Frequency Domain Analysis and Electrical Properties Test Method for PCB Dielectric Core Materials

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Author(s) Biography

Nicholas Biunno, Sanmina-SCI. He received a Ph.D. in Materials Science and Engineering from North Carolina State University in 1989. He has worked at ALCOA Electronic Packaging Corporation in new product development (flip chip assemble and failure analysis) prior to joining Zycon Corporation. He has been with Zycon, now Sanmina Corporation, for more then 8 years. In that time he has work on various projects including integrative passives product development and failure analysis of solder joint surface finishes. Nicholas has authored 27 publications and 2 US patents in electronic materials processing and characterization.

Istvan Novak is signal-integrity senior staff engineer at SUN Microsystems, Inc. Besides of signal-integrity design of high-speed serial and parallel buses, he is engaged in the design and characterization of power-distribution networks and packages for workgroup servers. He creates simulation models, and develops measurement techniques for power distribution. Istvan has twenty plus years of experience with high-speed digital, RF, and analog circuit and system design. He is Fellow of IEEE for his contributions to the signal-integrity and RF measurement and simulation methodologies.

Abstract

Self impedance of dielectric core material are being investigated in the frequency range of 100 MHz to 2 GHz. The full-sheet resonance (FSR) method of measuring dielectric constant and loss tangent has been modified to perform non-destructive test of fully fabricated printed circuit board core laminate and prepreg materials. This modified FSR test method employs VNA frequency domain analysis to extract dielectric constants and loss tangents for PCB material constructions. The FSR method as applied here also shows its usefulness as a quality control tool.

Full Sheet Resonance Theory and Test Method

The full-sheet resonance (FSR) technique may be used to determine the permittivity and also the dissipation factor of PWB materials in laminated and fabricated circuit boards [1], [2]. The test method is nondestructive and is used to measure bulk electrical properties of substrate materials. The frequency at which the measurement is made is limited by the plane dimensions (**a**, **b**) of the full sheet. The FSR method uses one-half wavelength resonance. Propagation of the resonance plane wave through the sheet is only dependent on the dimensions of the test plane and the dielectric constant of the material under test. Since the plane dimension and the resonance peak frequency (f_{mn}) can be measured with high precision, the dielectric constant can be determined with high accuracy by equation 1. Where c is the speed of light, f is the mode peak frequency, M and N are integers, a and b are the dimensions of the FSR plane. Obtaining *Er* for higher order modes (higher frequencies) are possible for the same board if the ratio of a to b is greater than two. The useful frequency range, in TEM_{10} mode, of the FSR method is about 100 MHz to 2 GHz. The limit to the test frequency band is determined by the dimensions of the FSR test structure.

$$\varepsilon_r' = \left(\frac{c}{2 f_{mn}}\right)^2 \left[\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2\right] \quad (1)$$

While other methods for obtaining Dk and Df are available, the main advantages for using a modified FSR method in PCB products are:

1. Low setup and test cost as compared to other methods to extract properties information. The test device consist of a 4 layer fabricated test board (see figure 4).
2. The modified FSR test method measures material properties in a fabricated product, similar to product shipped to the customer.
3. The test method does not require a knowledge of the thickness of the material under test. This eliminates the uncertainty of making thin film thickness measurements.
4. The source stimulus is by direct injection vs. radiative couple for the standard FSR test method. The effects of direct stimulus injections can then be de-embedded from the DUT during calibration.
5. A simple calculation is used to extract bulk D_k values. For the TEM_{10} resonant mode equation 1 reduces to;

$$\varepsilon_r' = \left(\frac{c}{2a\, f_{10}}\right)^2 \quad (1a)$$

Figure 1 shows a typical FSR self-impedance profile for a 0.001" thick dielectric ZBC1000™ power distributive core laminate. The test core sheet dimensions (a,b) are 9.990" by 4.990". The TEM_{10} resonance mode at 291 MHz is identified as shown in the figure. The S21 data extract method shows high sheet distributive Buried Capacitiance™ and lowest commercially available spreading inductance is also shown for reference.

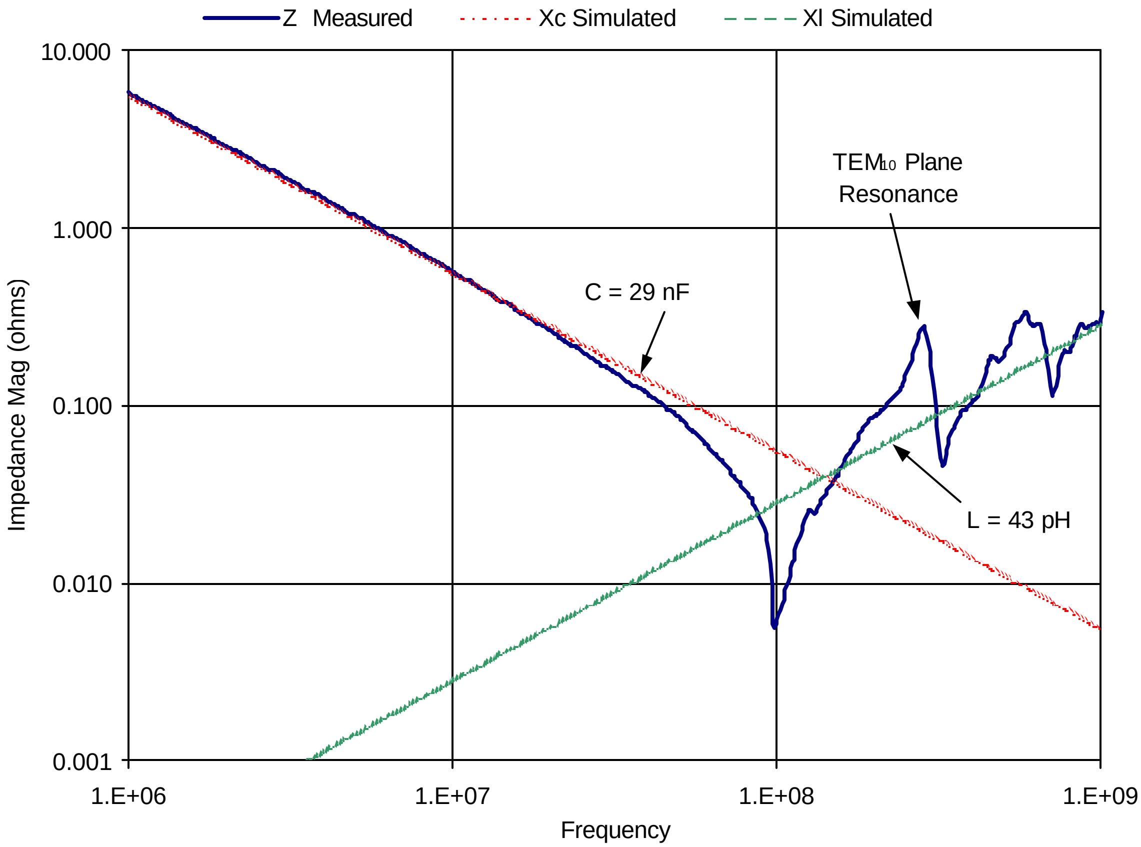

Figure 1 Typical self-impedance profile for a 0.001" thick dielectric core.

To measure electrical characteristics over a wider band of frequencies FSR test boards are fabricated with different dimensions for the FSR plane. Figure 2 shows self-impedance profiles for 8 different board sizes. The core under test was 1 oz. RTF foil with a 0.004" FR406 dielectric. The test boards all have the same 2 : 1 ratio for the dimensions of the sides. All test boards measure in this figure where fabricated on the same panel. The TEM_{10} resonance modes are clearly identified and in the range of 200 MHz for the 12.5" by 6.25" board up to 1.5 GHz for the 2" by 1" board. Table 1 shows a second generation FSR test board series currently being fabricated. The set of 9 test boards are to be all fabricated on the same panel. Thereby allowing the core laminate sheet to be characterized over an extended frequency band. Table 1 also lists the TEM_{10} frequencies (range of measurement) for D_k values of 2 and 5.

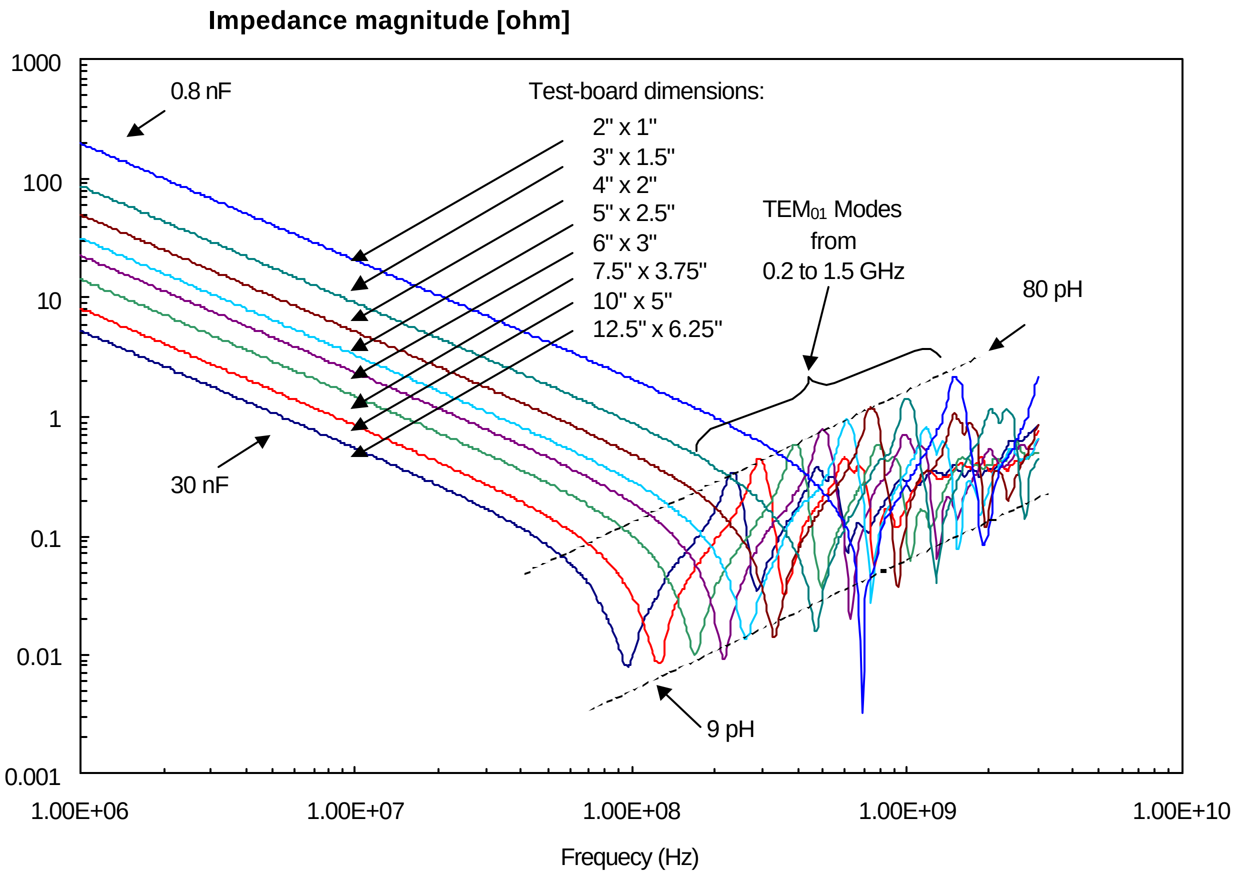

Figure 2. Self-impedance profiles for 1 oz. RTF foil FR406 0.004” FSR test boards

Test Board Size
Test Panel Ratio
2.75 : 1

	Copper Plane Dimensions			**Test Point Coordinate**		**Dk Range**	
						2.00	5.00
	A (in)		**B (in)**	**A" (in)**	**B" (in)**	**TEM (01) Peak Freq MHz**	
1	10.000	x	3.636	2.180	0.793	417	264
2	8.000	x	2.909	1.744	0.634	522	330
3	7.000	x	2.545	1.526	0.555	596	377
4	6.000	x	2.182	1.308	0.476	695	440
5	5.000	x	1.818	1.090	0.396	835	528
6	4.000	x	1.455	0.872	0.317	1043	660
7	3.000	x	1.091	0.654	0.238	1391	880
8	2.000	x	0.727	0.436	0.159	2086	1320
9	1.000	x	0.364	0.218	0.079	4173	2639

Table 1 FSR test board dimensions and predicted TEM_{10} peak frequencies

The modified FSR test vehicle is a four layer board with a single pair of via’s connected to the copper planes of the core under test.

The stack-up construction is shown in figure 3 with the 2 port VNA connections. The via pairs for each board are located at 1/6 of a diagonal from a corner. This gives a fixed test point relationship independent of the size of the board as shown in figure 4. The position of the via pair was chosen to obtain a maximum signal return of the plane resonance for the test structure. The selection of filler prepreg in the test board construction is balanced either side of the test core to maintain a fixed via height for both test ports. The via height from the surface pads to the copper planes of the test core is 0.022”. This via height remains fixed regardless of the thickness of the dielectric layer under test (DLUT). The four layer test board is fabricated using standard manufacturing methods for a foil construction multi-layer printed circuit board. The multi-layer test boards thereby simulate any changes in electric properties that may occur to the DLUT through the fabrication process.

FSR test boards are currently being fabricated with core DLUT thickness ranging from 0.001” to 0.015”. The corresponding percent resin content is in the approximate range of 35% to 70%. It should be noted that the test board construction can be changed from foil construction to core construction without changing any dimensions. Using a core construction FSR test board will allow B-stage prepreg materials to be electrically characterized under fully fabricated conditions. Full electrical characterizations matrixes are being considered for both core and prepreg DLUT with respect to foil types, resin types, percent resin content, glass types and dielectric thickness.

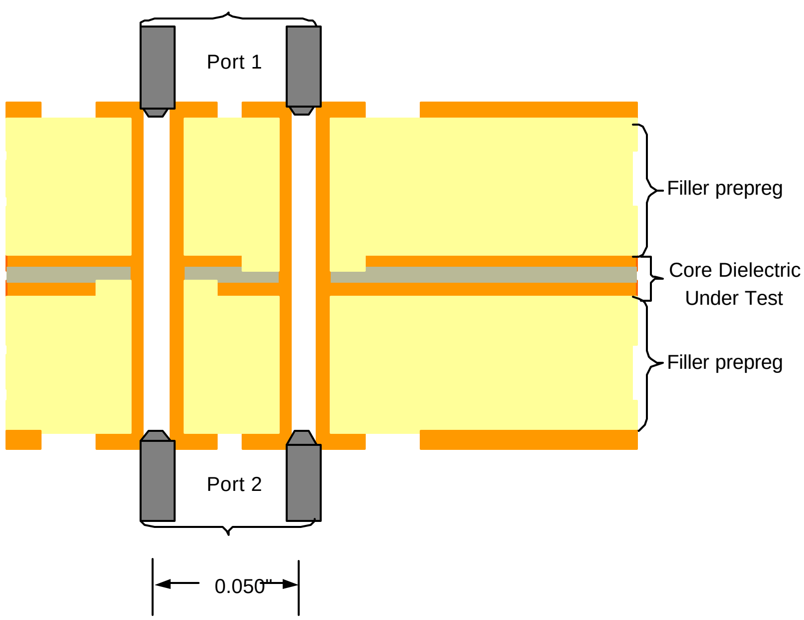

Figure 3 Cross-section view of the modified FSR test board.

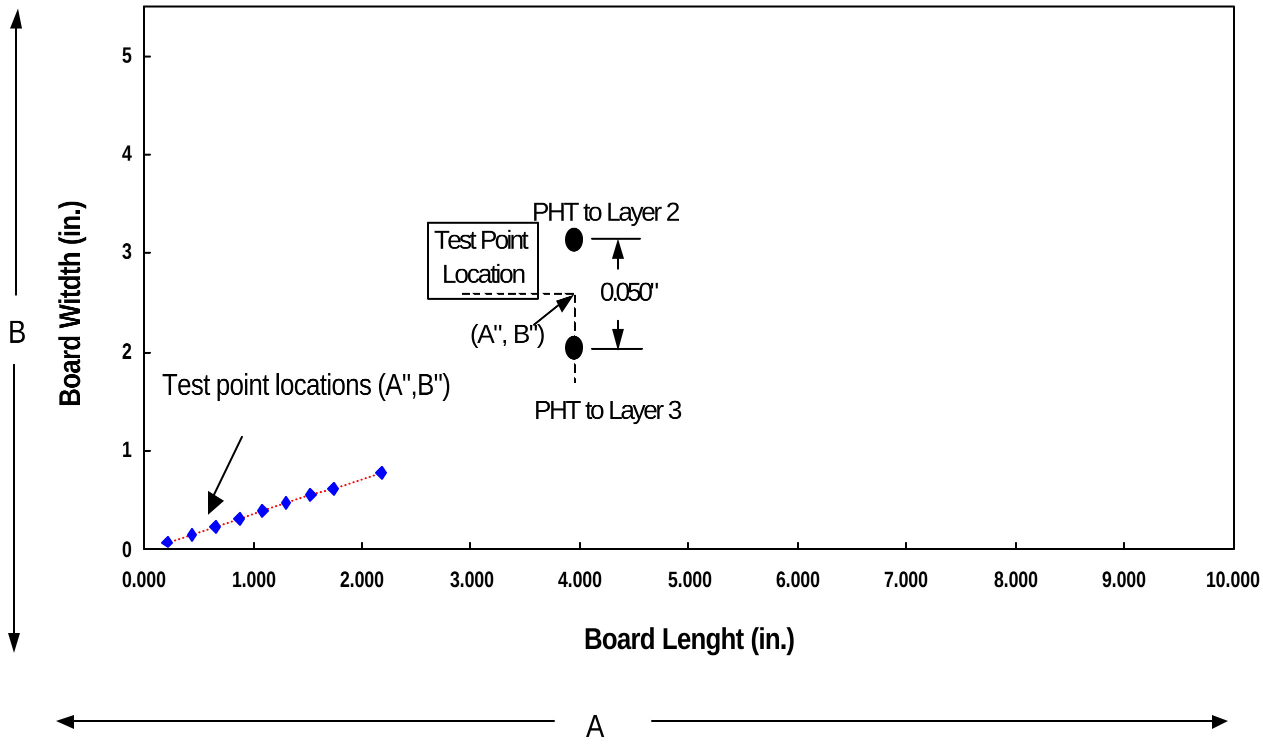

Figure 4 Plan-view of the modified FSR test board.

An Agilent model 8753ES vector network analyzer is being used to collect S-parameter data. The 2-port method developed here is a modification of the S21 test method developed by Novak [3] to measure self and transfer impedance of multi-layer print circuit board power distribution plane pairs. A full 2-port calibration method is used to obtain error correction parameters. The calibration method developed allows the test fixture to be de-embedded right to the DLUT plane.

Test probes are fabricated from semi-rigid 50 ohm coax with SMA male connectors. The probe tips are shaped to a point as shown in figures 3 and 5. The diameter of the vias are chosen such that the probe tips just enter the via holes without the probe wires going all the way into the via. The probe tips are held in place against the via pads with a light contact pressure. This contact arrangement for the probe tips insures repeatable measures for multiple contacts to the via pads.

For the full 2-port method, short-open-load calibration is done to the ends of the test cables. Isolation calibration is omitted due to the large dynamic range of the signal at the resonant frequency. Thru calibration is done with the test probes connected to the cables. The test probes make thru connection using the arrangement show in Figure 5. This thru test fixtures is fabricated in a coupon on the panel along with the FSR test boards. The onboard thru test fixture allows the vias to be de-embedded from the DLUT.

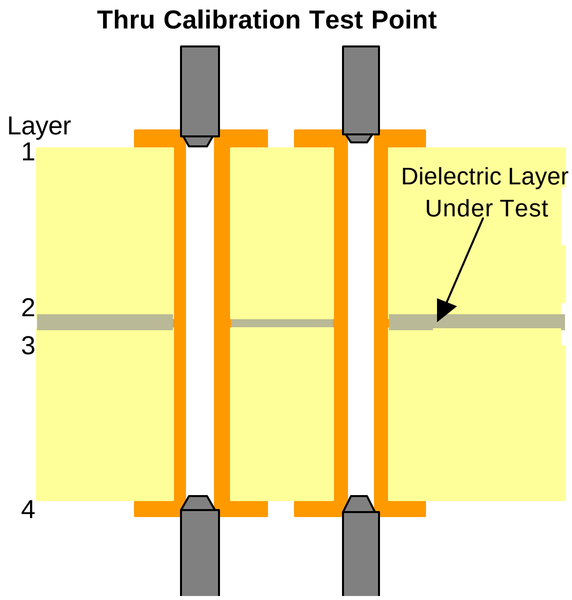

Figure 5. Cross-section view of modified FSR test board thru calibration test fixtures.

Dielectric Constants Measurements

Wide band (from 1MHz to 3 GHz) S21 data is first collected for a given DLUT for each test board on a fabricated panel. Up to 8 panels may be fabricated per DLUT being tested giving 8 data points for each of the 9 test board dimension given in table 1. The TEM modes and coarse peak resonant frequencies are then identified as shown in figure one.

After the TEM modes have been identified narrow band-width scans (from 50 to 150 MHz) are then performed centered on the resonance frequency. Figure 6 shows the impedance magnitude and phase for a narrow band scan of a 0.001" thick (9.990" x 4.990") DLUT. The next step is to determine the exact peak frequency for the resonance mode.

The peak frequency may be determined from obtaining the maximum value of the magnitude curve or the zero crossing of the phase curve. But there are several potential problems in using this method. Novak in [4] has shown that; (a) the first resonance peak may be suppressed by other modes and (b) the frequency of the first resonance peak on a lossy board depends on the definition of peak.

The issue of mode suppression by interference with other modes can be minimized by choosing a rectangular test plan with ratio's of sides **a** and **b** that are not whole numbers. Also, mode suppression is minimized by locating the test points near an edge away from the center lines of the test board.

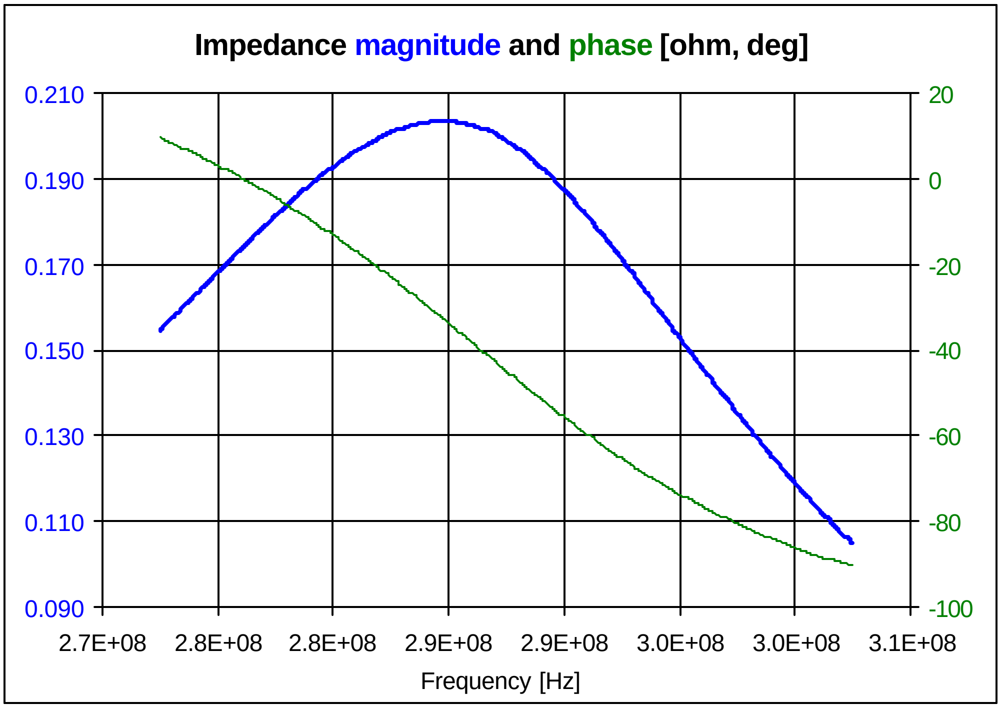

Figure 6. Impedance magnitude and phase for a narrow band-width scan about the TEM_{10} full-sheet resonance of a 1 mil dielectric core.

The second issue is more fundamental. In lossy FSR plane structures, impedance maxima and minima interact creating an overall impedance profile across the plane where the frequency of the first mode peak depends on how the peak is define. Simulations of lossy FSR structures have shown that defining the peak where the impedance magnitude has its maximum value will result in a negative error in the frequency estimate. Similarly, if the first frequency peak is defined were the phase angle is zero will result in a positive error in the frequency estimate. In both cases the error or the measured peak frequency depends on the location on the plane, therefore using these methods is not acceptable for determination of dielectric constants.

The method used here to determine dielectric constant is to define the modal peak frequency as the point were the second derivative of the phase crosses zero. Extracted simulations have shown that if the first modal peak is define at the second derivative zero crossing that the error in measuring the peak frequency is basically zero regardless of the location on the FSR plane.

Figure 7 shows the uncorrected dielectric constant measurements for 3 different FR406 DLUT's using the method described above. Each data point represents the average of 8 FSR test boards fabricated from the same production lot. The best and worst peak frequency measurement standard deviations were 0.3% and 1.9%. The D_k values are plotted against FSR test board length or ½ wavelength. The frequency range from longest to shortest board length is 289 to 1011 MHz. The measurements are uncorrected in the sense that the dielectric constants were determined using equation 1a. It is worth noting that values of dielectric constants in figure 7 are within 5% of reported values for these materials.

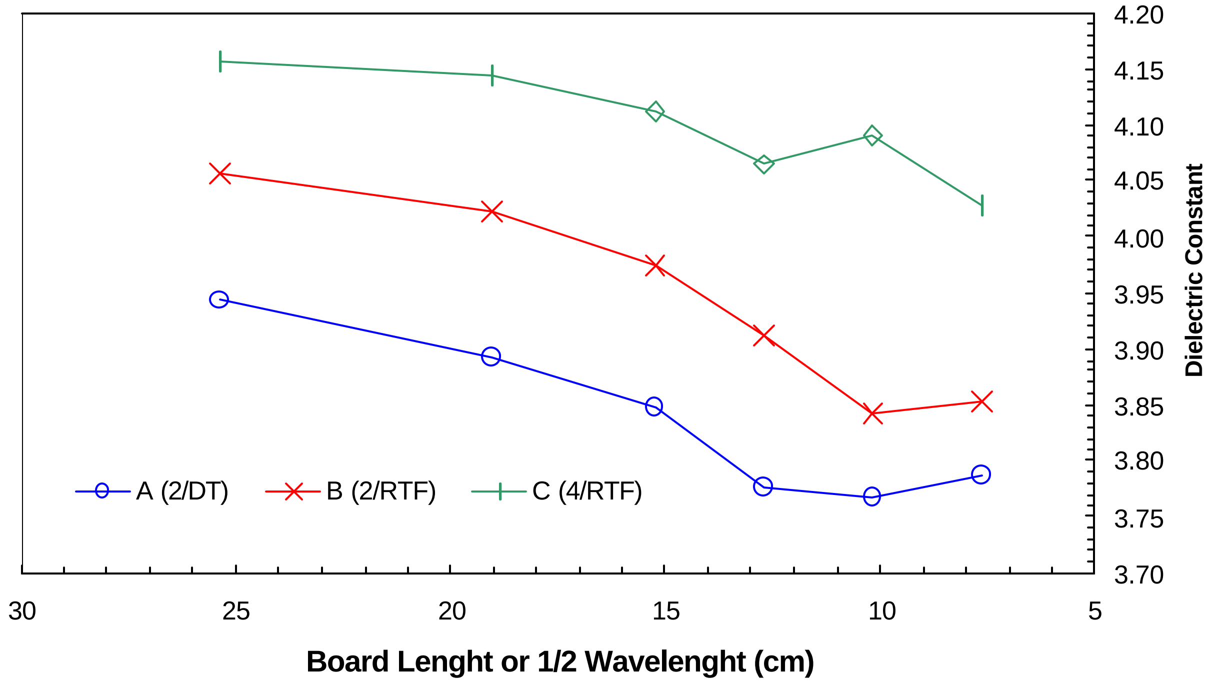

Figure 7 Un-corrected dielectric constants vs. board length for three different DLUT's. DLUT A is 0.002" with double treat foil, B is 0.002" with reverse treat foil and C is 0.004" with reverse treat foil.

Two fundamental issue become apparent at close examination of the data in figure 7. First is that the data shows the method to be sensitive to a change in resin content when comparing the same resin system (FR406) and foil types to two different thickness, 0.002" and 0.004" dielectrics. If we take the average of the A and B curves, for 0.002" thick dielectrics and compare it to the C curve for 0.004" the difference in dielectric constant is about 6%. This is comparable to the reported dielectric constants for the difference in the resin content of 58% for the 0.002" DLUT and 45% for the 0.004" DLUT.

The second issue is the difference in the A and B curves for the same resin system (FR406) and the same nominal thickness (0.002") with different foil types. The measured variation in DLUT thickness, by cross-section method for the A and B test boards is about 0.0002". The thickness variation alone can not account for uniform variation in D_k for the A and B curves. Using a larger matrix of DLUT's including different foil types this phenomenon shall be explored in greater detail.

While the uncorrected data given here shows a reasonable good agreement with D_k values determine by other methods several correction factors are being evaluated to reduce derived D_k value error and uncertainty. Equation 2 shows one such systematic error correction term that takes into account electric field fringing beyond the DLUT for an open wall resonator design [2].

$$e_r' = \frac{C + C_f}{C + \frac{C_f}{e_r'}} \left(\frac{c}{2 f_{mn}} \right)^2 \left[\left(\frac{m}{a} \right)^2 + \left(\frac{n}{b} \right)^2 \right] \qquad (2)$$

Loss Tangent Measurements

The measurement of loss tangent of PCB laminate materials is not as straightforward as dielectric constant extraction. To obtain useful information of dielectric loss tangent requires knowledge of the parameters affecting the quality factors for an FRS test structure. The unloaded quality factor Q_o of a FSR resonant cavity can be obtained [2] by combining the cavity's conductivity Q_C, radiation Q_R and dielectric loss Q_D

$$\frac{1}{Q_o} = \frac{1}{Q_C} + \frac{1}{Q_R} + \frac{1}{Q_D}, \tag{3}$$

were Q_D is related to the dielectric losses by

$$\frac{1}{Q_D} = \tan \delta_D = \frac{1}{Q_o} - \left(\frac{1}{Q_C} + \frac{1}{Q_R} \right). \tag{4}$$

The measured or loaded quality factor Q_l combines the cavity's internal quality factor Q_o with an external quality factor Q_e that represents external losses including port coupling. The loaded quality factor is given [5] by

$$\frac{1}{Q_l} = \frac{1}{Q_o} + \frac{1}{Q_e} = \frac{1+\kappa}{Q_o}, \tag{5}$$

were K is the cavity coupling coefficient.

A derived formulation for the conductivity quality factor for a FSR test structure is given by Taber [6], who obtained,

$$Q_C = \frac{\pi \mu_o f_{mn}\, t}{R_S} \tag{6}$$

where μ_o is free space permeability, t the thickness of the dielectric and R_s is the surface resistance including roughness of the copper planes. The radiative quality factor may be determined theoretically for the FSR test structure as in the case of [7] for a circular disk. Once Q_C and Q_R are determined the loss tangent for the dielectric can obtain from equation 4.

It should be noted that Q_C is directly proportional to dielectric thickness and inversely proportional to surface resistance R_S. Both dielectric thickness and surface resistance contributions to the FSR quality factor can be determined experimentally to a high precisions using the S21 parameter extraction method described above. Figure 8 shows the loaded quality factor for a 0.001" and 0.002" DLUT cores at f_{10} determined from the relationship

$$Q_l = \frac{d\theta}{df} \tag{7}$$

where *è* is the measured phase angle and df is the frequency interval for the narrow band frequency scan around f_{10}. Both resin (FR406) and foil type (double treat copper) were the same and only the thickness of the dielectric was changes for the two DLUT's. The increase in the measured quality factor for the

0.002” core is predominately due to the different in the dielectric thickness. In power distribution applications a reduction in the quality factor is desirable as shown here for ZBC-2000® and ZBC1000™ laminate cores.

Therefore, by careful measurement of the S21 parameter with respect to resin type, glass type, foil type (including roughness) and dielectric thickness for the FSR test vehicle describe herein certain electrical parameter important to high speed PCB design can be derived in the frequency range form 100 MHz to 2 GHz. Among the parameters to be determined are loss tangents due to dielectric materials and copper foils.

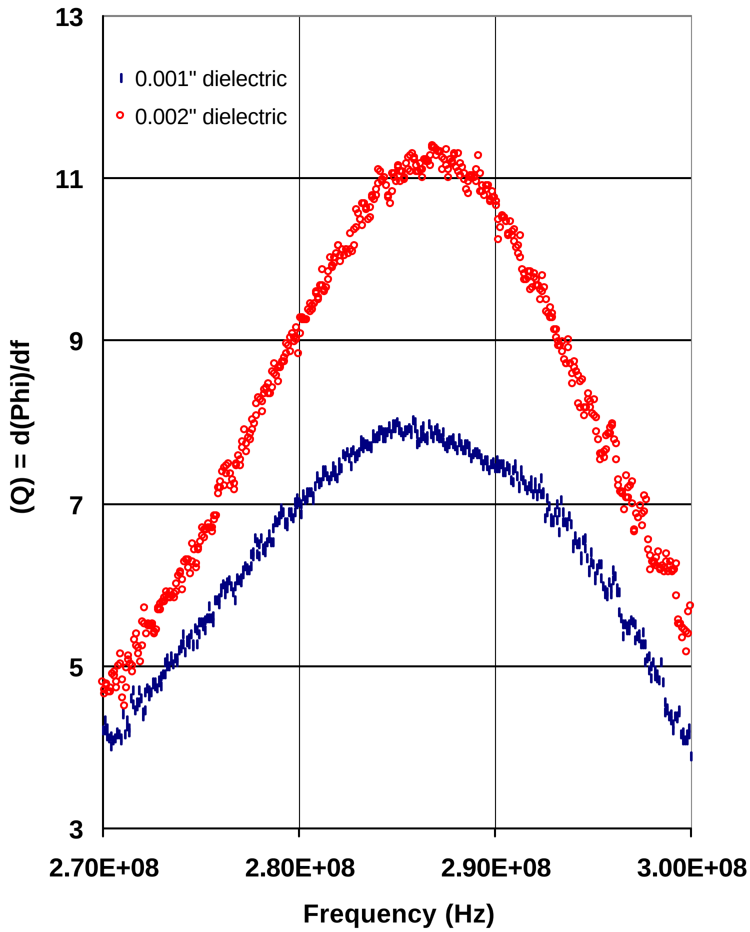

Figure 8. Derive loaded quality factor at the TEM_{10} resonance for 0.001” and 0.002” thick DLUT cores.

Conclusion

The direct stimulus FSR test method offers an alternative method for direct measurement of dielectric constant and loss tangents as a function of frequency. The useful measurement band width for this method is from 100 MHz to 2 GHz, which is an important band for current high speed designs. Direct stimulus FSR has the advantages of lower test method cost for insitu non-destructive measurements. The test method can be applied to both core laminate and prepreg PCB materials.

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