Calibration-Independent Measurements for Complex Permittivity Determination of Low-Loss Dielectric Materials at Microwave Frequencies

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Abstract

The work of this article is a contribution to the characterization of new materials at microwave frequencies and enrichment the existing database. The transmission/reflection technique for complex permittivity determination is employed to characterize a set of low-loss dielectric materials. The algorithm for permittivity extraction eliminates mathematically the systematic errors of the experimental setup. This technique needs two uncalibrated scattering parameter measurements by the Vector Network Analyzer; 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 Delrin, Peek, Spanish Peek, Nylatron, Vulkollan, Arnite and Celotex materials are measured over the X-band frequencies (8.2 - 12.4 GHz), and the average relative errors between the calibrated and uncalibrated results are calculated. As other non-resonant methods, rough results are indicated of the imaginary part of the permittivity for very low-loss samples.

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

1. Introduction

Application of materials in the microwave, aerospace, and communications demands an accurate knowledge of material properties such as complex permittivity and complex permeability [1, 2]. Active research fields like materials science and electrical and electronic engineering need necessarily information about permittivity and permeability for developing novel microwave materials. In the radar absorbing material design, the complex permittivity and/or permeability are the fundamental elements that have to be taken into count. The material characterization is an important issue in many industrial areas, and numerous microwave methods are proposed in literature. Each technique has its own benefits and limitations. Several factors influence the choice of technique to obtain the desired information on material under test MUT. For example, the frequency band, the sample size, contacting or non-contacting, material state (solid, liquid and powder), etc. are the major factors to take into consideration when selecting the characterization technique. In general, microwave methods can be categorized into three groups: 1) free-space techniques; 2) resonant or cavity perturbation techniques; 3) non resonant techniques based on coaxial or rectangular waveguide. The free-space methods are employed when material is available in a large sheet and when we want to characterize composite materials that their intrinsic heterogeneity does not permit to have small representative samples of the entire material. The free-space techniques are non-destructive and contactless. They are ideally suited at variable incidence of the electromagnetic wave and for high temperature measurements. But unwanted reflections surrounding objects and diffractions from the edges of the sample make the free-space measurements less accurate. The resonant methods [3] are more accurate, but they require elaborate sample preparation, and can be applied to medium- and low-loss materials at narrow frequency band. Microwave non resonant methods [4-7] are widely used over a wide range of frequencies, even though these techniques are less accurate than the resonant methods. In one- and/or two-port measurement techniques, the reflection and/or transmission coefficients of a sample material filled in the coaxial line or rectangular waveguide are measured using the Vector Network Analyzer VNA. Using the inverse procedure, the constituent parameters of the MUT are extracted. In these measurements, the cross section of the MUT is the same of the transmission line and only the dominant mode is assumed.

The work presented in this paper is a continuation of that published in [8], emphasizing the validity of the Transmission/Reflection T/R method in [8] for a variety of low-loss dielectric solid materials. Based on our knowledge, the permittivity information of these materials (Delrin, Peek, Spanish Peek, Nylatron, Vulkollan, Arnite, and Celotex) is unknown at X-band. This T/R technique is applied to uncalibrated scattering parameters (S-

parameters). However, the standard calibration manipulations are not needed; these manipulation procedures produce inevitable errors affecting the final results. The calibrated and uncalibrated measurement results are compared between them and the relative errors are calculated over the X-band frequencies.

2. Method

We consider the published T/R method in [8] for permittivity determination. This method is more flexible; and it can be applied to the calibrated or uncalibrated S-parameter measurements. This technique eliminates mathematically 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. [4][8][9]. 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 (Polytetrafluoroethylene), and the second with the MUT. A precise location of the sample in the waveguide is not needed. The rigorous mathematical approach of this method is based on the wave cascading matrix [8, 9] conducting to a nonlinear equation which the relative complex permittivity variable of the MUT is the single unknown. The nonlinear function is resolved using any two-dimensional root finding algorithms [10]. The reader is invited to consult [8] for more details.

3. Experimental Setup

We consider the measurement setup shown in figure 1. The MUT with thickness d=1 cm is imprecisely located in the WR90 rectangular waveguide of sections (22.86×10.16) mm². The E8634A VNA is connected to two coaxial-to-waveguide adapters. We suppose that only the dominant mode TE10 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 [8]. The Thru-Reflect-Line TRL calibration technique [11] is utilized for calibrating the experimental setup. All measurements are performed at [8.2-12.4] GHz band with 201 frequency points.
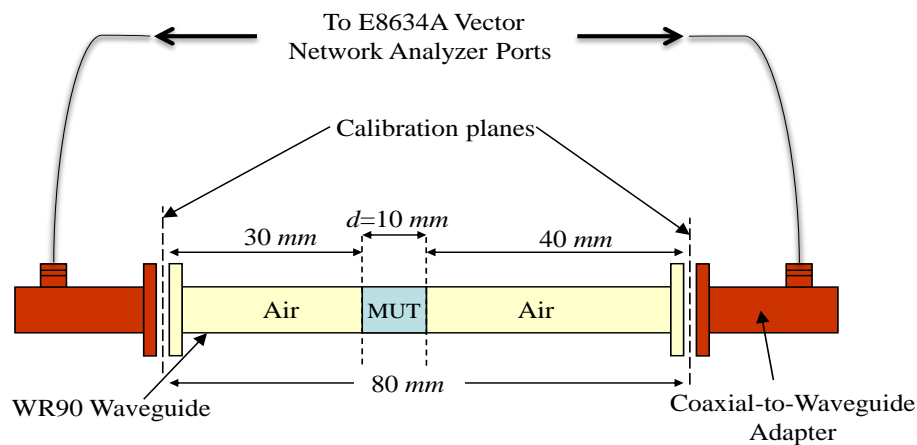

Figure. 1. The rectangular waveguides measurement setup.

4. Results and discussion

The method developed in the article [8] was used to determine the relative complex permittivity of five low-loss and two medium-loss dielectric materials, cited above. According to our knowledge, these materials are not cited in literature and especially their permittivity information over X-band frequencies. Given its stability, the relative complex permittivity of PTFE ε^*=2.04-j0.01 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. The table 1 presents the average values of the relative complex permittivity of the MUT $<\varepsilon^*_{calib}>$ and $<\varepsilon^*_{uncalib}>$, and the average relative error percentage on the real and imaginary parts defined as:

$$< \% \, \text{Error} \, \varepsilon' > = \left| \frac{< \varepsilon'_{uncalib} > - < \varepsilon'_{calib} >}{< \varepsilon'_{calib} >} \right| \times 100$$

$$< \% \, \text{Error} \, \varepsilon'' > = \left| \frac{< \varepsilon''_{uncalib} > - < \varepsilon''_{calib} >}{< \varepsilon''_{calib} >} \right| \times 100$$

$\varepsilon^*_{calib}=\varepsilon'_{calib}-j\varepsilon''_{calib}$ and $\varepsilon^*_{uncalib}=\varepsilon'_{uncalib}-j\varepsilon''_{uncalib}$ are the complex relative permittivity of the MUT determined from calibrated and uncalibrated S-parameter measurements respectively. The average values are evaluated using the standard average such as the number of measurements points is equal to 201.

$$< \varepsilon_{calib,uncalib}^{*} >= \frac{\sum_{i=1}^{201} \varepsilon_{calib,uncalib}^{*}}{201}$$

Table 1. Average relative complex permittivity $<\varepsilon_{calib}^{*}>$ and $<\varepsilon_{uncalib}^{*}>$ determined from the calibrated and uncalibrated scattering parameter measurements, respectively. $<\%Error\ \varepsilon'>$ and $<\%Error\ \varepsilon''>$ are, respectively, the average relative error percentage on the real and imaginary parts of the complex permittivity at X-band frequencies.

Materials	$<\varepsilon_{uncalib}^{*}>$	$<\varepsilon_{calib}^{*}>$	$<\%Error\ \varepsilon'>$	$<\%Error\ \varepsilon''>$
Delrin	2.9372-*j*0.0825	2.9380-*j*0.0805	0.027	2.484
Peek	3.2033-*j*0.0138	3.2032-*j*0.0130	0.00	6.154
Spanish Peek	3.0660-*j*0.0448	3.0662-*j*0.0431	0.00	3.944
Nylatron	3.2290-*j*0.0845	3.2284-*j*0.0804	0.018	5.099
Vulkollan	2.9892-*j*0.2130	2.9894-*j*0.2105	0.006	1.187
Arnite	3.0955-*j*0.0249	3.0949-*j*0.0232	0.019	7.327
Celotex	4.0230-*j*0.3526	4.0222-*j*0.3488	0.019	1.089

Calculations based on measured information show that the error in the real part is very small (close to zero), but that in the imaginary part can be large (within 7.5%) for the used low-loss materials. Like any other S-parameter based methods, this is a common phenomenon. We note according to the error values that the relative error in the imaginary part decreases considerably toward 1% for Vulkollan and Celotex samples. The latter two materials have significantly high dielectric losses compared to the other studied materials; it appears that the method is well adapted for medium-loss materials.

Figures 2 and 3 represent the variation of real and imaginary parts of the complex permittivity over the X-band. It is perceived that the permittivity values are very stable over the frequency range and near to the average values cited in the table 1; except the Celotex sample, that the real part decreases from 4.1 to 3.95. An overall view in both figures, the imaginary parts of all samples are not stable like the real parts, which explain the high average error values in the imaginary parts.
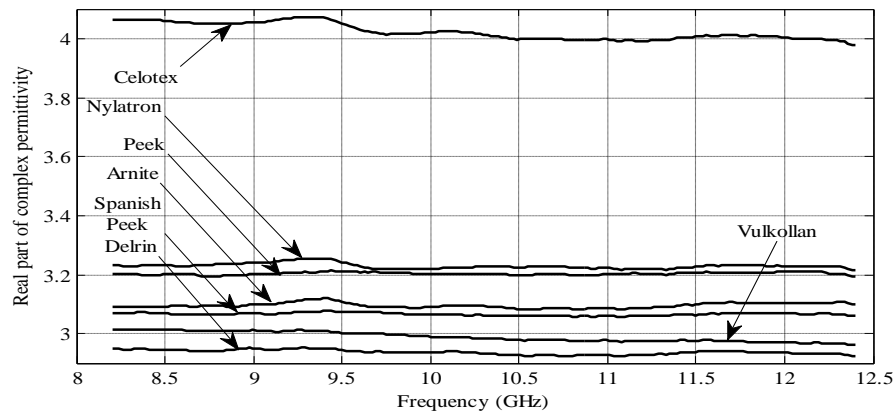

Figure. 2. Measured real part of the relative complex permittivity over the X-band using uncalibrated S-parameter measurements.
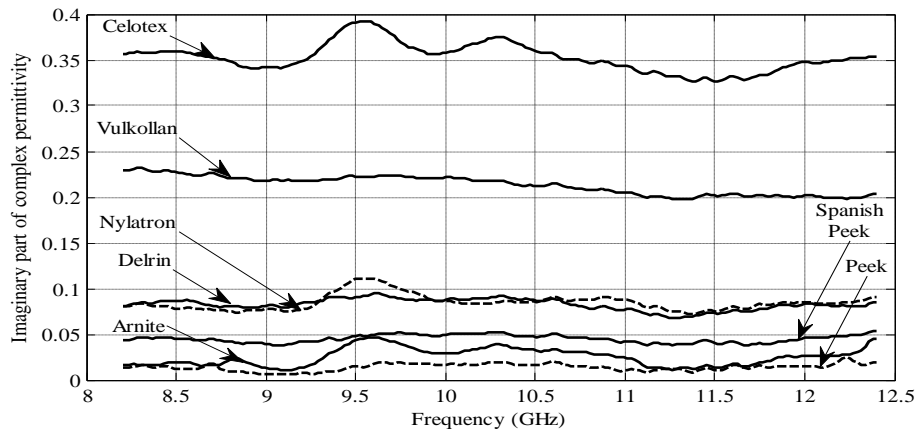

Figure 3. Measured imaginary part of the relative complex permittivity over the X-band using uncalibrated S-parameter measurements.

The table 2 shows real and imaginary data of the complex permittivity at five frequency points of the X-band extracted from the figures 2 and 3. Assuming that the experimental conditions are assumed the same for all samples, the errors produced between calibrated and uncalibrated measurements can be explained to the uncertainty in sample lengths

Table. 2. Measured real and imaginary parts of the relative complex permittivity of Delrin, Vulkollan, Spanish Peek, Arnite, Peek, Nylatron and Celotex materials at five frequency points on the X-band using uncalibrated *S*-parameter measurements.

Frequency (GHz) Materials	8.2	9	10	11	12.4
Delrin	$2.948\text{-}j0.080$	$2.951\text{-}j0.081$	$2.937\text{-}j0.088$	$2.928\text{-}j0.076$	$2.923\text{-}j0.085$
Vulkollan	$3.015\text{-}j0.229$	$3.011\text{-}j0.218$	$2.990\text{-}j0.221$	$2.987\text{-}j0.204$	$2.960\text{-}j0.203$
Spanish Peek	$3.070\text{-}j0.043$	$3.071\text{-}j0.039$	$3.066\text{-}j0.049$	$3.061\text{-}j0.041$	$3.059\text{-}j0.053$
Arnite	$3.091\text{-}j0.016$	$3.099\text{-}j0.013$	$3.091\text{-}j0.029$	$3.088\text{-}j0.024$	$3.098\text{-}j0.045$
Peek	$3.201\text{-}j0.012$	$3.203\text{-}j0.006$	$3.203\text{-}j0.016$	$3.202\text{-}j0.010$	$3.194\text{-}j0.019$
Nylatron	$3.232\text{-}j0.080$	$3.241\text{-}j0.077$	$3.220\text{-}j0.086$	$3.224\text{-}j0.087$	$3.217\text{-}j0.091$
Celotex	$4.064\text{-}j0.356$	$4.055\text{-}j0.342$	$4.021\text{-}j0.358$	$3.998\text{-}j0.344$	$3.979\text{-}j0.353$

Conclusion

We proposed a dielectric characterization of dielectric materials not cited in the literature. We used the Transmission/Reflection method previously published. This method needs two scattering parameter measurements. The first measurement has been performed with a filled rectangular waveguide by a standard dielectric that its complex permittivity is stable and well known over the X-band, and the second was performed, in the same experimental conditions, with the material under test. This technique is well suited for the calibrated or uncalibrated measurements. The relative errors between these two types of measures are calculated for each sample. Errors in the real parts are close to zero, but in the imaginary parts they are within 7% for very low-loss materials and within 1% for medium-loss.

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