Measurement of Uniaxial Anisotropy in Rogers RO3010 Substrate Material

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***Abstract*—A new technique using a dual mode "RA resonator" to measure uniaxial anisotropy in planar substrates is applied to Rogers RO3010 material. When this technique was previously applied to FR-4, an unexpected result (a horizontal dielectric constant less than the vertical dielectric constant) was obtained. It is hypothesized that the unexpected result is due to the fact that FR-4 is inhomogeneous. For example the glass fiber weave embedded in the FR-4 epoxy is not uniformly distributed. To test this hypothesis, similar measurements are performed on Rogers RO3010 material, which is strongly anisotropic, perfectly homogeneous, and is known from independent measurements to have a horizontal dielectric constant greater than the vertical. Several modifications to the original RA resonator that increase the frequency range over which useful measurements can be acquired are described and demonstrated.**

***Index Terms*—Anisotropy, dielectric constant, dispersion, electromagnetic analysis, method-of-Moments (MoM), printed circuit board (PCB), transmission line, uniaxial.**

I. Introduction

STRIPLINE based measurement of the dielectric constant of planar substrates [1] is common. However, such techniques are typically used for quality control, i.e., making sure that each manufactured batch of substrates has the same dielectric constant. Due to various error mechanisms, the actual value of the dielectric constant (which should be used for RF design) can be different.

Anisotropy measurements for planar substrates are rare due to the difficulty of making such measurements. Measurements that are reported [2], [3], yield the bulk dielectric constant. This can be done by laminating multiple boards together or by placing a board in the center of a rectangular waveguide and measuring the perturbation, among other ways. When using laminated boards, they can be cut in cross section, forming new substrates. The stripline resonator measurements are repeated with the new, reoriented, substrate material. However, resonator fields are composed of a mixture of both horizontal and vertical electric fields, Fig. 1. Thus the resulting dielectric constant measurement is actually a weighted average of the vertical and horizontal dielectric constants.

The technique reported in [4] explicitly takes into account

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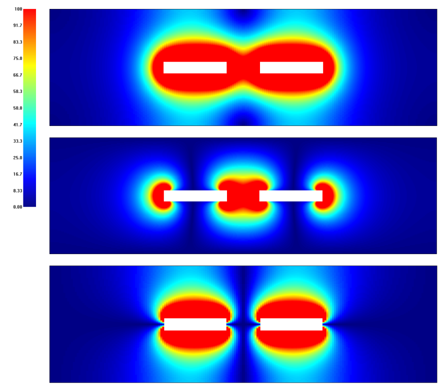

Fig. 1. Precisely calculated cross-sectional E-fields for the odd mode of a coupled line, total field (top), horizontal field (middle), and vertical field (bottom). One volt is applied between the two conductors. From [4].

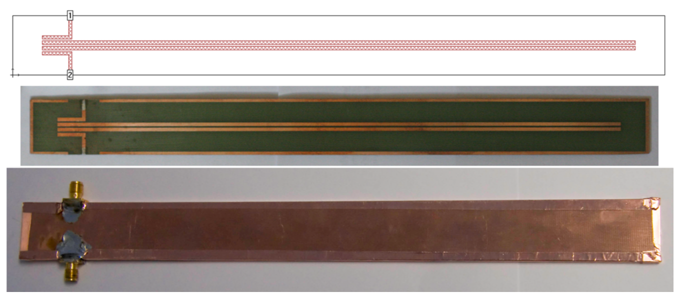

Fig. 2. The original RA resonator: Layout in Sonnet top, fabricated resonator middle, and completed resonator bottom. The resonators are 10 inches (254.0 mm) long. The input/output coupled region is 0.5 inches (12.7 mm) long. In this case, the resonators are on FR-4. From [5].

the fact that resonator fields are a mixture of horizontal and vertical electric fields. It has been applied to FR-4 with the result that the horizontal dielectric constant was found to be less than the vertical dielectric constant [5]. Unpublished measurements suggest the opposite situation. It is hypothesized that these unexpected results were obtained because the unpublished results use the measurement technique cited above (laminating multiple substrates and slicing in cross section, other methods are also referenced in [5]), while the technique used in [4] and [5] measures the dielectric constant predominantly in the surface of the substrate (as in Fig. 1, middle). To test this hypothesis, we perform the measurement on Rogers RO3010 material. It is perfectly homogenous and strongly anisotropic. Laminated and waveguide substrate measurements indicate the horizontal dielectric constant is higher than the vertical. Since this material is homogenous (on the scale of microwave circuits), the technique of [4] and [5] should give a qualitatively similar result.

II. Outline of the Technique

Previous planar dielectric constant measurement techniques start with a resonator formed from a length of stripline open circuited on both ends. The resonator is lightly coupled and the frequency of reflection coefficient (S_{11}) dips, or transmission coefficient (S_{21}) peaks are recorded. Combined with knowledge of the length of the resonator, an estimate of the dielectric constant is formed.

We start with measurement of a coupled line resonator (which we call an "RA resonator", [4] and [5]), Fig. 2. This is a dual mode microstrip or stripline resonator with both the even and odd coupled line modes exciting resonances. Key to this technique is that the even and odd modes each excite a different amount of vertical and horizontal electric fields. Initial measurements on FR-4, [4] and [5], using stripline achieved nearly four significant figures. A detailed error analysis, in [5], shows that uncertainty in the stripline air gap is a major error source. Thus, the measurements reported here are for microstrip. Air gap uncertainty is zero.

Fig. 3 shows measurements of a microstrip coupled line RA resonator on Rogers RO3010 similar in layout to Fig. 2. It is 10 inches (254.0 mm) long on a 0.025 inch (0.635 mm) substrate of Rogers RO3010. Measurements were taken up to 10 GHz, yielding nearly 100 resonances (the line is 25 wavelengths long at 10 GHz and there are two resonant modes per half wavelength). The 2-port resonator measurements are transformed into two sets of data, one which shows only even mode resonances and the other which shows only odd mode resonances. An Excel spreadsheet automatically finds each resonance, performs a quartic polynomial fit, and estimates each exact resonant frequency. The entire process is detailed in [5].

Next, two EM analyses are performed of the same resonator. One EM analysis typically assumes an isotropic substrate with the approximate average of the expected dielectric constants. The second EM analysis uses the expected anisotropic dielectric constants. All resonant frequencies are extracted from the EM data in the same manner as they were for the measured data. Note that the even mode resonances depend strongly on the vertical dielectric constant while the odd mode also depends on the horizontal dielectric constant. Qualitatively, the difference between the even and odd mode resonant frequencies corresponds to the difference between the horizontal and vertical dielectric constants. Quantitatively [5] we have

$$\begin{bmatrix} \varepsilon_{hm} \\ \varepsilon_{vm} \end{bmatrix} = \begin{bmatrix} \varepsilon_{ha} & \varepsilon_{hb} \\ \varepsilon_{va} & \varepsilon_{vb} \end{bmatrix} \begin{bmatrix} f_{ea}^{-2} & f_{eb}^{-2} \\ f_{oa}^{-2} & f_{ob}^{-2} \end{bmatrix}^{-1} \begin{bmatrix} f_{em}^{-2} \\ f_{om}^{-2} \end{bmatrix} \tag{1}$$

where v is vertical, h is horizontal, e is even mode, o is odd mode, a is EM analysis case a (usually isotropic) and b is EM analysis case b (usually the expected anisotropy). The right hand vector contains the measured resonant frequencies, the two matrices are the EM analysis dielectric constants and resulting resonant frequencies for the two EM analysis cases,

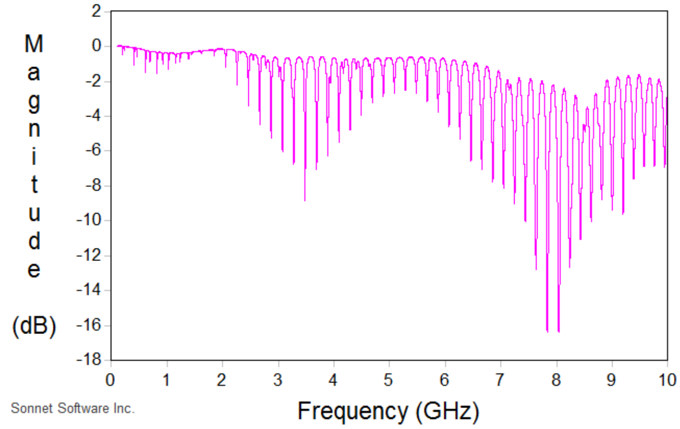

Fig. 3. The measured S11 of the dual-mode coupled line resonator on Rogers RO3010. Nearly 100 resonances, a mixture of even and odd modes, are captured.

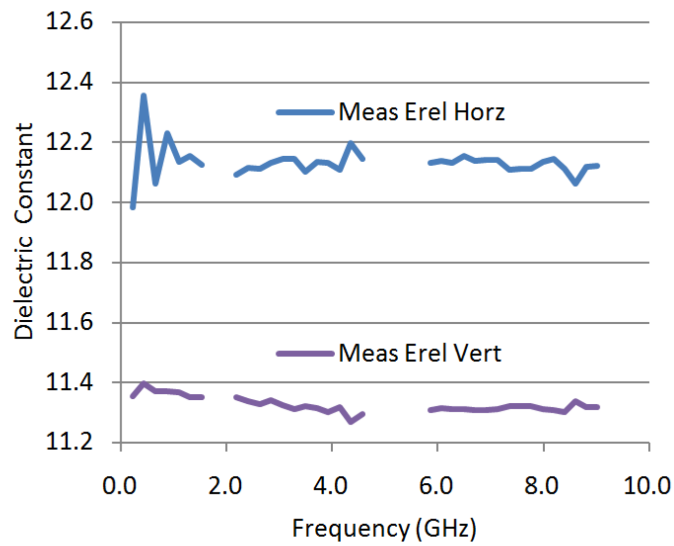

Fig. 4. The measured values of vertical and horizontal dielectric constants that were extracted from the measured data of Fig 2.

and the left hand side is the desired measured dielectric constants that are required to make the measured resonant frequencies consistent with the EM analysis resonant frequencies. We evaluate (1) for each pair of even/odd mode resonances. Each evaluation extracts one pair of measured horizontal and vertical dielectric constants, the left hand side of (1).

Fig. 3 shows S_{11} of the resonator that we built on Rogers RO3010 material. This response is a composite of both even and odd mode resonances. We numerically separate the even and odd mode resonances into two separate data sets and repeatedly apply (1) for each pair of even and odd mode resonances. One pair of horizontal and vertical dielectric constants is obtained for each evaluation. Fig. 4 shows the resulting extracted measured dielectric constants. Vertical and horizontal dielectric constants were expected to be 11 and 13. We measured 11.32 and 12.12. An additional EM analysis using the extracted measured dielectric constants yields almost exactly the same S-parameters as the measured data, Fig. 3. Measured versus calculated is shown for the highest frequency resonances, which show maximum differences, in Fig. 5.

III. Improving the RA Resonator

In Fig 3, we note that there is substantial modulation of the depth of the resonances across the 10 GHz band. In fact, some resonances are completely suppressed over several small bands. Since both even and odd mode resonances are needed in order to extract the measured dielectric constant, there are gaps in the results of Fig. 4 where some of the resonances are suppressed.

We determined that the suppression is due to the half inch (12.7 mm) input/output coupling region at the left end of the resonator. That section acts as an open circuited stub suppressing some RA resonator resonances and enhancing others. The solution is to eliminate the half inch (12.7 mm) input/output coupling sections and de-embed the length of the line connecting the port connector to the resonator coupling gap. The Sonnet layout is shown in Fig. 6, with the arrows on the port connecting lines indicating the desired reference plane. For ease of de-embedding, these port connecting lines should be 50 Ohms.

When this modification is made, Fig. 7 shows the resulting calculated RA resonator S_{11}. Note that most of the resonance depth modulation is gone. In addition, because of the reduced input/output coupling, the resonances are narrower allowing more accurate estimation of the measured resonant frequencies. On the other hand, the resonances are significantly shallower, which increases the effect of measurement noise. In this case, good even and odd mode resonances are extracted over the entire 10 GHz bandwidth. Fig. 8 shows the extracted measured dielectric constants.

The data for Fig. 8 is extracted from measurement of the improved resonator. Note that the scatter in the result is substantially reduced, especially at high frequency where the multi-wavelength long resonator is most sensitive to dielectric constant. We conclude a vertical dielectric constant of 11.00 and a horizontal dielectric constant of 11.91. Scatter in the extracted measurements suggests uncertainty in the fourth digit, especially for the horizontal dielectric constant.

Sensitivity of the extraction technique to the dielectric constants selected for EM analysis cases A and B was evaluated by numerical experiment. Significant sensitivity, on the order of 2%, was observed, but only for the horizontal dielectric constant below 1 GHz. This suggests that the slight increase in horizontal dielectric constant at lower frequencies in Fig. 8 might not be real; rather it could be due to the selection of EM analysis dielectric constants used in (1) different from the actual substrate. We do point out, however, that the dielectric constant of a lossy substrate cannot be constant at all frequencies without violating causality.

The differences between the results of Fig. 4 and Fig. 7 are likely due to some combination of substrate variation, measurement error, fabrication error, and extraction error. Rather than pursue these questions further, we instead suggest an additional improvement to the RA resonator.

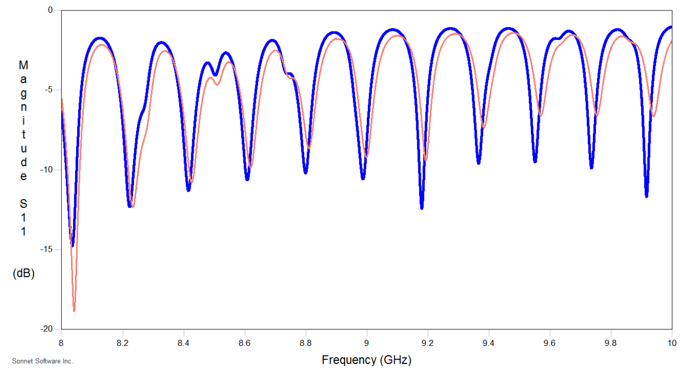

Fig. 5. Comparison of highest several dozen of the over 100 resonances from EM analysis using the extracted measured dielectric constants (thick, blue) and the measurement from which the dielectric constants were extracted (thin, orange). Lower frequencies show even less difference.

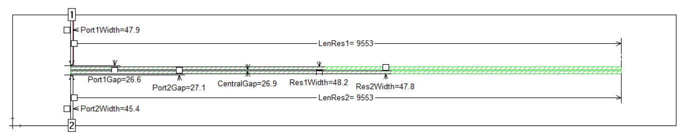

Fig. 6. The improved RA resonator used to extract better measurements of dielectric constant from Rogers RO3010 with detail of the input/output region superimposed on the right.

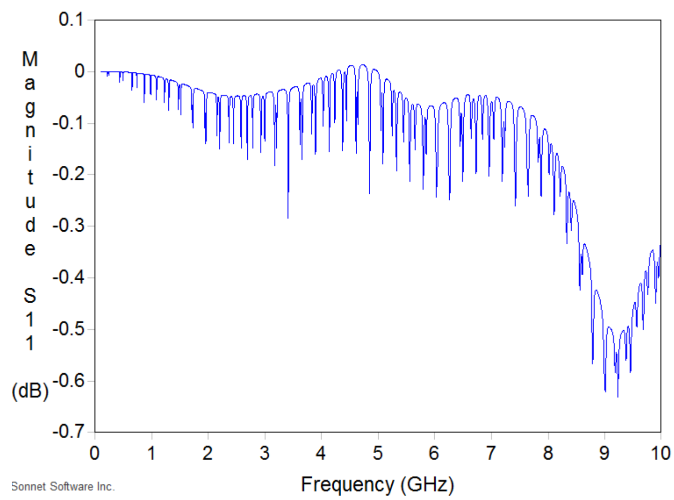

Fig. 7. The modified RA resonator shows reduced modulation of the depth of the resonances across the entire band.

IV. Additional Improvements

The above results are for a Rogers RO3010 substrate with a measured thickness of 0.049 inches (1.2446 mm), line widths of 0.048 inches (1.2192 mm) and gaps of 0.027 inches (0.6858 mm). Measured dimensions are shown in Fig. 6. We found that in some situations this larger substrate thickness experiences radiation from the transmission lines (which is included in the analyses reported here). This causes difficulty and increases error.

To avoid these difficulties and achieve the highest possible accuracy, radiation must be eliminated. One way is to use a thinner substrate. Another way is to do the analysis and measurement inside a box that is as small as possible. Fig. 9 illustrates one such proposed shielded resonator. The box is 0.300 inches (7.62 mm) across with the top cover 0.110 inches

(2.794 mm) above the top of the substrate. Coax connector tabs 0.020 × 0.100 inches (0.508 × 2.54 mm, connected to ports "1" and "2" in the figure) at 0.010 inches (0.254 mm) above the substrate surface are responsible for coupling to the resonator. Note that there is no physical connection between the connector tabs and the resonator. Thus, no soldering is needed. However, the coupling is very light and thus several of the lowest frequency resonances might be so shallow that they would be sacrificed. The box is 0.300 inches (7.62 mm) wide, which when combined with a 0.050 inch (1.27 mm) thick Rogers RO3010 substrate yields a first cavity resonance at 14.4 GHz, forming an upper frequency limit for this test fixture. Care should be taken that there is a snug fit between the edge of the substrate and the adjacent sidewall along the entire length of the resonator. Any air gap at that location increases error. The shielding of the RA resonator also has the advantage of allowing both a faster and a more accurate EM analysis than is possible with an unshielded resonator.

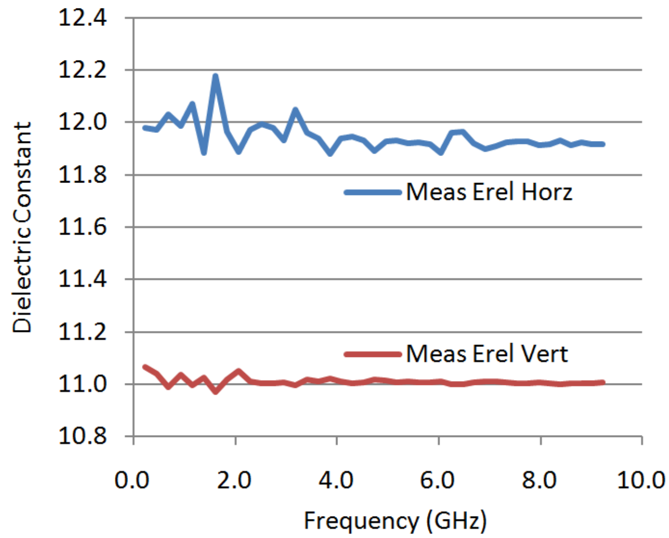

Fig. 8. The improved RA resonator results for a 0.049 inch (1.2446 mm) thick Rogers RO3010 substrate.

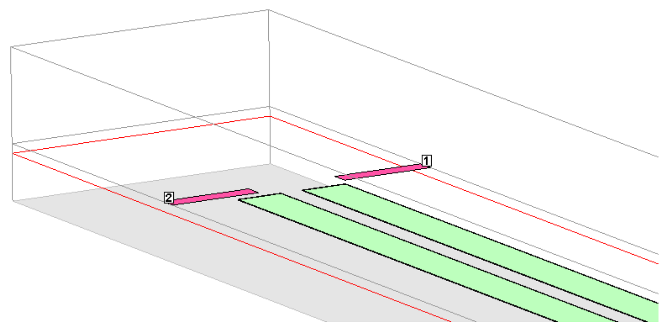

Fig. 9. 3-D view of the input section of the proposed shielded RA resonator. Input and output couplings are due only to the tabs ("1" and "2") from coax connectors, so no soldering is required. Meanwhile, the box eliminates measurement error induced by radiation.

V. Conclusion

We have extracted both horizontal and vertical dielectric constants for Rogers RO3010 material using measurements of a single dual mode resonator. Nearly 50 even and 50 odd mode resonances were evaluated and compared to results of an EM analysis, yielding the anisotropic dielectric constants. Several improvements for the resonator have been suggested and/or demonstrated. Successful measurements up to 10 GHz are reported.

VI. Acknowledgements

The assistance of John Reynolds of Rogers Corporation, Rogers, CT, in fabricating and measuring the RA resonators is gratefully acknowledged.

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