High Accuracy Broadband Measurement of Anisotropic Dielectric Constant Using a Shielded Planar Dual Mode Resonator

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Abstract—We investigate a proposed shielded dual mode planar "RA" resonator used for measuring the uniaxial anisotropic dielectric constants of planar substrates. Prior microstrip RA resonators have been unshielded, which introduces error due to radiation, especially for thick substrates. A detailed error evaluation is performed and presented. The resonator is long, allowing evaluation of nearly 100 resonances. Each pair of resonances of the dual mode resonator is evaluated to determine two substrate dielectric constants, one for horizontal (parallel to the substrate surface) electric field and the other for vertical electric field. Broad band anisotropic dielectric constants extracted from resonator measurements from 0.2 to 10 GHz are presented.

Index Terms—Anisotropy, dielectric constant, electromagnetic analysis, method-of-Moments (MoM), transmission line, uniaxial.

I. INTRODUCTION

K NOWLEDGE of substrate dielectric constant is critical for accurate design of planar microwave circuits. Formal industry standard measurements [1] are appropriate for quality control (e.g., making sure each batch of substrates are the same), but might or might not yield values appropriate for accurate EM analysis. Part of the problem is that such measurements typically assume the dielectrics are isotropic; that a single dielectric constant is appropriate for all electric field regardless of the direction of the electric field. In reality, few commercial substrates are isotropic.

Many microwave boards are composite, that is composed of two or more different materials, for example, Teflon and fiber glass, [2], and [3]. This is so the temperature coefficient of the board matches that of copper, important for mechanical durability. The overall temperature coefficient is a weighted average of the materials and is carefully matched to that of copper. However, the inhomogeneity introduces anisotropy. Anisotropy is typically also present in ceramic substrates when the grains of the ceramic are not spherical. Even widely used Alumina (an aluminum oxide ceramic) is anisotropic [4], with values of 8.607 (vertical) and 10.159 (horizontal)

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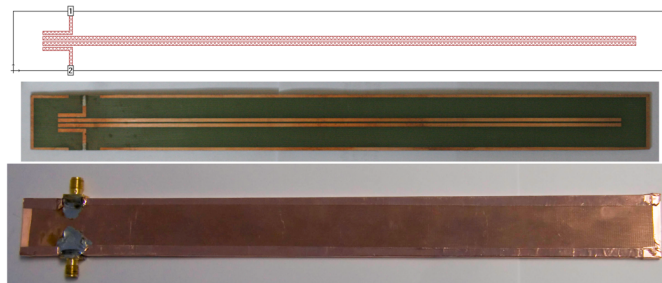
Fig. 1. The first RA stripline resonator: Layout in Sonnet top, fabricated resonator middle, and completed resonator bottom. The resonators are 10 inches long. The input/output coupled region is 0.5 inches long. In this case, the resonators are on FR-4, from [5].

reported. The classic value of 9.8 is a weighted average of these two values, appropriate for some applications but not for others.

Given the nearly universal presence of anisotropic substrates, it might seem strange that most microwave design incorrectly assumes all materials are isotropic, thus placing critical designs in jeopardy. The use of this assumption makes sense when we realize that 1) Most planar microwave design tools typically do not allow anisotropy, and 2) Values for substrate anisotropy are not available and are not easily measured.

Recently, precise EM analysis of uniaxial anisotropy became available in Sonnet® [5]. Based on that capability, a simple means of measuring anisotropy has been developed, [6] – [8]. Initial measurements were performed using a stripline resonator, Fig. 1, and several unshielded microstrip resonators. This paper reviews current progress with emphasis on the problems experienced. Then, the shielded dual mode resonator is proposed and investigated, offering a solution to many of these problems.

II. SUMMARY OF PREVIOUS WORK

In the classic resonator approach to measurement of dielectric constant, a resonator that includes the dielectric to be measured is constructed with very lightly coupled input and output. Resonances are measured and used in some manner to evaluate the unknown dielectric constant. Typically the

dielectric sample in the resonator experiences a range of electric field directions. Thus, if the dielectric is anisotropic, the resulting measurement is a weighted average of the different dielectric constants, depending on the percentages of the differing directions of electric field in the dielectric.

In [6], just such a resonator approach is proposed. The stripline (in this case) resonator does indeed impress a mixture of both vertical and horizontal electric fields on the embedding dielectric. Thus, it would seem that this resonator would also measure a weighted average of dielectric constants. However, this resonator is different: It is dual mode. The two modes (even and odd) of this "RA resonator" (initials of the authors of [7]) excite different percentages of vertical (perpendicular to the substrate surface) and horizontal (parallel to the substrate surface) electric field. This is the key. Using techniques detailed in [7], it is possible to reverse engineer the measured resonances and determine the vertical and horizontal dielectric constants that generate those resonances. This technique is strongly dependent on comparison with a high accuracy EM analysis of the resonators including anisotropy and thus a detailed error analysis is also provided in [7]. The entire process has been substantially automated in an Excel spreadsheet making it easy to deal with literally hundreds of resonances from a resonator.

An initial measurement of FR-4 was taken up to 2 GHz. Fig. 2 shows the second pair of measured even and odd mode resonances, where the resonator is one wavelength long. The original measurement has been numerically processed (as described in [7]) to separate the even and odd mode resonances into two separate data sets. This is especially important for stripline resonators because the even and odd mode velocities are the same (at least for the case of lossless isotropic dielectric), so it is impossible to separate the two resonances by simple inspection of the original data. Note that an extremely high density of data points across the band is required in order to precisely determine the resonant frequencies.

The dielectric constants extracted for two identically laid out resonators (R1 and R2) are listed in Table I (from [7]). An unexpected result is that the horizontal dielectric constant is less than the vertical. It is thought that this is because the dual mode resonators excite horizontal electric field primarily in the surface of the substrate. FR-4 is a fiber-glass-weave/epoxy composite. The epoxy has a lower dielectric constant and perhaps dominates the horizontal electric field for coupled lines. Any measurement that places horizontal electric field through the entire bulk of the substrate measures a higher horizontal dielectric constant. The higher, bulk, horizontal dielectric constant, if used for design, would yield incorrect results for coupled lines, which concentrate electric field in the surface of the substrate.

III. Improving the RA Resonator

The error analysis of [7] suggests that any air gap between the top of the conductor and the substrate pressed against it from above would dominate the error budget. Thus the first improvement is to switch to microstrip. There is now no air
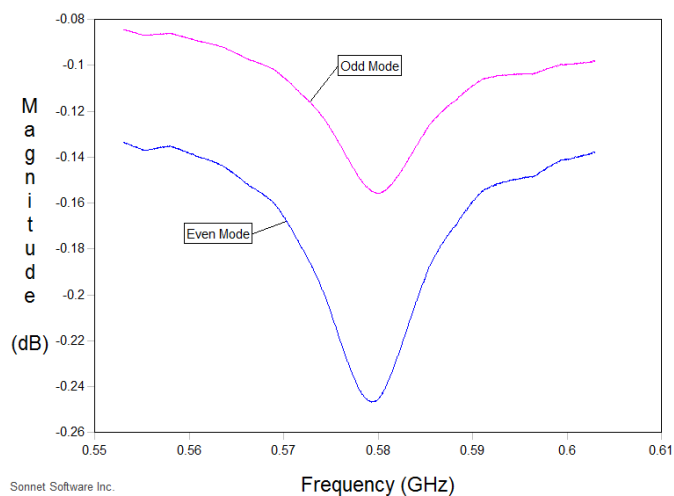

Fig. 2. The second pair of measured even and odd mode resonances of the resonator in Fig. 1.

TABLE I
EXTRACTED UNIAXIAL DIELECTRIC CONSTANTS FOR RESONATORS R1 AND R2

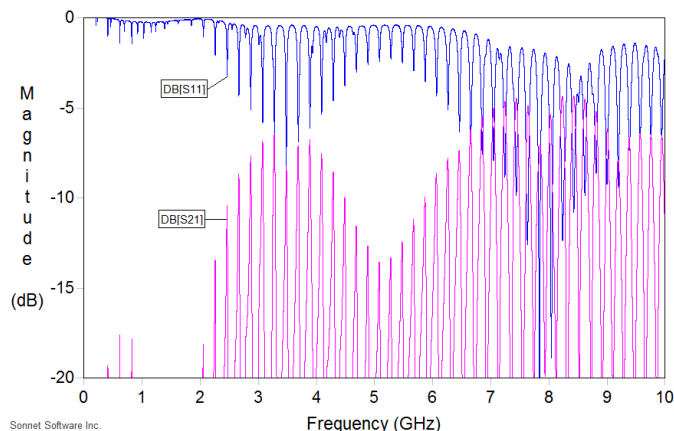| #	MHz	R1 ε_h	R1 ε_v	R2 ε_h	R2 ε_v
1	290	3.937	4.117	3.878	4.106
2	590	3.934	4.094	3.889	4.077
3	880	3.926	4.081	3.876	4.075
4	1170	3.935	4.074	3.906	4.078
5	1470	3.979	4.083	3.923	4.075
6	1760	3.990	4.076	3.936	4.072
7	2060	4.001	4.070	3.926	4.063

Fig. 3. Measured data from the microstrip RA resonator shows considerable modulation of the resonance depth across the band.

gap above the conductor. The trade-off is that the resonances are now less sensitive to the dielectric constant.

Selecting Rogers RO3010, which is known to be anisotropic and is perfectly homogeneous on the scale of microwave circuit dimensions, a microstrip RA resonator was built. Measurements were taken up to 10 GHz. Data was taken at nearly 100,000 frequencies in order to provide sufficient data for each resonance. However, there is now a substantial 'modulation' to the depth of the measured resonances, Fig. 3. As part of the process described in [7], the even and odd mode resonances are numerically separated from each other. The

separation plot is shown in Fig. 4. Note that some resonances are almost completely suppressed. Since both even and odd mode resonances are needed in order to determine the anisotropic dielectric constant, it is not possible to extract dielectric constants at all frequencies.

It was determined that the resonance suppression was due to the short, half inch long coupling sections at the left end of the resonators, Fig. 1. Fig. 3 and 4 show nearly 100 resonances, or nearly 50 even/odd mode resonance pairs. This makes the resonator about 25 wavelengths long at 10 GHz, making the coupling section as much as one wavelength long. Thus, it is the coupling section that causes the mode suppression. The 25 wavelengths long resonator also presents a major challenge for high accuracy EM analysis as an extremely fine mesh is required in order to make sure even the 100th resonant frequency is accurate.

We improved the resonator by simply removing the half inch input/output coupling section. The now open ends of the input and output lines now provide very light gap coupling to the resonator. An EM analysis of the improved resonator, as separated into even and odd modes, is shown in Fig. 5, with the layout of the coupling section shown in the inset. Note that all resonances are easily identified and the amplitude modulation of their depth is substantially reduced.

Because the coupling is now substantially reduced, the resonance depths are reduced making it harder to separate them from any measurement noise. However the resonance bandwidths are also reduced, so it is easier, when not limited by noise, to make an accurate resonant frequency determination. Fig. 6 shows the extracted dielectric constants. Note the clean, low scatter data from 0.2 to 10 GHz. There are, however, some obvious problems with the data of Fig. 5. We address those issues next.

IV. THE SHIELDED RA RESONATOR

The unshielded RA resonator described above encounters problems. Specifically, the substrate thickness (0.050 inches, 1.27 mm) is large enough that the transmission lines start to radiate over the upper frequency range. This has two effects. First it increases the loss of the resonators in that the multi-wavelength resonators become dipole antennas. Second, it introduces error into the calibration for both the measurement and the EM analysis. One manifestation of the calibration error is the appearance of gain at higher frequencies. This can occur in both EM analysis and in measurement.

Another manifestation of error introduced by radiation is that the EM analysis cannot be split into pieces. A common speed-up technique for EM analysis of large circuits is to split a circuit into many small pieces, analyze each piece, then connect the pieces back together using circuit theory. To do this for a resonator, perfect port calibration is required. Perfect port calibration is no longer possible when a circuit, especially a resonator, starts radiating.

To improve this technique further, we must eliminate radiation. This can be done by using a thinner substrate or by analyzing the circuit in a box. To reduce constraints on substrate thickness, we propose the shielded RA resonator, a
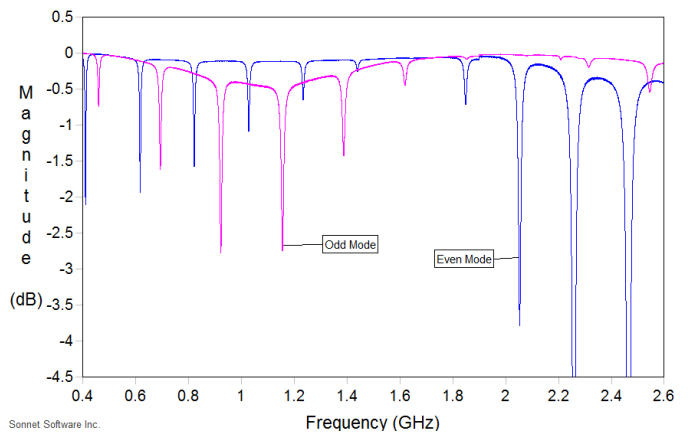

Fig. 4. A few resonances of the data in Fig. 3, now numerically separated into even and odd modes, showing the suppression of some of the resonances.
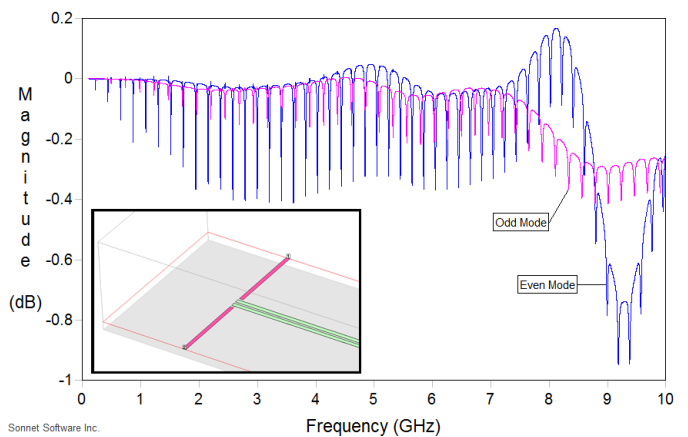

Fig. 5. Mode separation plot for the improved microstrip RA resonator (inset) shows substantially reduced mode suppression. S-parameters greater than zero dB are due to small asymmetries in the manufactured resonator and due to radiation corrupting the calibration.
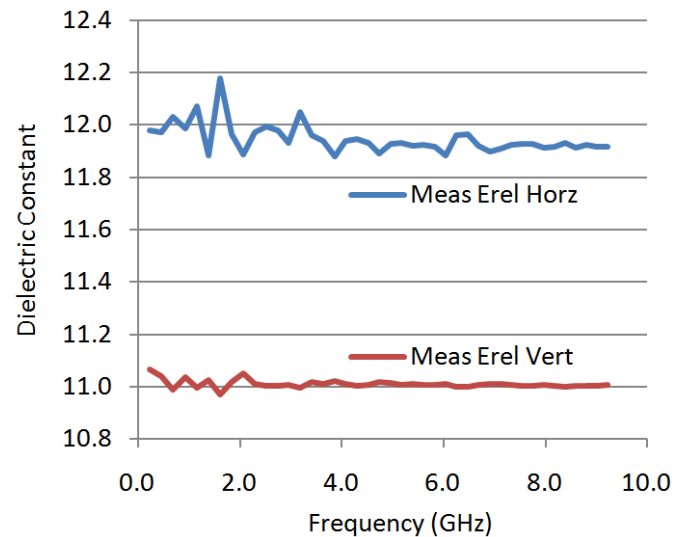

Fig. 6. The anisotropic dielectric constants extracted from measurements of the improved microstrip RA resonator. From [8].

portion of which is shown in Fig. 7. The shielding box that we

investigate here in detail has interior dimensions of 0.300 inch (7.62 mm) wide and 0.160 inches (4.064 mm) tall and 12 inches (304.8 mm) long. A 0.050 inch (1.27 mm) thick substrate with a dielectric constant of 11.0 yields a pair of box resonances at near 14.4 GHz and no other resonances until 19.5 GHz. An RA resonator placed on such a substrate should yield continuous good data at least up to the first box resonance frequency and perhaps beyond.

In the design we are evaluating, the input and output coupling sections are formed by the tabbed 0.050 inch (1.27 mm) wide center conductors of SMA connectors penetrating the sides of the box at one end of the RA resonator 0.010 inches (0.254 mm) above the 0.050 inch (1.27 mm) thick substrate. Coupling from these tabs is extremely light, Fig. 8, and a few of the lowest frequency resonances might need to be sacrificed. However, no electrical contact to the resonator is needed. The RA resonator is simply placed in the test fixture and the measurement taken.

V. Error Analysis of the Shielded RA Resonator

An extensive error analysis of the proposed shielded RA resonator of Fig. 7 was conducted. Error sources investigated include resonator length, width and gap, input/output coupling tab dimensions, substrate thickness, dielectric loss tangent, metal conductivity, metal thickness, line length, shielding box width, and EM simulation mesh size.

To evaluate error, we use an isotropic dielectric constant of 11.5 for EM analysis case A (see [7]). For EM analysis case B, we use 11.1 vertical and 11.9 horizontal. These first two sets of data are used to "calibrate" the dielectric constant extraction, in preparation for receiving measured data. We then use EM analysis to provide a third set of data from which to extract dielectric constants, treating this EM analysis data as though it were measured. This measurement stand-in EM analysis data uses a dielectric constant of exactly 12.0 vertical and 11.0 horizontal. Sensitivity to error in the dimensions of a measured resonator are determined by intentionally inserting dimensional errors into the measurement stand-in EM analysis and observing the resulting error in the extracted dielectric constants. If there were no error, the extracted dielectric constants would be exactly 11.0 vertical and 12.0 horizontal.

Several cases are of interest. For example, the extracted dielectric constants are sensitive to error in resonator substrate thickness. Standard deviation for a 0.0001 inch error in substrate thickness is 0.0055 for vertical dielectric constant and 0.0052 horizontal.

Of more importance is resonator gap error, with a standard deviation of 0.007 in horizontal dielectric constant for a change of 0.0001 inch in gap. Fig. 9 shows the extracted anisotropic dielectric constants when the measured resonator has a coupled line gap 0.005 inch less than the expected 0.025 inch. The distinctive variation with frequency is useful for identifying this type of error. It turns out that most error sources insert error with a unique frequency variation, thus aiding error source identification. Metal thickness is especially sensitive, with a horizontal dielectric constant standard deviation of 0.072 for a 0.0001 inch error in metal thickness.
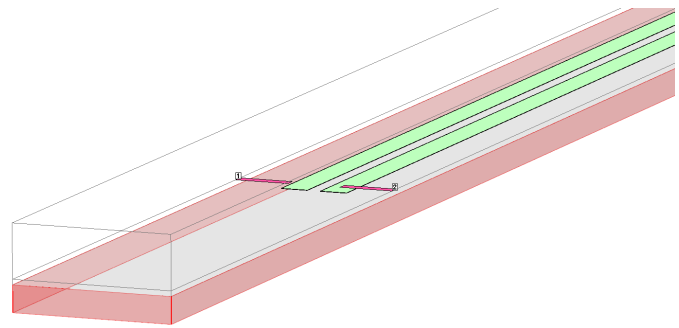

Fig. 7. The proposed shielded RA microstrip resonator includes input/output coupling from SMA connector center conductor tabs ("1" and "2") that make no physical contact to the resonator itself.
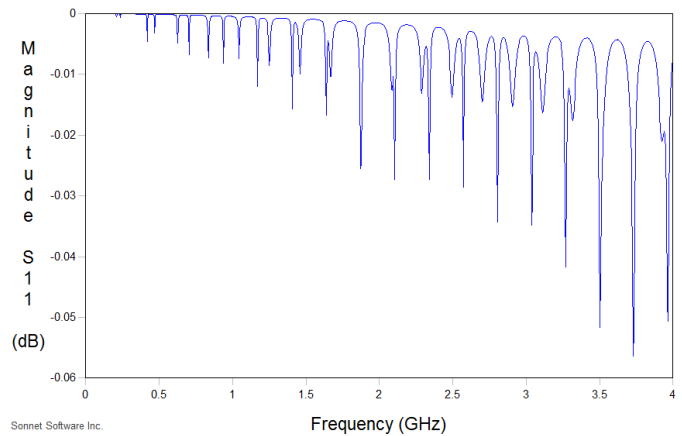

Fig. 8. A detail of the low frequency EM analysis calculated resonances of the proposed shielded resonator. The small depth of the lowest frequency resonances might render those resonances unusable when measured in the presence of noise.
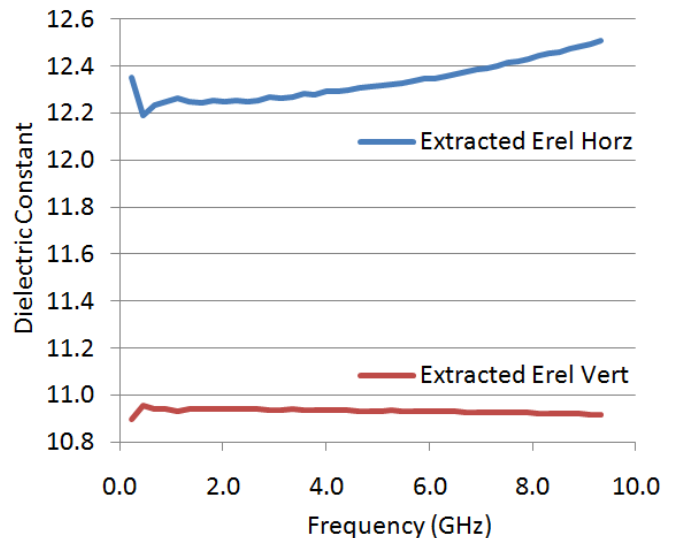

Fig. 9. The anisotropic dielectric constants extracted from a resonator on a substrate whose resonator coupled line gap is 0.005 inch narrower than the expected 0.025 inch gap. The distinctive frequency variation aids identification of gap width error when the resonator is constructed. If there were no error, the dielectric constants would be exactly 11.0 and 12.0 at all frequencies.

In this case, the error inserts no variation of the extracted dielectric constants with frequency, making precise knowledge of metal thickness critical. Vertical dielectric constant is insensitive to width and gap and metal thickness.

EM analysis error also contributes to error in the extracted dielectric constants. EM analysis error due to a finite EM mesh cell length of 0.010 inches is inconsequential. In contrast, EM mesh cell width proves important, but again only for horizontal dielectric constant, with a standard deviation of 0.04 for cutting the original 0.0025 inch cell width in half. If we assume linear convergence in EM analysis error (a common situation), then the total error is double that, or 0.08 for a 0.0025 inch EM mesh cell width. One approach is to use EM analysis with mesh cell width as small as possible. However, this can substantially increase EM analysis time. Fortunately this error is deterministic and it can simply be subtracted. In addition, if the critical dimensions of the actual measured resonator are known, all of the above described errors become deterministic and may simply be subtracted from the extracted results.

One error source not considered here is error due to surface roughness. While we found sensitivity to increased metal loss is inconsequential, surface roughness also effects a slowing of the wave velocity. Such an effect directly impacts the accuracy of this measurement. The surface roughness effect must be isolated and quantified. It cannot simply be allowed to remain as an error source in the result as the degree of its effect depends on line width and substrate thickness. If it is not quantified and removed, then the measured dielectric constant would erroneously appear to be a function of line width and substrate thickness. Based on experimental results not reported here, we expect this effect to be significant for very thin substrates.

VI. Conclusion

We have provided an overview of our recent efforts to perform precise broad band measurements of anisotropy in planar substrates using a dual mode resonator. In particular we have highlighted the problems that we have identified, and described and demonstrated solutions including the proposed shielded microstrip RA resonator.

VII. Acknowledgements

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