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Uncalibrated Microwave Measurements for Complex Permittivity Determination of Dielectric Materials at X-Band frequencies

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ABSTRACT

The transmission / reflection technique for complex permittivity determination is employed to characterize dielectric materials. The algorithm for permittivity extraction eliminates mathematically the systematic errors of the experimental setup. This technique needs two uncalibrated scattering parameter measurements using the Vector Network Analyser; the first is done with a partially filled rectangular waveguide by a standard dielectric Teflon sample (PTFE), and the second is performed with the sample under test. The relative complex permittivity of wood material is measured over the X-band frequencies [8.2 - 12.4] GHz and the average relative error between the calibrated and uncalibrated results is calculated. To improve furthermore the proposed method, the mobile average is applied to the experimental uncalibrated measurements and the results agree well with the calibrated measurements.

Keywords: Dielectric Materials, Complex Permittivity, Uncalibrated Measurements, X-band.

1. INTRODUCTION

The study of dielectric properties of materials finds its applications in various fields. Telecommunications and microwave industry applications require a precise knowledge of the complex permittivity of the used materials. However, the rectangular waveguides are widely used for broadband microwave characterization [1]. We present an iterative method based on the scattering parameters (Sij) calculation of the rectangular waveguide. The Sij parameters are measured in transmission/reflection (T/R) without calibration of the Vector Network Analyser VNA. The experimental technique involves placing the material under test MUT into a WR90 rectangular waveguide and measuring the Sij parameters. A second uncalibrated measurement under the same experimental conditions of another standard material (PTFE for example) is required to find iteratively the relative permittivity of the MUT. The permittivity of the standard material is accurately known throughout the X-band frequencies. The mathematical approach is rigorous without any approximation, taking into account all reflections of the electromagnetic wave on both sides of the sample. However, the method doesn't need any calibration operations of the VNA. It has been applied to the determination of the complex relative permittivity of natural wood at X-band. The experimental results are compared with those obtained by calibrating the VNA using the same proposed method.

2. THEORY

The complex permittivity of dielectric material is determined with the transmission / reflection (T/R) method [2] based on the S-parameter measurements. The MUT is machined to the same section dimensions of the WR90 rectangular waveguide.

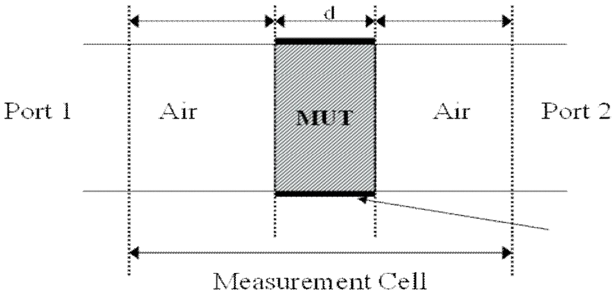

Figure 1. Measurement cell waveguide partially filled by the MUT sample.

The MUT is assumed non-magnetic (μ_r=1) and only the dominant mode TE_{10} propagates through the structure. The figure 1 presents the measurement cell partially filled by the MUT sample.

We calculate the transmission matrices M_i according to:

$$M_i = \frac{1}{S_{21i}}\begin{pmatrix} S_{12i}S_{21i} - S_{11i}S_{22i} & S_{11i} \\ -S_{22i} & 1 \end{pmatrix} \quad i = 1 \text{ or } 2 \tag{1}$$

M_1: corresponds to measurement that the waveguide is filled by the reference dielectric PTFE (Polytetrafluoroethylene) sample.

M_2: corresponds to measurement that the waveguide is filled by the MUT sample.

These two transmission matrices can also be written as a product of five matrices:

$$\begin{cases} M_1 = x.T_{ref1}.T_1.T_{ref1}^{-1}.y \\ \\ M_2 = x.T_{ref2}.T_2.T_{ref2}^{-1}.y \end{cases} \tag{2}$$

The impedance jumps Air/sample/Air cause reflections of the electromagnetic wave that whose transmission matrix is $T_{ref\,i}$.

$$T_{ref\ i} = \begin{pmatrix} \dfrac{1}{1-\Gamma_i} & \dfrac{\Gamma_i}{1-\Gamma_i} \\ \dfrac{\Gamma_i}{1-\Gamma_i} & \dfrac{1}{1-\Gamma_i} \end{pmatrix} \tag{3}$$

$$\Gamma_i = \frac{\gamma_0 - \gamma_i}{\gamma_0 + \gamma_i} \quad (\mu_r^* = 1) \tag{4}$$

$$T_i = \begin{pmatrix} e^{-\gamma_i d} & 0 \\ 0 & e^{\gamma_i d} \end{pmatrix} \text{ i= 1 or 2} \tag{5}$$

The errors matrices *x* and *y* are assumed unchanged during the measurements. They represent the systematic errors of the experimental setup like source and load match errors, tracking (frequency) errors, effects of wires carrying interconnections, hardware imperfections of VNA, etc. [1]-[3]. T_i is the transmission matrix of an ideal line with length *d* and γ the propagation constant.

$$\gamma_0 = j\frac{2\pi}{\lambda_0}\sqrt{1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2} \tag{6}$$

$$\gamma_i = j\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_{ri}^*\mu_r^* - \left(\frac{\lambda_0}{\lambda_c}\right)^2} \tag{7}$$

γ_0 and γ_i : The propagation constants in vacuum and the dielectric ε_{ri}^* respectively.

λ_c and λ_0 : wavelength cutoff of the waveguide and wavelength in free space respectively.

ε^*_{r1} and ε^*_{r2} are the complex permittivity of the PTFE and MUT samples respectively. To remove the influence of the two error-ports on the device parameters, a simple procedure based on the product and the inverse matrix is used. Matrix product of M_1 and M_2^{-1} is written in the form of equation (8).

$$M_1.M_2^{-1} = x.T_{ref1}.T_1.T_{ref1}^{-1}.T_{ref2}.T_2^{-1}.T_{ref2}^{-1}.x^{-1} \tag{8}$$

It is obvious that the matrix *y* is eliminated. The equation (8) shows that the matrices $M_1.M_2^{-1}$ and $T_{ref1}.T_1.T_{ref1}^{-1}.T_{ref2}.T_2^{-1}.T_{ref2}^{-1}$ are similar, this implies that they have the same trace [2][3], defined by the sum of the diagonal elements of the square matrix $M_1\ M_2^{-1}$.

$$Tr(M_1.M_2^{-1}) = Tr(T_{ref1}.T_1.T_{ref1}^{-1}.T_{ref2}.T_2^{-1}.T_{ref2}^{-1}) \tag{9}$$

Tr is the trace of the square matrix.

Let's $f(\varepsilon^*_{r2}) = Tr(T_{ref1}.T_1.T_{ref1}^{-1}.T_{ref2}.T_2^{-1}.T_{ref2}^{-1})$, *f* is a function of ε^*_{r1}, λ_0, λ_c and *d* where ε^*_{r2} is the single unknown. Many complex values of ε^*_{r2} can satisfy the function f. If a good initial guess of ε^*_{r2} is available, solving function *f* iteratively leads directly to the true value of ε^*_{r2}.

In this section, we have proposed a rigorous mathematical approach based on the wave cascading matrix without any approximation. This approach takes into account all reflections of the electromagnetic wave on both sides of the sample through the waveguide. The method is more flexible; and it can be applied to the calibrated or uncalibrated *S*-parameter measurements. The technique eliminates mathematically the out-port errors of the measurement cell. Two measurements in T/R are sufficient to evaluate the complex permittivity of the dielectric sample; the first is that the sample holder filled with the reference dielectric PTFE (ε^*_{r1}=2.1-*j*0.0016), and the second with the MUT. A precise location of the sample in the waveguide is not needed. The nonlinear function *f* is solved using any two-dimensional root finding algorithms.

3. EXPERIMENTAL SETUP AND RESULTS

We consider the measurement setup shown in figure 2. The MUT with thickness *d*=10 *mm* is imprecisely located in the WR90 rectangular waveguide of sections (22.86×10.16) *mm*². The E8634A VNA is connected to two coaxial-to-waveguide adapters. We suppose that only the dominant mode TE_{10} propagates in the structure. The dielectric samples are machined to the same waveguide sections. The uncalibrated S-parameters of PTFE and MUT are measured. Then, the computer program can determine the complex permittivity of the MUT. In the following section, the uncalibrated and calibrated results were compared for validation of the employed method proposed. The Thru-Reflect-Line TRL calibration technique [4] is utilized for calibrating the experimental setup. All measurements are performed at [8.2-12.4] GHz band with 201 frequency points. We apply the 3-points mobile average algorithm on the whole frequency domain values of obtained permittivity data without calibration of the VNA.

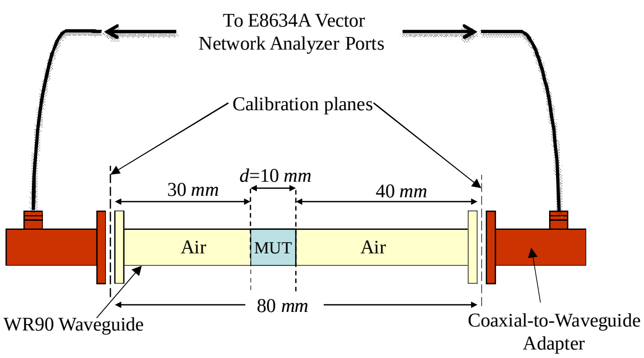

Figure 2. The rectangular waveguide measurement setup.

The proposed method was used to determine the relative complex permittivity of low- and medium-loss dielectric materials. Given its stability, the relative complex permittivity of PTFE (ε^*_{r1}=2.1-j0.0016) is taken as a reference dielectric and the S-parameters of PTFE sample are measured only once. A single specimen of each material is necessary to extract its dielectric constant. But, in this paper, we propose to determine the relative complex permittivity of natural wood at X-band. Another data of various materials can be found in previous works [2][5].

As an initial result extracted from the figure 3; the average value of the relative complex permittivity of the wood extracted from the uncalibrated measurements is 2.7134-*j*0.3134, with error of 0.02% on the real part and 1.06% on the imaginary part compared to the calibrated measurements. The point clouds on the plots of figure 3 are the uncalibrated measurements of the wood over the X-band. The offset of these points from the average value is caused by the length uncertainty between the PTFE and the wood samples and the experimental conditions are not really the same. As it is observed in figure 3, the mobile average improves furthermore the proposed method. It allows finding exactly the same results obtained by calibrating the VNA. However, all operations of assembly/disassembly necessary to calibrate the VNA are eliminated.

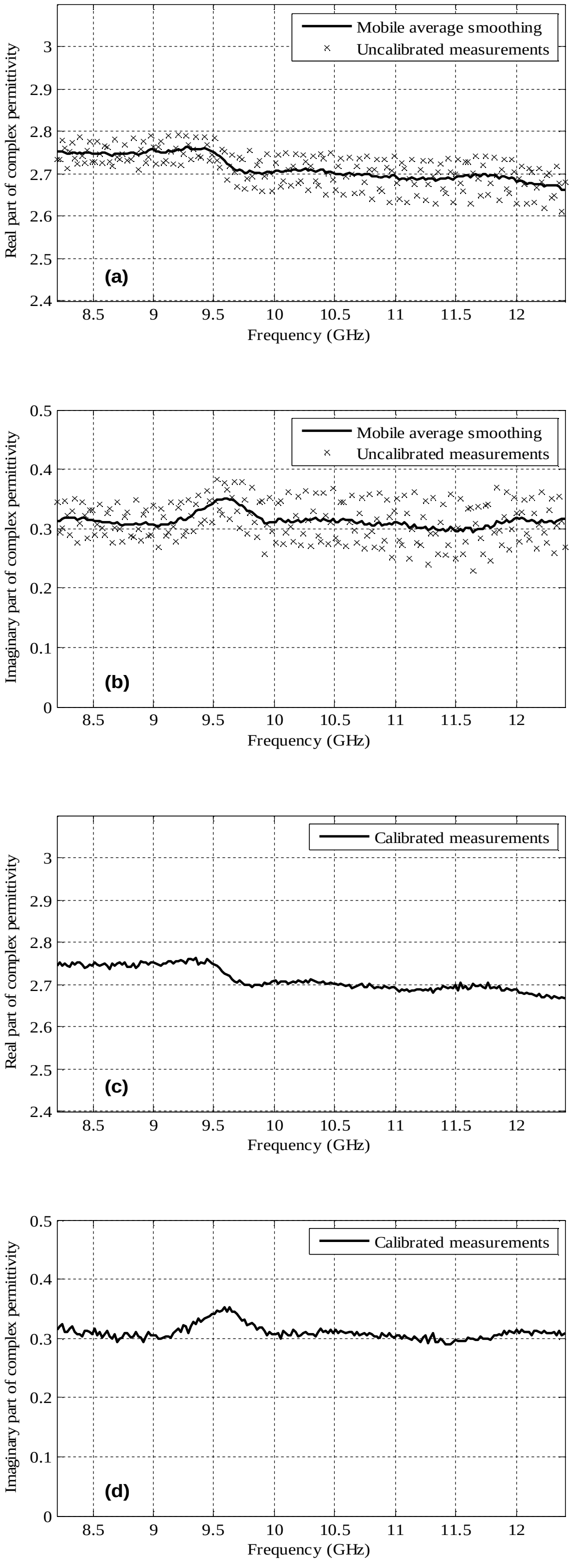

Figure 3. Experimental measurements of the complex relative permittivity of natural wood at X-band frequencies. The values of the real and imaginary parts of the permittivity are smoothed by mobile average and compared with the calibrated measurements results.

4. CONCLUSION

A microwave technique to extract the relative complex permittivity of solid dielectrics is proposed. The method is iterative based on the measurements of S-parameters by the Vector Network Analyzer. The method is able to eliminate systematic errors by using two samples. The first is the material under test and the second is the standard dielectric with well-known permittivity. The samples are pre-machined and characterized in similar experimental conditions. A routine based on the iterative resolution of nonlinear function is included into program to estimate the value of the complex permittivity of the material. The proposed method is improved by applying a mobile average of three points on the final uncalibrated results. The experimental part presents the application of the proposed method to the wood specimen. A rectangular waveguides in X band is used for a wide frequency characterization. The results show the validity of the proposed method for characterizing solid dielectric materials. Considering the simplicity and accuracy over a broad frequency band of the proposed approach, this method proves useful for the measurement of complex permittivity of dielectric materials with or without calibration of the Vector Network Analyzer.

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