Measurement of Dielectric Anisotropy of Microwave Substrates by Two-resonator Method with Different Pairs of Resonators

Plamen I. Dankov, Boyan N. Hadjistamov, Iliyana P. Arestova, and Valda P. Levcheva
Faculty of Physics, University of Sofia, Sofia, Bulgaria

Abstract — The measurement of the dielectric constant and loss tangent anisotropy of the planar RF substrates by the two-resonator method is considered in this paper. The principles of the separate determination of these parameters parallel and perpendicular to the substrate surface is discussed by three pairs of cavity measurement resonators, based on cylinder, reentrant, split cylinder and split post dielectric resonators. Examples of the measured anisotropy of known materials are presented.

1. INTRODUCTION
The measurement of the dielectric substrate parameters becomes one of the most important things connected with the modern RF electronics, computer and communication hardware. The main reason is the new modern manner of the electronic devices’ design, based on electromagnetic or schematic simulators, where the knowledge of the accurate values of the substrate dielectric constant and loss tangent has a decisive importance.

There are a variety of measurement methods for characterization of the dielectric parameters of PWB (Printed Wire Board) substrates [1]. The most spread of them is the standardized IPC TM-650 2.5.5.5 stripline-resonator method [2], widely used by the substrate producers. This method gives only the near-to-perpendicular values of the dielectric constant \( \varepsilon_r \) and loss tangent \( \tan \delta \). This increasing problem for the modern RF design can be overcame, if the anisotropy of the dielectric parameters has been determined (i.e., the different values of the parallel and normal dielectric parameters; \( \varepsilon_{\|} \neq \varepsilon_{\perp} \); \( \tan \delta_{\|} \neq \tan \delta_{\perp} \) — Fig. 1). A modified IPC TM-650 method (by Bereskin [3]) gives an opportunity to separate determine these parameters by “staking” of several thin substrates into a thick bulk sample and measurements in the both directions, but this method is rather inconvenient.

The main principle to determine of the substrate dielectric anisotropy is not new — to use a dual or triple modes resonator with dominant electric-field distribution parallel or perpendicular to the sample surface. The planar resonators are not very suitable for this purpose, because their modes have both parallel and normal \( E \)-fields in an arbitrary mixture (for example — the microstrip linear resonators). The cavity (bulk) resonators are more suitable for anisotropy measurements. Several years ago we introduced the two-resonator method [4–6], which is based on two different ordinary measurement cylinder resonators, marked as R1 and R2, supporting two suitable for anisotropy measurement modes — \( \text{TE}_{011} \)-mode in R1 (for determination of pure \( \varepsilon_{\|}, \tan \delta_{\|} \)) and \( \text{TM}_{010} \)-mode in R2 (for determination of pure \( \varepsilon_{\perp}, \tan \delta_{\perp} \)). The successes of this method depends on the accuracy of the analytical relations between the measured resonance parameters, resonance frequency \( f_{\text{meas}} \) and the unloaded quality factor \( Q_{\text{meas}} \), and the substrate dielectric parameters [4]. In order

![Figure 1: (a) Planar substrate with uniaxial anisotropy; (b) IPC TM-650 2.5.5.5 test method [2]; (c) Bereskin measurement fixture [3].](image)
to increase the measurement accuracy, we developed the two-resonator method with application of the 3D electromagnetic simulators as an assistance tools for the anisotropy measurements [7]. This allows us to use measurement resonators with more complicated shape [8, 9]. In this paper we systematize our experience to measure the dielectric anisotropy of planar substrates by the two-resonator method, extended with new pairs of measurement resonators.

2. TWO-RESONATOR METHOD WITH PAIR OF ORDINARY CYLINDER RESONATORS

Figures 2(a) and (b) presents two simplest cylindrical resonators with diameter $D_{1,2}$ and height $H_{1,2}$. They are designed to support different modes in order to evaluate the sample anisotropy by analytical method [4, 5]: TE$_{011}$-mode resonator $R_1$, which is suitable for measurement of the longitudinal parameters $\varepsilon_\parallel$ and $\tan\delta_\parallel$, and TM$_{010}$-mode resonator $R_2$ — for measurement of the normal parameters $\varepsilon_\perp$ and $\tan\delta_\perp$. The resonators need of disk samples with diameters, equal to the resonator diameters. Similar ability as $R_1$ resonator, but for samples with arbitrary shape, has the split-cylinder resonator SC (Fig. 2(c)) [9]. A set of pairs of $R_1$ and $R_2$ resonators with different diameters allows characterization of the dielectric anisotropy, $\Delta A_\varepsilon$ and $\Delta A_{\tan\delta_\varepsilon}$, in wide frequency range — $\Delta A_\varepsilon = 2(\varepsilon_\parallel - \varepsilon_\perp)/(\varepsilon_\parallel + \varepsilon_\perp)$ and $\Delta A_{\tan\delta_\varepsilon} = 2(\tan\delta_\parallel - \tan\delta_\perp)/(\tan\delta_\parallel + \tan\delta_\perp)$. The measuring errors by this method are evaluated as small enough: $<1.5\%$ for $\varepsilon_\parallel$, $<5\%$ for $\varepsilon_\perp$, $<7\%$ for $\tan\delta_\parallel$ and $<15\%$ for $\tan\delta_\perp$ in the case of typical substrates with thickness 0.15–2.0 mm. This relatively good accuracy is achieved mainly due to the use of equivalent parameters — equivalent resonator diameters and equivalent wall conductivity [4].

The measurement errors (especially for thin substrates) can be decreased additionally by utilization of 3D simulators for extraction of the dielectric parameters of the samples. The suitable 3D models of $R_1, R_2$ and SC resonators are drawn in Fig. 3. We use 3 main rules to construct these models for accurate and time-effective processing of the measured resonance parameters — stylized drawing of the resonator body with equivalent diameters $D_{1e}$ or $D_{2e}$, optimal number of line segments ($N = 72–180$) for construction of the cylindrical surfaces and suitable for the operating mode splitting (1/4 or 1/8), accompanying with the necessary boundary conditions.

The measurement procedure is as follows. First of all, we measure the resonance parameters of the empty cavity and by simulation of its 3D model we determine the effective diameter $D_{1e}$ and effective wall conductivity $\sigma_{1e}$, for which the measured and calculated parameters coincides,
f_{\text{osim}} \sim f_{\text{omeas}}; \quad Q_{\text{osim}} \sim Q_{\text{omeas}}. \quad \text{Then we measure the cavity with sample and after similar simulations we determine the corresponding dielectric parameters (longitudinal for R1 or perpendicular for R2 — Figs. 5(a), (b), (c)). The accurate determination of the both effective parameters is very important for the measurement error reduction and we always use this procedure for “daily” actualization of their values. The problem of the considered pair of simple cylinder resonators is the fixed frequencies of measurements, which depends mainly on the resonator diameter and the dielectric constant of the sample. This can be particularly avoided, using another pair of tunable resonators.}

3. TWO-RESONATOR METHOD WITH DIFFERENT PAIRS OF RESONATORS

As a pair of tunable resonators for realization of the two-resonator method in wide frequency range we utilize the split-coaxial resonator (SCoaxR), proposed in [9], as R1, and the reentrant resonator Re [8] as R2 — see Figs. 4(a), (b). The SCoaxR is a variant of the split-cylinder resonator with a pair of top and bottom cylindrical posts of height $H_r$ and diameter $D_r$ into the resonator body. The tuning of the resonance frequency is possible by the height $H_r$ of metal posts with more than one octave below the resonance frequency of the hollow split-cylinder resonator. The reentrant resonator is known low-frequency measurement structure. It has also an inner tuning cylinder of height $H_r$ and diameter $D_r$. The analytical solutions for the resonance parameters of these resonators do not ensure the needed accuracy for measurement purposes. Therefore, we use only 3D simulators as assistant tools during the anisotropy measurements. We follow the same principles to construct the 3D models of these complicated resonance structures — see Figs. 5(d), (f). The only problem is the determination of a new equivalent parameter — the height of the post cylinder $H_{re}$. The measurement procedure is similar, but have an additional step: 1) measurement of the resonator without inner post (to determine the outer equivalent diameter $D_{re}$); 2) measurement of resonator without sample (to determine the equivalent height $H_{re}$ and the effective wall conductivity $\sigma_e$); and 3) measurement of the resonator with sample (final extraction of the dielectric parameters). The last two steps should be repeated at each fixed height $H_r$.

A problem of the measurement reentrant and split-coaxial resonators is the lower unloaded $Q$ factors (200–1500) compared with these of the original cylinder resonators (3000–15000). In order to overcome this problem for measurements at low frequency, we propose a new pair of measurement resonators: split-post dielectric resonators SPDR of electric or magnetic type of splitting [1] — Figs. 6, 7. The main novelty of this pair is the inserted high-Q dielectric resonator DR, which set the operating frequency. We use DR’s from high-quality materials (sapphire, alumina, quartz, etc.) and this allows achieving of unloaded $Q$ factors about 5000–20000. The modeling and measurement principles of this pair of resonators are very similar. Here the knowledge of the actual parameters

![Figure 4](image-url)

Figure 4: Pair of tunable resonators: (a) split-coaxial cylinder cavity SCoaxR as R1; (b) Reentrant cavity Re as R2.

![Figure 5](image-url)

Figure 5: Calculated electric field distribution (scalar and vector) in the considered pairs of measurement resonators (as R1 or R2).
of the used DR’s is very important for the successful utilization of the method. The measurement procedure consists of 4 steps: 1) measurement of the empty resonator (to determine the equivalent diameter $D_e$ and effective wall conductivity $\sigma_e$); 2) measurement of resonator with foam support for the DR (if exists) (to determine the its parameters); 3) measurement of the resonator with DR and foam support (to extract the actual DR parameters) and 4) measurement of the resonator with DR and sample (extraction of the sample parameters). The variation of the frequency is achieved by DR replacement. We use DR’s with different shapes: cylinder, rectangular and ring. The DR’s dielectric constant should be not very high to ensure good accuracy.

4. TEST RESULTS FOR THE MEASURED ANISOTROPY OF TWO SAMPLES

It is very important to know the ability of the considered pair of resonators to measure “pure” longitudinal or “pure” transversal parameters of the samples and therefore, to evaluate the dielectric anisotropy $\Delta A\varepsilon$ and $\Delta A\tan\delta\varepsilon$. Fig. 8 presents the numerical results for the ratios $(f, Q)_{anisotropic}/(f, Q)_{isotropic}$ versus the anisotropy $\Delta A\varepsilon$, $\Delta A\tan\delta\varepsilon$ at a fixed sample height ($\sim 1.53$ mm). If this ratio is small, the corresponding resonator has ability to measure the “pure” dielectric parameters. The cylindrical resonators (R1, R2), the reentrant resonator Re and the split-coaxial resonator SCoaxR meet these requirements (error less than $\pm 0.2\%$ for the dielectric constant $\varepsilon_r$ and less than $\pm 1\%$ for the loss tangent $\tan\delta\varepsilon$, when the anisotropy is changed with $\pm 10\%$). Only the pure split-cylinder resonator SC has bigger error: $\pm 2.5\%$ for $\varepsilon_r$ and $\pm 10\%$ for $\tan\delta\varepsilon$.

Finally, the measured dielectric anisotropy for two known materials are given as illustration in Fig. 9. The first material is pure isotropic — 0.51-mm thick transparent polycarbonate. The
Figure 9: Measured dielectric parameters ($\varepsilon_\parallel$, $\varepsilon_\perp$, $\tan\delta_\parallel$, $\tan\delta_\perp$) of two materials with equal thickness: isotropic polycarbonate and anisotropic RO4003 substrate by different pairs of resonators.

measured “anisotropy” of this material is less than 3% for $\Delta A_\varepsilon$ and less than 11% for $\Delta A_{\tan\delta_\varepsilon}$ in wide frequency range 2–18 GHz. These data should be considered as a limit for ability of the two-resonator method to evaluate the practical isotropy. The second example is for the popular microwave non-PTFE reinforced substrate RO4003 ($h = 0.51$ mm). The mean measured anisotropy of the substrate in wide frequency range 2–18 GHz is $\sim 8.7\%$ for $\Delta A_\varepsilon$ and $\sim 48\%$ for $\Delta A_{\tan\delta_\varepsilon}$ (or $\sim 8.4\%$ for $\Delta A_\varepsilon$ and $\sim 35\%$ for $\Delta A_{\tan\delta_\varepsilon}$ at 12 GHz). These data are fully acceptable, nevertheless the catalogue data are $\varepsilon_r = 3.38$ and $\tan\delta_\varepsilon = 0.0027$ at 10 GHz.

5. CONCLUSIONS

The investigations show that the two-resonator method is fully acceptable for determination of the substrate dielectric anisotropy by the help of 3D simulators with error less than 3% for the dielectric constant and less than 10% for the dielectric loss tangent in wide frequency range by different pairs of measurement resonators.

ACKNOWLEDGMENT

The authors thank to the Scientific Research Found of the University of Sofia for the financial support.

REFERENCES