Experimental and Modelling the Combined Measurements Technique for Microwave Absorbing Coatings Testing with Finite Difference Time Domain Method

Abdulkadhim A. Hassan\textsuperscript{1} and Janan H. Saadie\textsuperscript{2}

\textsuperscript{1}Electrical Engineering Department, Faculty of Engineering, Kufa University, Al-Najaf, Iraq
\textsuperscript{2}Materials Engineering Department, Faculty of Engineering, Kufa University, Al-Najaf, Iraq
E-mail: abdulkadhim.shlash@uokufa.edu.iq

Abstract. Because of the structure property of radar absorbing coatings, using of the existing methods for testing these materials is quite difficult. In this paper, a combined-measurement technique was proposed for broadband characterization of microwave absorbing coatings using flanged rectangular waveguide sensor. The technique combines both frequency sweep reflections measurement and two-layer method to provide two different test conditions of the needed reflection coefficients necessary to extract both complex permittivity and complex permeability over a given frequency range. The first set of reflection coefficients is obtained by directly placing the sensor alongside the coating material and performing broadband measurement using frequency sweep over the selected frequency points of frequency range. The same procedure is applied on a combination of known material followed by the test material to measure the second set of the respective reflection coefficients. Finite Difference Time Domain (FDTD) method was employed to numerically calculate the sensor reflection coefficient and analyse the influence of the sensor geometry and coating material thickness on measurement accuracy. The measurement results of both complex permittivity and permeability for various samples of microwave absorbing coatings were agreed well with reference data. Simple interpolation approximation was introduced in their extraction process from multiple reflection coefficient data since they are frequency dependent parameters. The proposed technique speeds up and simplifies coating materials testing, while it decreases the error due to repeatability of measurement.

Keywords — Layered structure; FDTD; Coatings material; EM-Properties; Microwave measurement.

1. Introduction
Radar absorbers are commonly used in a diverse area of applications to reduce unwanted reflections from metal surfaces or in electromagnetic compatibility and shielding. To solve these problems, especially to reduce unwanted reflections, a layer (or layers) of wideband radar absorbing composite materials is placed or coated on metallic structures. These materials are characterized by both complex permittivity ($\epsilon_r = \epsilon (1 \tan \delta_r)$) and permeability ($\mu_r = \mu (1 \tan \delta_r)$). For the cases where misapplication or damage of radar absorbing coatings, the in situ or in the field electromagnetic (EM) properties measurement over broadband of frequencies is extremely challenging. This is due to that it is quite difficult to test radar absorbing materials coated on metallic structure using the existing methods since these methods need to
machine the sample to be tested according to the requirements of measurement process [1, 2, 3, 4, 5]. Moreover, most of these method are destructive, therefore, they are not suitable to be used for coating materials testing.

For nondestructive coating materials testing, it is necessary that the method of measurement used to be efficient enough, fast, accurate and directly applied. The Open-ended rectangular waveguide sensor is one of the promising techniques, which can be used for this purpose for many reasons. The openness in its structure, which diminishes some restrictions to sample preparation, as well as handling high power necessary to perform high loss material testing are the main reasons. This technique has been theoretically and technically studied and analysed and used for simultaneously measuring electromagnetic properties of compound materials among the others [6, 7, 8, 9, 10]. For r and r extraction using reflection only sensors, two-independent reflection coefficients are needed using three developed methods. The first one is called thickness-varying method (TVM) [10]. It makes two reflections measurements with two samples of same material of different thickness. Hence, this method is unsuitable for coating materials testing. The second method is sample-varying or two-layer method (SVM) [10]. In this method, the material is used to be tested first, then a combination of this material and another with known r and µ to test again. For the two mentioned methods, both εr and µr are measured at single frequency point. Thus, using them for broadband measurement requires to repeat the measurement at each frequency point over a given frequency band of interest. The third method is called frequency-varying method (FVM) [11]. In this method, the two reflection coefficients can be measured at two neighbour frequencies of f1 and f2 respectively. These frequencies must be separated by small value of frequency interval selected by rule of thumb. Hence, it becomes necessary to develop a technique for coatings material testing, which keeps the above mentioned merits of the sample-varying method as well as gets ride of frequency-varying method demerits.

Numerous measurement techniques have been developed to characterize coating materials as fabricated. These methods can be performed either directly [12, 13] or indirectly [14]. In [14] a loading fraction table, which relates test material thickness to both r and r, is utilized to determine these parameters. Also in [12] and [13] a direct method using horn antenna has been employed for measuring the reflection parameters from the incident plane wave on radar absorbing coatings. These methods can be applied to measure these parameters at single frequency point. In this work, a combined measurements technique was proposed for complex permittivity and complex permeability determination of microwave absorbing coatings. The technique is based on using of frequency sweep measurement technique in conjunction with two-layer method to directly measure the needed reflection coefficients over a given frequency range in only two steps. A set of reflection coefficients data is measured for test material first over the desired frequency points, then a combination of known r, µ and thickness material followed by test material is tested again to obtain another set of reflection coefficients data for the respective frequency points. The technique is aimed to simplify and speed up measurement process and improve accuracy by reducing repeatability of measurement if other existing methods are used. FDTD method was employed to calculate input reflection coefficients and extract both r and µ of test material by inverse problem since using of analytical procedures, in this case, becomes quite difficult. Simple interpolation approximation was used in extraction process of r and µ from the data sets of reflection coefficients since both r and µ are frequency dependent parameters. Error analysis was performed to access the influence of sensor flange size, measurement frequency and coating thickness on the measured reflection coefficients. To evaluate the performance of the proposed technique, both εr and µr of selected microwave absorbing coatings were measured over X-band. The obtained results of εr and µr measurements were validated by comparing with reference data published by companies and literatures to demonstrate the feasibility of the proposed technique.

2. Measurement Principles
The problem geometry is shown in Figure 1, where rectangular waveguide sensor with broad and narrow dimension of a and b respectively is placed against a single layer radar absorbing coatings of thickness d as depicted in Figure 1-a. The energy radiated from the sensor penetrates through the test material and then it reflects into the aperture. The reflection coefficient (Γ) measured at the aperture of the sensor carries the desired coating material electromagnetic properties and its thicknesses information described as Γ (f, a,b,ε(f),µ(f),d) [6]. Usually, to extract the parameters εr and µr of a test material, it needs at
least two independent reflection coefficients measured under different test conditions.

As can be seen from sensor reflection coefficient, the proposed technique is based on two facts: Firstly, for a given sensor dimension, both measurement frequency \((f)\) and thickness of test material \((d)\) are independent variables of the reflection coefficient, thus, by changing both of them, the reflection coefficient can be independently measured. Secondly, the electromagnetic properties of most of the solid materials (\(\epsilon_r\) and \(\mu_r\)) are varied slowly alone with frequency \([15]\), hence, both \(\epsilon_r\) and \(\mu_r\) can be accurately determined over frequency interval \((\Delta f)\) selected between two neighbor frequency points of a given frequency range. The selection of \(\Delta f\) is a critical task since both \(\epsilon_r\) and \(\mu_r\) of test material are frequency dependent. Thus, it should be appropriately selected in order for the reflection coefficient is to be changed enough so that it can be distinguished by measuring instrument. Consequently, simple interpolation technique is used in extraction process of these parameters from a set of reflection data measured by frequency sweep using Equation 1.

\[
\begin{align*}
\epsilon_r(f) & \approx \epsilon_r(f + \Delta f) \\
\mu_r(f) & \approx \mu_r(f + \Delta f)
\end{align*}
\]  

The polynomial given in Equation 1 needs the reflection coefficients measured at least two frequency points \((f_i\) and \(f_{i+1}\)) in order for both \(r\) and \(r\) to be reconstructed and the obtained results are taken as the actual interpreted values averaged over \(\Delta f\) such that:

\[
\begin{align*}
\epsilon_r(f_i) & \approx \epsilon_r\left(\frac{f_i + f_{i+1}}{2}\right) \approx \epsilon_r(f_{i+1}) \\
\mu_r(f_i) & \approx \mu_r\left(\frac{f_i + f_{i+1}}{2}\right) \approx \mu_r(f_{i+1})
\end{align*}
\]  

The proposed technique presented in this paper combines both frequency sweep technique of reflection coefficient measurement and two-layer method to provide two different conditions of testing. The first set of reflection coefficients data (both measured and calculated) over a given frequency range is obtained by placing the sensor against the test material as depicted in Figure 1-a. The second set of reflection coefficient data is obtained by placing the sensor against a combination of known material followed by test material as depicted in Figure 1-b. The two processes of measurement are described by simultaneous equations set using Equations 4 and 5.
Γ_{meas}^{i}[f_i + \Delta f, \varepsilon_r(f_i + \Delta f), \mu_r(f_i + \Delta f), d] = Γ_{calc}^{i}[f_i + \Delta f, \varepsilon_r(f_i + \Delta f), \mu_r(f_i + \Delta f), d] \quad (4)

Γ_{meas}^{i+1}[f_i + \Delta f, \varepsilon_r(f_i + \Delta f), \mu_r(f_i + \Delta f), d, d] = Γ_{calc}^{i+1}[f_i + \Delta f, \varepsilon_r(f_i + \Delta f), \mu_r(f_i + \Delta f), d, d] \quad (5)

Where, Γ_{meas} and Γ_{calc} are the measured and the calculated reflection coefficients at frequency points of \( f_i \) and (\( f_i + \Delta f \)) respectively and \( i = 1, 2, 3,...N-1 \) is the number of frequency points over a given frequency range. The other symbols are pictorially defined as depicted in Figure 1. When implementing the proposed technique, the broadband frequency sweep of reflection coefficients is measured, then from the set reflection coefficients data, both \( \varepsilon_r \) and \( \mu_r \) can be extracted with values averaged over two neighbour frequency points. The same process is used throughout the entire range of the frequency.

3. Numerical Formulation of the Problem

3.1. Reflection Coefficient Calculation Using FDTD Method

The computational domain of FDTD method of the problem is shown in Figure 2. It consists of finite size flange rectangular waveguide sensor placed against the combination of known EM parameters and thickness material followed by radar absorbing coating to be tested with known thickness and unknown \( \varepsilon_r \) and \( \mu_r \).

![Figure 2](image)

Figure 2. FDTD computational domain of the problem.

Considering only the dominant (\( TE_{10} \)) mode, the FDTD method adopts numerically a full-wave direct solution of time-dependent curl Maxwell’s equations, which describe the near-field interaction between the electromagnetic field and a medium using Equations 6 and 7.

\[
\frac{\partial H}{\partial t} = -\frac{1}{\mu}(\nabla \times E) \quad (6)
\]

\[
\frac{\partial E}{\partial t} = \frac{1}{\varepsilon}(\nabla \times H) \quad (7)
\]

To solve Equations 6 and 7, accurate central difference approximations of second order are applied for the derivatives of the space and time of both electric (E) and magnetic (H) fields according to Yee procedure [16]. Following Yee procedure, the vector Equations 6 and 7 are translated into a six scalar
first-order set of partial differential equations in x, y and z coordinates. For x coordinate, the E and the 
H field’s components, are given using Equations 8 and 9 respectively.

\[
\frac{\partial E_x}{\partial t} = \frac{1}{\epsilon_r \sqrt{\epsilon_o \mu_o}} \left( \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \right) \tag{8}
\]

\[
\frac{\partial H_x}{\partial t} = -\frac{1}{\mu_r \sqrt{\epsilon_o \mu_o}} \left( \frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} \right) \tag{9}
\]

The same procedure is applied using Equations 6 and 7 for y and z coordinates. The six scalar 
equations of Equations 6 and 7 represent the FDTD method basis. As shown in Figure 2, the 
computational domain of the problem is divided into two regions. Region 1 which includes the interior of 
the probe space surrounded by waveguide walls, which are assumed to be perfect conductors. Region 2 
includes the two-layer structure with different EM-properties and thicknesses backed by perfect conductor. 
The constitutive parameters r and r of test material used for the problem under consideration can be 
constant, or change with frequency. This allows modeling of material properties for lossless and lossy 
materials over required broadband analysis and measurement. The total spaces, including the two regions 
discretized using Yee procedure into cells. The field propagation through a one cell distance requires 
time step t of minimum value calculated according to the Courant condition for stability using Equation 
10.

\[
\Delta t \leq \frac{1}{c \left[ \frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2} \right]^{1/2}} \tag{10}
\]

In this work, a 3D FDTD special grids cell size of \(\Delta x\), \(\Delta y\), and \(\Delta z\) were used to increase the FDTD 
computation accuracy. Constitutive parameters were used with effective values averaged at different 
interfaces to calculate field components. Mur absorbing boundary condition (ABC) of the first-order 
[17] was used for the problem spaces of at radial boundary to limit the domain of the computational. A 
Gaussian pulse of forward-moving was taken as excitation source lunched at the plane of excitation located 
a distance away from the aperture and normally incident on the material under test. The distribution of 
the fields in the test material and the sensor were calculated after the final steady state has been reached. 
The sensor aperture input admittance was obtained from the calculated components of the fields within 
test material. The sensor complex reflection coefficient, \(\Gamma\), was calculated using Equation 11.

\[
\Gamma = \frac{Y_a - Y_0}{Y_a + Y_0} \tag{11}
\]

where, \(Y_a\) is the aperture admittance and \(Y_0\) is the waveguide equivalent characteristic admittance.

3.2. Numerical Validation and Analysis

To validate and assess the accuracy of the FDTD algorithm, the complex reflection coefficient of the 
sensor (both magnitude and phase) is to be calculated for the sensor termmimated with the test material 
using a 3D code developed for this purpose. A series of numerical simulations and experiments were 
conducted at (8.2 12.4 GHz) frequency range using rectangular waveguide sensor (WR-90) and network 
analyzer (HP8510B). The sensor flange dimension is taken to be 50.0 mm [18]. Two different radar 
absorbing coatings were used for this purpose. The first test material was GEC-9052 radar absorbing 
coatings with thickness of 2.44 mm while the second one is 1164 radar absorbing coating of 1.16 mm 
thickness. The FDTD simulations and measurements were carried out at frequency of 10 GHz and the 
results are shown in Table 1. From the Table 1, it can be seen that the data obtained by the FDTD 
method is closely followed the measured results. The obtained results validate the computational tool.

An analysis was performed using FDTD simulations to evaluate sensor flange size influence on the 
accuracy of reflection coefficient measurement for a given operating frequency. Figure 3, shows the 
variations of the sensor reflection coefficient terminated by coating material sample as the flange size varies 
from the minimal (30 mm) to largest considered values calculated at 9 GHz and 11 GHz respectively. 
As shown in the figure, the reflection coefficient variation at 11 GHz is less than that obtained at 9 
GHz. This is reasonable since that the radiation losses increases at higher frequencies. Another test was 
performed to investigate coated material thickness on the measured reflection coefficient.
Table 1. The FDTD results versus experiments data of reflection coefficient for different radar absorbing coatings.

| Sample   | Method      | Γ (Magnitude) | Γ (Phase) |
|----------|-------------|---------------|-----------|
| GEC- 9052 | FDTD Model  | 0.4306        | -135.37   |
|          | Experiment  | 0.4261        | -132.97   |
| 1164     | FDTD Model  | 0.8095        | -61.19    |
|          | Experiment  | 0.8036        | -63.56    |

Figure 3. Variation of reflection coefficient versus sensor flange size at different frequencies.

Figure 4 shows the deviation (in %) in reflection coefficient compared with the result calculated for the case of the sensor with infinitely large flange due to the variations in the size of the flange normalized to the test material wavelength ($\lambda_m$). Two thicknesses of radar absorbing coating of 0.1 $\lambda_m$ and 0.2 $\lambda_m$ were considered in this analysis. As shown in the figure, the effect of size of the flange on reflection coefficient for thick sample case is less than that obtained for the thin sample. This is due to that the measured reflection coefficient for high loss materials (as in the case of radar absorbing coating) decreases for thick coated material.

From Figures 3 and 4, it can be seen that the variation of sensor flange size has negligible effect on sensor reflection coefficient provided that tested material is lossy enough. This a necessary condition to ensure that any reflection of the spurious signal from the flange boundaries has no effect on the measurement. For the cases examined in this analysis, the variations of the reflection coefficient have a dependence of oscillatory damped with the flange size of the sensor.

4. Experimental Verifications

The measurement set up is depicted in Fig. 5, where the sensor is pressed alongside the coating material, and then the reflection coefficient (Γ) is measured using network analyzer. The measured and FDTD calculated reflection coefficients are used to determine both the $\epsilon_r$ and $\mu_r$ parameters of test material by numerical inversion process. As shown in Fig. 5, the system of measurement consists of two parts. One is the hardware consisting of waveguide and network analyzer used to transfer the desired $\epsilon_r$ and
Figure 4. Variation of reflection coefficient versus flange size for lossy material of different thickness.

μr information from the measurement results of reflection coefficient (Γ). The other part is the software algorithms developed to calculate sensor reflection coefficients at different conditions of testing and extract the desired εr and μr from measured results of Γ.

Figure 5. Measurement setup.

A series of measurements were carried out on various microwave absorbing coatings using the proposed technique to determine both εr and μr of several coating materials at X-band. The sensor used was rectangular waveguide (WR-90) and the frequency sweep measurement of reflection coefficients was performed using a HP 8510B network analyzer. The inverse problem of εr and μr extraction can be solved by Newton-Raphson method or Levenberg-Marquardt method [19]. Starting with good initial guess, the given iterative algorithms, in most cases, guarantee convergence. The first test was carried out on 1164 radar absorbing coatings of 1.2 mm thickness to evaluate the influence of flange size on the measured values of εr and μr at 10 GHz. Two flange sizes of 40 mm and 50 mm were selected for this purpose. The known material used in the measurement is Teflon with thickness of 8 mm. This value is experimentally chosen to obtain two reflection coefficients carrying different information for a range of
coating material thickness from 1 to 5 mm. The reasons for choosing Teflon as known material are that it is semi-rigid with low loss and low dispersion making it suitable for this purpose. Table 2 shows the obtained results.

Table 2. Comparison of the calculated values of $\epsilon_r$ and $\mu_r$ for flange with different sizes.

| Flange Size (mm) | $\epsilon_r$ | $\tan\delta\epsilon_r$ | $\mu_r$ | $\tan\delta\mu_r$ |
|------------------|--------------|------------------------|--------|-------------------|
| 40 mm            | 14.89        | 0.023                  | 1.26   | 1.21              |
| 50 mm            | 14.92        | 0.0220                 | 1.31   | 1.22              |
| Reference Data   | 14.95        | 0.0222                 | 1.35   | 1.22              |

From the Table 2, it is obvious that a 50 mm flange size results agreed well with the reference data [10] as compared to the results of 40 mm flange size. The obtained results clearly show the influence of the sensor flange size on both $\epsilon_r$ and $\mu_r$ measurement. A broadband frequency sweep measurement [20] was carried out on ECCOSORB MF.116 radar absorbing coatings with 1.22 mm thickness to evaluate the performance of the proposed technique compared to the two-layer method results. Eight frequency points were selected over the given frequency band with frequency interval ($\Delta f$) of 0.5 GHz.

The measured results of both $\epsilon_r$ and $\mu_r$ and reference data are shown in Figure 6. Figure 6-a shows the real parts of both $\epsilon_r$ and $\mu_r$ while the loss tangents are shown in Figure 6-b. As shown in the figure, although the difference between the results of the two methods is obvious, the whole tendency of the measured results using the proposed technique agrees well with the reference data. It is obvious that two-layer method results exhibit marked diversity in both real and imaginary parts of the measured $\epsilon_r$ and $\mu_r$ if it is used alone. This is may be due to the repeatability of measurement process, where two mechanical operations are required at each frequency point, while the proposed technique shows results a relatively reasonable and smooth for a given range of frequency.

![Figure 6](a) ![Figure 6](b)

**Figure 6.** Broadband measurement of complex permittivity and complex permeability using the proposed technique and Two-layer method for MF-116 radar absorbing coating.

Another experiment was performed to evaluate coating material thickness influence on $\epsilon_r$ and $\mu_r$ measurement accuracy. The $\epsilon_r$ and $\mu_r$ measured results of a coating material with three different thicknesses using the proposed technique are presented in Figure 7. Figure 7-a shows the results of real parts of $\epsilon_r$ and $\mu_r$ and Figure 7-b shows the results of their loss tangents. The thicknesses of the used
samples are 2.08 mm, 4.16 mm and 6.24 mm respectively. Eleven frequency points were selected over the given frequency range with frequency interval of 0.4 GHz. It is clear that good agreement is achieved between the results of measurement and the reference values, but the effect of thickness on measurement accuracy and sensitivity is obvious also. The 6.24 mm thickness results of coating showed a deviation relatively larger in the loss tangents compared to 4.16 mm and 2.08 mm sample thicknesses. For this sample thickness, the loss tangent ($\tan\delta\epsilon$) becomes minus. The sample with small loss tangent ($\tan\delta\epsilon \leq 0.1$) and too thick are the main reasons for obtaining this result. Furthermore, the waveguide sensor with the open end is suitable to be used for high-loss materials measurement. So, getting a reasonable accuracy for loss tangent ($\tan\delta$) with a value of less than 0.1 is difficult. In this work, the actual value of loss tangent is about 0.06. The obtained results of the experiments indicate that the proposed technique presented in this paper is reliable and effective for in situ determining simultaneously both $\epsilon_r$ and $\mu_r$ of radar absorbing coatings. Future research work such as analysis of sensitivity and improvement of inverse algorithms should be addressed.

Figure 7. Measured results of a ferrite absorber with three different thicknesses (a) Real parts (b) Loss tangent.

5. Conclusion
A non-destructive measurement technique for broadband determination of complex permittivity and complex permeability of radar absorbing coating materials was presented. The technique was employed based on combining of both frequency sweep of reflection coefficient measurement and two-layer method using flanged rectangular waveguide sensor. FDTD method has been successfully employed to numerically model the problem geometry, where using of the analytical approaches, in this case, is quite difficult. Analysis results of uncertainty of sensor reflection coefficient measurement performed using FDTD simulations and experiments have shown that sensor flange size, measurement frequency and coating material thickness are the dominant factors affecting the accuracy and sensitivity of $\epsilon_r$ and $\mu_r$ measurements. Results of measured $r$ and $\mu$ of selected microwave absorbing coatings have demonstrated, in comparison with published data, the feasibility of the proposed technique for testing of high loss coating materials with a thickness of several millimetres. The technique has the advantages that it performs measurement of independent reflection coefficients sets with only two mechanical operations over a given frequency band of interest, thus speeding up and simplifying the measurement process and error factors due to repeatability of measurement can be reduced. More over the technique can be extended to be used for multiparameter measurement of multilayer radar absorbing coatings.
References

[1] Lin M, Duane MH, Afsar MN. Cavity-Perturbation Measurement of Complex Permittivity and Permeability of Common Ferrimagnetics in Microwave-Frequency Range. IEEE Transactions on Magnetics [Internet]. Institute of Electrical and Electronics Engineers (IEEE); 2006 Oct;42(10):28857. Available from: http://dx.doi.org/10.1109/tmag.2006.879885

[2] Goncalves F, Pinto A, Mesquita R, Silva E, Brancacio A. Free-Space Materials Characterization by Reflection and Transmission Measurements using Frequency-by-Frequency and Multi-Frequency Algorithms. Electronics [Internet]. MDPI AG; 2018 Oct 18;7(10):260. Available from: http://dx.doi.org/10.3390/electronics7100260.

[3] Wolfson BJ, Wentworth SM. Complex permittivity and permeability measurement at elevated temperatures using rectangular waveguide. Microwave and Optical Technology Letters [Internet]. Wiley; 2003 Jul 31;38(6):4993. Available from: http://dx.doi.org/10.1002/mop.11086.

[4] Salahun E, Queffelec P, Le Floch M, Gelin P. A broadband permeameter for in situ measurements of rectangular samples. IEEE Transactions on Magnetics [Internet]. Institute of Electrical and Electronics Engineers (IEEE); 2001 Jul;37(4):2743. Available from: http://dx.doi.org/10.1109/20.951293.

[5] Pinho MS, Gregori ML, Nunes RCR, Soares BG. Performance of radar absorbing materials by waveguide measurements for X- and Ku-band frequencies. European Polymer Journal [Internet]. Elsevier BV; 2002 Nov;38(11):23217. Available from: http://dx.doi.org/10.1016/s0014-3057(02)00118-0.

[6] Ghass MT, Simms D, Zoughi R. Multimodal Solution for a Waveguide Radiating Into Multilayered Structures-Dielectric Property and Thickness Evaluation.2009. IEEE Transactions on Instrumentation and Measurement [Internet]. Institute of Electrical and Electronic Engineers (IEEE); 2009 May;58(5):150513. Available from: http://dx.doi.org/10.1109/tim.2008.209133.

[7] Shoujun Wang, Maode Niu, Deming Xu. A frequency-varying method for simultaneous measurement technique on parameters $\epsilon$ and $\mu$ of high-loss materials. IEEE Transactions on Microwave Theory and Techniques [Internet]. Institute of Electrical and Electronics Engineers (IEEE); 1998 Apr;47(2):47681. Available from: http://dx.doi.org/10.1109/22.739296.

[8] Seal MD, Hyde IV MW, Havilla MJ. NONDESTRUCTIVE COMPLEX PERMITTIVITY AND PERMEABILITY EXTRACTION USING A TWO-LAYER DUAL-WAVEGUIDE PROBE MEASUREMENT GEOMETRY. Progress In Electromagnetics Research [Internet]. EMW Publishing; 2012;123:12342. Available from: http://dx.doi.org/10.2528/pier11111108.

[9] Niu Maode, Su Yong, Yan Jinkui, Fu Chenpeng, Xu Deming. An improved open-ended waveguide probe and a rigorous full-wave multimode model. Journal of Electromagnetic Waves and Applications [Internet]. Informa UK Limited; 2006 Jan;20(14):203752. Available from: http://dx.doi.org/10.1163/156939306779322693.

[10] Karli R, Ammor H, Terhzaa J, Chabi M, Mediavilla Snchez . Design and construction of miniaturized UWB microstrip antenna with slots for UWB applications. Microwave and Optical Technology Letters [Internet]. Wiley; 2014 Dec 18;56(2):603. Available from: http://dx.doi.org/10.1002/mop.28869.

[11] Shoujun Wang, Maode Niu, Deming Xu. A frequency-varying method for simultaneous measurement of complex permittivity and permeability with an open-ended coaxial probe. IEEE Transactions on Microwave Theory and Techniques [Internet]. Institute of Electrical and Electronic Engineers (IEEE); 1998 Apr;47(2):21457. Available from: http://dx.doi.org/10.1109/22.739296.

[12] Zhou J, Bie S, Wan D, Xu H, Xu Y, Jiang J. Realization of Thin and Broadband Magnetic Radar Absorption Materials With the Help of Resistor FSS. IEEE Antennas and Wireless Propagation Letters [Internet]. Institute of Electrical and Electronic Engineers (IEEE); 2015;14:247. Available from: http://dx.doi.org/10.1109/lawp.2014.2349533.

[13] Guan S, Wang Y, Jia D. A Field Performance Evaluation Scheme for Microwave-Absorbing Material Coatings. Coatings [Internet]. MDPI AG; 2017 Mar 2;7(3):38. Available from: http://dx.doi.org/10.3390/coatings7030038.

[14] Rothwell EJ, Temme A, Frasch LL. Characterisation of properties of conductor-backed MagRAM layer using reflection measurement. Electronics Letters [Internet]. Institution of Engineering and Technology (IET); 2012 Aug 30;48(18):11313. Available from: http://dx.doi.org/10.1049/el.2012.1184.

[15] Yang RB, Hsu SD, Lin CK. Frequency-dependent complex permittivity and permeability of iron-based powders in 218 GHz. Journal of Applied Physics [Internet]. AIP Publishing; 2009 Apr;105(7):07A527. Available from: http://dx.doi.org/10.1063/1.3068039.

[16] YEE, Kane. Numerical solution of initial boundary value problems involving Maxwell’s equations in isotropic media.1966. IEEE Transactions on antennas and propagation.14(3):302-307.

[17] Mur G. Absorbing Boundary Conditions for the Finite-Difference Approximation of the Time-Domain Electromagnetic-Field Equations. IEEE Transactions on Electromagnetic Compatibility [Internet]. Institute of Electrical and Electronic Engineers (IEEE); 1981 Nov;EMC-23(4):37782. Available from: doi:10.1109/t EMC.1981.949507.
[18] Takanobu Ohno, Kouji Omata, Kouji Wada, Osamu Hashimoto. A tunable bandpass filter using tapped $\lambda/4$ resonators loaded with inductive variable capacitor. 2006 Asia-Pacific Microwave Conference [Internet]. IEEE; 2006 Dec; Available from: http://dx.doi.org/10.1109/apmc.2006.4429639.

[19] PRESS, W. H. Teukolsky SA, Vetterling WT, and Flannery BP. Numerical recipes in C.1992.the art of scientific computing,657-659.

[20] Abdulkadhim Hassan, Al-Modaffer, Janan Saadee. Broadband Thin Sheet Radar Absorbers Characterization Using Frequency-swept Open-ended Waveguide Probe Technique and FDTD Modeling.2019.INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY.14(3).175-184.