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A Proposed Uniaxial Anisotropic Dielectric Measurement Technique

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***Abstract*— The popular printed circuit board (PCB) material, FR4 is composed of a glass fiber weave embedded in epoxy. Because the epoxy and the glass fiber have different dielectric constants, the dielectric constant experienced by electric field in the substrate depends on the direction of the electric field. Error in knowledge of this anisotropy causes error in the electromagnetic (EM) analysis of any circuits being designed. An "average" dielectric constant can be used, however the correct average depends on the specific field configuration and thus on the specific circuit layout. As such, both accurate knowledge of dielectric anisotropy and the ability to perform EM analysis including anisotropy is important. This paper proposes a new dual mode resonator for measurement of dielectric anisotropy, specifically uniaxial anisotropy where there is one dielectric constant for electric field perpendicular to the substrate surface, and a second dielectric constant for all electric field tangential to the substrate surface. The technique proposes to compare EM analysis results to measurements to determine the anisotropy. In this paper, we describe and simulate the proposed approach and illustrate evaluation of the expected error.**

***Index Terms*— Anisotropy, dielectric constant, dispersion, electromagnetic analysis, FR4, measurement, method-of-Moments (MoM), printed circuit board (PCB), transmission line, uniaxial.**

I. Introduction

SUBSTRATE materials formed from a composite of materials that have different dielectric constants are potentially anisotropic. Typically, there is one dielectric constant for electric field perpendicular to the substrate and a second dielectric constant for electric field parallel to the substrate. This is known as uniaxial anisotropy. Generally accepted electromagnetic (EM) analysis methodology attempts to measure and/or select some kind of average dielectric constant and use that value in EM analysis as if the substrate were homogeneous (i.e., same dielectric constant for all directions of electric field). Unfortunately, the optimum "average" dielectric constant depends on the relative mix of vertical and horizontal electric field as determined by the specific circuit being analyzed. Thus, an average dielectric constant that works for one circuit might not work for another circuit.

Critical to solving this problem is precise knowledge of the actual anisotropic substrate dielectric constants. This investigation uses stripline, Fig. 1, to evaluate FR-4, a common material for printed circuit boards (PCB). It is formed of a glass weave encapsulated in epoxy. These same concepts also apply to microwave substrates that involve a glass fiber/Teflon composite, even if the glass fiber is not in the form of a woven cloth.

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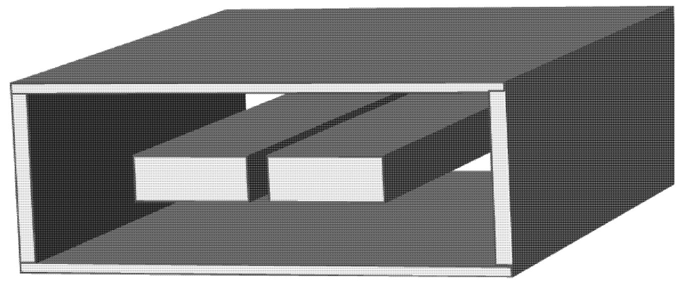

Fig. 1. Coupled stripline has ground above and below. Vertical sidewalls are critically important to make sure the two grounds are at the same potential and thus share equal amounts of ground return current. The lines are uniformly surrounded in uniaxial anisotropic dielectric. The object is to measure the anisotropy based on the different field configurations of even and odd modes.

We have found that discussions on this topic are sometimes frustrated by lack of common coordinate systems. Those working primarily with transmission lines place the *z*-axis in the direction of propagation, the *x*-axis tangential to the substrate surface and the *y*-axis vertical in a right-handed fashion. Those who work with circuits place the z-axis vertical with *x*- and *y*-axes tangential to the substrate surface.

For this work, rather than explicitly referring to *x*-, *y*-, and *z*-axes, we refer to horizontal (tangential to the substrate surface) and vertical (perpendicular to the substrate surface) directions. We also refer to transverse (perpendicular to the direction of propagation) and longitudinal (in the direction of propagation) directions. We hope this terminology is clear to workers from either field.

II. The Single Mode Stripline Resonator

The proposed technique is based on a dual mode stripline resonator. Typically, stripline resonator techniques lightly couple to a resonator. Combined with knowledge of the length of the resonator, the resonant frequency determines the dielectric constant of the substrate. Error sources include fabrication tolerances, measurement error, and open end fringing capacitance. All three sources can be quantitatively bounded, an effort required for a useful measurement.

The open end fringing capacitance is particularly important. Fringing capacitance off the open end of a half wavelength long resonator lowers the resonant frequency. This in turn, if uncorrected, makes the resulting measurement of dielectric constant high. Fortunately, the open end capacitance is easily evaluated by numerical EM analysis, allowing its effect to be removed to within the accuracy it has been calculated.

An additional source of error is the air gap between the two substrates that are sandwiched together to form the stripline. The gap is caused by the thickness of the resonator metal. Typically, the two substrates are compressed tightly together in an attempt to eliminate at least a portion of the air gap.

We note that while the precise location of the sidewalls for stripline, Fig. 1, are not critical, they are absolutely required (perhaps formed from vias) for successful operation. Stripline assumes equal ground return current on both ground planes. If the two ground planes are not in solid electrical contact, the ground planes can float to different potentials and carry different portions of the ground return current. Spurious operation is then seen. In particular, if there is any stripline circuitry, say a via from other circuitry below penetrating one ground plane and contacting a stripline conductor, that causes an imbalance in the ground return current, the ground planes must be shorted together (with vias) in the immediate area in order to assure equal current in each ground plane. In the extreme situation, if one ground plane carries all of the ground return current, a mode similar to microstrip results, with a completely different characteristic impedance.

III. THE DUAL MODE STRIPLINE RESONATOR

The proposed dual mode resonator is composed of a coupled stripline. A cross-section is shown in Fig. 1. The two modes consist of the even mode, where current flows in the same direction on each conductor, and the odd mode, where current flows in opposite directions on each conductor. The electric fields for these modes is shown in Fig. 2 (even mode) and Fig. 3 (odd mode). The fields are plotted over the transverse cross-section of a coupled stripline at the open end of a short length of line. The cross-sectional fields are nearly identical in form along the entire length of a resonator. For the even mode there is 1 Volt excitation between both lines and ground. For the odd mode, there is 1 Volt impressed between the two lines. The fields for the odd mode are stronger because the odd mode has a lower characteristic impedance and thus higher current.

These are the actual, numerically evaluated fields, not artistic impressions. The lines are each 60 mils (0.060 inch) wide and 10 mils thick. The excessive thickness allows easy visualization of the fields involved with metal thickness. There is a 40 mil gap between the lines and 120 mils ground plane to ground plane and 400 mils side to side. There are conducting sidewalls along the entire perimeter. The dielectric constant everywhere is 4.2. The entire structure is lossless. All numerical EM analysis in this paper uses Sonnet [1].

The top image in each figure shows the magnitude of the total electric field. The magnetic field lines (often artistically and creatively drawn for this type of line) correspond to constant color contours. The electric field lines are everywhere

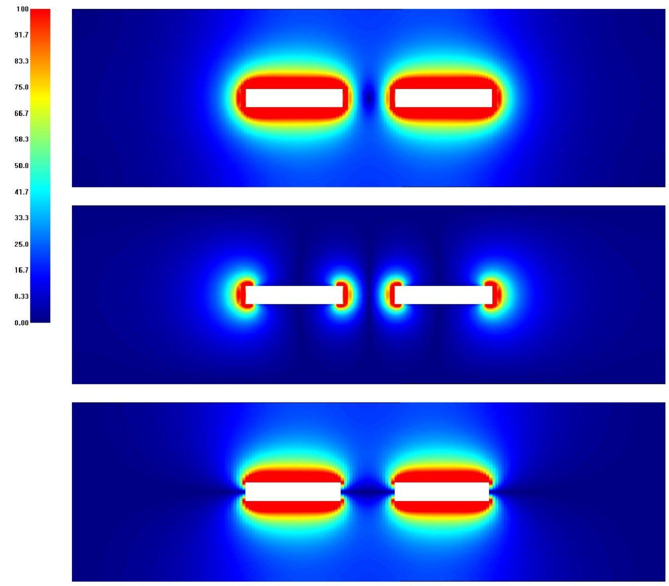

Fig. 2. Even mode electric field of coupled stripline. Fields are taken in the transverse plane at an open end with 1 Volt applied between both lines and ground. The scale on the left is in Volts per meter. The top image is the total electric field, the middle image is the magnitude of the horizontal component. The bottom image is the magnitude of the vertical component.

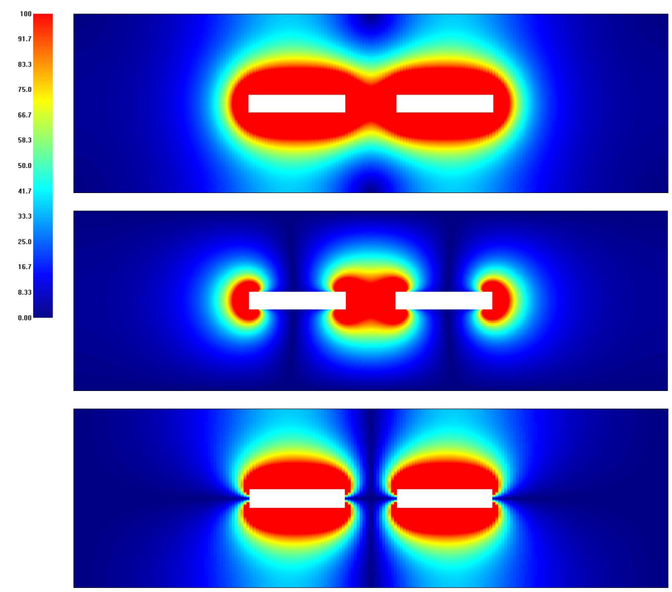

Fig. 3. Odd mode electric field of coupled stripline. One Volt is applied between the two lines. All other information is the same as Fig. 2. Fields are stronger for the odd mode because the odd mode impedance is lower, resulting in higher current.

perpendicular to the magnetic field lines. The important qualitative result to see in viewing these figures is the ratio of transverse horizontal electric field (middle image in each figure) to the transverse vertical electric field (bottom image) averaged over the entire cross-section. Compensating for the fact that the odd mode fields are stronger, we see that the total ratio of vertical to horizontal is almost the same for each mode. The proposed technique relies on the ratio being different for each mode. We are now left with the question of whether the difference will be large enough to allow us to tease out the value of the different dielectric constants. This question must be answered quantitatively.

IV. Anisotropic Dielectric Constant Evaluation

The proposed dual mode resonator, Fig. 4 (top), is excited by a port on both sides of a high voltage open end. For this work we anticipate using 60 mil wide lines with various separations. The substrate thickness is also 60 mils. The gap for Fig. 4 is 60 mils. The resonator length is 10 inches. This fits conveniently on a 12 inch board and should allow investigation of over half a dozen resonances within the expected several GHz measurement bandwidth. Note that the resonator is perfectly symmetric about the center line of the gap between the coupled lines. This is critical.

Fig. 5 shows the EM analysis of the first resonance of the 2-port resonator. We include a 0.7 mil gap between the two substrates to model the air gap that is required by the metal thickness. Metal and dielectric losses are included. Measured data is expected to be similar, but with measurement noise added. While interesting, the raw 2-port measurement does not reveal the resonances that correspond to the even and odd modes separately. This is because the 2-port excitation results in a weighted superposition of both modes. To find resonances for just one mode, we must modify the 2-port data.

Specifically, we must connect the 2-port resonator data into a circuit that excites exclusively either the even or the odd mode. This is accomplished with the schematics of Fig. 4 (from AWR Microwave Office). For the even mode, Fig. 4 (middle) we connect both ports together. For the odd mode, Fig. 4 (bottom) we connect port 2 to ground and leave the 2-port's own ground terminal connected to a floating ground (terminal 3 on each 2-port). In anticipation of comparing directly to measurements, we include a connector model for each of the two physical ports. The details of the connector model will be determined by measurements of the connector itself. For a perfectly symmetric 2-port, these schematics mathematically place a perfect magnetic conducting wall down the center of the gap in the first schematic and a perfectly conducting electric wall in the second schematic. This is exactly what we need for even and odd mode excitations.

Fig. 6 shows the first (lowest frequency) even and odd mode resonances with isotropic dielectric (dielectric constant 4.2) everywhere. Note that the even mode has a lower resonant frequency. This is because the even mode open end fringing capacitance is higher. The resonant frequencies are 287.30 and 287.85 MHz respectively to the nearest 50 kHz. The even mode is 0.55 MHz lower than the odd mode.

Fig. 7 shows the same even and odd mode resonances for a horizontal dielectric constant of 4.3 and a vertical dielectric constant of 4.1. The resonant frequencies are now 289.60 (even) and 289.20 MHz (odd). The even mode is now 0.40 MHz higher than the odd mode. This means that if we can discern a difference of about 1 MHz (less than 0.5%) in the even and odd mode resonances, then we can discern a 0.2 difference between horizontal and vertical dielectric constants.

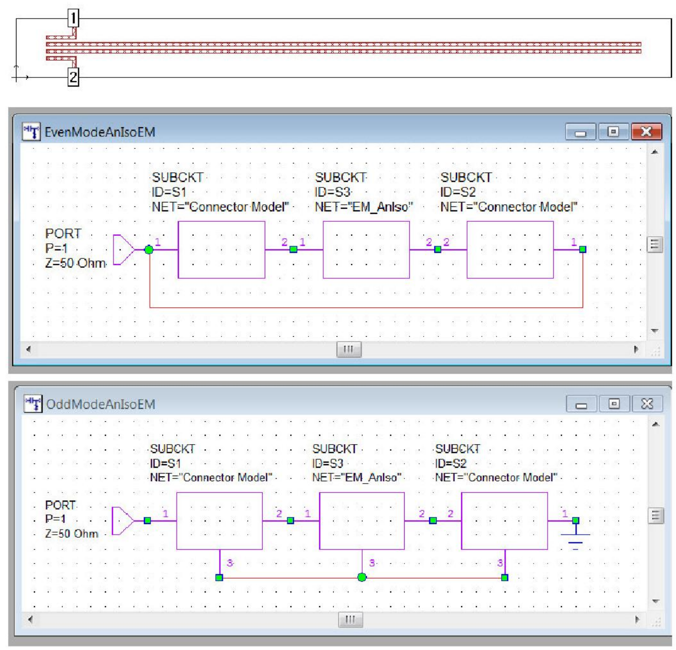

Fig. 4. The symmetric dual mode resonator layout viewed from above (top) and schematics for connecting the 2-port resonator so that only the even mode (middle) or odd mode (bottom) are excited.

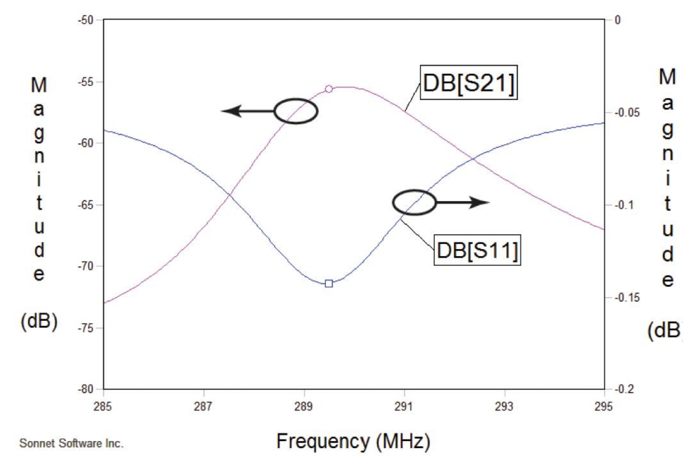

Fig. 5. The 2-port EM calculated S-parameters of the first resonant frequency of the dual mode resonator of Fig. 4 (top). Both even and odd modes are excited.

Normally such a small difference between two separate measurements would be overwhelmed by manufacturing tolerances. However, this is not the case here as we only have the one measurement from which both resonances are mathematically extracted. The fabrication error is exactly the same for both resonances and does not compromise the evaluation of the degree of anisotropy, which is based on the difference between the resonant frequencies.

V. EM Analysis Error Impact

A full analysis of the various error sources is too extensive to report here. Instead, we illustrate the process of evaluating EM analysis error and its impact with several examples. First, the accurate evaluation of the degree of anisotropy (i.e., the difference between horizontal and vertical dielectric constants) is dependent on accurate EM evaluation of the isotropic even and odd mode resonances.

First, we perform an EM analysis on a similar dual mode half wavelength resonator where the ends of the resonator are terminated in the perfect short circuit formed by the conducting walls at the edge of the substrate, which are an integral part of this EM analysis. Thus, the short circuit inductance on the end of each resonator is exactly zero for both even and odd mode resonances. In this case, we would expect to see even and odd mode resonances to be exactly the same for homogeneous (i.e., no air gap) lossless isotropic dielectric, and indeed they are.

The EM analysis that we use typically converges asymptotically [2] to the exact answer as cell (mesh) size is decreased. So, for the actual resonator, we evaluate the open end even and odd mode capacitances, 0.1269 and 0.03029 pF respectively. Then we cut the cell size in half. The total EM analysis error should decrease by about half. The new results are 0.1273 and 0.03039 pF. The differences are about 0.5% (even) and 0.4% (odd), on the order of the differences we see in resonant frequencies. However, note that both capacitances increased by about the same percentage. Their differences (which impact, to some degree, the evaluation of the degree of anisotropy) change by about 0.1%.

We can actually go further than simply quantifying the error. The error, in this case, is well behaved [2]. So once we have a good estimate of how much the error is, we simply subtract the error from the answer. In this case, the next step is to determine how much cell (mesh) size error affects the evaluation of the dielectric constants. Once this affect is estimated, it is simply subtracted from the result.

VI. Conclusion

We have proposed a new technique for precise measurement the dielectric constant of uniaxial anisotropy, where there is one dielectric constant for horizontal electric field and another for vertical. The technique is especially precise for determining the degree of anisotropy (i.e., the difference between horizontal and vertical dielectric constants). We have also provided illustrations of error evaluation, critical to a useful measurement. Actual measurements are expected to be presented at the conference.

Acknowledgements

We acknowledge discussions with Chad Morgan of Tyco Electronics on FR4 anisotropy with respect to high speed digital differential pair transmission lines for inspiring this measurement approach.

References

[1] http://www.sonnetsoftware.com.

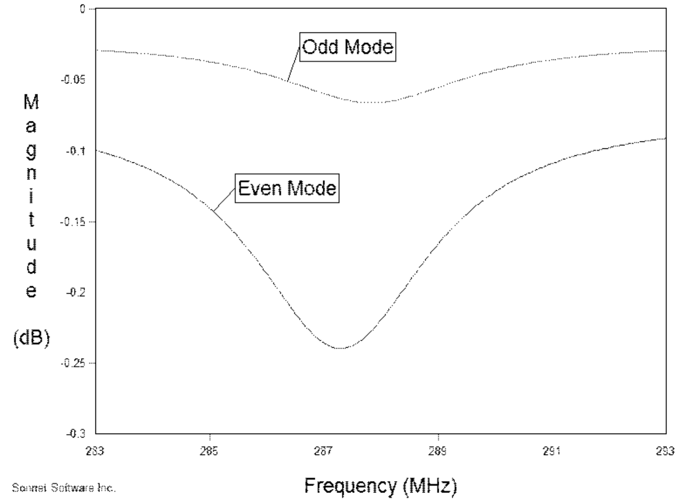

Fig. 6. When isotropic dielectric is used in the EM analysis, the odd mode resonance is slightly higher in frequency than the even mode because the odd mode open end fringing capacitance is smaller than that of the even mode.

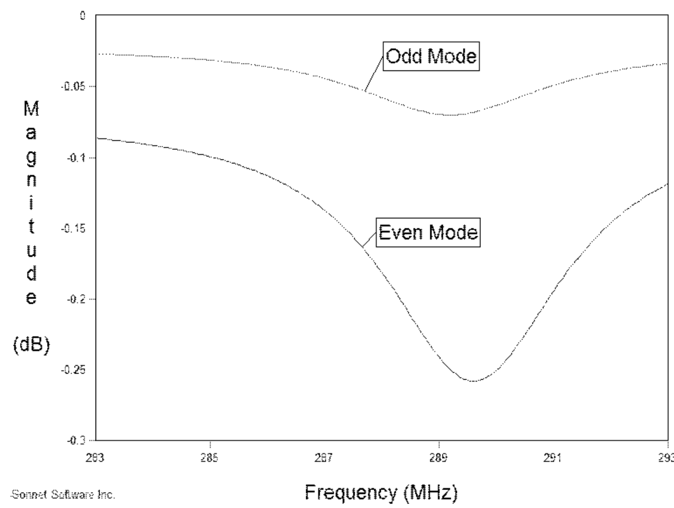

Fig. 7. When anisotropy is introduced in the dielectric, the odd mode resonance is now lower in frequency. The change in the relationship between the even and odd mode resonant frequencies is due to anisotropy.

[2] J. C. Rautio, "An Ultra-High Precision Benchmark For Validation Of Planar Electromagnetic Analyses," *IEEE Tran. Microwave Theory Tech.*, Vol. 42, No. 11, pp. 2046–2050, Nov. 1994..