ARPN Journal of Engineering and Applied Sciences

A NEW ENGINEERING APPROACH TO EVALUATE THE DIELECTRIC PROPERTIES OF MATERIALS IN K-BAND FREQUENCY USING RECTANGULAR WAVEGUIDE MEASUREMENTS

Rachid Lahbibi, Hassan Ammor and Hassan Elmajid
Research Team in Smart Communications (ERSC formerly known as LEC) - E3S Research Center, EMI. Mohamed V University in Rabat, Morocco
E-Mail: rachidlahbibi@research.emi.ac.ma

ABSTRACT

A new engineering approach for measuring dielectric properties of materials at K-Band frequencies is developed. The proposed approach is based on applying the rectangular waveguide measurements. The material sample under test (MSUT) is loaded into the K-band rectangular waveguide WR42. The present method is comprised of two parts. The first one concerns the extraction of Scattering Parameters using Ansoft HFSS Solver, and then calculates them as a function of the complex permittivity adopting transmission matrices (direct problem). The square sums of errors between the simulated and calculated S-parameters are minimized using a nonlinear optimization algorithm. The second part aims to extract the complex relative permittivity from the simulated S-parameters (inverse problem). An innovative algorithm is developed to look for complex relative permittivity. A comparative study is elaborated; the Nicholson Ross method (NRM) is used to determine the complex relative permittivity of the tested materials in order to compare them with the results obtained using our method. The percentages of errors between the values obtained by NRM and those achieved using our technique are assessed and minimized. The achieved results have demonstrated a good agreement.

Keywords: complex relative permittivity, dielectric material, K-band, rectangular waveguide, optimization algorithm, NRM.

INTRODUCTION

Application of materials in the aerospace, microelectronics, microwave and communication industries requires the exact knowledge of material parameters such as permittivity and permeability [1-2]. Indeed, the evaluation of these material properties proves to be of great interest in scientific and industrial applications. A reliable and accurate evaluation method of complex permittivity of practical materials is a betting problem. In the literature, several techniques have been proposed on extracting complex permittivity and complex permeability of dielectric materials [3-2].

The rectangular waveguide technique is one of a class of two ports measurement (Transmission/ Reflection).It has been widely used as an easy way to determine the complex permittivity of dielectric materials in the microwave frequency [2-4]. Due to its relative convenience and simplicity, the Transmission/Reflection (TR) method is used in measurement technique [5].

In general, this technique makes use of the reflected and/or transmitted waves by and through a dielectric-filled transmission line rectangular waveguide transmission line in order to analytically or numerically determines the dielectric properties of the material [6].

The main aim of our study is to contribute for the establishment and validation of simulation of complex permittivity of a homogeneous dielectric material at the K-band frequencies using a two-port rectangular waveguide. The present paper branches out into two related stages. The first one is the “direct problem” in which the calculated and simulated S-parameters are determined as a function of the electromagnetic properties of materials in the rectangular waveguide and their geometrical dimensions. The second stage (Inverse problem) is concerned about the implementation of a computational modeling to predict the dielectric behavior of the tested materials over the K-band frequencies. This algorithm is based on the use of transmission matrices (ABCD parameters) combined with Fminunc Unconstrained Minimization function in MATLAB optimization. Finally, in order to verify the present approach, Nicholson Ross method is employed. The complex permittivity of Teflon, Nylon, FR4 at the K-band frequencies are then determined, and the average relative errors between the proposed method and iterative Nicholson Ross method are estimated. The obtained results showed the algorithm efficiency, which open perspectives for the characterization of different low loss materials in microwave frequency range and for the determination of other useful dielectric parameters such as the complex permeability.

THEORETICAL ANALYSIS

Definition of dielectric properties

Generally, there are two interpretations of dielectric properties of materials: macroscopically and microscopically. From the macroscopic standpoint, they represent the relationship between the applied electric field strength $\bar{\boldsymbol{E}}$(V/m^2) and the electric displacement $\bar{\boldsymbol{D}}$(C/m^2) in the material. Regarding the microscopic point of view, dielectric properties represent the polarization ability of molecules in the material corresponding to an externally applied electric field E. In engineering practices, the macroscopic interpretation of dielectric properties of material is frequently used. In this paper, such a characterization of dielectric properties of a material is implemented by the use of a scalar, effective complex

VOL. 13, NO. 12, JUNE 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

permittivity ε_e^*, to account for EM features (polarization and capacitance and dielectric losses) of the material:

$$\varepsilon_e^* = \varepsilon_e' - j\varepsilon_e'' = \left(\varepsilon' + \frac{\sigma''}{\omega}\right) - j\left(\varepsilon'' + \frac{\sigma'}{j\omega}\right)$$

Where ε_e' is the real part of ε_e^*, which represents the ability of a material to store the incident EM energy through wave propagation, ε_e'' is the imaginary part of ε_e^* and represents the degree of EM energy losses in the material, j is the imaginary number.

$\varepsilon^* = \varepsilon' - j\varepsilon''$ is the complex permittivity (F/m) and $\sigma^* = \sigma' + j\sigma''$ is the complex electric conductivity (Ω/m) and $\omega = 2\pi f$ is the angular frequency (rad/s). The dimensionless relative permittivity ε_r^* is more frequently used, which is defined as:

$$\varepsilon_r^* = \frac{\varepsilon_e^*}{\varepsilon_0} = \frac{\varepsilon_e' - j\varepsilon_e''}{\varepsilon_0} = \varepsilon_r' - j\varepsilon_r'' \qquad (2)$$

Where ε_0 is the the permittivity of free space and $\varepsilon_0 = 8.85 \times 10^{-12}\ F/m$. The real part of the relative permittivity is known as dielectric constant and the imaginary part as loss factor. The ratio between the loss factor and the dielectric constant is called loss tangent. For dielectric materials , $\varepsilon_r'' \geq 0$ and $\varepsilon_r' \gg \varepsilon_r''$: $\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'}$.

Dielectric constant and loss tangent are functions of measurement frequency, material homogeneity and anisotropy, moisture, and temperature in the material.

Direct problem

The problem of measuring relative complex permittivity of a solid sample, which is inserted in the rectangular waveguide transmission line, is depicted in Figure-1. In the analysis, it is assumed that the sample is isotropic, symmetric, homogenous, and flat.

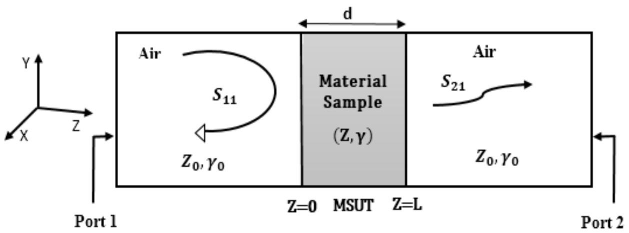


Figure-1. Rectangular waveguide loaded with dielectric sample.

This section presents computation of the ABCD parameters of rectangular waveguide loaded with a dielectric sample (see Figure-1). Assuming that only the dominant TE10 mode propagates in the loaded waveguide ,the formulation of the S -parameters can be expressed in terms of material sample thickness (d) and unknown permittivity ε_r and unknown permeability μ_r using ABCD parameters as follows [7], [8]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh(\gamma d) & Z\sinh(\gamma d) \\ \sinh(\gamma d)/Z & \cosh(\gamma d) \end{bmatrix} \qquad (3)$$

Where, Z,Z_0 and γ are respectively, the wave impedance of the material sample, characteristic impedance and the propagation constant, which can be expressed as:

$$\gamma = \left(\left(\frac{\pi}{a}\right)^2 - \omega^2\mu_r^*\varepsilon_r^*\right)^{\frac{1}{2}} \qquad (4)$$

$$Z = \frac{j\omega\mu}{\gamma} \qquad (5)$$

$$Z_0 = \frac{j\omega\mu_0}{\gamma_0} \qquad (6)$$

Where (a) is the appropriate (maximum) cross-sectional dimension of the waveguide, μ_r^* and ε_r^* are the complex permeability and the complex permittivity relative of material and ω is the angular frequency.

The S-parameters are related with the ABCD parameters by the following conversion equations [9]:

$$S_{11} = \frac{A + \frac{B}{Z_0} - CZ_0 - D}{A + \frac{B}{Z_0} + CZ_0 + D} \qquad (7)$$

$$S_{22} = \frac{-A + \frac{B}{Z_0} - CZ_0 + D}{A + \frac{B}{Z_0} + CZ_0 + D} \qquad (8)$$

$$S_{21} = \frac{2}{A + \frac{B}{Z_0} + CZ_0 + D} \qquad (9)$$

$$S_{12} = \frac{2(AD - BC)}{A + \frac{B}{Z_0} + CZ_0 + D} \qquad (10)$$

with Z_0 : the characteristic impedance.

Inverse problem: The new approach

For extracting the complex permittivity, from the simulated S-parameters, in a given sample with a specific prior knowledge of its thickness, an optimization method on MATLAB [10] is used through a function error which finds the minimum of a scalar function of several variables from an initial guess of the complex relative permittivity ε'r=1.2, ε''r=0.001 by using optimization settings with maximum number of function evaluations is equal to 1000, and termination tolerance on the function value is equal to 10^{-04} in order to find the complex permittivity of the dielectric sample to match the simulated S_{ij}^{Sim}-parameters and calculated S_{ij}^{C}-parameters.

The error function, which has to be minimized, is written as follows:

$$F(\varepsilon_r', \varepsilon_r'') = \sqrt{\sum\left(Real(S_{ij}^C - S_{ij}^{Sim})\right)^2 + \left(Imag(S_{ij}^C - S_{ij}^{Sim})\right)^2}$$

With $S_{ij} = S_{ij}(\varepsilon_r', \varepsilon_r'')$ and $i, j = 1,2$ (11)

VOL. 13, NO. 12, JUNE 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Comparative study: Nicholson Ross method

To verify the efficiency of developed algorithm, the Nicholson Ross (NR) method is used to compare the results achieved with it. This technique combines the values of S_{11} and S_{21} to develop an equation system that allows the estimation of the complex electromagnetic constants. The NR method works well for frequencies away from the TEM mode. Near resonance, however, the method loses sensitivity for low-loss materials [11].

This method obtains the permittivity using the following constants [12] [13]:

$$K = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}^2} \tag{12}$$

Using the constant K, it is possible to obtain the reflection and transmission coefficients, Γ and T respectively:

$$\Gamma = K \pm \sqrt{K^2 - 1} \tag{13}$$

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} K \tag{14}$$

After the calculation of the reflection and transmission coefficients and knowing that the propagation constant has to be $|\Gamma| \leq 1$, is possible to obtain the values of the complex permittivity (ε_r^*) .

$$\gamma = \frac{\ln(\frac{1}{T})}{d} \tag{15}$$

$$\gamma_0 = j\frac{2\pi}{\lambda_0} \tag{16}$$

$$\varepsilon^* = \frac{\gamma}{\gamma_0}\left(\frac{1-\Gamma}{1+\Gamma}\right) \tag{17}$$

SIMULATION RESULTS

To validate the direct problem, the scattering parameters of the tested structure were extracted with FR4 sample using the procedure described earlier and measured using the 3-D electromagnetic software Ansoft HFSS as shown in Figure-2 and Figure-3.The comparison between simulated and calculated values shows the accuracy of the simulation procedure in this study, but it is also observed a slight difference. To understand this difference, it is important to mention that the simulation configuration takes place in an ideal environment, where temperature, misalignment, and air gap effects are not taken into account.

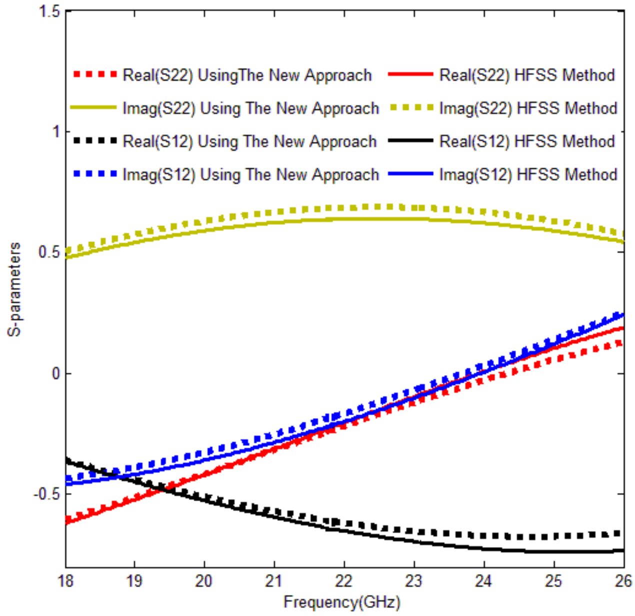


Figure-2. Simulated and calculated S_{12} and S_{22} parameters of FR4 sample.

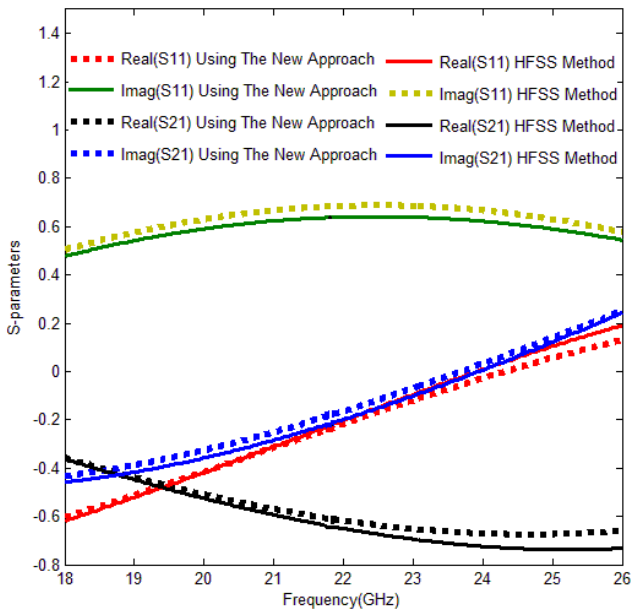


Figure-3. Simulated and calculated S_{11} and S_{21} parameters of FR4 sample.

To verify the validation of the inverse problem, using the approach described earlier, the complex permittivity(ε_r^*) of three materials, cited above, were evaluated in the frequency band [18-26.5 GHz] (with rectangular waveguide dimensions a=10.66 mm, b=4.31 mm).In the first estimate, for the starting frequency initial guess was good for the complex permittivity ε'_r=1.2, ε''_r=0.001 by using optimization settings with maximum number of function evaluations= 1000, and termination tolerance on the function value = 10^{-04}.

ARPN Journal of Engineering and Applied Sciences

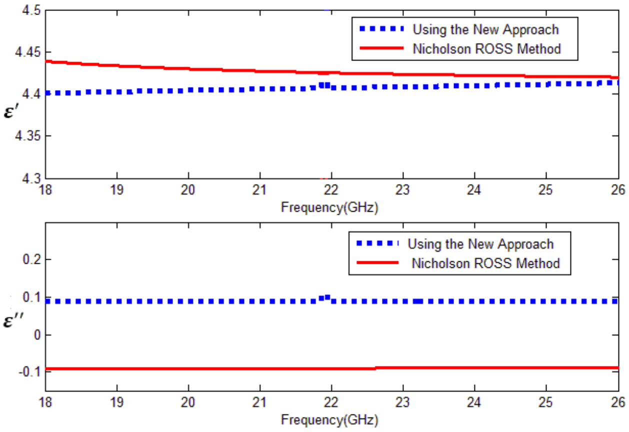
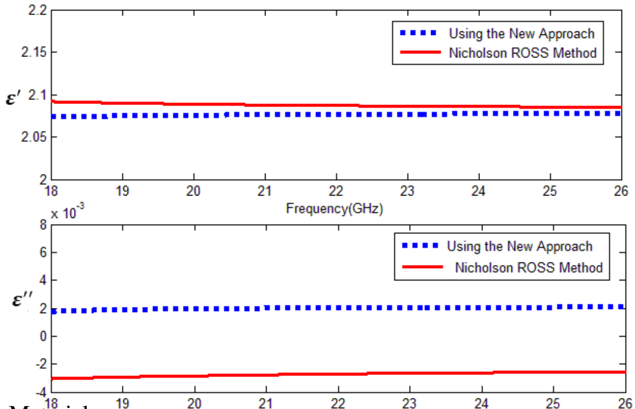


Figure-4. Complex relative permittivity of FR4 sample calculated using the new approach compared with Nichloss Ross method.



Materials

Figure-5. Complex relative permittivity of Tefon sample calculated using the new approach compared with Nichloss Ross method.

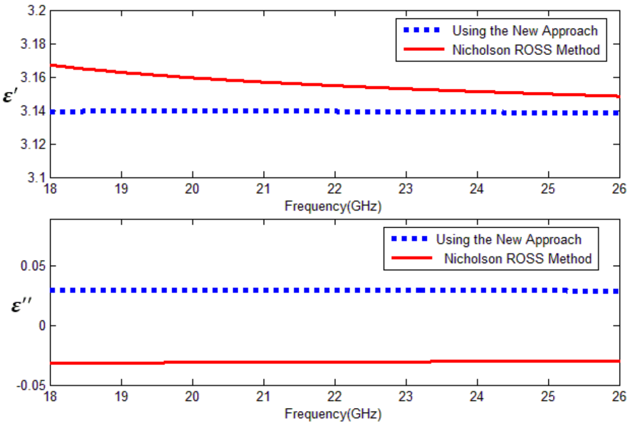


Figure-6. Complex relative permittivity of Nylon sample calculated using the new approach compared with Nichloss Ross method.

For error estimations, several factors which affect the accuracy of the complex permittivity determination are extensively treated in the literature [2][13][14].In simulation configuration, the sample length, the sample holder length, the reference planes, and uncertainty in magnitude and phase of Sij parameters are accurately known. In our case, we are focused on the average relative error percentage on real and imaginary parts of relative complex permittivity between the values obtained by Nichloss Ross method and those achieved using our technique.

Table-1. The average values of the complex relative permittivity (calculated using two different methods), and the average error percentage on the real and imaginary parts of the complex permittivity over K-band.

Materials	ε_r^*		% Error ε_r'	% Error ε_r''
	New Approach measurements	Nicholson Ross measurements		
FR4	4.4398- 0.0895i	4.4161- 0.0900i	0.5349	0.6257
Teflon	2.0764- 0.0020i	2.0873- 0.0027i	0.5275	6.0426
Nylon	3.1392- 0.0296i	3.1555- 0.0307i	0.7201	3.5734

As can be seen, the percentage errors on the real part of relative complex permittivity are negligible (between 0.53 % and 0.72 %) and for the imaginary part, the percentage errors are between 0.62 % and 6.04 % for the tested samples over K band, which explains the performance of the new method developed in this paper compared with Nicholson Ross.

CONCLUSIONS

A new procedure of rectangular waveguide structure for the determination of complex permittivity of solid materials at K-band frequencies has been proposed. The method is based on simulating the S_{ij} parameters of each sample using electromagnetic three dimensional simulation Software Ansoft HFSS. The simulated parameters are then compared with the calculated values using Transmission Matrix (ABCD).This new approach makes it possible to determine the complex permittivity of dielectric material. By matching the calculated value with simulated value of the S-parameters of an K-band rectangular waveguide, loaded by different materials samples. The results obtained using this approach are in good agreement with the results obtained by Nicholson-Ross Technique, which guarantees the application of the simulation methodologies for the prediction of dielectric properties of different building materials across the K band.

REFERENCES

[1] D.K. Ghodgaonkar, V.V. Varadan, V.K. Varadan. 1989. IEEE Trans. Instrum. Meas. 38, 789-793.

[2] J. Baker-Jarvis. 1990. Transmission/Reflection and Short-Circuit Line Permittivity Measurements, National Institute of Standards and Technology, Boulder, Colorado. 80303-3328.

[3] D.K. Ghodgaonkar, V.V. Varadan, V.K. Varadan. 1989. A free-space method for measurement of dielectric constants and loss tangents at microwave frequencies, IEEE Trans. Instrum. Meas.38: 789-793.

[4] U. C. Hasar. 2009. Permittivity Measurement of Thin Dielectric Materials from Reflection-Only Measurements using one-port Vector Network Analyzers, Progress in Electromagnetic Research PIER. 95: 3653808.

[5] H. Zhou, G. Lu and all. 2009. An Improved Method of Determining Permittivity and Permeability by S Parameters, PIERS Proceedings, Beijing, China. 23-27.

[6] Bois. K. J, Handjojo. L. F, Benally. A. D, Mubarak. K, and Zoughi. R. 1999. Dielectric Plug-Loaded Two-Port Transmission Line Measurement Technique for Dielectric Property Characterization of Granular and Liquid Materials. IEEE Transactions on Instrumentation and Measurement. 48, 6, 1141-1148.

[7] D. Pozar. 2003. Microwave Engineering, 3rd edition. New York: Wiley.

[8] R. Ludwig and P. Bretchko. 2000. RF Circuit Design: Theory and Applications. Upper Saddle River, NJ: Prentice-Hall.

[9] D. M. Pozar. 1998. Microwave Engineering. 2nd edition, John Wiley & sons.

[10] 2001. Optimization Toolbox User's Guide, The MathWorks, Version 2.

[11] J.B. Jarvis *et al.* 2005. Measuring the Permittivity and Permeability of Lossy Materials: Liquids, -Metals, Building Materials and Negative-Index Materials. National Institute of Standards and Technology.

[12] W. B. Weir. 1974. Automatic Measurement of Complex Dielectric Constant and Permeability at Microwave Frequencies. Proceedings of the IEEE. 62(1): 33-36.

[13] M. Nicolson, G. F. Ross. 1970. Measurement of the Intrinsic Properties of Materials by Time-Domain Techniques. IEEE Transactions on Instrumentation and Measurement. im 19(4): 377-382.

[14] H.Elmajid, J.Terhzaz, H.Ammor. 2015. A New Method to Determine the Complex permittivity and Complex permeability of Dielectric Materials at X-Band Frequencies. IJMOT.34-39.