and low loss materials and assumed to be linear, isotropic, and homogeneous. It is also assumed that the thicknesses of both layers are known. For a uniform, isotropic and homogenous media with the medium permittivity ε and the medium permeability μ, Maxwell differential equations are given using (1) and (2):

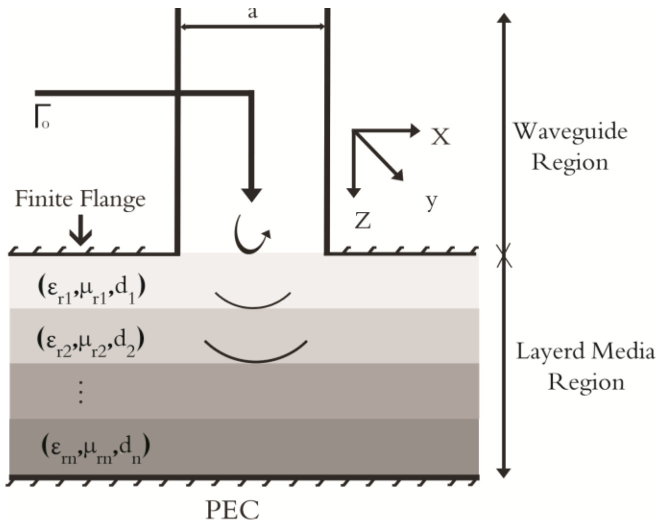


Figure 1. Geometry of the proposed technique

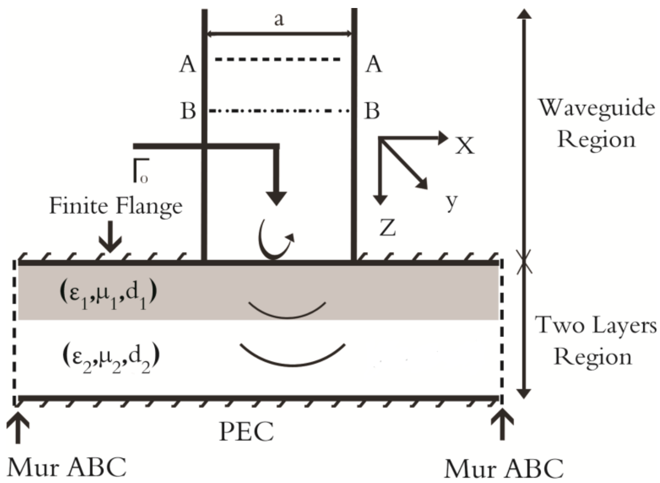


Figure 2. Schematic diagram of two layers sample testing

$$\nabla x E = -\mu \frac{dH}{dt} \quad (1)$$

$$\nabla x H = \varepsilon \frac{dE}{dt} \quad (2)$$

Equations (1) and (2) can be expressed in a 3D rectangular coordinate system (x,y,z) to obtain the system of Maxwell's differential equations. To numerically solve these equations, Yee [24] has proposed an approach which divides the medium of interest into a mesh of lattices with dimensions of δx, δy, and δz. Rectangular three dimensions cells were used to divide the available FDTD space of the problem with the sizes of Δx, Δy and Δz in x, y and z axis respectively. A space lattice point (i,j,k) is then denoted as:

$$(i, j, k) = (i\Delta x, j\Delta y, k\Delta z)$$

where Δ is the space increment. The electromagnetic fields (*E* and *H*) are assumed interleaved around a cell with origin located at i, j, k with *E* field located 1/2 cell width in the direction of its orientation from the origin and *H* field is offset 1/2 cell in each direction. Following Yee procedure, the central difference approximation is used on both the time and space first-order partial differentiation for equation. (1) in *i* direction to obtain discrete approximation. This gives:

$$\mu \frac{H^{n+1/2}_{xi,j,k} - H^{n-1/2}_{xi,j,k}}{\Delta t} = \frac{E^{n}_{yi,j,k} - E_{yi,j,k-1}}{\Delta z} - \frac{E^{n}_{zi,j,k} - E^{n}_{zi,j-1.k}}{\Delta y}$$

Rearranging gives:

$$H^{n+1/2}_{xi,j,k} = H^{n-1/2}_{xi,j,k} + \frac{\Delta t}{\mu \Delta z}[E^{n}_{yi,j,k} - E^{n}_{yi,j,k-1}] - \frac{\Delta t}{\mu \Delta y}[E^{n}_{zi,j,k} - E_{zi,j-1,k}]$$

The same procedure can be followed to obtain the other field's central difference approximation using (1) and (2) respectively. Absorbing boundary condition (ABC) is used to truncate the computational domain of the problem. Usually more than one mode is excited inside the rectangular waveguide. In this work the dominant mode (TE_{10}) is only considered, therefore a simple ABC is adequate for this purpose. A fine spacing cell with dimensions of Δx =0.05 mm, Δy =0.05 mm, Δz =0.05 mm is used within the probe and the MUT to increase the calculation accuracy. The constitutive parameters with effective (average) values are used to calculate field components at different interfaces. Various approximately absorbing boundary conditions have been proposed. The first-order Mur absorbing boundary condition [25] is used at plane A-A' of the waveguide and at the radial boundary of the problem space to limit the computational domain and increase the computational efficiency. A forward-moving TE_{10} wave is lunched at the excitation plane B-B'. The distribution of the field in the multilayer medium and the probe are calculated using Yee cell procedure. The source is assumed to be turned on time t = 0 and propagation of waves from the source is computed at each of the spatial lattice points by using the finite difference equation to march forward in time. This process continuous until a desired final steady state has been reached. The input admittance of the probe aperture is obtained by calculating field's components within multilayer medium. According to the transmission line theory, the probe complex reflection coefficient, Γ_o, is calculated at sampling point located away from the aperture to avoid higher order modes that may exist at the aperture multilayer medium interface boundary using (3).

$$\Gamma_0 = \frac{Y_a - Y_0}{Y_a + Y_0} \quad (3)$$

where Y_a and Y_0 are the aperture admittance and the equivalent characteristic admittance of the waveguide, respectively.

III. FDTD MODELING VALIDATION

A code of 3D is developed to calculate the probe input admittance and its reflection coefficient for different physical conditions of the measurement using FDTD modeling. Several simulations are conducted for different samples of radar absorbing materials to calculate the probe reflection coefficient using WR-90 rectangular waveguide probe and the obtained results are compared with the published data to verify the developed FDTD code. To achieve this purpose a comparison is made between the results of calculated reflection coefficient using FDTD modeling and those obtained from analytical formulation of reflection coefficient derived for multilayer sample under assumption that probe flange is infinite in extend and previously published in [11]. In this work, the flange dimension of the waveguide probe is taken to be 50.0 mm[15][16]. The comparison is made for two cases; the single layer case when the material under test (RAM 9052) with complex permittivity of 18.18 – *j*0.418 and complex permeability of 1.55 – *j*1.984 and thickness of 4.18 mm is only considered and the case when a combination of material under test followed by known material to form two layers sample. Teflon as a low loss material is chosen to be a known material [11]. The obtained results are calculated at *f* =10 GHz. Table I show the results obtained for the two cases. From the table, it is clear that a good agreement between FDTD results and analytical data is obtained. For the two cases, the variation in the reflection coefficient obtained analytically closely follows the simulation results of FDTD modeling validating the computational tool.

TABLE I. COMPARISON OF THE REFLECTION COEFFICIENT RESEULTS OBTAINED USING FDTD MODELING VERSUS ANALYTICAL DATA [11] FOR SINGLE LAYER AND TWO LAYERS SAMPLE. RESULTS WERE CALCULATED AT F =10 GHZ.

Sample	Model	Γ (Magnitude)	Γ (Phase in Degree)
Single layer	FDTD	0.4291	-140.29
	Analytical [11]	0.4364	-139.08
Two layers	FDTD	0.4086	-141.39
	Analytical [11]	0.4160	-138.58

IV. TWO LAYERS PERFORMANCE ANALYSIS

The parameters ε_r and μ_r of material under test extracted using reflection only probe are taken to be those values obtained by inverse problem which minimize the difference between the theoretical (Γ^{thy}) and measured (Γ^{mea}) values of the probe reflection coefficient. These two reflection coefficients should be obtained under two different measurement conditions. Under these circumstances, the parameters ε_r and μ_r are obtained to be the roots of the two function given in (4) using search algorithm

$$
\begin{aligned}
f(\varepsilon_r, \mu_r) &= \Gamma_1^{thy} - \Gamma_1^{meas} \\
g(\varepsilon_r, \mu_r) &= \Gamma_2^{thy} - \Gamma_2^{meas}
\end{aligned} \tag{4}
$$

It is clear from (4) that in order to obtain accurate extraction of material under test parameters, an accurate knowledge of the theoretical reflection coefficient prediction is needed. Using the proposed technique, Γ^{thy} is obtained using FDTD modeling for the geometry of the problem under consideration since it quite difficult to use analytical procedure. The two reflection coefficients (Calculated and measured) are made by first applying the probe to the material under test (Γ_1) and then applying the probe to a multilayer material (Γ_2). Hence, an error analysis becomes necessary to investigate the effects of the properties of known material combined with the material under test on the accuracy of the measured and calculated reflection coefficient.

In order to get a better insight into the nature of the problem, a series of experiment are conducted for this purpose. Measurements corresponding to the two selected samples of known-material combined with the material under test are performed using HP-8510B automatic network analyzer over X-band of microwave frequency range (8.5 – 12.5 GHz). Fig. 3 shows variations of the calculated and the measured reflection coefficients tested for two conditions when only a single layer of MUT (single layer) is used, and the case when two layers (both MUT and known material) are used . For two-layer case, two known materials are suggested; the first one is low loss material while the second one is high loss material. The material under test used in first case is high loss material with thickness of 3.5 mm and complex permittivity of $\varepsilon_r = 16 - j0.96$ and complex permeability of $\mu_r = 1.5 - j\,1.02$. For the second case, the measurements are performed with two steps. In the first step, the same MUT is combined with low loss material (Teflon) of 3.175 mm thickness while in the second step a high loss material with complex permittivity of $\varepsilon r = 18.1 - j\,0.416$ and complex permeability of $\mu r = 1.8 - j\,2.149$ and thickness of 2.1 mm is combined with the MUT. It is clear from the figure that the magnitudes of reflection coefficient for the case of single layer over a given frequency range is higher than that for the case of two layers (both of low loss and high loss of known-material). This is due to that in lossy materials, the fields' decay faster by which the reflection decreases. Also, the magnitudes of reflection coefficient for two layers sample with low loss known material is higher than that of two layers with high loss known materials. This is because that the reflection coefficients in case of using high loss known-material decays faster than in the case of using known-material with low loss. Moreover, Fig. 3 shows that as the high loss known-material becomes too thick, the variation in the reflection coefficient (both the amplitude and the phase) becomes duller, and finally tends to be very small for thicker samples. This is because the two layers sample is so lossy that the decaying reflection wave from the short-circuit plate can not influence the input wave on the flange plane as compared to the case when the known material used is low loss material On the other hand, using Low-loss known material layers provide for more field penetration than lossy known material layers and thus produce less error in the values of extracted MUT parameters. The results obtained in this analysis show that using of high loss materials as known material layer strongly affects the sensitivity and the accuracy of the measurement. It can be concluded that it is important to choose a proper known material for testing using this technique. Hence, low-loss materials such as Teflon, nylon, plexiglass, and PVC are suggested to be used as a known material layer. This was also validated by [14].

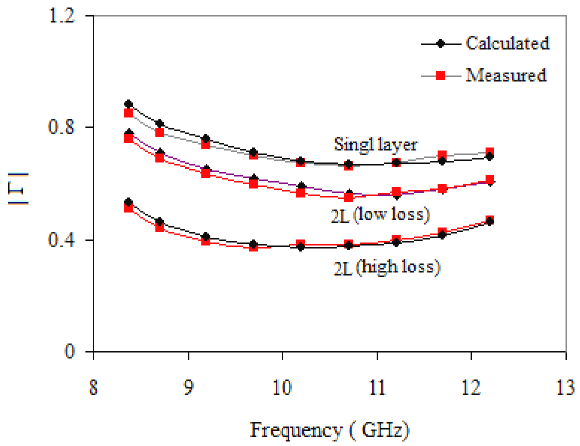


Figure 3. Variations of the magnitude of the calculated and measured reflection coefficients of high loss materials for case of (a) Single layer sample. (b) Two layers low loss known sample (c) Two layers high loss known sample

V. VARIFICATION OF EXPERIMENTS

The conclusions obtained from the numerical analysis in the previous section have been verified experimentally. The main goal of this paper is to extract both ε_{r1} and μ_{r1} of high loss material using FDTD modeling for the geometry shown in Fig 2. Several simulations are conducted to calculate probe reflection coefficients in conjunction with sets of experiments for this purpose. Since two complex quantities are to be determined (ε_{r1} and μ_{r1}), two complex reflection coefficients are needed. Hence, two tests should be performed, one sample of material under test with unknown electromagnetic properties to test first, then to test again a combination of this sample and another one whose ε_r and μ_r are known, forming a multilayer sample. These two tests provide two conditions needed to obtain two complex reflection coefficients. Then, a right ε_{r1} and μ_{r1} pair should lead the calculated reflection coefficients as little difference as possible to the measured ones. These two reflection coefficients (the measured and calculated) can be described by a set of simultaneous equations using (5)

$$\Gamma_{m1} = \Gamma_{C1}(\varepsilon_{r2}, \mu_{r2}, f, d_2)$$
$$\Gamma_{m2} = \Gamma_{C2}(\varepsilon_{r1}, \varepsilon_{r2}, \mu_{r1}\mu_{r2}, f, d_1, d_2) \quad (5)$$

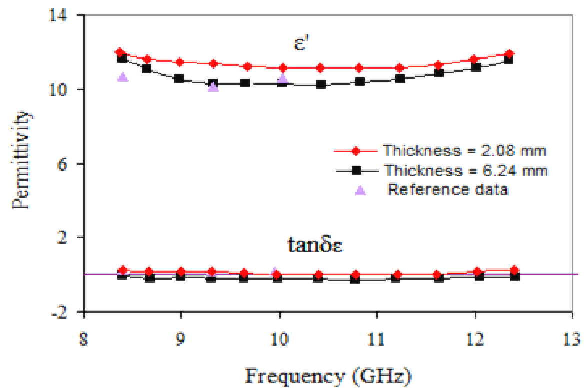
from which we are able to work out through numerical iterations using optimization technique by inverse problem to obtain both complex permittivity $\varepsilon_r = \varepsilon'(1-j\tan\delta_\varepsilon)$ and complex permeability $\mu_r = \mu'(1-j\tan\delta_\mu)$ at operating frequency f; the other symbols are defined pictorially in Fig. 2. Several experiments on various samples of radar absorbing materials are performed over X-band (8.2 – 12.4 GHz) in order to extract their EM-properties. The first set of experiments is performed and the measurement results of a ferrite absorber complex permittivity and permeability is presented in Table II and Compared with corresponding reference data given by the ECCOSORB MF Technical Bulletin and the Marconi Company. The experimental procedure used for this purpose is with two steps. First, the calculated and measured reflection coefficients are performed for a single layer sample of 4.1 mm thickness with unknown properties ε_{r1} and μ_{r1} and then the calculated and measured reflection coefficients are performed for a combination of the same sample and a Teflon as known-material sample of 3.175 mm thickness is used. From the table, it can be seen that the data obtained using the proposed technique and reference data are fairly consistent. Both ε_{r1} and μ_{r1} are extracted iteratively by imposing the measured values of reflection coefficients on the calculated reflection coefficient using FDTD modeling. A second set of experiments is performed to investigate the influence of MUT sample thickness on the extracted parameters. Fig. 4 shows the measurement results of the same ferrite absorber with two different thicknesses value of 2.08 mm and 6.24 mm using the proposed technique over a given frequency range. Fig.4 (a) shows variation of complex permittivity (both ε' and loss tangent $\tan\delta_\varepsilon$) while Fig.4 (b) shows variation of complex permeability (both μ' and loss tangent $\tan\delta_\mu$). It can be seen from the figure that good agreement between the measured results and the reference data is achieved, but the thickness effect on sensitivity and accuracy is also obvious. The results of sample with thickness of 6.24 mm show a relatively larger deviation in the loss tangents (especially the $\tan\delta_\varepsilon$ becomes minus). The sample has a small $\tan\delta_\varepsilon$ (≤ 0.1) and whose thickness is too thicker are the dominant reasons. The obtained results suggest that the open-ended waveguide sensor is at its best for measuring high-loss materials, so it difficult to get reasonable accuracy for $\tan\delta_\varepsilon$ which is less than 0.1(here, the actual $\tan\delta_\varepsilon$ is about 0.06).

TABLE II. COMPARISON BETWEEN THE FDTD RESULTS VERSUS REFERENCE DATA OF THE COMPLEX PERMITTIVITY AND PERMEABILITY OF RAM MATERIAL UNDER TEST. RESULTS WERE CALCULATED AT F = 10 GHZ

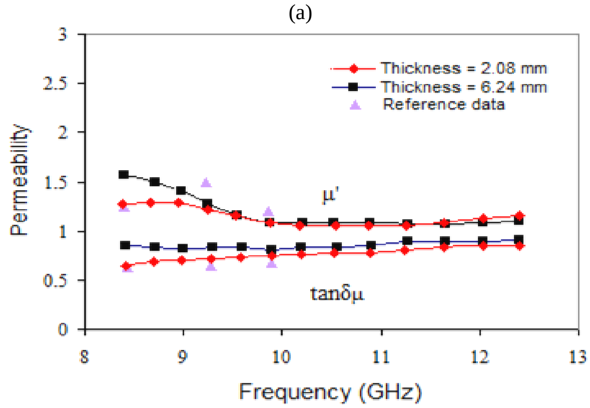
Parameter Method	Complex Permittivity		Complex Permeability	
	ε'	$\tan\delta_\varepsilon$	μ'	$\tan\delta_\mu$
FDTD Model	15.32	0.051	1.65	0.726
Reference data	15.64	0.048	1.71	0.742

VI. EM-PROPERTIES EXTRACTION

This is an inverse problem to determine both complex permittivity ε_{r2} and complex permeability μ_{r2} of the tested sample as shown in Fig. 2. Iterative-Optimization technique is used to extract them. By using the Γ value, both obtaining from FDTD modeling and experiment value, these parameters can be extracted. The extracted material parameters ε_{r1} and μ_{r1} are taken to be those values that minimize the difference (δ) between the theoretical and measured values of the waveguide reflection coefficient under two measurement conditions using (5). The permittivity and permeability of the MUT are then found by solving the nonlinear system of (5) numerically using search algorithm. The inverse problem can be solved by using the Newton-Raphson method or the Levenberg-Marquardt method [26]. At the beginning, initial values of ε_{r1} and μ_{r1} are assumed, then Γ_{C1}, Γ_{C2} are calculated numerically with FDTD modeling using (3). If the difference of the two functions using (5) is greater than a user desired tolerance δ , new values of ε_{r1} and μ_{r1} will be updated automatically. Then a new value is evaluated for the difference of two equations from the new values of ε_{r1} and μ_{r1}. This procedure is repeated until the value of the difference is less than δ. A computer program was written to implement this optimization procedure. In this paper, the inverse problem is solved by using Newton-Raphson method. Starting with good initial guesses, this iterative algorithm guarantee a correct convergence in most cases but the converge process is very time-consuming especially for multiparameter measurement (more than two parameters).



(a)



(b)

Figure 4. Variation of EM-parameters of a radar absorbing material with sample thickness (a) complex permittivity. (b) Complex permeability

It is to be noted that errors due to extraction of both complex permittivity and permeability using two layers method have been extensively studied in [14]. One of these errors is that accurate parameters extraction is predicated in part on having accurate knowledge of the theoretical reflection coefficient. Using an approximate solution for Γ^{thy} introduces additional errors which is one of the stated goals of this paper. This approximate solution is usually obtained from the developed theoretical formulations of the problem under consideration which are derived based on the assumption that the probe flange is infinite in extend, which cannot be practically realized. In this paper FDTD modeling is suggested to reduce the error that may occur due to using these theoretical formulations.

VII. CONCLUSIONS

A multilayer media non-destructive technique for characterizing the electric and magnetic properties of conductor-backed absorbing materials using a finite-flanged rectangular waveguide probe is presented. FDTD modeling is applied to account for finite flange dimension and numerically calculate the probe reflection coefficient at different physical conditions. It is found that the measurement accuracy using the proposed technique is highly dependent on how much known-material layer is lossy. Low-loss known-material layers provide for more field penetration than lossy known-material layers and thus produce less error in the measurement. Results of the variation of complex permittivity and permeability (real and imaginary parts) with sample thickness over a given frequency range have shown that the imaginary parts (loss tangent) of permittivity has large deviation with respect to the reference data especially for thicker sample. Moreover, the accuracy of measurement becomes poorer as the thickness increases for thicker lossy coating. Therefore, the proposed technique is particularly suitable for the measurement of high-loss materials with a several-millimeter thickness such radar absorbing coatings. The measurement results have shown the validity of using FDTD method in modeling the geometry of the problem where it is quite difficult to use the analytical procedure by a coverage the limitation with the formulations developed under assumption of infinite flange of the probe.

The measurement geometry described in this paper is limited to two media, which yield enough information to determine simultaneously electric and magnetic parameters. Since the probe's reflection coefficient is sensitive to permittivity, permeability, thickness and the operating frequency, the technique can be extended to include multilayer structure problems to perform simultaneous multiparameter measurement.

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