A Nondestructive Technique for EM-Parameter Determination of Compound Materials using Rectangular Waveguide Sensor and Layered Material Media

Abdulkadhum A. Hassan [1], Janan H. Saadie[2]

[1] Department of Electrical Engineering, Faculty of Engineering, Kufa University, Al-Najaf, Iraq
[2] Department of Material Engineering, Faculty of Engineering, Kufa University, Al-Najaf, Iraq

Abstract— In this paper, an improved technique of using open-ended rectangular waveguide sensor for simultaneous non-destructive complex electromagnetic parameters determination of compound absorbing materials is developed. The technique is based on employing a layered material medium, which consists of material to be tested and known materials, sandwiched between sensor aperture and perfect conductor plate to obtain two complex reflection coefficients necessary to achieve this purpose. Finite-Difference Time-Domain method is adapted to account for the finite flange size of the sensor and numerically calculate the sensor reflection coefficient under different test conditions. The technique can be employed for cases of single layer and multilayer medium planar sheet measurement. The parameters of the material under test are obtained by fitting both the calculated and measured reflection coefficients using the iterative optimization technique. The details related to the analysis, FDTD modeling and testing procedure of the proposed technique is discussed. The simulations and experimental results are compared with the published data by literatures and companies to validate the proposed technique. The technique is promising for potential applications such as design and fabrication of sheet or layered coating materials and nanocomposite material and bio-medium characterization.

Keywords— FDTD; Non-destructive test, Dielectric and magnetic characterization, layered medium, rectangular waveguide sensor.

I.   INTRODUCTION

Radar absorbing materials (RAMs) is essential in a wide range of applications such as radar detection, shielding and electromagnetic compatibility technology [1-5]. These materials are usually designed and fabricated from compound materials as a sheet or coated on metallic structures in order to reduce unwanted reflections or to reduce the radar cross section area of an object. Moreover, these materials are usually used in a specific application to provide a certain performance of reflectivity over a given frequency range especially at microwave and millimetre wave [6]. The design of radar absorbing materials is constrained by many factors, including thickness, weight, and absorbing properties, which are described by both complex permittivity $\varepsilon_r = \varepsilon' - j\,\varepsilon''$ and complex permeability $\mu_r = \mu' - j\mu''$ over broadband frequency range. These properties are strongly influenced by the frequency at the microwave frequency range [7-8].

For many years, evaluation of electromagnetic properties of materials has been known to be a fundamental aspect of microwave and millimetre-wave technology especially radar absorbing materials [9-11]. It has aroused considerable interests in developing measurement techniques to characterize these materials quickly, accurately, and conveniently. Recently, various techniques are proposed and developed to characterize electromagnetic properties of radar absorbing materials at microwave frequency range with their respective advantages and drawbacks among the others is open-ended rectangular waveguide sensor [12-13]. This technique is widely used to determine both complex permittivity ε_r and complex permeability μ_r over a wide band of frequency range [14] due to its simplicity and openness in its structure. Moreover, it requires less sample preparation. These merits make the technique suitable for characterizing the electromagnetic properties of materials under laboratory and field conditions since the sensor is placed directly against the material under test [15]. Currently, Finite Difference Time Domain (FDTD) method is employed to simulate absorbing ability of radar absorbing materials to electromagnetic waves [16]. Also, with increasing the use of nanocomposite materials, there is a demand for characterization of these materials, starting from the designing process up to the fabrication stage [17] due to its ability to handle complex structures and geometries. In this paper, a technique of using rectangular

waveguide sensor irradiating into a layered material medium in conjunction with FDTD method is proposed to simultaneously determine both complex permittivity and permeability (ε_r and μ_r) of compound absorbing materials. The structure, which consists of material under test backed by known low loss material, is sandwiched between sensor aperture with finite flange and perfect conductor plate to measure two complex reflection coefficients necessary to determine ε_r and μ_r. FDTD method is employed to theoretically calculate the sensor reflection coefficients under different physical test conditions. It is also can be evolved to simulate the design of the electromagnetic wave absorber. The calculated reflection coefficients of the sensor are imposed on the measured values to extract ε_r and μ_r by iterative-optimization technique over an X-band of microwave frequency range. To effectively model these materials, the thickness variation and frequency characteristics of ε_r and μ_r of these materials are studied. The FDTD simulations and measurement results on selected samples of compound absorbing materials are presented and some guidelines for this technique of measurement are highlighted.

II. PRINCIPLES AND ANALYSIS

Figure 1 shows the geometry of the proposed technique used to perform ε_r and μ_r measurement. As shown, the geometry consists of finite flange open-ended rectangular
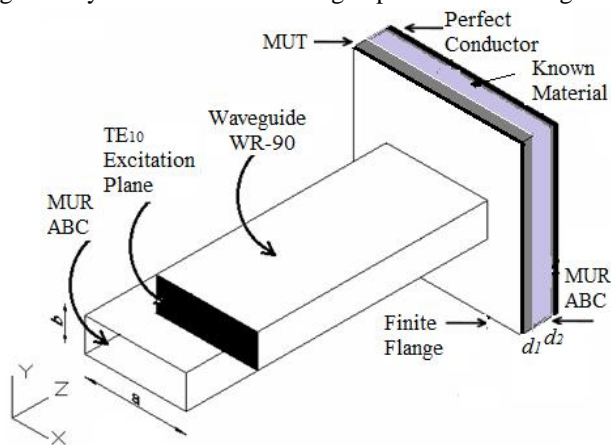

Fig.1: Geometry of the proposed technique:

waveguide sensor in Cartesian coordinates with wide and narrow dimensions (*a* and *b*) placed directly against layered material medium consisting of the material under test with unknown ε_r and μ_r and known thickness d_1, followed by known ε_r, μ_r and thickness material and the whole structure is backed by a perfect conductor to increase measurement sensitivity. The backing known material used should be low loss material to increase measurement accuracy [18]. As shown in Fig. 1, the reflection coefficient symbolized Γ_o (*a, b*, ε_r, μ_r, *f, d*) is a complicated function of the waveguide sensor dimension

a, b, test frequency *f*, sample thickness *d*, and the parameters of the material under test ε_r and μ_r. The energy radiated from the sensor penetrates through the layered material medium and reflected back into the aperture. Consequently, the reflection coefficient calculated at the sampling point carries the desired information of material under test. The EM-parameter extraction of material under test by the inverse problem process includes finding the values of ε_r and μ_r which minimize the difference between the reflection coefficient theoretically determined (Γ_{th}) and the measured one (Γ_m) obtained under different test conditions. Therefore, for accurate extraction of ε_r and μ_r, the theoretical reflection coefficient of the sensor must be accurately predicted. Using the approximate solution for theoretical reflection coefficient introduces error in the extracted values of ε_r and μ_r. Hence, the problem geometry is formulated using FDTD method to account for the finite size of waveguide flange and accurately predict the reflection coefficient under different test conditions.

1. The Proposed Technique

The main objective of this work is to develop a technique for simultaneous ε_r and μ_r determination of compound absorbing materials during the design phase and fabrication process respectively. In principle, to extract four parameters, two complex reflection coefficients are required. For measurement purposes, in order to determine two complex quantities (ε_r and μ_r) with the assumption that the material under test is backed by conductor, it is necessary to perform a certain experimental procedure to measure the needed two independent complex reflection coefficients under two different test conditions. Physically, the two conditions can be achieved by different ways. Using the proposed technique, the following two ways can be performed to obtain these two conditions as shown in Fig. 2 (*a* and *b*).

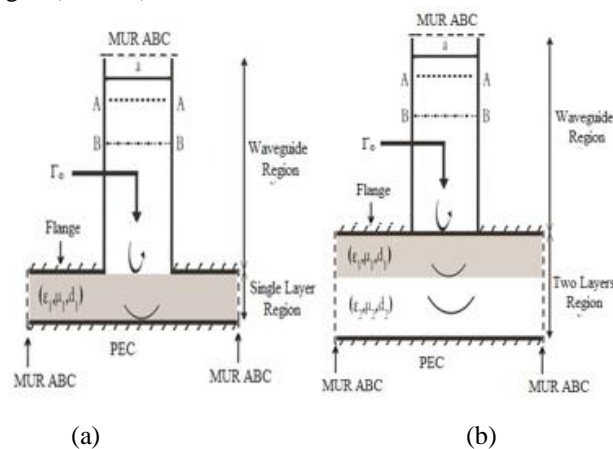(a)   (b)

Fig.2: Conditions of reflection coefficient measurement
(a) Single layer test (b)Two layers test
1.1 *Single-Layer Test*

This test is to be performed to obtain one of the two needed reflection coefficients. In this test, the material under test with unknown ε_r and μ_r and known thickness d_1 (only single layer) is sandwiched between the rectangular waveguide sensor and the perfect conductor as shown in Fig. 2 (a). The measured reflection coefficient ρ_{m1} is described using (1):

$$\rho_{m1} = \Gamma_o(\varepsilon_r, \mu_r, f, d) \tag{1}$$

As can be seen in (1), the reflection coefficient is frequency dependent while the frequency is an independent variable. It is to be noted that both complex permittivity ε_r and permeability μ_r of most materials are also frequency dependent and they are slowly varying with frequency.

1.2 *Multilayer Structure Test*

This test is to be performed to obtain the second reflection coefficient. A medium with two layers is used for this purpose as shown in Fig. 2 (b). In this test, the sensor is placed in close contact with a multilayer structure consisting of the material under test with unknown ε_r and μ_r followed by known material and the whole structure is backed by the perfect conductor. The measured reflection coefficient ρ_{2m} is described using (2):

$$\rho_{m2} = \Gamma_o(\varepsilon_r, \varepsilon_r', \mu_r, \mu_r', f, d, d') \tag{2}$$

Where ρ_{m1} and ρ_{m2} are the reflection coefficients measured at different test conditions, ε_r, ε_r', μ_r and μ_r' are relative permittivity and relative permeability of the tested sample and known material, d_1 and d_2' are thicknesses of material under test and known material respectively. It is to be noted that using medium with two layers provides enough information to extract ε_r and μ_r of material under test (using both single layer and two layers tests) while using only single layer test provides the required information if frequency-varying method or thickness-varying method is employed. The proposed technique can be also applied to perform multiparameter measurement (complex permittivity, complex permeability, and thickness) using a medium with N different layers. The rectangular waveguide sensor used in the measurement has practically a flange with finite dimension which makes it possible to test high loss sheet samples. For finite flange rectangular waveguide sensor, by using the FDTD method, both electric and magnetic fields distributions are calculated at different physical test conditions. Consequently, the reflection coefficient Γ_0 of the sensor can be determined according to the theory of transmission-line.

2. Numerical Modeling using FDTD Method

The Finite-Difference Time-Domain method has been initially proposed by Yee [19] to numerically solve the Maxwell equations and developed by Taflove [20]. It has been proven to be the most popular numerical technique successfully applied for the solution of electromagnetic problems with complex geometries [21]. In this paper, FDTD method is employed to calculate the sensor aperture reflection coefficient since it is quite difficult, in this case, to apply the analytical approach. Figure 2 (a and b) shows the analytical model of the problem in 3D Cartesian coordinates considering only the dominant TE$_{10}$ mode of the field with sensor dimensions of a and b respectively. The boundary space of the problem is divided into two regions. The first region is the interior of the waveguide (region 1) while the second region is the multilayer structure backed by perfect conductor. Each region within the geometry is assumed to be linear, isotropic and homogeneous in nature and characterized by both ε and μ. The set of Maxwell's curls equations are given using (3) and (4):

$$\frac{\partial E}{\partial t} = \frac{1}{\varepsilon} \nabla x H \tag{3}$$

$$\frac{\partial H}{\partial t} = -\frac{1}{\mu} \nabla x E \tag{4}$$

Using 3D Cartesian coordinate system (x,y,z), eqs. (3) and (4) are expressed in a system of six coupled Maxwell's differential equation. For x-coordinate of both electric and magnetic fields' components, the differential equations are described using (5) and (6):

$$\frac{\partial H_x}{\partial t} = -\frac{1}{\mu}\left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z}\right) \tag{5}$$

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z}\right) \tag{6}$$

Yee has proposed an approach to numerically solve these equations by which the problem space is divided into a mesh with lattices. A point *(i,j,k)* in lattice space is denoted as:

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

where Δ is the increment in x, y, z directions. According to Yee procedure, both electric field E and magnetic field H are distributed to be interleaved with respect to cell whose origin is located at *(i, j, k)*. The components of both electric and magnetic fields are updated in discrete time-steps of Δt interval. Mathematical theorems for the FDTD formulation, concerning issues such as accuracy, convergence, computational complexity and stability is provided in [20]. Following Yee procedure, the x-direction

components of both electric and magnetic fields are described using (7) and (8):

$$H_x^{n+\frac{1}{2}} = H_{x(i,j,k)}^{n-\frac{1}{2}} - \frac{\Delta t}{\mu}\left(\frac{E_{z\,(i,j+1,k)}^n - E_{z\,(i,j,k)}^n}{\Delta y} - \frac{E_{y\,(i,j,k+1)}^n - E_{y\,(i,j,k)}^n}{\Delta z}\right) \qquad (7)$$

$$E_x^{n+1}{}_{(i,j,k)} = E_{x\,(i,j,k)}^n + \frac{\Delta t}{\varepsilon}\left(\frac{H_{z\,(i,j,k)}^{n+1} - H_{z\,(i,j-1,k)}^{n-\frac{1}{2}}}{\Delta y} - \frac{H_{y\,(i,j,k)}^{n+\frac{1}{2}} - H_{y\,(i,j,k-1)}^{n-\frac{1}{2}}}{\Delta z}\right) \qquad (8)$$

Following the same procedure, the other field components can be obtained and will not repeat here. It is to be noted that in this formulation the EM parameter ε and μ of material under test can be constant, or they can be changed with frequency. This allows modeling of material properties for lossless and lossy over required broadband analysis. The total space of the problem is discreetized into cubic cells with fine space dimensions to increase the accuracy of calculations. To limit the domain of computational space, the simulation of open problems is usually carried out by placing absorbing boundary conditions (ABCs) in the terminating planes of the grid. In this paper first-order Mur ABC [22] is used for the following reasons:

- It can be applied to the boundary with a dielectric discontinuities

- As compared to other absorbing boundary conditions, It is computationally much easier to implement.

A forward-moving TE_{10} wave is lunched at the excitation plane A-A'. Maxwell's equations solving algorithm involves a continuous sampling of electric and magnetic fields in a finite region at equidistance points in a spatial lattice. The electromagnetic field component distribution (both electric field and magnetic field) is observed within waveguide and multilayer structure until the steady state condition is obtained. The sampling point (B-B') is chosen to be located far away from aperture to avoid higher order modes. The complex reflection coefficient Γ_o of the sensor is calculated by applying transmission-line theory using (9):

$$\Gamma_o = \left|\Gamma_o\right|e^{-j\phi_{\Gamma_o}} = \frac{Y_a - Y_o}{Y_a + Y_o} \qquad (9)$$

where *Ya* is the aperture admittance and Y_o is the characteristic admittances of sensor aperture.

III. SIMULATIONs AND EXPERIMENTAL RESULTS

1. FDTD Scheme Validation

To verify and validate the FDTD formulation of the problem using the proposed technique, the complex reflection coefficients of X-band rectangular waveguide sensor irradiating into layered material medium is calculated using 3D FDTD code developed for this

purpose. In this work, we passed the developed code by comparing the results of numerical simulations of reflection coefficients with those obtained experimentally using standard WR-90 rectangular waveguide with flange length chosen to be 50 mm [23]. The comparison is made for two cases; the case when only the material under test as shown in Fig. 2 (a) is considered and for the case when a medium of two layers is considered as shown in Fig. 2 (b). In the first case, the sample used is compound absorbing material with ε_r =14.95 - j.0. 3318 and of μ_r = 1.35 – j 1.647 and thickness of 2.8 mm while for the second case, the same sample under test is used followed by the second layer with known ε_r and μ_r and thickness and the whole structure is backed by a perfect conductor. Teflon as low loss material is chosen [18] to be known material with thickness of 8 mm. Simulations and measurements are performed at a frequency of 10 GHz using a HP-8510B automatic network analyzer and the results are shown in table 1. For the two considered cases, the FDTD simulations and experimental results are in good agreement validating the computational tool.

Table 1. Comparison of the sensor reflection coefficient obtained using FDTD modeling versus experimental results for two cases considered. Results are obtained at f = 10 GHz.

Case	Method	$\left|\Gamma\right|$ (Magnitude)	Γ (Phase) (Phase in Degree) dedeDegree)
Single layer	FDTD	0.4391	**-139.38**
	Experiment	0.4424	**-138.17**
Two layers	FDTD	0.4062	**-140.28**
	Experiment	**0.4132**	**-137.98**

2. EM-Parameter Determination

The analysis based on FDTD modeling in the previous sections is to be verified experimentally in order to assess the validity of the proposed technique for simultaneously determination ε_r and μ_r of compound absorbing materials. Several experiments are conducted for this purpose over the given microwave frequency range. Table 2 shows a comparison between the measured results of ε_r and μ_r of a compound absorber sample and corresponding previously published data in [24] where it is seen that they are fairly consistent. The FDTD calculations and measurement are performed at a frequency of 10 GHz with sample thickness of 2.08 mm. The extraction process of both ε_r and μ_r are performed iteratively using numerical optimization technique.

Table.2: Comparison between the measured results of ε_r and μ_r of a compound absorbing material and reference data Results are obtained at f = 10 GHz.

Method	$\varepsilon_r = \varepsilon' - j\varepsilon''$		$\mu_r = \mu' - j\mu''$	
	ε'	ε''	μ'	μ''
Proposed Technique	15.21	0.37	1.73	0.87
Reference Data[24]	15.26	0.68	1.71	0.84

As stated in previous sections, the sensor reflection coefficient is sensitive to more than one variables with operating frequency as independent variable while both ε_r and μ_r are frequency dependent (*i.e* $\varepsilon_r(f)$ and $\mu_r(f)$). Also, the sample thickness is another limiting factor in the measurement process. Another test is performed to study the influences of these factors on ε_r and μ_r measurement. The variations of real parts and imaginary parts of both ε_r and μ_r are separately investigated with frequency and sample thickness in this study and the results are illustrated in Fig. 3(a and b). Figure 3-a shows the real parts (ε' and μ')variations of the ε_r and μ_r while the variations of the imaginary parts ($\tan\delta_\varepsilon$ and $\tan\delta_\mu$) of ε_r and μ_r are shown in Fig. 3-b. The measurements are performed on another compound absorbing material with two thicknesses having a ratio of 2. The first sample thickness is chosen to be 2.44 mm and the second one is of 4. 88 mm thickness. Twelve frequency points are selected for the measurement to cover the X-band frequency range. It is clear from the two figures that good agreement is obtained between the measured values (both real parts and imaginary parts for sample of 2.44 mm thickness. For sample with 4.88 mm thickness, a large discrepancy is observed in the results of measurement for both permittivity and permeability. The results obtained showed that the sample thickness has an influence on measurement accuracy and sensitivity. It is quite difficult to obtain accuracy in measurement of thicker sample high loss materials such compound materials. This is due to. that the reflection decreases with increasing the thickness of absorbing material. This is the reason why thickness measurement accuracy becomes poorer for thicker lossy materials. Hence, backing the layered material medium by perfect conductor enhances the measurement sensitivity and accuracy.
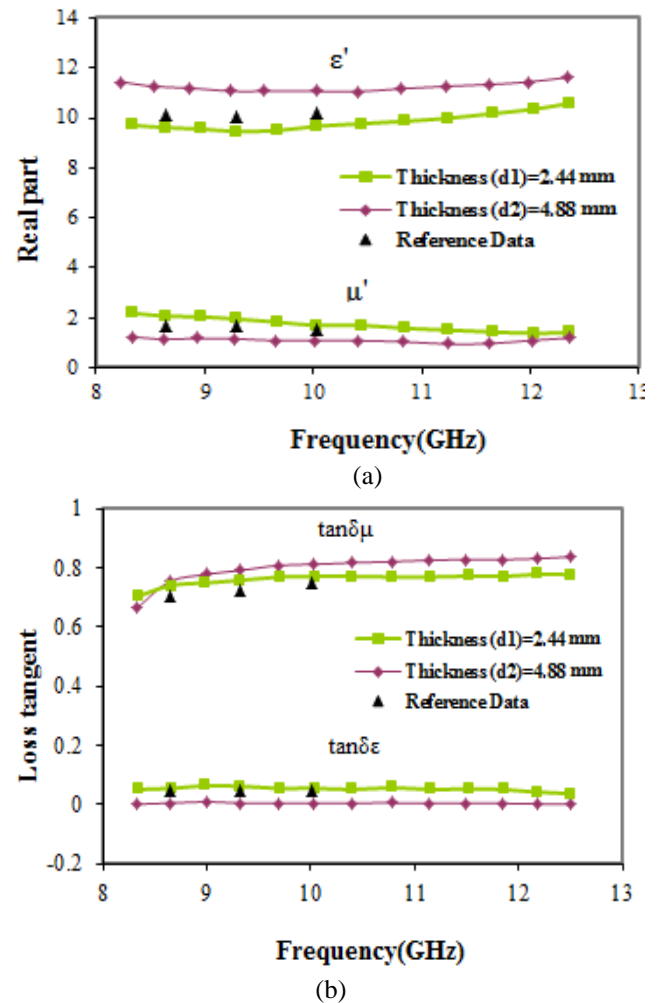

(a)

(b)

Fig.2: The measured permittivity and permeability of compound absorbing material with two thicknesses compared with reference data. (a) Real parts (b) Loss tangent.

IV.   PARAMETERS ε_r, μ_r EXTRACTION

For open-ended rectangular waveguide loaded with material under test, the reflection coefficient (or its equivalent aperture admittance Y_a) is theoretically formulated as a function of sample ε_r and μ_r parameters, sample thickness d and operating frequency f. As with most material characterization methods, there exists no closed form, which relates both ε_r and μ_r to the theoretical reflection coefficient (Γ^{thy}). Hence, in order to simultaneously extract ε_r and μ_r, inverse problem technique must be employed numerically for this purpose using an iterative optimization technique. By using the Γ_0 value, both obtaining from theoretical analysis and experimental under two different test conditions, the complex parameters ε_r and μ_r of the tested sample can be extracted. In this regard, the extracted values of ε_r and μ_r should be those values taken by which the difference between the calculated and the measured values of the sensor reflection coefficient is minimized by inverse

problem. Consequently, an iterative solution using optimization technique is sought to compute ε_r and μ_r for a given value of reflection coefficient Γ_o to optimize the objective function φ using (10).

$$\phi(f_i,\varepsilon',\varepsilon'',\mu',\mu'') = \sum_{i=1}^{N} (\Gamma_m(f_i) - \Gamma_c(f_i,\varepsilon',\varepsilon'',\mu',\mu'',d))^2 \quad (10)$$

where f_i is the operating frequency of the measurement data set measured at N frequency points. It is clear from (10) that by using the values of the measured and the FDTD calculated reflection coefficients, the objective function (φ) can be optimized iteratively. Minimizing process usually starts with initial guess values for ε_r and μ_r. These iterative algorithms are guaranteed in most cases to produce a correct convergence, but this process consumes much time. The technique discussed in this paper is easy to use. It needs only reflection coefficient measurement, then the remaining task is to process the measurement data in a convenient way.

V. CONCLUSION

An improved technique for simultaneous non-destructive EM-parameter of sheet compound absorbing material determination using rectangular waveguide sensor irradiating into layered medium has been numerically investigated and assessed. The FDTD simulations and experiments results of both ε_r and μ_r variations (real and imaginary parts) with the thickness of the sample over an X-band of the microwave frequency range have shown that the sample under test thickness is strongly influencing ε_r and μ_r measurement accuracy. The obtained results suggest that using the proposed technique for ε_r and μ_r measurement is suitable for high loss materials with a thickness of several millimeters. For this reason, the layered structure is backed by a perfect conductor to improve measurement accuracy and sensitivity. The proposed technique can be applied to test a single layer and multilayer material under test where it is quite difficult to use the traditional methods such as thickness-varying method and frequency-varying method for this purpose. The measurement geometry described in this paper is limited to two layer structure, which yield enough information to determine simultaneously electric and magnetic parameters. Since the sensor's reflection coefficient is sensitive to ε_r and μ_r and sample thickness, the technique can be used to perform simultaneous multiparameter measurement (both complex permittivity and permeability and thickness).

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