Characterization of Microwave Dielectric Materials with the Aid of 3D Electromagnetic Simulators

Valda Levcheva[1], Plamen Dankov[2], Iliyana Arestova[3] and Chavdar Levtchev[4]

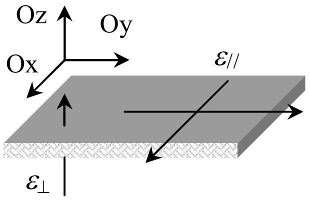
Abstract – **A brief review of methods for characterization the dielectric materials in microwave frequency range are presented. Results for some known dielectric substrates obtained with the aid of 3D electro-magnetic simulators are presented.**

Keywords – **Microwave Dielectric Materials, Complex Permittivity Measurements, Anisotropy.**

I. INTRODUCTION

The dielectric materials are widely used in microwave frequency range as substrates, waveguides, absorbers, components, antenna radomes, etc. The most of modern artificial materials are reinforced, composite or laminated. They have different values of longitudinal and transversal dielectric constant, $\varepsilon_\perp \neq \varepsilon_{//}$ [1].

The successful design of planar passive or active devices with CAD is very sensitive to the value of the complex permittivity of the material. The general description of the electromagnetic properties of a certain dielectric material is given by the complex permittivity tensor (Fig.1).



$$\varepsilon_r = \varepsilon_0 \begin{pmatrix} \varepsilon_{\|} & 0 & 0 \\ 0 & \varepsilon_{\|} & 0 \\ 0 & 0 & \varepsilon_{\perp} \end{pmatrix}$$

Fig. 1. Definition of transversal $\varepsilon_\perp$ and longitudinal permittivity $\varepsilon_{//}$ in anisotropic dielectric substrate

The permittivity is written as $\varepsilon = (\varepsilon_r' - j\varepsilon_r'')\varepsilon_0 = \varepsilon_r\varepsilon_0$, where ε_0 is the permittivity of vacuum and ε_r is the relative complex permittivity. The real part of permittivity ε_r' is a measure of the phase changes as a signal propagates through material, while ε_r'' is related to the signal attenuation and includes both dielectric and d.c. conductivity losses. Generally the loss in material is expressed in terms of the loss tangent $\tan\delta_\varepsilon = \varepsilon_r''/\varepsilon_r'$. If the anisotropy is neglected the design accuracy decreases for microwave components and devices like coplanar waveguides and feeds, grounded coplanar wave-guides, radiating patches, filters (Fig.2), dividers, matching components, devices supported high-order modes like T- and Y-junctions, steps, stubs, gaps, etc.

The manufacturers like ROGERS Corp., ARLON, NELTEC, etc. give data for permittivity measured with the test method, described in the document IPC TM – 650 2.5.5.5 [3]. However this is near-to-transversal permittivity, because the method [3] uses a linear strip line-resonator where only the part of the electric field is normal to the substrate plane.

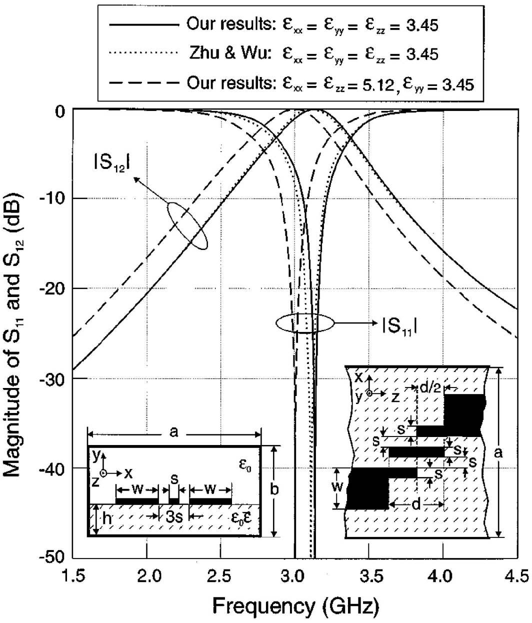


Fig. 2. Return and insertion losses of coupled-line bandpass filter on isotropic and anisotropic substrate [2]. The central frequency of the filter in the anisotropic case is 4,5% below that in the isotropic case

There is a need of fast, exact and easy method for measurement of every particular dielectric material consignment.

II. METHODS FOR MEASUREMENT OF THE PERMITTIVITY

A lot of measuring methods of the dielectric constants exist: transmission line or waveguide methods, cavity measurement methods, free space methods. The measurement of the dielectric constant involves the measurement of quantities like propagation constant, resonance frequency, quality factor, reflection and transmission coefficients etc., which are functionally related to the dielectric constant in a known manner. Different models can be used for this purpose: dispersion equation model of the structure (*DEM*), perturbation approximation model (*PAM*), *3D-simulation model* (*3DM*). Exact analytical solutions (*DEM*) are possible

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[1] Valda Levcheva is with Sofia University, Faculty of Physics, E-mail: Levcheva@phys.uni-sofia.bg

[2] Plamen Dankov is with Sofia University, Faculty of Physics, E-mail: Dankov@phys.uni-sofia.bg

[3] Ilyana Arestova is with Sofia University, Faculty of Physics, E-mail: Ilar@phys.uni-sofia.bg

[4] Chavdar P. Levchev E-mail: Levchev_ch@yahoo.com

for relatively simple-shape cavities. *PA Models* could be used when the sample volume is small compared with the whole cavity volume e.g. the usability of the *PA Models* is mainly restricted to low-permittivity and low-loss materials with small thickness. Almost all of the electromagnetic structures can be simulated by 3D electromagnetic simulators. The *3D model* reproduces the performance of the structure with enough accuracy and is fast enough. The dielectric constant data reported in the product literature should not be used directly for engineering design. The utilization of the *3DModels* gives the opportunity to obtain the parameters of dielectric materials with high accuracy – better than 5% for permittivity and 15% for loss tangent.

The most accurate methods for dielectric parameter measurements are the cavity-resonance methods (Fig. 3). The split-cylinder resonator (**R3**) allows non-destructive measurements of the complex permittivity $\varepsilon_{//}$ [4] without necessity to manufacture special samples. The re-entrant cavity (**R4**) (Fig. 3d) enables to measure the permittivity normal to the face of the material $\varepsilon_{\perp}$ at frequencies from 100 MHz to 2 GHz.

The cavity-resonance methods provide high complex permittivity measurement accuracy even for low-loss materials. The orientation of applied electric field determines if longitudinal or transversal permittivity is measured [4]. Two-resonator method for separately measurement of the longitudinal (or in-plane permittivity components $\varepsilon_{//}$ and tan $\delta\varepsilon_{//}$) and transversal (normal to the plane of the sample permittivity components $\varepsilon_{\perp}$ and tan $\delta\varepsilon_{\perp}$) dielectric parameters of anisotropic materials is proposed in [5, 6].

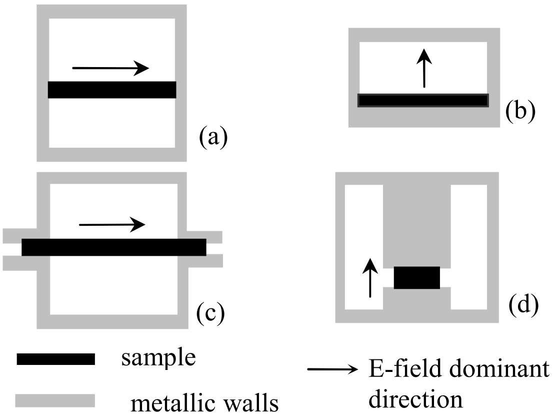

Fig. 3. TE$_{011}$ mode cavity **R1** (a), TM$_{010}$ mode cavity **R2** (b), TE$_{01}$ split-cavity **R3** (c), Re-entrant resonator **R4** (d)

Our investigations show that the 3D-electromagnetic simulators are useful assistant tools for measurement of the dielectric materials parameters [1]. We describe how to use the electromagnetic simulators for measurement purposes and to create and optimize the *3D Models* in [7]. We utilize *3D Model* of the cavity resonator. Our approach is to create the simplified *3D Model* of the geometry of the resonator. First we determine the values of its equivalent parameters (equivalent diameter and equivalent wall conductivity of the empty resonator) with the aid of electromagnetic simulators. If there is symmetry in the E-field distribution we simulate only a part of it (1/4 or 1/8 of the resonator). That way we decrease the computational time. Then we simulate the part of the resonator with a dielectric sample in it. Thus we calculate the dielectric parameters of the dielectric sample assisted by 3D simulator. Fig. 4 illustrates the *3D-model* of the TE$_{011}$ cavity resonator. In [8] we investigate the *3D-model* of the re-entrant resonator. The complexity of the structure does not allow exact analytical solution which limits the use of this resonator. The *3D model* of the re-entrant resonators improves their applicability and accuracy for measuring purposes.

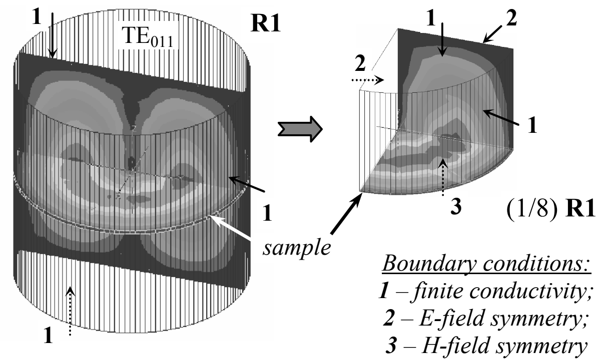

Fig. 4. Example with *3D* model of the resonance cavity **R1** and its equivalent = (1/8) **R1**. Boundary conditions and pictures for E-field distribution are given in xy- and yz-planes

Another application of the resonance methods is determination of the complex dielectric parameters of the absorbing materials (if the effect over the resonance frequency is not so big) [9]. We can use for example the two-resonator method with cavity cylindrical resonators, and that way we separate the influence of the dielectric and magnetic properties of the investigated material over the resonance characteristics of two different suitable modes: TE$_{011}$ for dielectric parameters measurements and TE$_{112}$ for pure magnetic parameters measurements [9]. After that we can characterise the additional losses and time delay by the aid of 3D simulator. The main disadvantage is that the results are valid in narrow frequency band.

Exact analytical solutions for the resonance characteristics of the simple shape cavity resonators only are feasible in practice. Numerical methods are applicable for more complicated structures like re-entrant or split-cavity resonators (Fig. 3 c, d). The aid of the 3D electromagnetic simulators facilitates considerably obtaining the complex permittivity of the dielectric materials. That way we facilitate the utilization of the resonance methods.

There is eigen-mode solver in electromagnetic simulators which we can use for finding the resonant frequencies of lossy structures and can calculate the unloaded *Q*-factors of the cavity. The structures are solved without ports and sources. This is the reason the calculated *Q*-factor not to include losses due to ports and sources. Unloaded *Q*-factor is the energy lost due to lossy material.

The utilization of 3D simulators as assistant tool for measurement of the dielectric parameters of materials is very powerful and helpful method.

III. RESULTS

We have done a lot of measurements of different materials utilizing *PEM*, *DEM* and mainly *3DModels* of the resonance cavities. The main principles of building the *3D Models* of the used resonators are discussed in [7]. The steps for realization of the two-resonator method are described in [10]. Here we present measurement results for the complex permittivity of some known substrate materials. The transversal dielectric parameters of several commercial substrates obtained by *DEM, PEM* and *3DM* are given in Tables I and II (for RO4003 with different thicknesses).

TABLE I

TRANSVERSAL DIELECTRIC PARAMETERS OF DIFFERENT SUBSTRATES

Substrate (*h*, mm)	*PEM*	*DEM*	***3DM***
	$\varepsilon_\perp$ /tan $\delta_{\varepsilon\perp}$	$\varepsilon_\perp$	$\varepsilon_\perp$ /tan $\delta_{\varepsilon\perp}$
RO3003 (0.2575)	3.044 / 0.0015	2.980	2.970 / 0.0010
RO4003 (0.2075)	3.436 / 0.0029	3.320	3.380 / 0.0025
RO3203 (0.2700)	3.036 / 0.0021	2.970	2.950 / 0.0016
NH9300 (0.2550)	2.854 / 0.0190	2.795	3.000 / 0.0010

TABLE II

TRANSVERSAL DIELECTRIC PARAMETERS OF RO4003 SUBSTRATES WITH DIFFERENT THICKNESSES

Substrate height, (*h*, mm)	*PEM*	*DEM*	***3DM***
	$\varepsilon_\perp$ /tan $\delta_{\varepsilon\perp}$	$\varepsilon_\perp$	$\varepsilon_\perp$ /tan $\delta_{\varepsilon\perp}$
0.205	3.420 / 0.0036	3.391	3.390 / 0.0055
0.520	3.390 / 0.0029	3.386	3.300 / 0.0050
0.820	3.400 / 0.0032	3.399	3.320 / 0.0048
1.530	3.380 / 0.0029	3.366	3.420 / 0.0032

A very good agreement between the calculated dielectric parameters with different methods is noticed (the deviation is about 3%). This fact confirms the applicability of the proposed measurement methods and especially the *3DM*. The utilization of the *3D simulation models* of the resonance cavities is free of perturbation technique limitations and could be appropriate for estimation of thick and high-permittivity materials. Also the *3D Model* gives the opportunity to obtain the loss tangent of the materials in easy manner.

An example with measured dielectric parameters of the isotropic material Lexan (Table III), obtained by *3D M*odels of different cavity resonators – re-entrant, TM_{010} and TE_{011}, is given.

TABLE III

DIELECTRIC PARAMETERS OF THE ISOTROPIC MATERIAL LEXAN

(h = 0.510 mm)

Lexan	Re-entrant (*3DM*)	TM_{010} (*3DM*)	TE_{011} (*3DM*)	Catalogue data (f_r = 12 GHz)
ε_r	2.81	2.73	2.76	2.75 ± 0.05
tanδ_ε	0.00585	0.0044	0.0048	0.00454

The results show that this material is isotropic and the proposed methods could be successfully applied for characterization of dielectric substrates with high accuracy.

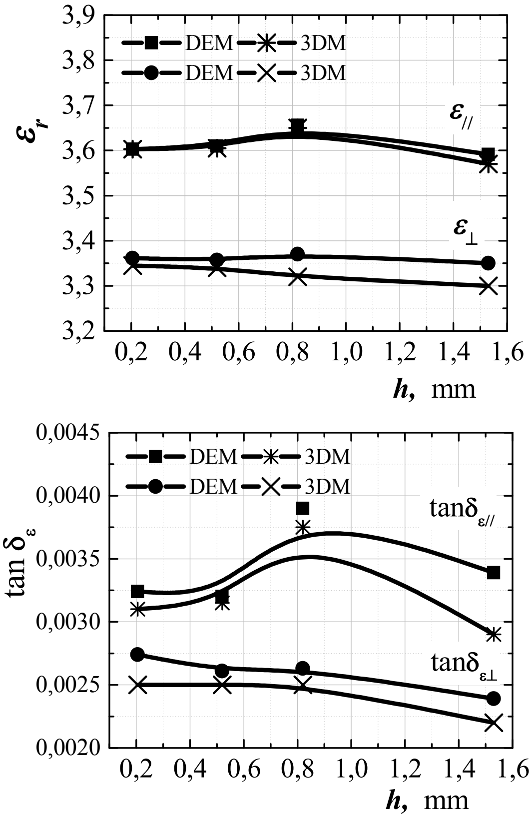

Fig. 5. Dielectric parameters obtained by the different cavity models (*DEM* and *3DM*) for anisotropic substrate material RO4003

We can apply our *3D Models* for easy measurement of the dielectric anisotropy of materials. An example with several samples of anisotropic material is shown in Fig. 5. The thickness of the samples is in the range h = 0.2 – 1.5 mm. The results obtained by *3DModels* and *DEM* are shown. The differences between the values for the transversal and the longitudinal permittivity are about 10%. This means that the material is anisotropic.

The values for $\varepsilon'_{\perp}$ obtained by *3DModels* and *DE Models* as well as for $\varepsilon'_{\|}$, are very close. The same is the situation for $\tan\delta_{\varepsilon\perp}$ and $\tan\delta_{\varepsilon\|}$ as can be seen from Fig. 5.

IV. CONCLUSIONS

The utilization of *3DModel* of the cylindrical resonators for measurement of dielectric materials permittivity is described in the paper. Simple measuring resonators are used. They are easy to draw and simulate. The *3D models* give the opportunity to obtain the parameters of dielectric materials with high accuracy – better than 2% for permittivity and 5% for loss tangent. Examples with obtained values for complex permittivity components of substrate materials Lexan and RO4003 are given. Enough accuracy for dielectric constant anisotropy and loss tangent anisotropy is obtained. The next step of our future work is to apply optimized *3D simulation models* for investigation of the cavity resonators with more complicated shapes, like Courtney and split-cavity resonators. Results are equipment and simulator type independent.

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