Improved technique for radar absorbing coatings characterization with rectangular waveguide and numerical modeling

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ABSTRACT

For materials characterization, several methods have been developed. Most of them need a sample to be machined prior to testing process. Hence, they are destructive and cannot be used for in-situ radar absorbing coatings testing. This requires employing a suitable measurement technique to extract their electromagnetic properties quickly and accurately. In this paper, the swept frequency of probe reflection technique is proposed for broadband nondestructive radar absorbing coatings characterization using finite flange open-ended rectangular waveguide. The technique is based on the fact that the frequency of measurement is an independent variable of probe's reflection coefficient by which its data set of selected frequency points can be directly measured in one step by varying the frequency. Finite-difference time-domain (FDTD) method was adopted to calculate probe reflection coefficients at different test conditions. Simple interpolation approximation was employed since they are frequency dependent parameters. Error analysis was numerically performed to evaluate the influences of both flange size and coated material thickness on the accuracy of the measurements, which are carried out on several samples of radar absorbing coatings at X-band to verify the proposed technique. Comparing with the existing methods, the proposed technique simplifies and speeds up measurement process and improves its repeatability and accuracy.

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1. INTRODUCTION

In diverse areas of microwave and millimeter wave's practical applications, it is required to reduce electromagnetic waves reflections from metallic surfaces or for shielding. In these situations, radar absorbing materials made from wideband composite materials coated on metal plates with one layer (or layers) can be used to solve these problems [1]–[5]. These materials can be designed with specific values of both relative complex permittivity (ε_r) and relative complex permeability (μ_r) such that they can effectively absorb electromagnetic wave energy either over broadband or at discrete points of frequency band. For the cases when it is required to study the frequency dependence of reflections from the designed radar absorbing coatings or where damage or misapplication of radar absorbing coating, the in the field testing is essential to evaluate their performance over the operating frequency range [6]. Hence, it becomes necessary, in these situations, to develop measurement techniques to achieve these purposes in a convenient way quickly and accurately. The microwave usage for industrial testing is increased due to its ability in accurately performing frequency dependence measurement of material's electromagnetic properties (ε_r and μ_r). For materials characterization, several techniques have been developed to extract simultaneously ε_r and μ_r such as cavity resonator method, free space method [7], reflection/transmission method [8] and methods of transmission lines [9]. Most of these methods need a sample to be machined prior to testing process and, hence, they are destructive and cannot be used for *in-situ* testing of radar absorbing coatings due to their metallic structures, which limit testing process using the aforementioned methods. However, practically, radar absorbing coatings need to be tested or characterized as fabricated. This can be done by employing measurement technique suitable to extract these parameters using a probe, which provides the necessary conditions of such applications of measurements. Currently, radar absorbing coatings are characterized by directly measuring the reflection coefficient using horn antenna from reflected wave of a plane wave incident normally on coatings at a given frequency point [10]. The drawback of this method is that the horn antenna should be carefully designed in order to obtain approximated plane wave at the aperture of the antenna. To the best knowledge of the author, no appreciate work is available in the open literatures used for broadband testing of radar absorbing coatings indirectly except [11], [12] where instead of determining these parameters from the measured reflection coefficients, a loading fraction table is utilized to determine both ε_r and μ_r. Despite that the method is indirect, a relationship between ε_r and μ_r and the loading fraction should be prepared at each frequency point prior to the measurement process.

Because of the metallic structure and high loss nature of radar absorbing coatings, there are several advantages which make using of open-ended rectangular waveguide probe suitable to perform nondestructive *in-situ* radar absorbing coatings testing. The openness in its structure and a relatively handling high power are the most important reasons. This probe was investigated both in theoretical and technical by many interests and used for nondestructive measurement of both ε_r, μ_r of high-loss sheet composite materials at single frequency points, among the others [13]–[20]. Also, in the most of theoretical formulations, the probe reflection coefficient, symbolized as Γ (f, a, b, d, ε_r, μ_r), has been developed analytically under the assumption that the probe flange is infinitely large, which cannot be physically realized. For practical use, the flange size of the probe is finite in length. Hence, to ensure measurement accuracy, an alternative numerical technique can be employed, instead, to obtain a better approximation of determination of probe reflection coefficients, where using analytical methods, in this case is too difficult.

The objective of this paper is to present a technique for *in- situ* broadband simultaneously ε_r and μ_r determination of radar absorbing coatings with single layer using reflection-only flanged rectangular waveguide probe placed in close contact with test material. The fact on which the technique based is that the probe reflection coefficient is a complex function of different variables; the most important of which is the measurement frequency (f). Consequently, a broadband measurement process can be performed by varying measurement frequency in one step on the same sample using frequency sweep measurement of probe reflection coefficients over the entire of the given frequency band. The probe reflection coefficient is numerically formulated using finite-difference time-domain (FDTD) method to calculate reflection coefficients seen by the probe aperture at different measurement conditions. Simple interpolation approximation is employed to reconstruct ε_r and μ_r of tested material from two measured independent reflection coefficients of two neighbor points of frequency since they are frequency dependent parameters. Also, FDTD simulation is performed to analyze the probe flange size and coated material thickness influences on accuracy of reflection coefficient measurement. The extraction of these parameters is performed iteratively using optimum cost function. The results of experiment of ε_r and μ_r are presented for several radar absorbing coatings to demonstrate the validity and feasibility of the proposed technique.

2. PRINCIPLES OF THE MEASUREMENT

Figure 1 depicts the problem configuration, where a rectangular waveguide probe with the broad and narrow dimensions (a and b) connected to finite size flange is placed against single layer radar absorbing coating as test material with unknown EM-properties (ε_r and μ_r) and known thickness d. Assuming the dominant TE_{10} mode is excited inside the waveguide, the measured probe reflection coefficient (ρ) is described using (1) [16]:

$$\rho = \Gamma(a, b, f_i, \varepsilon_r(f), \mu_r(f), d) \tag{1}$$

It is clear in from (1) that the measured probe reflection coefficient is governed by more than one variable. This makes the probe reflection coefficient to be a complicated function of probe dimensions (a and b), measurement frequency (f), the test material thickness (d) and both complex permittivity ε_r (f)=ε'(1-$j\tan\delta_\varepsilon$) and complex permeability μ_r (f)=μ'(1-$j\tan\delta_\mu$). For multi-parameter measurement, the associated mathematical truth states that if there are *n* unknown to be determined, it needs to perform *n* measurements even to obtain one of them. Hence, the extraction process of ε_r and μ_r of test material using reflection-only probe requires measuring at least two complex reflection coefficients performed at two different conditions of testing. Based on (1), different techniques have been proposed to measure probe reflection coefficient, via changing sample thickness (*d*) or via changing part of test material or changing measurement frequency (*f*). These methods are called thickness-varying method (TVM) and sample-varying method (SVM) [13] and frequency-varying method [21] respectively. Each method has its own advantages and drawbacks making each one suitable to meet a certain measurement requirement. In general, these methods cannot be employed for testing radar absorbing coatings due to its metallic structure limitation. In this work, frequency sweep technique is proposed to measure probe reflection coefficients by changing measurement frequency (*f*) for broadband ε_r and μ_r parameters determination of radar absorbing coatings. The proposed technique allows to measure reflection coefficients data sets in one step over a given frequency range at two different test conditions for each frequency point. In his regard, the measurement frequency (*f*) is varied such that for a given frequency point (f_i), the required two reflection coefficients are measured at two adjacent frequencies f_i and f_i' respectively. These two frequencies must be spread from each other by a certain frequency interval (Δf) such that the two measured reflection coefficients contain at least partly different information and can be distinguished by network analyzer. The set of the two simultaneous equations, which represents the measured reflection coefficients, can be described using (2) and (3).

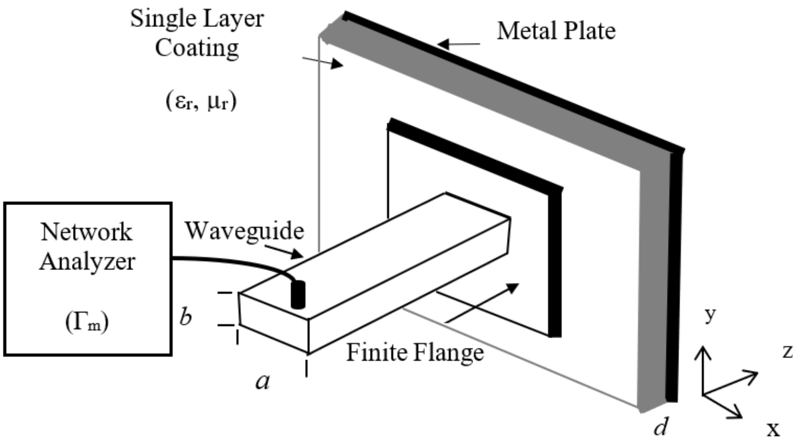

Figure 1. Configuration of the problem

$$\rho_1 = \Gamma(f_i, \varepsilon_r(f_i), \mu_r(f_i), d \tag{2}$$

$$\rho_2 = \Gamma(f_i', \varepsilon_r(f_i'), \mu_r(f_i'), d) \tag{3}$$

$$i = 1,2,3, \ldots\ldots N$$

where $f_i' = f_i + \Delta f$, ρ_1 and ρ_2 are the measured reflection coefficients at f_i and f_i' respectively and *N* is frequency the points number. Most commonly, the material EM-properties are numerically extracted by imposing the measured probe reflection coefficient (Γ_{meas}) to the theoretical calculated one (Γ_{thy}) by iterative optimization techniques using (4):

$$\Gamma_{meas}(f_i, \varepsilon_r(f), \mu_r(f), d) = \Gamma_{thy}(a, b, f_i, \varepsilon_r(f), \mu_r(f), d) + \gamma_i \tag{4}$$

where γ_i is the measurement error, which is frequency dependent and the other symbols defining are pictorially depicted in Figure 1. In general, the proposed technique is based on two facts to perform broadband reconstruction of both ε_r and μ_r of radar absorbing coatings. Firstly, as can be seen in (1), that frequency of measurement is an independent variable, hence, the reflection coefficient can be changed by changing frequency of measurement. Secondly, for most of solid materials, both εr(*f*) and $\mu_r(f)$ themselves are functions of measurement frequency, which may vary slowly or rapidly with the frequency depending on the nature characteristics of radar absorbers. Therefore, simple approximation interpolation technique is introduced in ε_r and μ_r reconstruction process to improve the accuracy of measurement from reflection data of the frequency sweep. Considering two facts, both $\varepsilon_r(f)$ and $\mu_r(f)$ can be reconstructed from the two reflection coefficients measured at f_i and $f_i^{'}$ respectively by using the following simple interpolation approximation:

$$\varepsilon_r(f_i) \approx \varepsilon_r(\frac{f_i+f_i^{'}}{2}) \approx \varepsilon_r(f_i^{'}) \tag{5}$$

$$\mu_r(f_i) \approx \mu_r(\frac{f_i+f_i^{'}}{2}) \approx \mu_r(f_i^{'}) \tag{6}$$

It is clear from (5) and (6) that in order to identify probe reflection coefficients at two neighbor frequencies f_i and $f_i^{'}$, an appropriate frequency interval should be with a value to produce enough change between these two reflection coefficients so that they can be distinguished by network analyzer. Also, it should be selected as small as possible to obtain improvement in the accuracy of the measurement. It is to be noted that the frequency interval with appropriate value can be determined using rule-of-thumb or by the analysis of sensitivity and numerical simulation.

3. REFLECTION COEFFICIUENT FORMULTION

3.1. Using analytical methods

It is apparent in (4) that the accuracy of ε_r and μ_r extraction depends on how accurately the theoretical reflection coefficient is formulated. For rectangular waveguide probe, the formulations of reflection coefficient are analytically developed using different analytical approaches under the assumption of infinite size of probe flange. The probe reflection coefficient using the existing spectral-domain analysis (SDA) [22] developed to extract complex relative permittivity (ε_r) of materials is considered for this purpose. The problem geometry using this analytical approach is shown in Figure 1, where a radar absorbing coating characterized by both ε_r and μ_r is to be tested using rectangular waveguide probe whose open end, in this case, is cut into a metal flange with size assumed to be infinitely large. Considering only TE_{10} mode, the probe aperture normalized input admittance Y_n is given by:

$$Y_n = \frac{Y_a}{Y_o} = \frac{j}{(2\pi)^2 \mu \sqrt{1-\left(\frac{\lambda_O}{2a}\right)^2}} \left[\int_{R=0}^{\infty} \int_{\theta=0}^{2\pi} \Im\{(\varepsilon\mu - R^2 \cos^2\theta)\left(2C_\varphi + \frac{J\Im}{x_z}\right)\} R d\theta dR\right] \tag{7}$$

where Y_a is probe aperture admittance and Y_o is the unbounded medium admittance, d is the coating material thickness, ε and μ are EM properties of test material and a and b are the dimensions of the probe. The reflection coefficient (Γ) seen by the aperture of the probe can be calculated using (8):

$$\Gamma = \frac{1-Y_n}{1+Y_n} \tag{8}$$

The theoretical complex reflection coefficient of the probe is calculated using (7) and (8) respectively.

3.2. Using FDTD method

For the problem under study using probe with a flange of finite size, numerical modelling based on FDTD method was adopted to calculate probe reflection coefficient since using of analytical method, in this case, is quite difficult. The problem FDTD computational domain is illustrated in Figure 2. It consists of two regions, the interior of waveguide which is air-filled region and exterior region represented by the test material backed by metal plate. The medium of each region is characterized by constitutive parameters ε and μ, which is assumed to be isotropic, linear, homogenous, and source-free (J=0). The interior walls and the flange of the probe are assumed to be made from a perfect conducting material with its center chosen as the origin of the 3D Cartesian coordinates. It is also assumed that only the TE_{10} dominant mode signal is used to excite the waveguide propagating in the positive z- direction from the excitation plane. The interaction of the near field at the probe aperture with the test material is described by the time domain set of Maxwell's curl equations using (9) and (10):

$$\mu \frac{dH}{dt} = -\nabla x E \tag{9}$$

$$\varepsilon \frac{dE}{dt} = \nabla x H \tag{10}$$

where E and H denote the electromagnetic field vectors components. Following the standard FDTD procedure developed by Yee [23], the FDTD computational domain is divided into spatial grids of 3D orthogonal cubic shape with a unit cell of Δx, Δy, and Δz positioned at (i, j, k) respectively. The condition for stability in FDTD algorithm for 3D should satisfy courant condition using (11):

$$v\Delta t \leq [\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}]^{-1/2} \tag{11}$$

where v is the medium light velocity and Δt is time increment. In this work, for time-marching system to be stable and to avoid aliasing, both spatial and time intervals have been chosen to satisfy (11). In order to increase FDTD method efficiency, the open boundary of the problem simulation is truncated using absorbing boundary conditions (ABCs). For the problem under study, Mur absorbing boundary conditions [24] are adequate to be employed to truncate the radial boundary of the computational domain because the radiation from the probe is limited. A Gaussian pulse was used as excitation source to illuminate the computational domain with the envelope given by:

$$G(t) = Exp\left\{-[\frac{(nc\Delta t - T_o}{w}]^2\right\} \tag{12}$$

where T_o is the time offset and w is the pulse width parameter. The sampling point of the fields is chosen to be located a way from the probe open end to avoid the modes of high order, which may exist due to discontinues between the different interfaces. The constitutive parameters values of different media are averaged at the boundary of the interface between test material and the probe region. The reflection coefficient of the probe (Γ) seen by the probe aperture is calculated using (8) when the fields steady-state condition is reached.

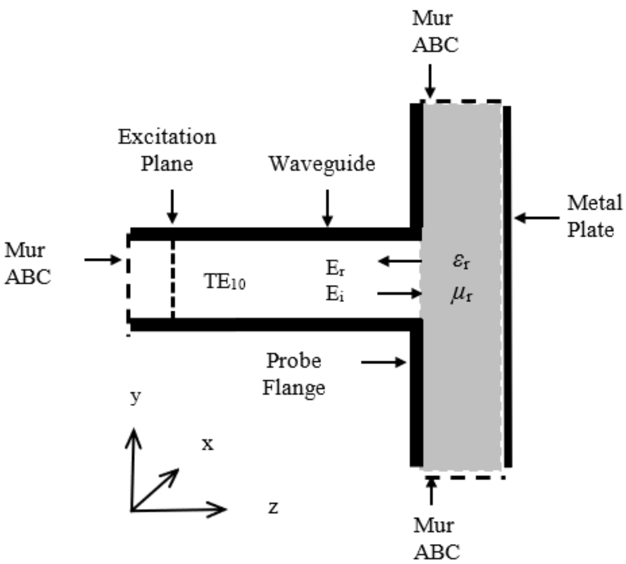

Figure 2. The problem FDTD computational domain

4. NUMERICAL ANALYSIS

The FDTD formulation of the probe complex reflection coefficient performed in the previous section is numerically calculated using a developed code with 3D. The obtained results are to be validated and verified by comparing with the data obtained experimentally and analytically. The complex reflection coefficient ($\Gamma=|\Gamma|e^{\phi\Gamma}$) results of FDTD simulation using X-band waveguide radiating into a radar absorbing coating is compared first with the experiment results and then with the results obtained analytically developed based on spectral-domain analysis model using (7) and (8) respectively. The test material used was GEC-9052 radar absorbing coatings with complex permittivity of (18.18-j0.418) and complex permeability of (1.55-j1.984) and 1.22 mm thickness. The obtained results in polar format are shown in Figure 3. It shows that the FDTD simulation results agree well with the measured data validating the computational tool. On the other hand, the spectral domain model results show a discrepancy with both FDTD simulations results and the measured data. The reason for this discrepancy may be due to the way by which the spectral domain analysis model formulation was developed. Practically, the probe flange used is with finite size of 50 mm dimension [25], thusly a computational error can be introduced in the probe reflection coefficient results compared to the results of measured ones. This error contributes to the overall error of ε_r and μ_r extraction process.

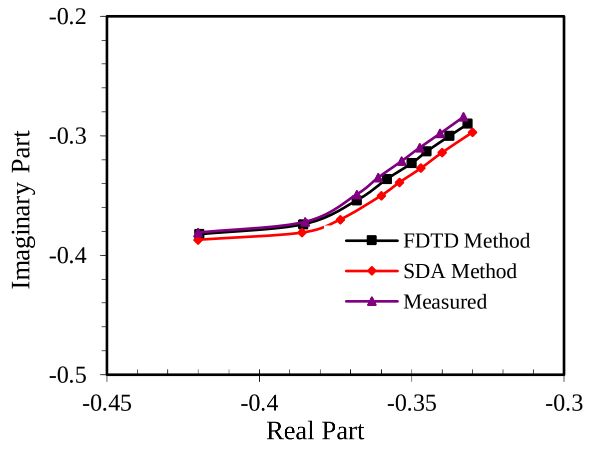

Figure 3. Comparison of the complex reflection coefficients calculated using FDTD method and spectral domain analysis model results versus measured results

An analysis was accomplished to numerically evaluate the flange size of the probe influence on reflection coefficient measurement for two cases. The first case considered is the variation of measurement frequency while the second case considered is the variation of both ε_r and μ_r of lossy material under test. Figure 4 illustrates the reflection coefficient magnitude variation of the probe loaded by high loss material as the size of the flange varies from minimal value (30 mm) to the largest considered value (70 mm) calculated at two different frequencies of 9 GHz and 12 GHz, respectively. From the figure, it is clear that the reflection coefficient magnitude shows variation at 12 GHz less than the variation obtained at 9 GHz. This is due to increasing of the losses of radiation at high frequencies. Also, it is obvious that the magnitude variation of the reflection coefficient becomes duller for flange size greater than 50 mm (for the case of 9 GHz frequency).

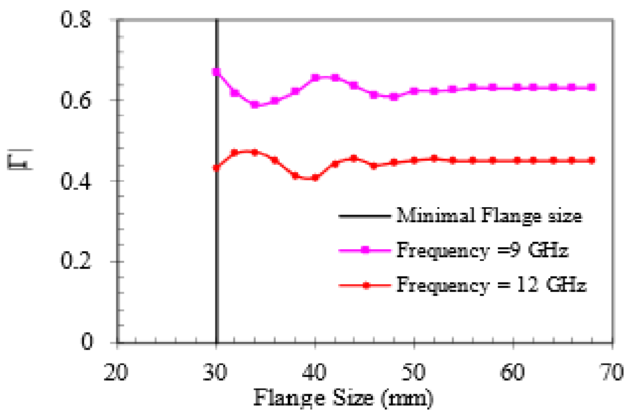

Figure 4. Reflection coefficient magnitude variation with size of probe flange

Figure 5 shows the deviation in percentage in the calculated magnitude of reflection coefficient (relative to that calculated for the case when infinite flange probe is used) due to variation of normalized probe flange size to the wavelength inside the test material. In this analysis, two different lossy materials were considered. They are generally lossy material and high loss material. The simulation was performed at frequency of 10 GHz using 1.2 mm thickness for each sample. It is obvious from the figure that the reflection coefficient deviation decreases for material of high loss as compared to that for the generally lossy material. The analysis results obtained show that for generally lossy material, the dimension of the flange at least chosen to the distance as large as possible at which the field has negligible decay. For high loss materials, due to the fact that the electromagnetic field is greatly depressed and distributed over a limited distance around the waveguide aperture consequently, a probe flange with adequate dimensions can be practically used. In fact, both the flange of the probe in conjunction with backing metal plate guide the wave inside the test material toward its edges acting as parallel transmission line. For thin or low loss material, using finite size of probe flange may cause a significant inaccuracy in the measurement due to the spurious reflection at the test material edges. However, for high loss materials the finite size of flange influence on measurement is less because the distribution of EM fields is with a limited distance around the aperture of the probe consequently. A definite dimension of the flange can practically be used. The results of FDTD analysis showed that the probe can be designed with flange size adequate to obtain the desired measurement accuracy of both ε_r and μ_r depending on the nature characteristics of the material to be tested and the frequency of measurement.

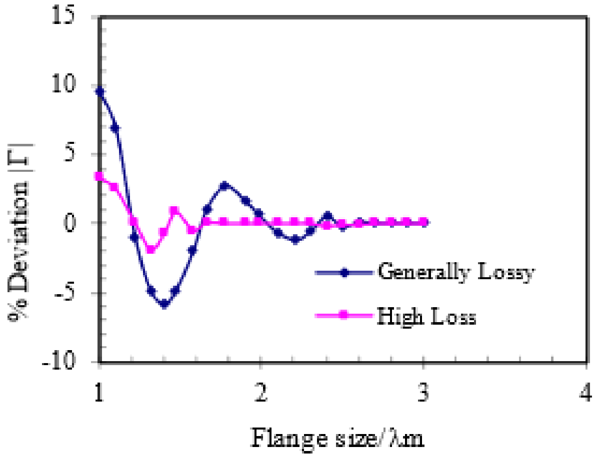

Figure 5. The reflection coefficient magnitude variation with flange size for different materials

5. EM-PARAMETER EXTRACTION

The extraction process is used to retrieve or estimate both complex ε_r and μ_r of a test material by inverse problem. This is necessary since the forward theoretical formulations developed for probe reflection coefficients are noninvertible directly in a straightforward fashion. Thus, numerical search algorithms are iteratively used to extract them by fitting the measured reflection coefficients to the theoretically calculated. To determine both ε_r and μ_r simultaneously, it makes the problem of 2-parameter extraction (ε_r and μ_r).

Mathematically, the truth associated with the multi-parameter measurement states that if there are n parameters to be determined, it needs to measure n reflection coefficients even though only one of these parameters is needed to be determined. Hence, in order to extract both ε_r and μ_r, at least two complex reflection coefficients are needed independently measured under two conditions of testing. Using the proposed technique, the two reflection coefficients for a given frequency point f_i are measured at two different frequencies f_i and f_i' by varying the frequency of measurement in one step for all selected frequency points (i=1, 2, 3, …, N) over the given range of frequency. It is to be noted that the selection of f_i and f_i' should satisfy (5) and (6) respectively. The extraction of both ε_r and μ_r is numerically performed by fitting the measured reflection coefficients (Γ_{meas}) to the calculated ones (Γ_{calc}), for two conditions of testing using (13) and (14).

$$\Gamma_{meas}(f_i, \varepsilon_r, \mu_r, d) = \Gamma_{calc}(f_i, \varepsilon_r, \mu_r, d) + \gamma_i \tag{13}$$

$$\Gamma_{meas}(f_i', \varepsilon_r, \mu_r, d) = \Gamma_{calc}(f_i', \varepsilon_r, \mu_r, d) + \gamma_i' \tag{14}$$

Consequently, for given Γ, ε_r and μ_r are computed from (13) and (14) using two-dimensional search algorithms such as the Evenberg-Marquardt or Newton-Raphson algorithms. The solutions of (13) and (14) suffer from the possibility of obtaining to the local minima convergence. In order for the solution to be converged with global minima using the available search algorithms, the difference between the measured and the calculated reflection coefficient of the optimum cost function (*F*) should be minimized using (15):

$$F = \frac{1}{N}\sum_{i=1}^{N}\left|\Gamma_{meas}(a,b,\varepsilon_r,\mu_r,f,d) - \Gamma_{calc}(a,b,\varepsilon_r,\mu_r,f,d)\right|^2 \quad (15)$$

For both (13) and (14) over a given frequency band of interest. In this work, Newton-Raphson method was employed to extract both ε_r and μ_r of radar absorbing coatings.

6. EXPERIMENATAL RESULTS

The numerical analysis based on FDTD method was experimentally verified using the measurement system shown in Figure 6. A thru-reflect-line calibration method was used to calibrate X-band rectangular waveguide [26]. Different samples of radar absorbing coatings were tested by employing the proposed technique to extract both ε_r and μ_r using vector network analyzer (HP8510B). To verify the probe flange size influence on ε_r and μ_r measurement, probe with different flange sizes were used. Table 1 shows the measured values of ε_r and μr of X_1 sample radar absorbing coating with 2.08 mm thickness. The results were obtained using both spectral domain analysis model for the case of infinite extend of the probe flange and FDTD modeling for probe with 40 mm and 50 mm flange sizes respectively. The measurement was performed at frequency of 10 GHz. As expected, it is clear that the discrepancy in the measured values of ε_r and μ_r obtained using spectral-domain model are higher compared to the published data [13]. This discrepancy in the measured results is reasonable due to that analysis model and FDTD method for different probe flange sizes at f=10 GHz (Δf=0.3 GHz) the assumption of an infinite extension of the probe flange was made in the formulation of the reflection coefficient. For FDTD modeling of the problem, the results of 50 mm flange size agree well with the published data while for 40 mm flange, the FDTD results show a small discrepancy with published data. This discrepancy is produced due to the influence of using small size of probe flange (less than the required size) resulting in presence of more scattering at the edges of the probe aperture by which the reflection coefficient is highly affected.

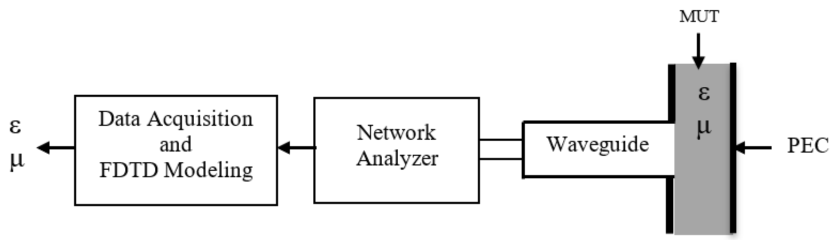

Figure 6. Measurement system

Table 1. The measured results of ε_r and μ_r of X_1 radar absorbing coating obtained using spectral domain

Flange size (mm)	Method	ε'			
40	FDTD	10.74	-0.006	1.29	0.65
50	FDTD	10.63	-0.005	1.33	0.64
Infinite	SDA	11.53	-0.016	1.24	0.83
	Reference (13)	10.40	-0.005	1.35	0.64

Another set of experiments were carried out using the proposed technique to study the frequency dependence of both ε_r and μ_r of radar absorbing coatings over given frequency range. The results of the extracted ε_r and μ_r values of MF-116 radar absorbing coating with 1.4 mm thickness are presented in Figure 7. The real parts variations of both ε_r and μ_r with frequency are shown in Figure 7(a) while the variations of their loss tangents are shown in Figure 7(b). A good agreement can be observed between the results of measurement and the data provided by Eccosorb® MF technical bulletin. Another important parameter that should be taken into consideration when performing testing of radar absorbing coating is test material thickness. To achieve this purpose, three thicknesses of X_2 sample radar absorbing coating of 1.22 mm, 3.66 mm and 6.10 mm were selected for this test performed over a given frequency range and the results are illustrated in Figure 8. The variations of the extracted real part of both ε_r and μ_r with the frequency are shown in Figure 8(a) whiles Figure 8(b) shows the variations of the extracted their loss tangent. It shows that the extracted values of the real and imaginary parts of both ε_r and μ_r of the test material with 1.22 mm and 3.66 mm thicknesses agree well with the data provided by manufacture especially for real parts, although the results show a tendency of differences between them especially real part of ε_r. This is due to thin sample since the test material is backed by a conductor, a strong interrogation between the magnetic field and test material is produced resulting a relatively accurate measured result of μ_r while a weak interrogation between the electric field and test material is produced resulting a relatively inaccurate measured result of ε_r. Also, it can be observed that the test material thickness affects the accuracy measurement of ε_r and μ_r especially loss tangent of ε_r. A relatively large deviation in $\tan\delta_\varepsilon$ of 6.10 mm thickness sample results was obtained; whose values become the minus compared with 1.22 mm and 3.66 mm thicknesses samples results. It is to be noted that the test material used in the measurement has $tan\delta\varepsilon = 0.06$. The obtained results from this study show that the tested material loss factor value and its thickness are the dominant reasons that influencing the accuracy of measurement such that obtaining a reasonable accuracy in the measurement becomes difficult for thick sample whose $tan\delta\varepsilon \leq 0.1$. For high loss material, this is because of decreasing of reflections as the test material thickness increases. In general, for high loss materials, it is the inherent limitation of reflection-only method that it suffers poor accuracy in the measurement for low values of their loss factor. Also, the thickness measurement of radar absorbing coatings becomes poorer for thick samples. Hence, it becomes necessary that the test material thickness is properly chosen to obtain the required accuracy in the measurement using the proposed technique.

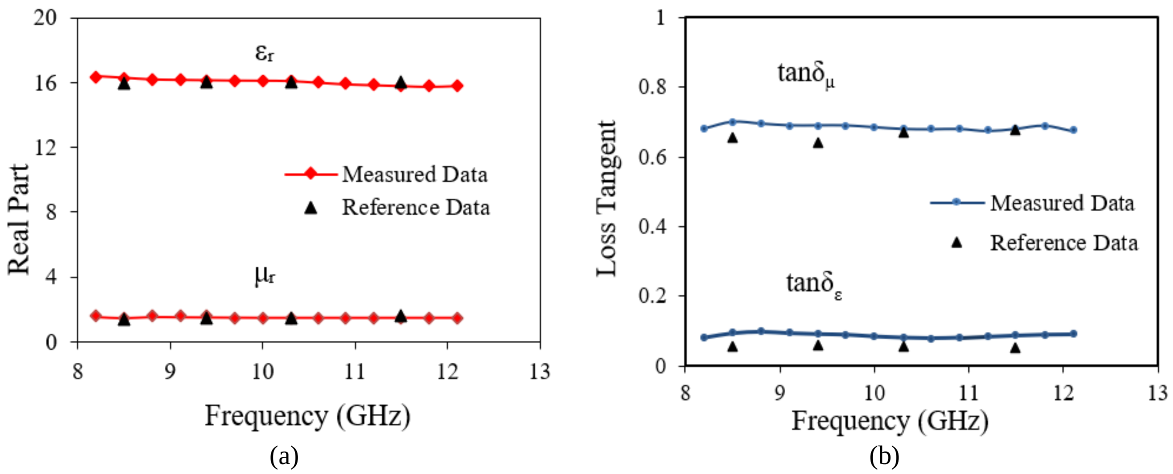

Figure 7. Frequency dependence of complex permittivity and complex permeability of MF-116 radar absorbing coating Δf=0.250 GHz (a) real parts and (b) imaginary parts

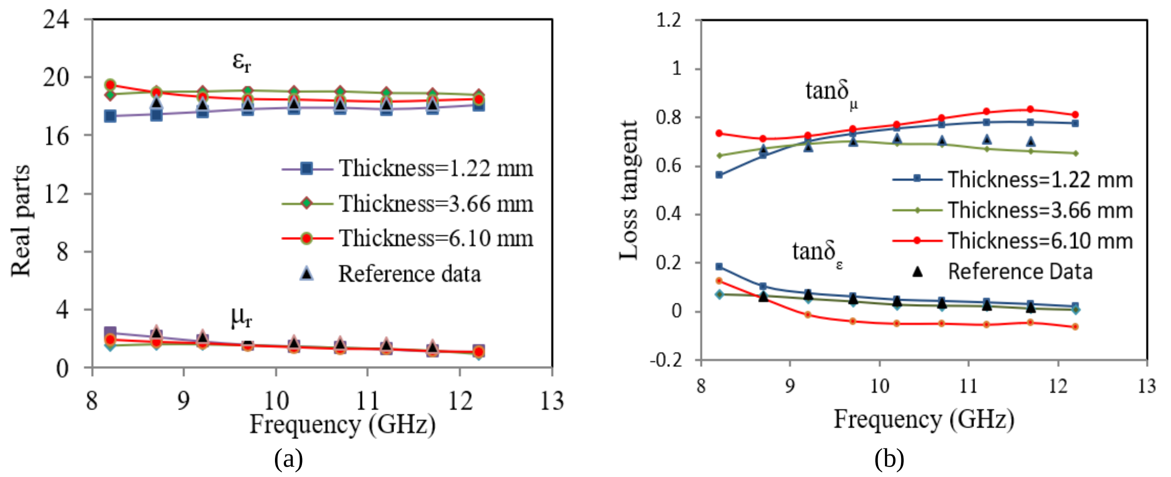

Figure 8. Frequency dependence of complex permittivity and complex permeability of X2 radar absorbing coating for different sample thicknesses, Δf=0.250 GHz (a) real parts and (b) Imaginary parts

7. CONCLUSION

In this paper, a new technique of swept-frequency with interpolation approximation is introduced for simultaneously broadband *in-situ* ε_r and μ_r of radar absorbing coatings determination using open-ended rectangular waveguide probe. The goal is to develop a technique to achieve this purpose in a convenient way, where using the existing methods becomes impossible or quite difficult. Also, the probe reflection coefficients of finite dimensions of the flange directly placed on the material to be tested is successfully calculated and analyzed for different test conditions using FDTD method, where it becomes difficult to be analytically formulated. The successful results of experiments validated by the published data and corresponding data provided by companies illustrate good prospects and feasibility of the proposed technique for *in-situ* EM-properties characterizing and testing of radar absorbing coatings. Also, the obtained results showed that both flange size and thickness of coated material are the limiting factors in the accuracy of measurement. The main feature of the proposed technique is that it needs only one frequency sweep of reflection coefficients measurement data set over a given band of interest, and thus, speeds up and simplifies the process of measurement. Furthermore, this technique improves the measurement accuracy and its repeatability compared to the other methods currently employed for testing radar absorbing coatings. The proposed technique can be extended to perform measurement of multi-parameter such as simultaneously determination of ε_r, μ_r and thickness of radar absorbing coatings, which will be considered in the near future.

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