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A New Method to Determine the Complex Permittivity and Complex Permeability of Dielectric Materials at X-Band Frequencies

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***Abstract*- This paper presents a simple waveguide measurement technique to determine the complex permittivity and complex permeability of a dielectric material. The dielectric sample is loaded in the transmission line rectangular waveguide WR90. The S-parameters of the waveguide are measured by Network analyzer and calculated as a function of the complex permittivity and complex permeability using theory of transmissions lines. Using the MatLab Optimization Tools, a simple MatLab scripts is written to look for complex permittivity and complex permeability of a dielectric material so as to match the measured and calculated values of S-parameters. The complex permittivity and complex permeability of Teflon, Nylon and Delrin at the X-band frequencies are then determined.**

***Index Terms*- Complex permittivity, Complex permeability, Dielectric material, Optimizations Methods, Rectangular Waveguide.**

I. INTRODUCTION

Knowledge of complex permittivity ε^* and complex permeability μ^* of materials proves to be of great interest in scientific and industrial applications [1]. The complex permittivity and complex permeability are an essential property of dielectric materials hence its determination is very important. Various microwave techniques, each with its unique advantages and constraints [2-3], are introduced to characterize the electrical properties of materials. In the literature, several techniques have been proposed on extracting complex permittivity and complex permeability of dielectric materials [2-5]. The rectangular waveguide technique is one of 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 [4-5]. Due to its relative convenience and simplicity, the transmission/ reflection (TR) method is used in broad-band measurement technique [6].

The goal of this work is to present a new method to determine the complex permittivity and complex permeability of a homogeneous dielectric material at the X-band frequencies using a two-port rectangular waveguide measurement. This method is based on the use theory of transmissions lines combined with Fminsearch function in MatLab optimization, to estimate the complex permittivity and complex permeability of a homogeneous dielectric material which cancels the error between the measured and calculated values of S-parameters of rectangular waveguide loaded by a material sample.

II. THEORETICAL ANALYSIS

This section presents computation of the Transmission Reflection (T/R) method of rectangular waveguide loaded with a dielectric sample presented in figure1.

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
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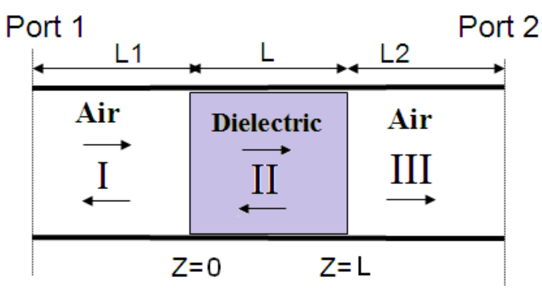

Fig.1. Rectangular waveguide loaded with dielectric sample

The S- parameters are obtained from an analysis of the electric field at the sample interfaces. Assuming only the TE_{10} dominant mode in the rectangular waveguide, the spatial distribution of the electric fields in the regions I, II, and III can be written as [5]:

$$E_I = \exp(-\gamma_0 z) + \alpha_1 \exp(\gamma_0 z) \quad (1)$$
$$E_{II} = \alpha_2 \exp(-\gamma z) + \alpha_3 \exp(\gamma z) \quad (2)$$
$$E_{III} = \alpha_4 \exp(-\gamma_0 z) \quad (3)$$

Where

$$\gamma = j\sqrt{(\frac{\omega}{c})^2\mu_r^*\varepsilon_r^* - (\frac{2\pi}{\lambda_c})^2} \;;$$
$$\gamma_0 = j\sqrt{(\frac{\omega}{c})^2 - (\frac{2\pi}{\lambda_c})^2}$$

$\boldsymbol{\lambda_c}$ is the cutoff waveguide, γ_0 and γ are the propagation constants in vacuum and material, ε_r* and μ_r* are the complex permittivity and complex permeability relative of material, ω is the angular frequency and c is the speed of light in vacuum. The constants α_i are determined from the boundary conditions [7].

Tangential component of the electric field is continuous at sample interfaces:

$$E_I(z = 0) = E_{II}(z = 0) \quad (4)$$
$$E_{II}(z = L) = E_{III}(z = L) \quad (5)$$

Tangential component of the magnetic field is continuous at sample interfaces:

$$\frac{1}{\mu_0}\frac{\partial E_I(z = 0)}{\partial z} = \frac{1}{\mu}\frac{\partial E_{II}(z = 0)}{\partial z} \quad (6)$$
$$\frac{1}{\mu}\frac{\partial E_{II}(z = L)}{\partial z} = \frac{1}{\mu_0}\frac{\partial E_{III}(z = L)}{\partial z} \quad (7)$$

Where L is the sample length, by solving equations (4), (5), (6), and (7) we can obtain the following explicit expression for scattering parameters, in the case of homogeneous isotropic materials is assumed that S_{12}= S_{21}.

$$S_{11} = \left[\frac{X(1 - Y^2)}{(1 - X^2Y^2)}\right] \quad (8)$$
$$S_{12} = \left[\frac{Y(1 - X^2)}{(1 - X^2Y^2)}\right] \quad (9)$$
$$S_{22} = \left[\frac{X(1 - Y^2)}{(1 - X^2Y^2)}\right] \quad (10)$$

When we can define reflection (X) and transmission coefficient (Y) by the following expression:

$$X = \frac{\gamma_0 - \gamma}{\gamma_0 + \gamma} \quad \text{and} \quad Y = \exp(-\gamma L)$$

It is assumed that the sample plane coincides with the measurement calibration plane. This is not the case in general. However, one can transform the reference plane position by a simple procedure. To accomplish this we proceed by assuming that the most general expression for scattering parameters is given by:

$$S_{11ref} = R_1^2 S_{11} \quad (11)$$
$$S_{12ref} = R_1^2 R_2^2 S_{12} \quad (12)$$
$$S_{22ref} = R_2^2 S_{22} \quad (13)$$

where

$$R_1 = \exp(-\gamma_0 L_1) \text{ and } R_2 = \exp(-\gamma_0 L_2)$$

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
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with L_1 and L_2 are the distances from the calibration reference planes to the sample ends. R_1 and R_2 are the respective reference plane transformation expressions.

III. COMPLEX PERMITTIVITY AND COMPLEX PERMEABILITY ESTIMATION

This section presents computation of the complex permittivity and complex permeability in a given sample with a specific prior knowledge of the thickness of dielectric sample. For this an optimization method on MATLAB [8], by using a function error which finds the minimum of a scalar function of several variables from an initial estimate and optimization settings to find the complex permittivity and complex permeability of the dielectric sample to match the measured S_{ij}^{m}-parameters and calculated S_{ij}-parameters. The error function we want to minimize is written as follows:

$$F(\varepsilon_r', \varepsilon_r'', \mu_r', \mu_r'') = \sum \left(\left(Real(S_{ij} - S_{ij}^{m}) \right)^2 + \left(Imag(S_{ij} - S_{ij}^{m}) \right)^2 \right) \quad (14)$$

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

IV. EXPERIMENTAL RESULTS

We consider the measurement setup shown in figure 2. The S-parameters at reference plane was measured by placing one of the samples in an X-band transmission line rectangular waveguide WR90 (a=22.86mm and b=10.16mm) and using the E8634A Network Analyzer. Before the measurement, the Thru–Reflect–Line (TRL) calibration technique is used in this measurement system to provide the ultimate accuracy by minimizing the measurement residual errors [9] [10], and to measure the S_{ij}-parameters at the reference plane. The dielectric of length L = 10 mm is provided between two sections of the air with lengths L1=30mm and L2=40mm as shown in figure2. All measurements are performed at [8.4-12.4] GHz band with 201 frequency points.

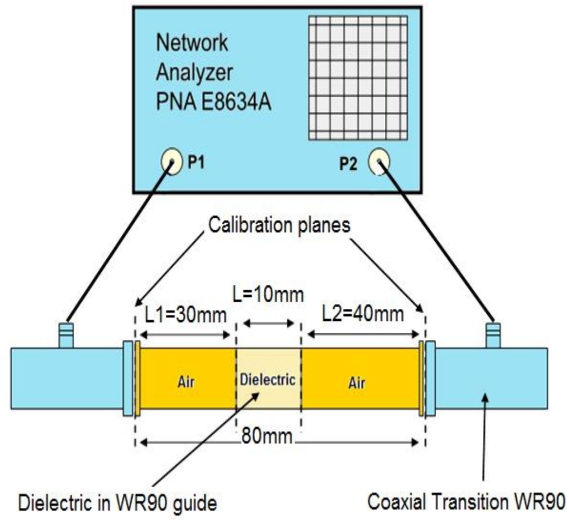

Fig.2. Rectangular waveguide measurement setup

To validate the direct problem, the S-parameters of Teflon sample (ε_r'=2.08, ε_r''=0.002) and (μ_r'=1.00, μ_r''=0.001) are calculated using the procedure described in section 2 and measured using Network Analyzer as shown in figures 3 and 4. It is seen from these results, an excellent agreement between the measured and calculated S_{ij}-parameters.

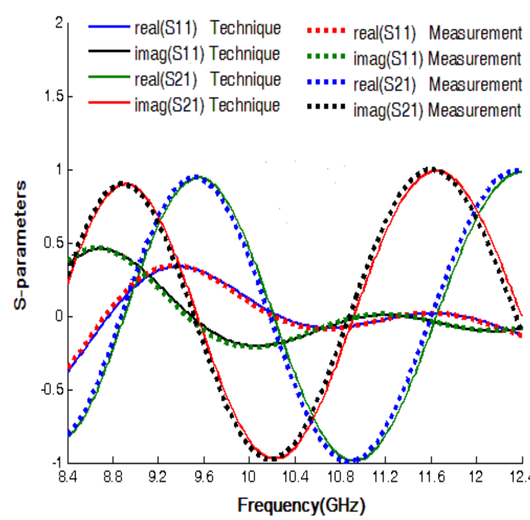

Fig.3. Measured and Calculated S_{11} and S_{21} parameters of Teflon sample

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
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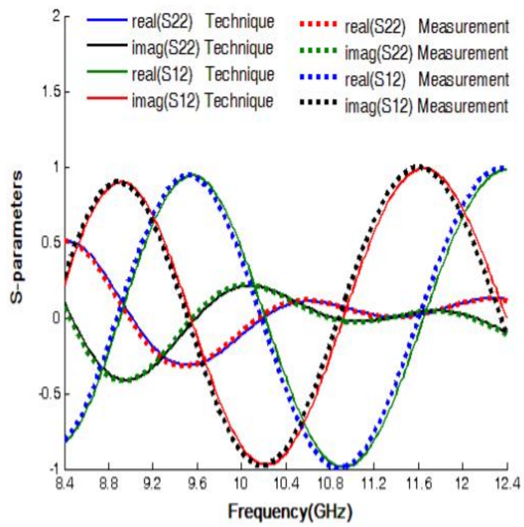

Fig.4. Measured and Calculated S_{22} and S_{12} parameters of Teflon sample

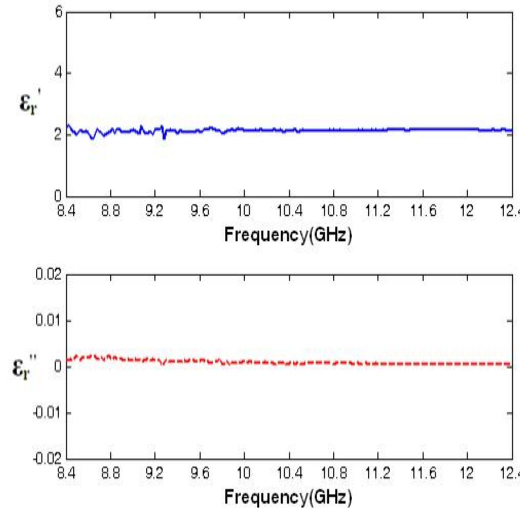

Fig.5. Complex permittivity of a Teflon sample over X-band frequencies

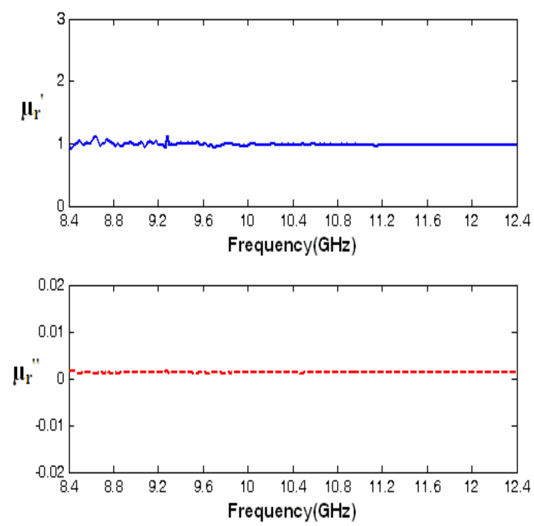

Fig.6. Complex permeability of a Teflon sample over X-band frequencies

Using the procedure described in section 2 and 3, the complex permittivity (ε_r',ε_r'') and complex permeability of the Teflon sample (ε_r'=2.08, ε_r''=0.002, μ_r'=1.00, μ_r''=0.001) with dimensions a_s=22.86mm, b_s=10.16mm and L=1cm were estimated in the frequency band 8.4-12.4GHz and presented in figure 5 and 6. In the first estimate, for the starting frequency the good initial guess for the complex permittivity and complex permeability (ε_r'=1.0, ε_r''=0.001) and (μ_r'=0.6, μ_r''=0.001) was choosing so that the function optimization converges to the correct solution. The results obtained, in this work, are in good agreement with the results given in the literature [4] [10].

To validate this technique, the complex permittivity and permeability of another's samples of Nylon (ε_r'=3.1, ε_r''=0.03) ; (μ_r'=1.00, μ_r''=0.001) and Delrin (ε_r'=2.9, ε_r''=0.05); (μ_r'=1.00, μ_r''=0.001) were estimated in X-band frequencies by application the procedure described in this work and presented in figures 7, 8, 9 and 10. The results obtained are in good agreement with the results given in the literature [4] [11] [12].

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
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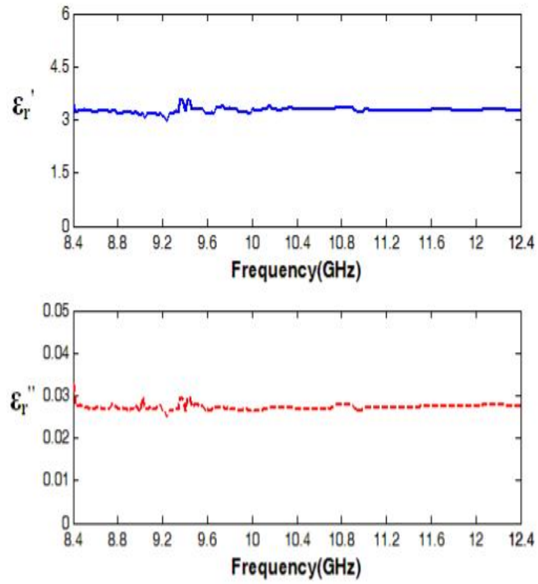

Fig.7. Complex permittivity of a Nylon sample over X-band frequencies

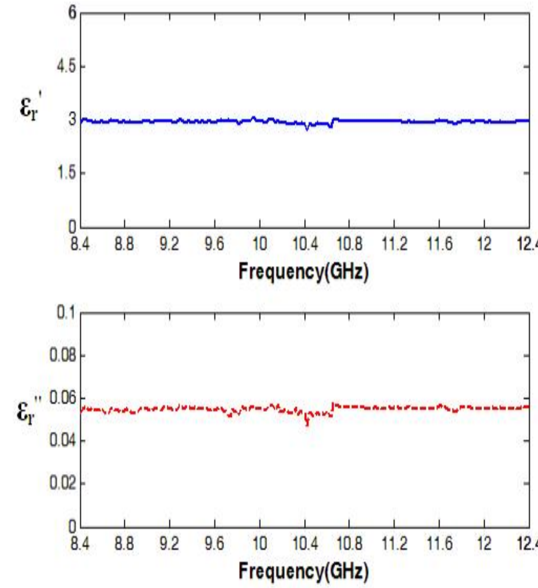

Fig.9. Complex permittivity of Delrin sample over X-band frequencies

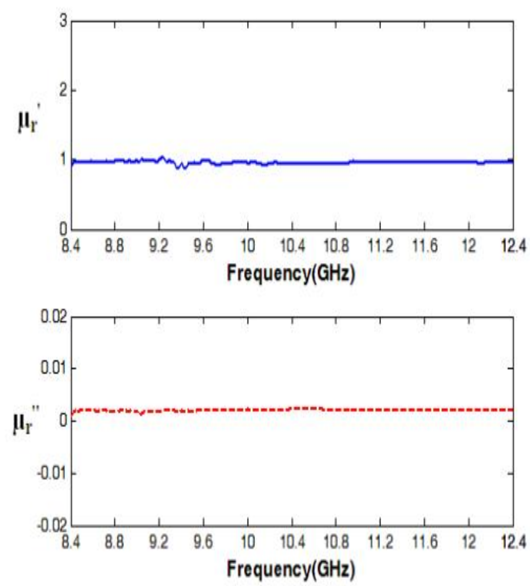

Fig.8. Complex permeability of a Nylon sample over X-band frequencies

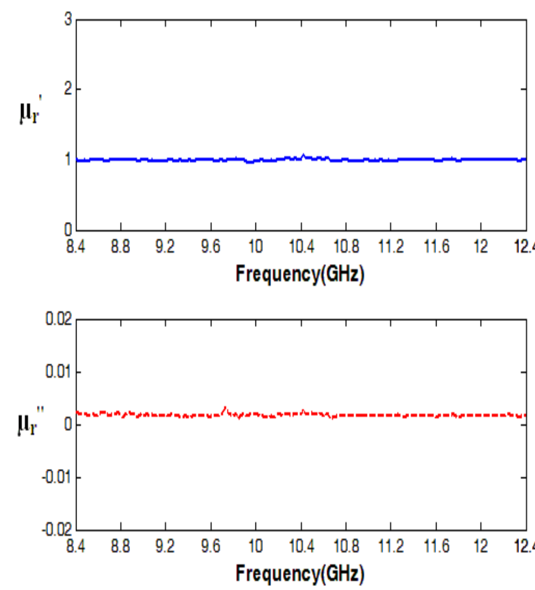

Fig.10. Complex permeability of Delrin sample over X-band frequencies

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,

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V. CONCLUSION

In this paper, a new method is presented to determine the complex permittivity and complex permeability of a dielectric material at X-band frequencies using two-port rectangular waveguide. The S-parameters was measured using the E8634A Network Analyzer and calculated using theory of transmissions lines, the method developed in this article makes it possible to determine the complex permittivity and complex permeability of dielectric material. By matching the calculated value with the measured value of the S-parameters of an X-band rectangular waveguide, loaded by different material samples. The results obtained using this technique, are in good agreement with values of complex permittivity and complex permeability obtained from another method in the literature.

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