Shielded Dual Mode Microstrip Resonator Measurement of Uniaxial Anisotropy

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***Abstract*—An improved technique to measure uniaxial anisotropy in planar substrates is described. This technique builds on previous work performed with stripline. The improved approach offers substantially larger bandwidth, lower error, and ease of measurement. An almost complete automation of the entire calibration and measurement extraction process is described. It is also demonstrated that the horizontal (parallel to substrate surface) dielectric constant is less than the vertical dielectric constant for glass fiber weave reinforced substrates for the purposes of microstrip and stripline design. This directly conflicts with bulk measurements of dielectric constant and is believed due to microstrip horizontal electric field concentrating in the substrate surface. This is supported by measurements of a homogeneously ceramic loaded substrate showing the expected relationship. Effects of EM analysis accuracy, metal roughness, metal thickness, and edge profile (due to etching) are found to be important.**

***Index Terms*—Anisotropy, dielectric constant, dispersion, electromagnetic analysis, measurement, method-of-moments (MoM), microstrip, resonator, transmission line, uniaxial.**

I. Introduction

ANISOTROPY (different dielectric constants for different directions) has been ignored in much of applied planar microwave design because dielectric constant values are not readily available and because their effects are not easily included in microwave design. This is disturbing because anisotropy can exceed 10% and is present in all composite substrates (e.g., glass embedded in epoxy, etc.), and is present in most ceramic substrates (whenever the ceramic particles are not spherical). Numerous heuristic “rules-of-thumb” have developed, for example, “On this substrate, design the filter for 12% more bandwidth than what you actually want. Then the fabricated filter will be close to the desired bandwidth.” Fig. 1, from [1], illustrates the problem. With precise knowledge of anisotropy and with a way to include it in EM analysis, filters can now be directly designed for the desired bandwidth.

Anisotropy is also a major unaddressed problem in signal integrity. Very long, very high speed digital busses use stripline so that even and odd modes are equalized. However, this is true only for an isotropic substrate. Anisotropy can result in significant difference between even and odd mode velocities, even in the case of stripline, with severe signal integrity consequences.

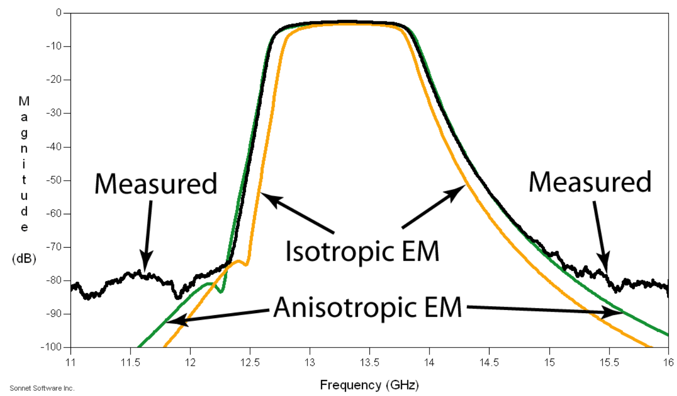

Fig. 1. When an anisotropic substrate is modeled as if it were isotropic, the resulting filter center frequency (which is more dependent on the vertical dielectric constant) might be right, but the bandwidth (more dependent on horizontal dielectric constant) is wrong.

Previously, the only way to include anisotropy was by means of 3-D volume meshing EM (electromagnetic) tools. Volume meshing tools tend to be inefficient for planar circuits, and thus are difficult to use for that purpose. Recently, anisotropy has been included in at least one widely used commercial planar EM tool [2], [3] and a broad band resonator based technique to accurately measure anisotropy as experienced by planar circuits, has been developed [4] – [7]. Here, we explore improvements in this technique, describe how the process has been automated, and explore results for several substrates. In particular, the effects of EM analysis accuracy, metal surface roughness, metal thickness, and the cross-sectional profile of the metal edge (due to etching) have been found to be important and are discussed in detail.

A detailed bibliography of planar substrate dielectric measurement techniques is provided in [8].

II. An Overview of the Technique

We deal with uniaxial anisotropy, in that there is one dielectric constant for vertical (perpendicular to the substrate surface) and a different dielectric constant for horizontal

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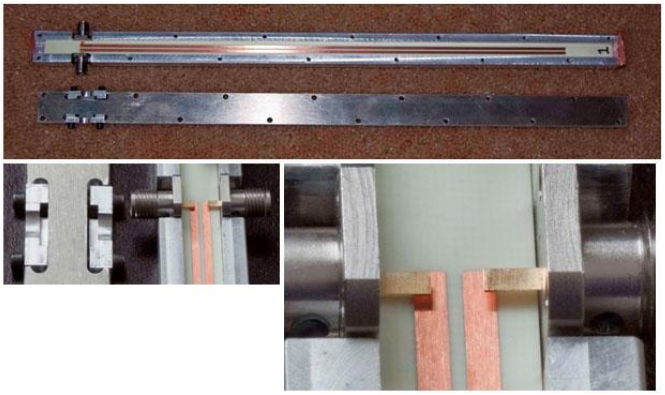

Fig. 2. A 25.4 mm (10 inch) long RA resonator on Rogers RO4350B laminate, lightly coupled at the ends via SMA connector tabs. The resonator is nearly 25 wavelengths long at 16 GHz.

electric field. To illustrate how we measure anisotropic dielectric constant, we start with an isotropic example. In this case, one might use a microstrip resonator that is open on both ends. If we very lightly couple into the resonator, we can measure the frequency at which it is one half wavelength long. If we know the physical length and we can precisely evaluate the resonant frequency for a known substrate dielectric constant, we can then determine the actual dielectric constant.

When we use this technique to measure an anisotropic substrate, we find that the extracted "effective" substrate isotropic dielectric constant is (incorrectly) dependent on line width and substrate thickness. If we have coupled lines, we find that the extracted isotropic dielectric constant does not work for coupling between the lines. These problems occur because our initial measurement of the effective substrate isotropic dielectric constant depends on the specific ratio of horizontal and vertical electric field excited by the microstrip resonator. The effective isotropic substrate dielectric constant is a corresponding weighted average of the actual vertical and horizontal dielectric constants. When the circuit changes, the weighting changes and the extracted effective substrate isotropic dielectric constant changes.

For measuring uniaxial anisotropy, we use a coupled line resonator, Fig. 2. The RA resonator (named with the initials of the authors of [5]) has both even and odd modes. Each mode has a different ratio of vertical and horizontal electric fields. Thus, even mode and odd mode resonances are each dependent on the two dielectric constants, and each in a different way. For example, the even mode tends to be mostly dependent on the vertical dielectric constant while the odd mode is also dependent on the horizontal dielectric constant. By precisely measuring the even and odd mode resonant frequencies and comparing those results with precise EM analysis results, we can determine the vertical and horizontal dielectric constants that generated the measured even and odd mode resonances [4] – [7].

Normally, resonator measurements are restricted to one, or to a few frequencies, the frequencies where the resonator resonates. To achieve broad band measurements, we make the resonator as long as is practical. For example, a 10 inch long resonator on a low dielectric constant substrate is nearly 25 wavelengths long at 16 GHz, realizing nearly 50 pairs of even/odd mode resonances, which in turn yield nearly 50 measurements of anisotropic dielectric constant from 0.3 to 16 GHz.

Previous work [5] was performed in stripline, which requires more effort to fabricate than microstrip and is also sensitive to air gaps. Unshielded microstrip is band limited, especially with thick, low dielectric constant substrates because a long resonator becomes an excellent antenna at higher frequencies.

For those reasons, we use a shielded microstrip resonator, Fig. 2. The inner dimensions of the shield are 7.62 mm (0.300 inch) side-to-side, 3.81 mm (0.150 inch) ground-to-top cover, and 30.48 cm (12 inches) end-to-end. Small coupling to the resonator is provided by the SMA connector tabs floating about 0.254 mm (0.010 inch) above the substrate surface. Substrate samples are prepared and simply placed in the fixture. There is no soldering. Small Styrofoam spacers press the substrate down when the cover is in place. The substrate samples have a full ground plane on the bottom side.

III. Measurement Work Flow

When a new substrate or resonator geometry is considered, an extraction must be calibrated. The calibration process is performed once, and then multiple measurement extractions can be performed in quick succession.

To start the calibration process, we perform two EM analyses of the proposed geometry, which we call "EM Case A" and "EM Case B". Case A typically uses whatever we expect the actual anisotropic dielectric constants to be. Case B can be anything different from Case A, but we usually make it isotropic using a value between the two anisotropic values. The differences in resonant frequencies between the two cases determine the sensitivity of each even/odd mode resonance pair to the vertical and horizontal dielectric constants. Knowledge of these sensitivities allows us to extract the vertical and horizontal dielectric constants from measurements of the actual even and odd mode resonances.

In order to get enough data points covering each resonance to accurately determine the resonant frequency, a frequency step size of 200 kHz is usually used yielding a full 16 GHz EM data set of 80 000 points.

If there were no error sources and the EM Case A and B analyses exactly match the fabricated geometry, we would be done. Instead, we must characterize and, where possible, remove error sources. This is done by performing additional sensitivity analyses, [4] – [7]. For example, the actual fabricated line width might be slightly different from that assumed for EM Cases A and B. To characterize the error introduced by this difference, we perform an additional EM analysis with a line width slightly different from EM Case A. We then treat this new EM analysis as though it were a measurement and extract dielectric constants from its resonances. The extraction assumes the nominal line width, but the resonances are from an analysis with a different line

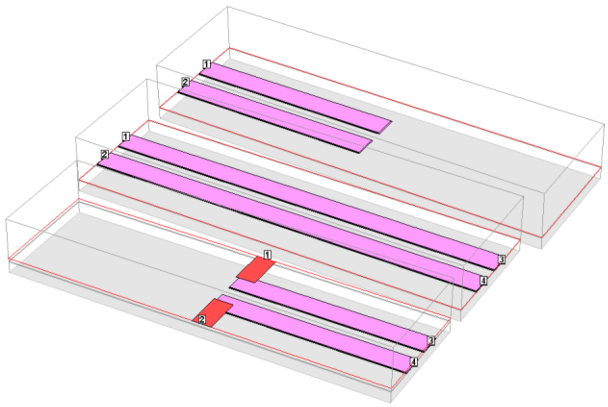

Fig. 3. The resonator is divided into three unique 25.4 mm, one inch (box size) sections for EM analysis. Because perfect port calibration is realized, the sections are connected together using circuit theory yielding extreme accuracy for the full 10 inch resonator over the entire 16 GHz bandwidth.

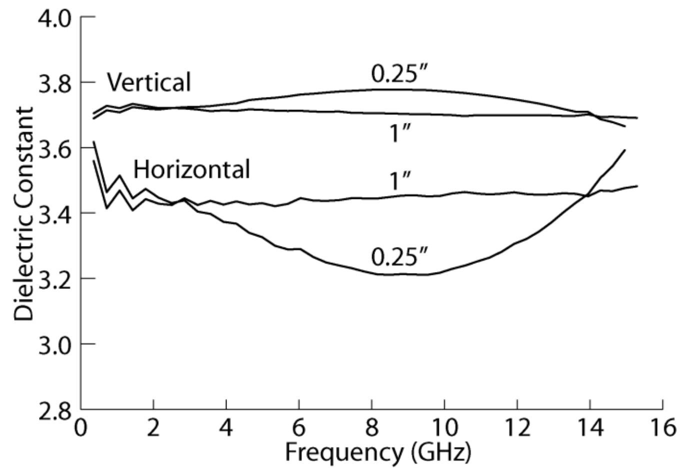

Fig. 4. Calibration using the one inch sectioning strategy (Fig. 3) yields a reasonable extraction (1" curves) of measurements of an actual resonator. A quarter inch sectioning strategy fails due to port calibration problems.

width, and the extracted dielectric constants are in error. This error is the sensitivity of the extraction to differences in line width. We use the sensitivity to compensate actual measured results for the actual non-nominal line width.

We determine sensitivities and compensate for the following error sources:

1) Non-nominal line width.
2) Non-nominal gap/separation between lines.
3) Non-nominal substrate thickness.
4) Non-nominal resonator length.
5) Non-nominal metal thickness.
6) Non-nominal metal surface roughness.
7) Non-nominal metal (etching) edge profile.
8) EM analysis error due to cell width.
9) EM analysis error due to cell length.

Each of these error sources requires one additional EM analysis to determine sensitivity. Once the sensitivity is determined, then extracted dielectric constant results are appropriately compensated.

The large number of high accuracy EM analyses required can take a considerable length of time. In addition, manually creating, executing, and processing each EM analysis result is error prone. Therefore, we have completely automated this process with a MATLAB® based interface. The user enters the resonator dimensions and parameters. All of the required geometries are automatically created and the EM analyses executed. Then, upon specifying the location of the EM analysis results, the Excel spreadsheet based extraction automatically reads and processes all of the calibration EM analysis results. The user time required is only a few minutes, even if the total computer time is several days.

The calibration is performed once for each resonator geometry. Then multiple measurements are processed in quick succession. In order to accurately determine resonant frequencies, there should be 100 or more measured data points for each resonance. Since measured resonances are narrow and noisy, a frequency step no larger than 100 kHz is commonly used. A full 16 GHz data set comprises 160 000 data points. Modern network analyzers conveniently measure 20 000 data points at a time. So we take measurements 20 000 points at a time and place the results in consecutively numbered files. After specifying the first data file, the Excel spreadsheet automatically reads and processes the entire set of files. Results are available in about three minutes.

One error source not listed above is error due to truncation of the Green's function calculation in the EM analysis (which realizes faster EM analysis) used to calibrate the extraction. After significant effort, we were unable to achieve useable results with anything but a full calculation of the Green's function. Any attempt to duplicate results presented here should bear this in mind.

IV. EM Analysis Accuracy

This technique is centrally dependent on the accuracy of the EM analysis used to calibrate the extraction. The EM analysis used in this work has been shown to converge linearly to the correct answer to below the 0.1% error level [9]. Because Sonnet® converges linearly, we can remove most of the EM analysis error by comparing results from analyses using two different mesh sizes, one half the size of the other. Error due to cell (subsection) length must be treated separately from error due to cell width [9].

Analysis of a resonator that is 25 wavelengths long at over 80 000 frequencies and simultaneously realizing results accurate to within a few 10's of kHz at 16 GHz is an extreme problem. We solve this problem by breaking the 25.4 cm (10 inch) long resonator into multiple 2.54 cm (1.0 inch) pieces. We use a mesh of 2.54 μm (0.001 inch) square cells (subsections), or 200 per wavelength at 16 GHz. Success using this strategy requires perfectly (to within numerical precision) calibrated ports. Sonnet's ports are perfectly calibrated provided the port connecting lines are not over-moded [10], [11].

Fig. 3 shows the three unique sections that are analyzed. Line width is 1.524 mm (0.060 inch), gap is 0.762 mm (0.030

inch) and substrate thickness is 0.762 mm (0.030 inch). They are connected by circuit theory into a full 25.4 cm (10 inch) resonator. An advanced interpolation is used. The interpolation was checked by verifying that direct analysis at each frequency (over a narrow band) gives exactly the same resonant frequencies. An extraction spreadsheet was fully calibrated using this strategy. An example extraction from measured data is shown in Fig. 4. The method to extract anisotropic dielectric constants from this data is detailed in [4] – [7].

High accuracy EM analysis at 80 000 frequencies of a dual mode resonator 25 wavelengths long requires a few hours. There are various methods to realize faster analysis; however, most of these methods introduce sufficient error to cause this technique to fail.

For example, also shown in Fig. 4 is the result of an extraction calibrated using EM analysis with the resonator sectioned into 6.35 mm (0.250 inch) pieces. Note that there is considerable error, which is maximum at about 7 GHz and is zero at 14 GHz. The sections are precisely one half wavelength long at 14 GHz, placing the ends of each 6.35 mm (0.250 inch) long section at a current null, where port calibration error in the form of a series inductance would have no effect. The port calibration in Sonnet requires that there be no evanescent/fringing field coupling between ports on opposite ends of the lines (side-by-side ports have no restriction). In the quarter inch section analysis, the opposite ports are eight substrate thicknesses apart and should have extremely small fringing field coupling. However, even that small error, inserted into a low loss resonator multiple times, has a large effect. This illustrates that extracting dielectric constants from EM analysis of resonators is a very sensitive tool for diagnosing EM analysis problems.

V. Other Error Sources

A new surface roughness model has recently been developed [12], [13]. It is well known that skin effect and surface roughness increase resistive loss. Sometimes forgotten is that skin effect includes an inductive surface reactance that is equal to the surface resistance [14]. The surface reactance increases with frequency in the same manner as the skin effect resistance, with the square root of frequency. Since inductive reactance increases proportionally with frequency, skin effect inductance must be inversely proportional to the square root of frequency. In other words, skin effect inductance decreases with frequency. Models of skin effect inductance that have inductance increasing with frequency are fundamentally incorrect.

Based on experimental results [12], [13], it is found that surface roughness inductance at least approximately follows the same inverse proportionality to the square root of frequency. The effect is especially large for narrow lines, usually encountered when using thin substrates. Since increased inductive surface reactance lowers resonant frequencies, its effect should be included in extractions of

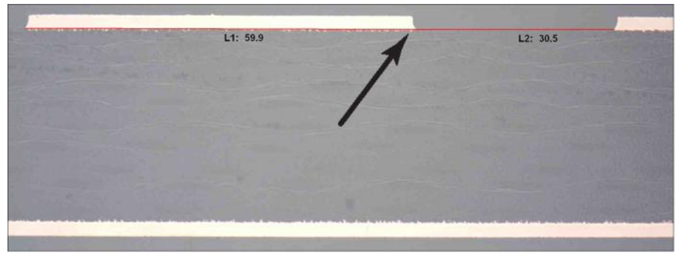

Fig. 5. A cross-sectional micro-photograph shows the diagonal edge profile due to etching. Including the effect of this profile is critical in extracting the horizontal dielectric constant. It has essentially no influence on the vertical dielectric constant.

dielectric constant. Otherwise the extracted dielectric constants will (incorrectly) appear to be a function of metal roughness as reported experimentally in [12], [13]. The effect of roughness is explored in the results presented below.

Edge profile is the non-vertical metal edge caused by etching of thick metal. The sensitivity of the extraction to edge profile is determined by EM analyzing thick metal with the top sheet narrower than the bottom sheet. Both edge profile and metal thickness are found to have substantial effect on the horizontal dielectric constant. Little effect is seen on vertical dielectric constant. When metal has a square edge profile, the top and bottom corners of the metal edge are equally sharp. More charge accumulates on the bottom edge because it is closer to the substrate. When the top edge is etched further back, that edge becomes obtuse and is less attractive to charge. In addition, the top edge is now partially shielded from the substrate by the acutely sharp bottom edge. This means more horizontal electric field is forced into the substrate at the sharper lower corner, lowering resonant frequencies. This effect is explored below.

VI. Measurement Results

Two sets of five resonators each were fabricated on Rogers RO4350B™ laminate. This substrate is a glass fiber weave reinforced substrate. The first set has a measured metal thickness of 50.8 μm (0.0020 inch), Fig. 5, and a surface roughness of 3 μm RMS measured by white light interferometry for identically manufactured foil. The top side of the metal foil is assumed smooth. The edge profile angle is 70 degrees. All other dimensions are as specified in section IV and Fig. 3. Fig. 6 shows a measurement of one of the resonators with over 180 000 data points. The measurement is numerically separated into even and odd modes and anisotropic dielectric constants are extracted with the result in Fig. 7. Average dielectric constants for all the measurements are 3.633 ± 0.003 vertical and 3.399 ± 0.009 horizontal with the standard deviation taken across the five sample averages. This standard deviation corresponds to fabrication variation.

The standard deviation was also calculated across the band, which corresponds to variation with frequency due to dispersion plus variation due to random measurement error. Average standard deviation is ± 0.014 vertical and ± 0.025 horizontal. Anisotropy (normalized to the vertical dielectric constant) is 6.4%.

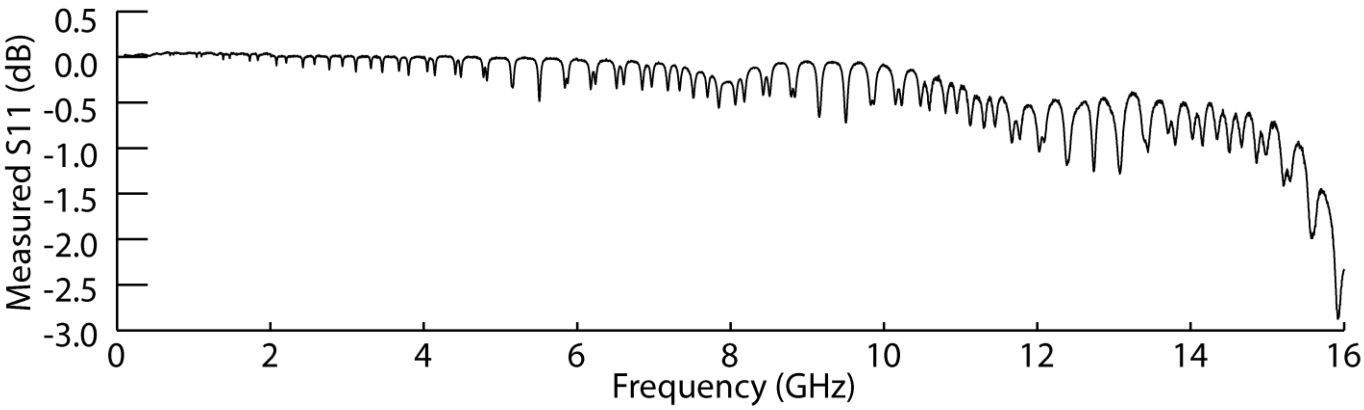

Fig. 6. Measured data for one of the 10 inch resonators on Rogers RO4350B laminate. The full data set is 160 000 data points. This image resolution allows one pixel for every 50 data points. Nearly 100 even and odd mode resonances are present.

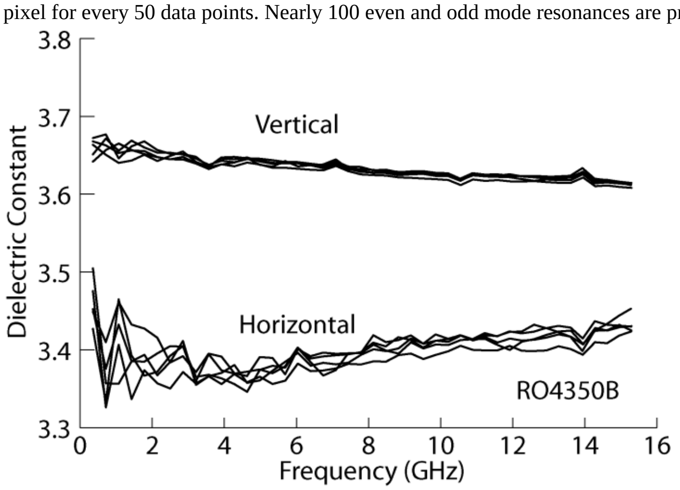

Fig. 7. Extracted anisotropic dielectric constants for Rogers RO4350B laminate show the horizontal dielectric constant lower than the vertical, as expected for a fiber glass weave composite substrate. These results are compensated for the inductive effect of a metal roughness of 3 μm RMS.

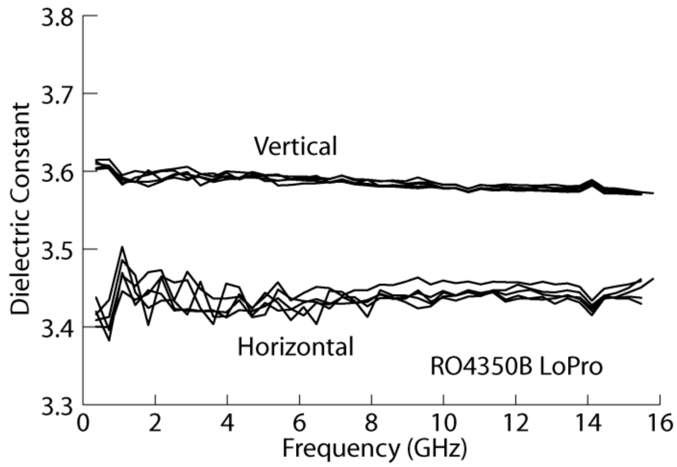

Fig. 8. Extracted anisotropic dielectric constants for a second set of five resonators on Rogers RO4350B laminate using and compensated for a low profile, 0.5 μm RMS roughness foil. A reasonably weighted average of the two dielectric constants (which is used for manufacturing quality control) is identical to a similar average taken from Fig. 7.

The second set of resonators have identical dimensions except that the metal surface roughness is 0.5 μm RMS and the metal thickness is 30.5 μm (0.0012 inch). The edge profile angle is 60 degrees as measured in cross section. Results are shown in Fig. 8. Average dielectric constants for all measurements are 3.586 ± 0.003 vertical and 3.438 ± 0.006 horizontal with the standard deviation indicating fabrication variation. The average standard deviation corresponding to dispersion plus measurement noise is ± 0.015 for both vertical and horizontal. The anisotropy is 4.1%.

Small discontinuities can be seen every 3.5 GHz in some of the data of Fig. 7 and 8. This is due to the 1 inch sectioning strategy described above. One inch is exactly one half wavelength at 3.5 GHz.

Note that a reasonably weighted average of the two dielectric constants is identical for both sets of resonators. This raises the concern that the usual [15] clamped stripline measurement that is used for manufacturing quality control, which assumes isotropy, can be insensitive to manufacturing variability in which one dielectric constant increases while the other simultaneously decreases, as seen in Fig. 7 and 8.

In addition, note that the dispersion (variation with frequency) of the vertical and horizontal dielectric constants are oppositely directed. Thus, a weighted average of the two tends to decrease dispersion. In fact, if the average could be weighted as desired (perhaps by selecting appropriate line dimensions), dispersion could possibly be eliminated. However, the even and odd mode dispersion cannot be the same because their respective vertical and horizontal components must be different.

Since anisotropic variation can affect design success, we suggest that evaluation of anisotropic dielectric constant should be adopted as a standard part of the manufacturing quality control process.

Edge profile angle is by far the most significant error source, but only for the horizontal dielectric constant. For example, for the first set of resonators, the actual edge profile angle is about 70 degrees. If we incorrectly assume it is 90 degrees, we extract a horizontal dielectric constant 0.072 higher. For the second set of resonators, it is 0.065 higher. Vertical dielectric constant is essentially unchanged.

It is inconvenient to include the actual edge profile in EM analysis. Rather, it is often desired to analyze a layout using a 90 degree edge profile. We note that if the horizontal dielectric constant is modified as determined above, then using a square edge profile produces exactly the same resonant frequencies as an EM analysis using the actual edge profile and the actual horizontal dielectric constant. We have seen applied work where a designer adjusts the isotropic dielectric constant to match measured resonant frequencies. This is equivalent to adjusting both the vertical and horizontal dielectric constants to compensate for the actual edge profile angle. This is incorrect as only the horizontal dielectric constant should be adjusted.

For example, the actual edge profile angle for the first set of resonators is 70 degrees and the actual (extracted) horizontal dielectric constant is 3.399. If we instead analyze the resonator with an edge profile angle of 90 degrees and a horizontal dielectric constant of 3.471 (= 3.399 + 0.072), then we see exactly the same resonances. Thus, by adjusting the horizontal dielectric constant, we can compensate for the fact that we are EM analyzing with a 90 degree edge profile angle, rather than the actual 70 degree edge profile angle. A different metal thickness or a different edge profile angle requires a different horizontal dielectric constant adjustment.

For roughness, if we ignore the 3 μm RMS metal roughness for the first set of resonators, then the extracted dielectric constant is 0.03 (horizontal) and 0.10 (vertical) higher. If we incorrectly assume the metal thickness is 0.0010 inch, instead of the actual 0.0020 inch, the vertical dielectric constant is unchanged and horizontal is extracted 0.14 lower. All other error sources are found to have small significance.

The calibrated extraction reported here is based on extreme accuracy EM analysis (i.e., very fine mesh size), and whatever EM analysis error remains is compensated by convergence analysis as described above. If one now wishes to determine the EM analysis error in this, or any other EM analysis, select appropriate dielectric constants and EM analyze the described resonator. Then treat the EM analysis as though it were a measurement of the resonator and extract the dielectric constants to which the calculated resonances correspond. Due to EM analysis error, the extracted dielectric constants will be different from what was originally specified in the EM analysis. This difference indicates the degree of EM analysis error. This is in fact what we did for the “Alt” curves, Fig. 4.

Additionally, one can compensate for EM analysis error if the error corresponds purely to error in shunt per-unit-length capacitance. If the error corresponds to series per unit length inductance (for example, error due to surface roughness), then adjusting dielectric constants is not appropriate. Such an adjustment does indeed yield the correct resonant frequencies; however, the characteristic impedance of the line is now significantly in error.

We measure the horizontal dielectric constant to be lower than the vertical. This is in direct conflict with bulk measurements of glass fiber weave composites where the horizontal dielectric constant is observed to be higher, for example, [16]. Bulk measurements probe the dielectric constant with horizontal electric fields (which are parallel to some of the glass fiber) through the entire thickness of the substrate. Thus, the observed horizontal dielectric constant is an average of the glass and epoxy throughout the entire thickness of the substrate. In contrast, a microstrip coupled line generates horizontal electric field preferentially at the surface of the substrate. Board fabrication generally includes a “butter” layer on the top and bottom, with no glass, just epoxy. Thus, microstrip’s horizontal electric field sees less glass and more epoxy, and thus the horizontal dielectric constant for microstrip is observed to be less than the vertical dielectric constant. In fact, an improved model of such a composite substrate can be formed by explicitly including the butter layer, cladding an anisotropic core.

We also measured an anisotropic substrate that is homogenous on a macroscopic scale; there is no butter layer. RA resonators were fabricated on ceramic loaded (no fiber glass weave), Rogers RO3010™ laminate. Results are in Fig. 9. This is an unshielded resonator; however, we are able to get results up to 10 GHz because the high dielectric constant suppresses radiation. We observe the horizontal dielectric constant to be higher than the vertical, as expected for such substrates. Thus when an inhomogeneous (e.g., glass fiber weave reinforced) substrate is used for microstrip or stripline circuitry, then a microstrip or stripline resonator should be used to measure dielectric constants. Microwave cavity resonator results are appropriate only for homogeneous materials, or for applications that excite horizontal electric field in the entire volume of the substrate, for example, radomes as in [16].

For the purposes of microstrip and stripline excitation, fiberglass weave reduces horizontal dielectric constant. Ceramic with non-spherical grains that preferentially orient horizontally increases horizontal dielectric constant. Rogers 4350B laminate includes both fiber glass weave and ceramic filler. It appears, in this case, that the fiber glass weave dominates. We suggest that a perfectly isotropic dielectric constant can realized by an appropriate mixture of glass fiber weave and ceramic, provided it is consistent with mechanical and thermal constraints.

VII. CONCLUSION

We demonstrate an improved measurement of anisotropic dielectric constants using the shielded microstrip RA resonator. We show that glass reinforced substrate materials have a horizontal (parallel to the substrate surface) dielectric constant that is lower than the vertical dielectric constant, in direct conflict with microwave cavity resonator measurements, and that this conflict is resolved when we realize that the horizontal fields in microstrip are preferentially confined to the substrate surface where there is reduced glass content.

Measurements are extended to 16 GHz and a detailed error analysis indicates error due to metal edge profile angle, metal surface roughness, and metal thickness dominate. These, and other error sources, are characterized and compensated, yielding results with small, quantified error. EM analysis that incorrectly assumes a 90 degree metal edge profile can be precisely compensated by modifying the horizontal dielectric constant (vertical dielectric constant is unchanged). It is pointed out that manufacturing error in anisotropy can remain undetected by quality control measurements that assume

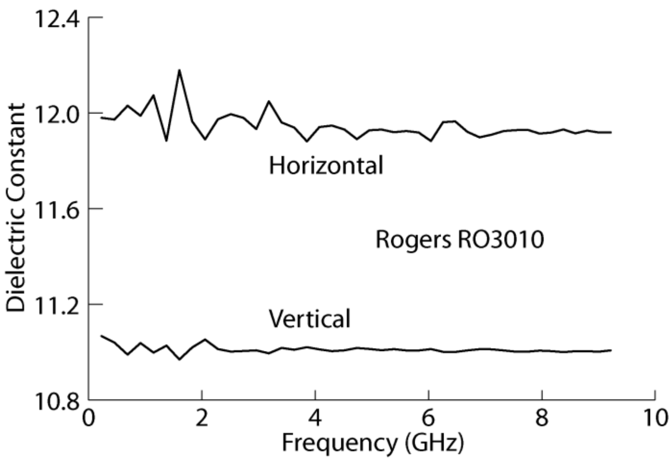

Fig. 9. Anisotropic results measured for Rogers RO3010 laminate. We see the horizontal dielectric constant higher than the vertical as expected from bulk measurements and as expected for a macroscopically homogeneous anisotropic substrate.

isotropy.

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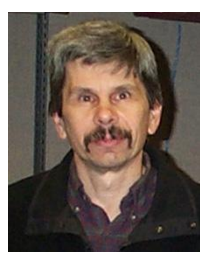
From 1978 to 1986, he was with General Electric, initially with the Valley Forge Space Division, then with the Syracuse Electronics Laboratory. During this time, he developed microwave design and measurement software and designed microwave circuits on alumina and on GaAs. From 1986 to 1988, he was a Visiting Professor with Syracuse University and Cornell University. In 1988, he joined Sonnet Software, Liverpool, NY, full time, a company he had founded in 1983. In 1995, Sonnet Software was listed on the Inc. 500 list of the fastest growing privately held U.S. companies, the first microwave software company ever to be so listed. Today, Sonnet Software is the leading vendor of high accuracy three-dimensional planar high-frequency electromagnetic analysis software.

Dr. Rautio was the recipient of the 2001 IEEE Microwave Theory and Techniques Society (IEEE MTT-S) Microwave Application Award. He was appointed MTT Distinguished Microwave Lecturer for 2005 – 2007 lecturing on the life of James Clerk Maxwell.



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