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Anisotropic Design Considerations for 28 Gbps Via to Stripline Transitions

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Abstract

For 28-56 Gb/s design the homogeneous isotropic material assumption is a key impediment in model to measurement correlation. Without accurate dielectric material models, it is impossible to close the loop between electromagnetic modeling and actual operation. Epoxy/glass PCB materials present a layered-anisotropic dielectric profile that varies in the x, y, and z direction. We will show that by using anisotropic dielectric models the modeling/simulation/measurement loop can be closed with simulation models of single-ended and differential vias. A simple experimental design will used to identify z-axis dielectric properties, and combined with GMS-Parameter measurements of x-y-axis properties. Accurate dielectric models for use in the modeling and simulation of trace and via structures will be demonstrated.

Author(s) Biography

Scott McMorrow, Consultant – R&D, Teraspeed® Consulting – A Division of Samtec. - Scott is an expert in high-performance design and signal integrity engineering, with a broad background in complex system design, interconnect and signal integrity engineering, modeling and measurement methodology, and professional training, spanning over 25 years.

Ed Sayre, NESA System Consultant, Teraspeed® Consulting – A Division of Samtec. - Dr. Sayre holds a BEE, an MEE, and a PhD, in Electrical Engineering. He has held a number of academic faculty positions in Electrical Engineering, and in 1973 established NESA, a leading design firm for Gigabit links and interconnects over PCBs, as well as cable for Fibre Channel, Infiniband, CX4 and Gigabit Ethernet protocols. CX4 and GigabitEthernet protocols.

Chudy Nwachukwu received his MBA in Operations and Supply Chain Management from Arizona State University, and holds a M.S.E.E. degree in digital communications from Saint Cloud State University in Minnesota. He manages the Signal Integrity laboratory and Engineering Application Development for Isola USA Research and Development in Chandler, Arizona.

Background

For 28-56 Gb/s design the homogeneous isotropic material assumption is a key impediment in model to measurement correlation. Without accurate dielectric material models, it is impossible to close the loop between electromagnetic modeling and actual operation. Epoxy/glass PCB materials present a layered-anisotropic dielectric profile that varies in the x, y, and z direction. We will show that by using anisotropic dielectric models the modeling/simulation/measurement loop can be closed with simulation models of single-ended and differential vias. A simple experimental design will used to identify the permittivity for x/y-axis E-Fields, and combined with GMS-Parameter measurements of z-axis E-field permittivity. Accurate dielectric models for use in the modeling and simulation of trace and via structures will be demonstrated.

28-56 Gb/s designs require the rigorous control of interconnect losses and impedance in the signal transmission path. In previous generations of designs, dielectric materials have been generally modeled with perfect isotropic properties that are uniform in all directions of propagation. This is convenient from the material modeling and electromagnetic analysis point of view, but is quite naive. Common PCB materials are a mixture of multiple constituents, including fiberglass, epoxy, various polymers, silica, quartz, and various other elements that combine into what we call core or prepreg laminate sheets. In the 10-28 Gb/s design regime it is now common to consider the anisotropic effects of the fiberglass used in the construction of printed circuits for propagation on traces. In the 28-56 Gb/s design regime, it will be equally important to consider how anisotropic material properties influence signal propagation through traces and vias.

X/Y-axis signal propagation anisotropy is familiar to the modern designer as laminate weave skew. This form of layered-anisotropy occurs because the dielectric properties of the material vary locally over and under stripline and microstrip traces, due to the physical structure of the fiberglass used in PCB laminates. What is not so familiar is that this formally represents one in a class of electromagnetic dielectric mixing problems (EM Mixing) that determine the effective permittivity of dielectrics with respect to the direction of signal propagation. The direction of propagation is important when computing the effective permittivity of any dielectric. For mixtures of materials, effective permittivity of the mixture is determined by the physical structure of the mixture, and the E-Field direction. For signals guided by traces and vias on epoxy/fiberglass laminates, it is clear that the physical structure of the dielectric mixture is different with different directions of propagation, and clearly very different when viewed from the perspective of traces vs. via transitions. These significant structural differences result in profoundly different EM Mixing results, which in turn account for a 10% to 20% variation in the permittivity "seen" by traces and vias.

First, we will show the theoretical foundation behind the phenomena of Electromagnetic Mixing for a variety of materials and problems. Second, using this foundation, we will develop simple experiments with Ansys HFSS FEM full-wave electromagnetic solver which will demonstrate the EM Mixing problem with various mixtures of common PCB materials, showing the directional impact on permittivity, and its implications for modern designs. Third, using our experience with HFSS, we develop a generalized class of PCB measurement structures designed to illustrate the variation of EM Mixing permittivity with direction of propagation, utilizing simple single-ended trace and via structures that can be measured, and used to develop accurate material models. Finally, these accurate anisotropic dielectric models will be utilized to "close the loop" between theory, modeling, and measurement. Conclusions will be drawn with respect to the applicability of these methods in the improvement of design of 28-56 Gb/s vias, RF measurement launches, connector and package transitions.

Epoxy Fiberglass Laminates

PCB laminates are inhomogeneous structures constructed from multiple dielectric and metal layers. Thus, the anisotropic nature of PCBs introduces a spatial variation of the dielectric characteristics of the substrate with respect to direction (X, Y & Z-axis). These dielectric materials are manufactured by impregnating and strengthening a woven fiberglass fabric with epoxy resin. Glass styles of varying thickness, spread and weave pattern are bound together with resin in different volume proportions to achieve a desired thickness or dielectric performance. See definitions and illustrations of glass styles below:

Expanded Weave – Glass spread more than standard in one Direction

- Open Weave – Same as Expanded
- Open Filament – Same as Expanded

Spread Glass – Glass Spread by a number of different ways

- Mechanically Spread (MS) Glass – Glass is Mechanically spread in both the warp and fill directions.

- Square Weave – Glass that has a balanced density and/or yarn Counts in warp and fill directions.

- Flat Glass – Glass is made from fibers with little or no twist.

Inhomogeneous mechanical and dielectric characteristics of PCB laminates create an environment that is not only non-uniform, but also layered. As can be seen in Figure 1, various styles of fiberglass create variations in the structural dielectric characteristics as seen by traces, planes, and vias. In recent years, an increase in the usage of spread and square weaves helps in the variation of properties, but does not eliminate all variation. Gaps and weave thickness variations continue to exist across and between fiber bundles in the grain direction, which cannot be fully eliminated. This contributes to anisotropic variation.

Along the PCB x-axis and y-axis it is easily apparent that the fiberglass weave establishes some manner of variation in the dielectric. This has been discussed in the literature. However, in the z-axis, epoxy/fiberglass laminates form a layered dielectric system, with glass fabric surrounded on each side by an epoxy filler layer. These ply are layered to form the complete PCB substrate, which contains a large number of the laminate sheets. Each sheet contains one of many sets of individual epoxy/fiberglass/epoxy layer sets. Since the physical environment along the X, Y, and Z PCB axis are different, we can expect that the dielectric properties are also different.

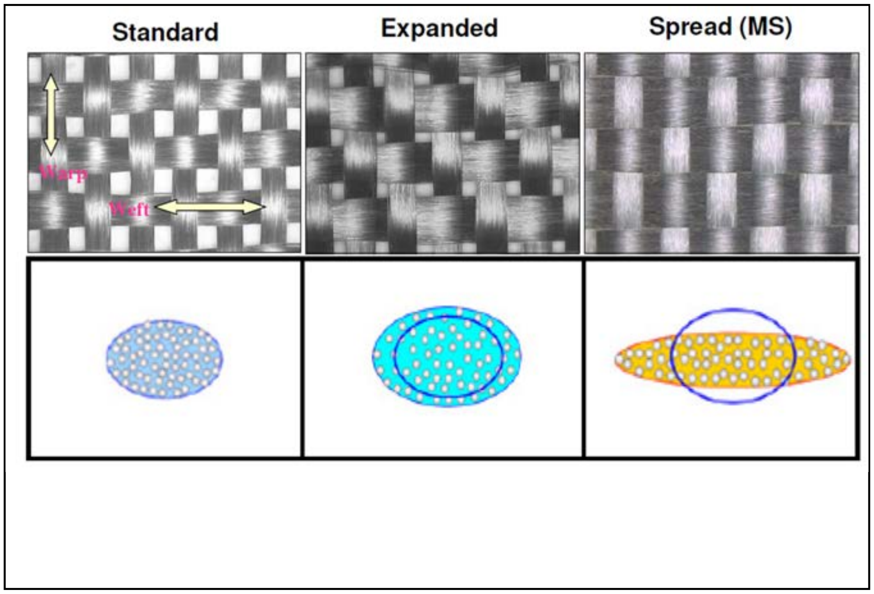

Figure 1

Clad PCB Material as a Linear Non-isotropic Dielectric Media

The role of PCB material in electronic design is, as the reader knows, both mechanical as well as electrical in function. The cladding after processing provides the signal and return paths for the signals and the resin and dielectric sandwich provide the support and insulating isolation required by the circuitry. As the data rates in digital communications have risen to beyond 10Gbps, the details of the PCB material configuration and dielectric properties have become more important.

The general relationship in PCB material between the electric vector intensity $\vec{E}$ and the electric flux density $\vec{D}$ is no longer co-linear and simple[1]. In general, the relationship must be expressed as a matrix expressing the coupling between the various vector components of the electric vector intensity and the components of electric flux density as shown below:

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[1] "Field and Waves in Communication Electronics", Chapter 13, by Simon Ramo, John R. Whinnery, Theordore Van Duzer, 3rd Edition, John Wiley & Sons, Inc. 1994.

$$\begin{bmatrix} D_x \\ D_y \\ Dz \end{bmatrix} = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix} \cdot \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$$

Stripline consists of a signal conductor lying between and parallel to two conducting planes located above and below the signal conductor. Such a structure can, to an excellent approximation, support a Transverse Electric-Magnetic (TEM) wave in which the electric and magnetic fields are at right angles to each other as well as mutually at right angles to the direction of propagating energy.   In systems which employ PCB media to carry the signal conductors, the signal conductor is a copper foil laminated onto usually surrounded by a permeating composite resin and glass reinforcing woven mat materials. Such a TEM stripline structure is shown in figure 2 below:

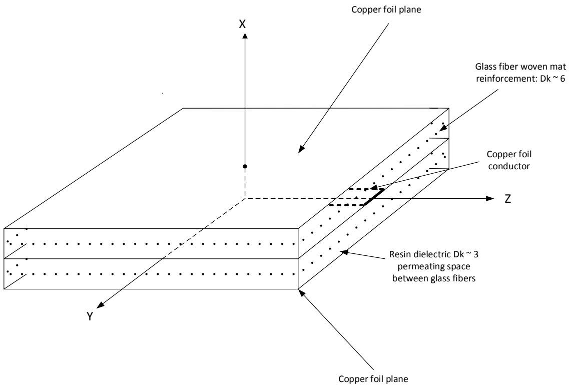


FIGURE 2

Note that the electric fields are predominately in the vertical “X” direction, but also to a lesser extent in the “Y” direction. Because the signal conductor is an excellent conductor, there is little or no electric vector in the “Z” direction. In this coordinate system, shown above, the relationship between the electric field and electric flux density can be written:

$$\begin{bmatrix} D_x \\ D_y \\ Dz \end{bmatrix} = \begin{bmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix} \cdot \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$$

The lack of coupling between vector components somewhat simplifies solutions but does not explain the difference in the various components of the dielectric constants. This is best explained by analogy.

Consider a capacitor cube made up of PCB material aligned with the electric field as shown in Figure 3 below:

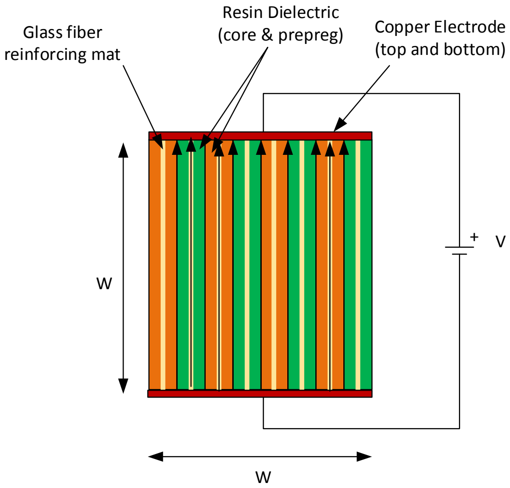


Figure 3

This can be thought of as two capacitors in parallel; one made up of a resin block and the second a block made up of glass reinforcement mats. The capacitance can be shown to be:

$$C_{parallel} = C_{resin} + C_{glass}$$

where:

$$C_{resin} = \varepsilon_o \cdot Dk_{resin} \cdot W \cdot \Delta$$

$$C_{glass} = \varepsilon_o \cdot Dk_{glass} \cdot W \cdot (1 - \Delta)$$

and,

$\Delta =$ the decimal percentage fill of resin

When a typical value for resin dielectric constant is chosen the tradeoff in percentage fill and glass Dk can be demonstrated, as in Figure 4.

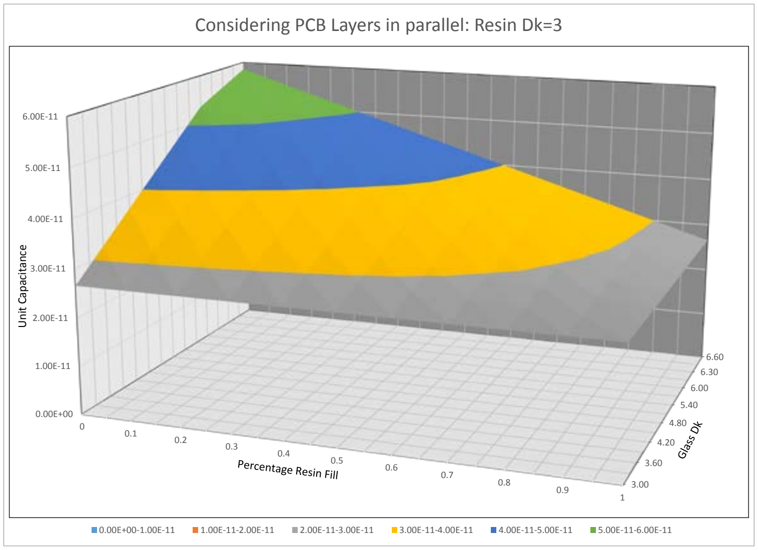


Figure 4

Depending on the Dk of the glass and percentage of resin fill, there can be nearly a 2:1 change in capacitance.

There is a second condition to be considered, namely, when the electric field intensity is at right angles to the planar boundaries of the PCB material. Once again, by analogy,

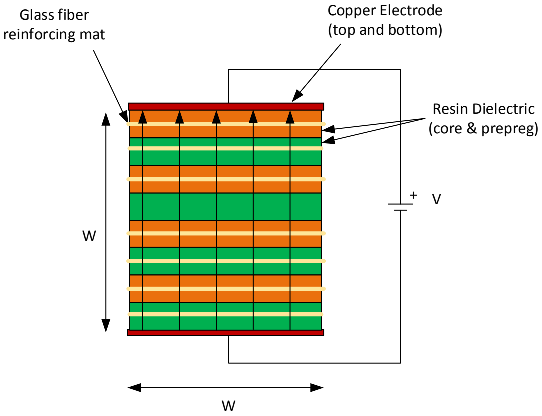


Figure 5

$$\frac{1}{C_{series}} = \frac{1}{C_{resin}} + \frac{1}{C_{glass}}$$

where :

$$C_{resin} = \varepsilon_o \cdot Dk_{resin} \cdot W \cdot \Delta$$

$$C_{glass} = \varepsilon_o \cdot Dk_{glass} \cdot W \cdot (1 - \Delta)$$

and,

$\Delta =$ the decimal percentage fill of resin

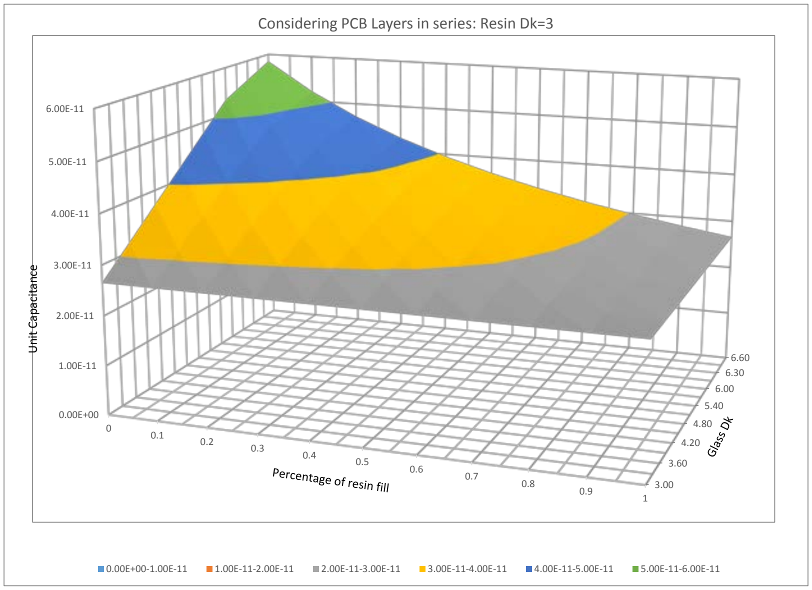


Figure 6

The results are similar in that in those regions where the glass predominates on a volumetric basis, the capacitance is higher.

However, when the two results are compared, the parallel capacitance in all cases is either larger or equal to the serial capacitance. This can be seen in the results shown below:

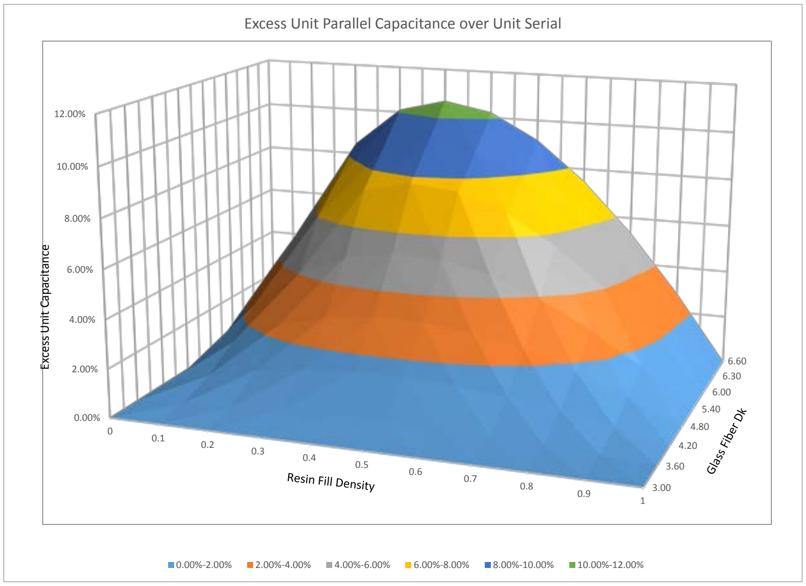


Figure 7

Discussion of Parallel and Series Capacitive Effects in PCB Stripline and Vias

These results show that there is a slightly different capacitance experienced by the electric field intensity $\vec{E}$ vector depending on whether the electric intensity is parallel or normal to a PCB planar interface.

TEM stripline Electric fields have predominately normal components to the PCB interfaces. Consequently, the Electric field lines "see" the PCB as a series accumulation of resin and glass reinforcement dielectrics. Thus, one sees that the impedance predicted from PCB "weighted average value" dielectric constant to be slightly above that measured.

TEM differential stripline Electric fields have predominately parallel components between the signal conductors and predominately normal components in the fringing fields outside of the signal conductor pair. The small but significant difference in the capacitive environment seen by the parallel and normal E-field components will lead to wave splitting and waveform distortion, especially in fast rise time serial digital trace pairs.

In the case of differential vias terminating connector pins, as seen in Figure 8 below, the Electric fields are essentially parallel to the layer boundaries. In this case, the Electric fields see a parallel capacitive environment. The impedance will be equivalent to the impedance computed with the PCB "weighted average value" dielectric constant. There will also be no wave splitting.

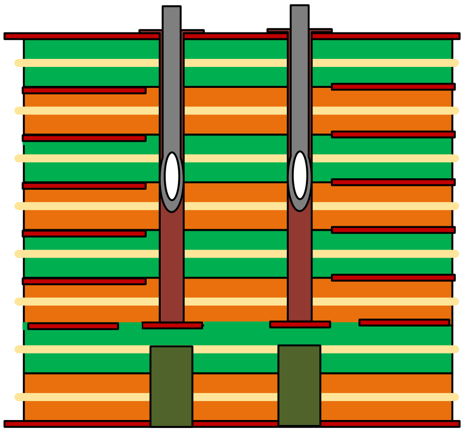


Figure 8

Electromagnetic Mixing Experiments

A pure example of the electromagnetic mixing problem of layered dielectrics can be demonstrated with coaxial transmission lines operating in the TEM mode. In this mode

E-fields are normal to the signal conductor surfaces. Test structures can be created using the normal field configuration shown in Figure 9 below.

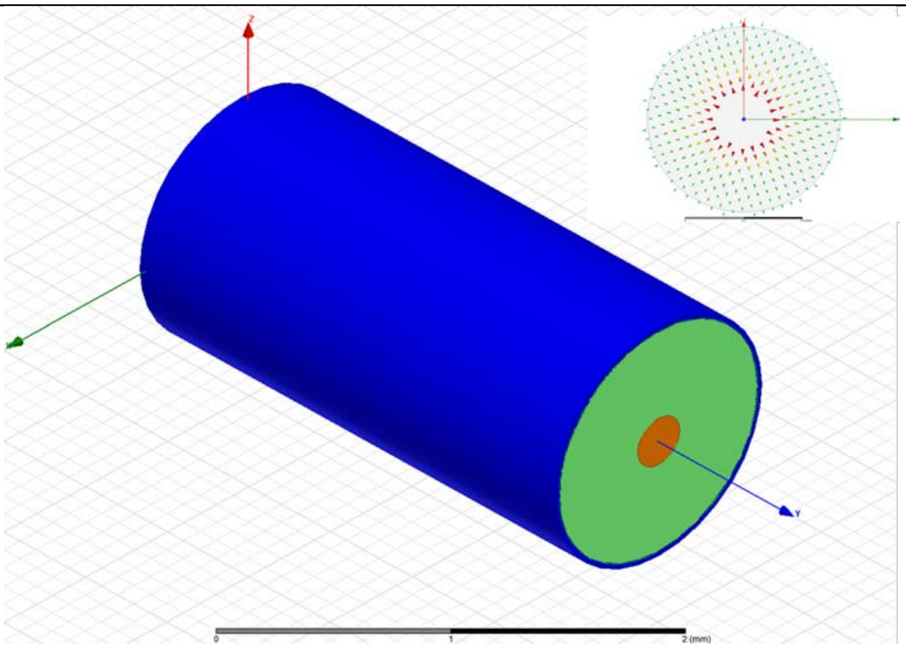


Figure 9 - Coax Test Structure as a metaphor for signal via with grounds. Classic TEM propagation with E-field orthogonal to conductor surfaces.

To mimic the dielectric layering seen by a via penetrating PCB laminates (Figure 8), a coaxial test structure of layered dielectrics can be utilized as shown below in Figure 10. A 100 mil long section of coax was built with layered epoxy/fiberglass/epoxy sections that are approximately equivalent to the layering of a 4 mil thick laminate using 1078 fiberglass. These are replicated across the length of the coaxial cylinder.

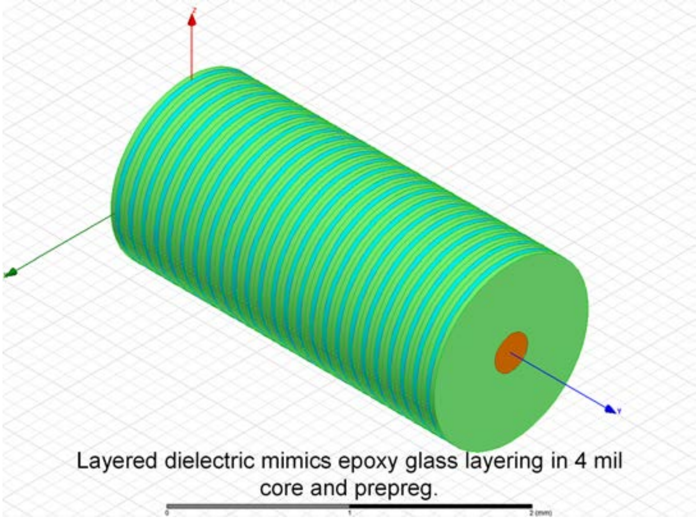


Figure 10 - Layered dielectric mimics epoxy glass layering in 4 mil core and Prepreg.

By volume, the resin to glass ratio for this design is 66.6%, which is in the middle of the range for typical dielectrics. The epoxy to glass permittivity is adjusted in the design to create a mixture average of 3.5, also typical for low loss high performance laminate materials. In Ansys HFSS, electromagnetic wave ports were placed on the coax and used to optimize the structure dimensions to 50 ohm impedance with a pure mixture of epoxy and glass at an Er of 3.5.

Once optimized, the epoxy and glass mixture was swept, while keeping the mixture average at Er of 3.5. Return loss of the structure and insertion phase were monitored to determine if there was any shift in impedance or propagation velocity that would indicate a change in the effective Er. The electromagnetic simulation results are consistent with theory, and are shown in Table 1 below. With a wide ranging mixture variation, there is no change in the impedance of the structure, or the phase of the S12 path, indicating that, for via-like structures with well-controlled signal and ground return paths orthogonal to the layering, the effective dielectric constant of the material layering is effectively the dielectric constant of the mixture average. Permittivity of the dielectric in the X and Y direction is therefore constant, and dependent on the layered mixture average.

Epoxy Er	Glass Er	Average Er	Return Loss	S12 Phase
3.5	3.5	3.5	-54.37	-57.09deg
3.442	3.617	3.5	-53.23	-57.1deg
3.383	3.733	3.5	-53.58	-57.09deg
3.325	3.85	3.5	-54.19	-57.09deg
3.267	3.967	3.5	-53.33	-57.1deg
3.208	4.083	3.5	-53.5	-57.09deg
3.15	4.2	3.5	-53.4	-57.09deg
3.092	4.317	3.5	-54.5	-57.09deg
3.033	4.433	3.5	-54.2	-57.09deg
2.975	4.55	3.5	-53.28	-57.09deg
2.917	4.667	3.5	-53.28	-57.09deg
2.858	4.783	3.5	-54.47	-57.08deg
2.8	4.9	3.5	-52.26	-57.1deg
2.742	5.017	3.5	-53.31	-57.09deg
2.683	5.133	3.5	-53.34	-57.09deg
2.625	5.25	3.5	-53.36	-57.09deg

Table 1 – All dielectric mixture combinations perform identically to average.

To mimic the dielectric layering seen by a stripline signal trace propagating between planes (Figure 5), a coaxial test structure of concentric dielectric rings can be utilized as shown below in Figure 11. A 100 mil long section of coax was built with concentric epoxy/fiberglass/epoxy sections that represent the layering of 1-ply of laminate on each side of an infinitely thin stripline trace. These 3 concentric rings fill the entire volume of the coaxial transmission line, and are of equal volume.

By volume, the resin to glass ratio for this design is also 66.6%, adjusted to create a mixture average of 3.5. In Ansys HFSS, electromagnetic wave ports were placed on the coax and used to optimize the structure dimensions to 50 ohm impedance with a pure mixture of epoxy and glass at an Er of 3.5.

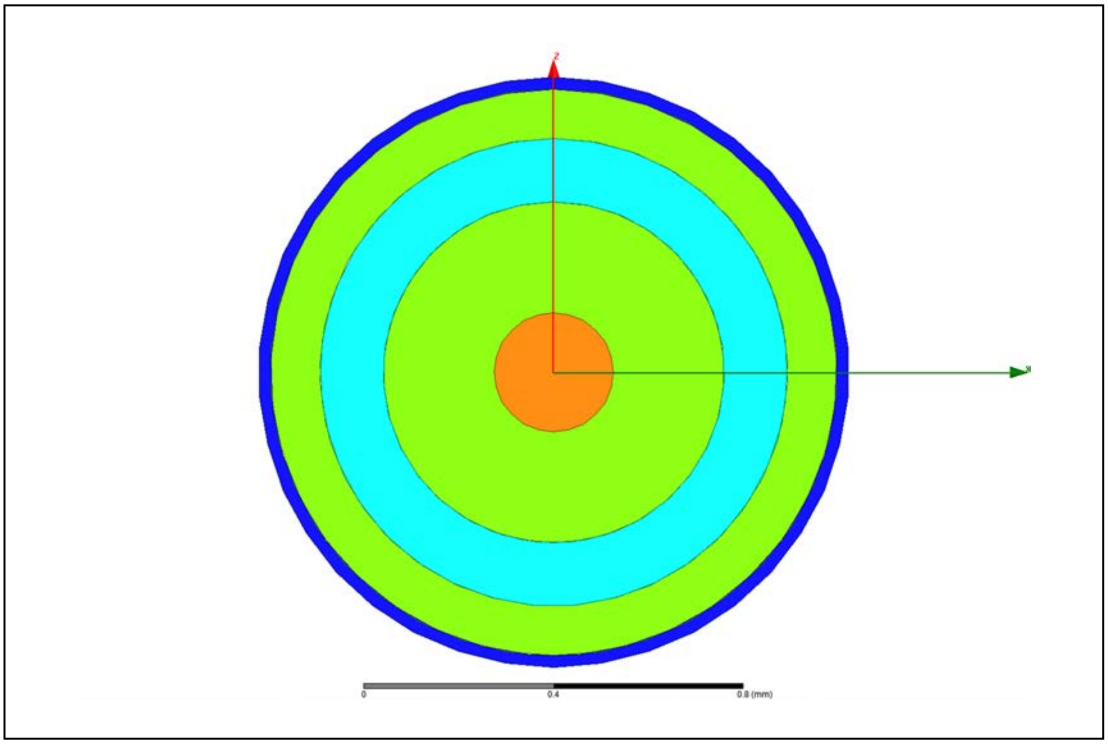


Figure 11 - Layered dielectric mimics epoxy glass layering in 1-ply of laminate material. Equivalent to trace fields in Z-axis normal to X/Y-axis.

Once optimized, the epoxy and glass mixture was swept identically to the previous design, while the mixture average was maintained at Er of 3.5. Impedance of the structure was measured. The electromagnetic simulation results are consistent with theory, and are shown in Table 2 below. As the mixture permittivity ratio is increased, the impedance of the coax increases, indicating that, for stripline trace structures with E-fields orthogonal to the layering, the effective dielectric constant of the layered dielectric decreases with the ratio of the glass to epoxy permittivity. Permittivity of the dielectric in the Z direction is therefore variable, and dependent on the layered mixture Er ratio. This is an important conclusion.

From first principles, and numerical electromagnetic experiments, we have determined that the effective dielectric constant of layered PCB laminates is dependent on the E-field direction. Measurement of epoxy-fiberglass laminate material will therefore show an anisotropic directional component to the dielectric permittivity that is equivalent to the mixture average for X/Y-axis E-field components, and lower than the mixture average for Z-axis E-field components. The implications for this are profound. For an electromagnetic simulation model of a trace-via transition to be accurate, the layered anisotropic dielectric properties of the laminate must be accounted for.

Standard PCB laminate material property measurements are taken with E-fields oriented along the Z-axis. For TEM stripline traces and TEM planar cavity model modeling this is reasonably accurate. However, for X/Y-axis E-field orientation as seen in via structures, in stripline fringe fields, and in differential trace field, using the Z-axis dielectric properties alone will cause a shift in both the predicted propagation delay and impedance.

Epoxy Er	Glass Er	Z(average)	Impedance
3.5	3.5	3.5	49.96
3.442	3.617	3.5	50.14
3.383	3.733	3.5	50.34
3.325	3.85	3.5	50.55
3.267	3.967	3.5	50.79
3.208	4.083	3.5	51.06
3.15	4.2	3.5	51.34
3.092	4.317	3.5	51.64
3.033	4.433	3.5	51.95
2.975	4.55	3.5	52.29
2.917	4.667	3.5	52.65
2.858	4.783	3.5	53.02
2.8	4.9	3.5	53.42
2.742	5.017	3.5	53.83
2.683	5.133	3.5	54.27
2.625	5.25	3.5	54.73

Table 2 – Impedance results indicate an effective Er change with mixture variation in the Z-axis E-field direction.

Experimental Design of Anisotropy Test Board

Measurement investigation of X/Y/Z-axis material anisotropy was performed with the Teraspeed® Consulting Anisotropy Test Board (Figure 12). This board is designed with 4 basic structures: A via stub resonator; a thru via structure; microstrip traces for GMS-parameter material property de-embedding; and stripline test traces for material property de-embedding.

Classic relative X/Y axis anisotropy is investigated using the GMS-parameter de-embedding process. This is not intended to be a rigorous characterization of statistical variation, but is useful for establishing baseline material properties for signal propagation on microstrip and stripline traces. All layers of this PCB are constructed with exactly the same laminate system, 1078 fiberglass weave and resin content, to establish a uniform dielectric environment. A typical stackup is shown in Figure 13. Identical boards with several recent advanced materials from Isola were fabricated and tested. For this paper, data from Isola Tachyon® and Chronon will be shown. (Measurement data was incomplete at the time of paper submission. Additional measurement information and conclusions will be presented at the conference.)

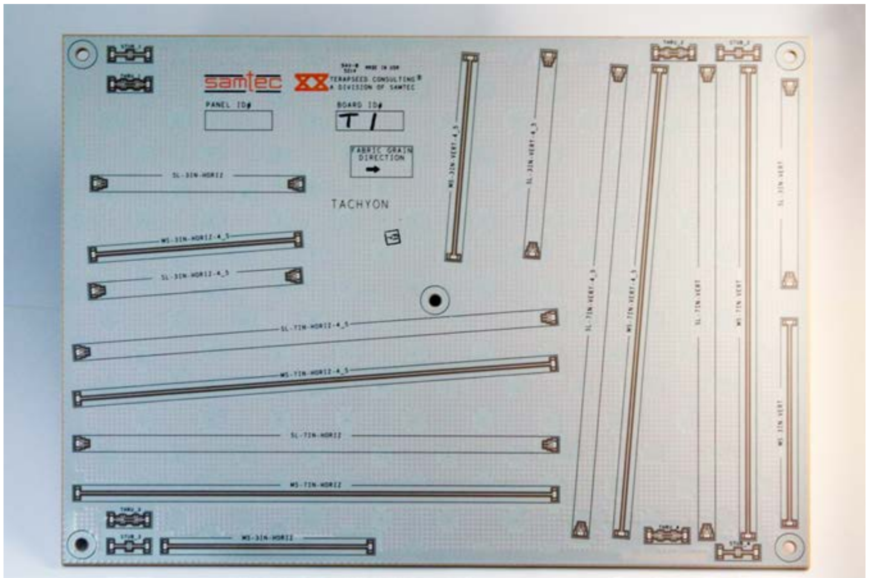
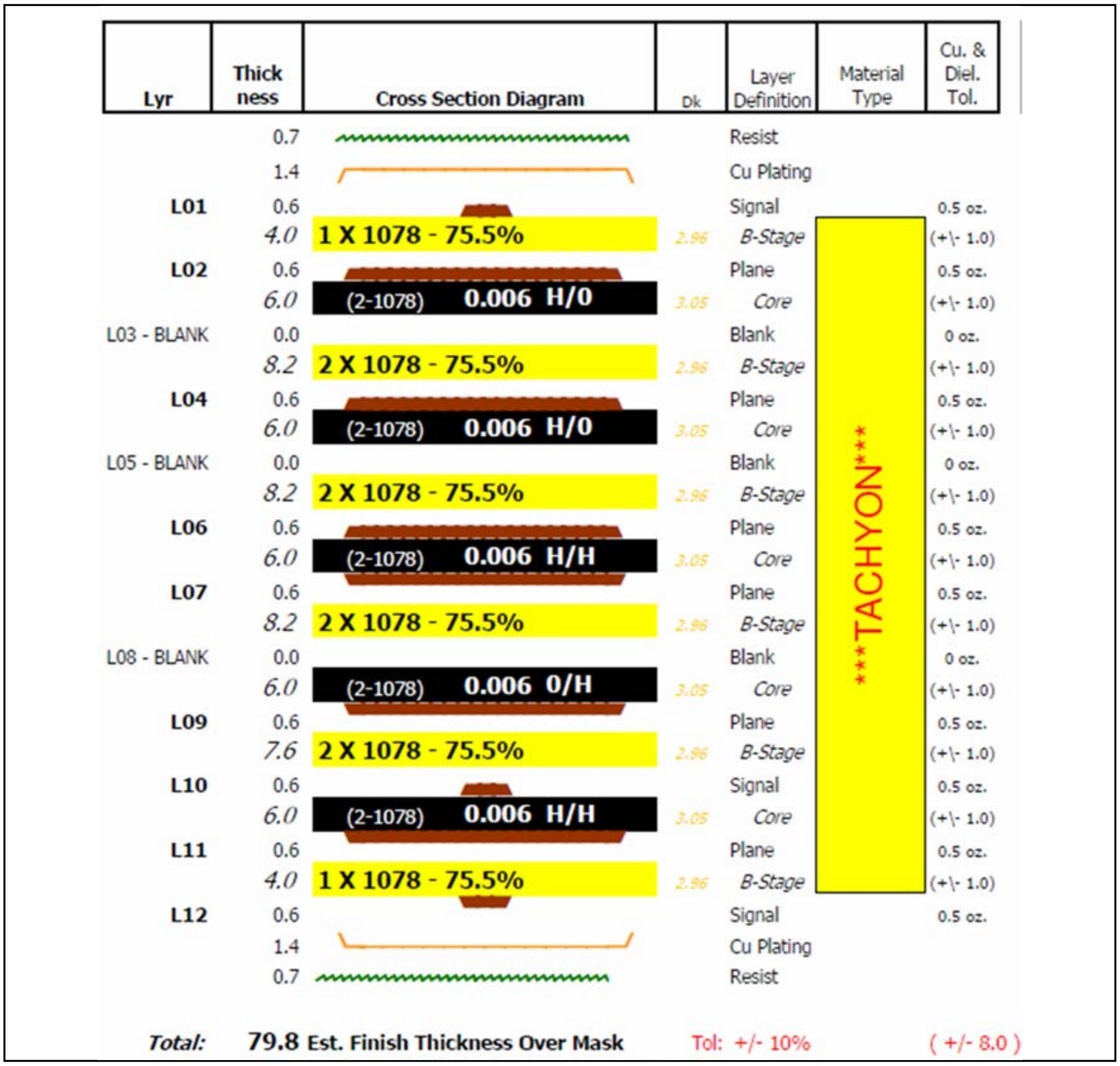


Figure 12 – Teraspeed® Consulting Anisotropy Test Board



Lyr	Thick ness	Cross Section Diagram	Dk	Layer Definition	Material Type	Cu. & Diel. Tol.
	0.7			Resist		
	1.4			Cu Plating		
L01	0.6			Signal		0.5 oz.
	4.0	**1 X 1078 - 75.5%**	*2.96*	*B-Stage*	***TACHYON***	(+\- 1.0)
L02	0.6			Plane		0.5 oz.
	6.0	(2-1078) **0.006 H/0**	*3.05*	*Core*		(+\- 1.0)
L03 - BLANK	0.0			Blank		0 oz.
	8.2	**2 X 1078 - 75.5%**	*2.96*	*B-Stage*		(+\- 1.0)
L04	0.6			Plane		0.5 oz.
	6.0	(2-1078) **0.006 H/0**	*3.05*	*Core*		(+\- 1.0)
L05 - BLANK	0.0			Blank		0 oz.
	8.2	**2 X 1078 - 75.5%**	*2.96*	*B-Stage*		(+\- 1.0)
L06	0.6			Plane		0.5 oz.
	6.0	(2-1078) **0.006 H/H**	*3.05*	*Core*		(+\- 1.0)
L07	0.6			Plane		0.5 oz.
	8.2	**2 X 1078 - 75.5%**	*2.96*	*B-Stage*		(+\- 1.0)
L08 - BLANK	0.0			Blank		0 oz.
	6.0	(2-1078) **0.006 0/H**	*3.05*	*Core*		(+\- 1.0)
L09	0.6			Plane		0.5 oz.
	7.6	**2 X 1078 - 75.5%**	*2.96*	*B-Stage*		(+\- 1.0)
L10	0.6			Signal		0.5 oz.
	6.0	(2-1078) **0.006 H/H**	*3.05*	*Core*		(+\- 1.0)
L11	0.6			Plane		0.5 oz.
	4.0	**1 X 1078 - 75.5%**	*2.96*	*B-Stage*		(+\- 1.0)
L12	0.6			Signal		0.5 oz.
	1.4			Cu Plating		
	0.7			Resist		
Total:	**79.8**	**Est. Finish Thickness Over Mask**		Tol: +/- 10%		(+/- 8.0)

Figure 13 – Isola Tachyon® Test Board Stackup

Tachyon® laminate materials are designed for very high-speed digital applications. Tachyon® products use spread glass and reduced profile copper to mitigate skew and improve rise times, reduce jitter, increase eye width and height. Use of ultra-smooth copper is enabled by very high adhesive bond between the resin and the metal. Tachyon has a nominal dielectric constant (Dk) of 3.02, nominal dissipation factor (Df) of 0.0021, depending on resin content. It is, however, not a Dk flat material and has varying anisotropic properties in all directions.

Chronon has been engineered to mitigate/eliminate skew issues by utilizing spread glass and a resin system with Dk matched to the glass system. This is what we like to call an *effectively isotropic* material with a Dk of about 3.5 and a Df of about 0.004 for most available prepreg and core variations. It was chosen for this test board to provide a test of its isotropic properties and to determine if it can not only effectively eliminate differential signal skew, but also improve the predictability of z-axis via transition modeling.

The primary test structure for investigation is the via stub resonator shown in Figure 14. A microstrip trace feeds a classic quarter wave resonant structure. The resonant frequency of this via depends on its length, and the permittivity of the dielectric mixture. If the mechanical dimensions of the structure are known, an accurate measure of the dielectric mixture properties in the X/Y-axis E-field direction can be obtained through simulation with HFSS. Resonant frequency of the circuit depends on the length of the via, fringe capacitance around the pads, and the properties of the dielectric.

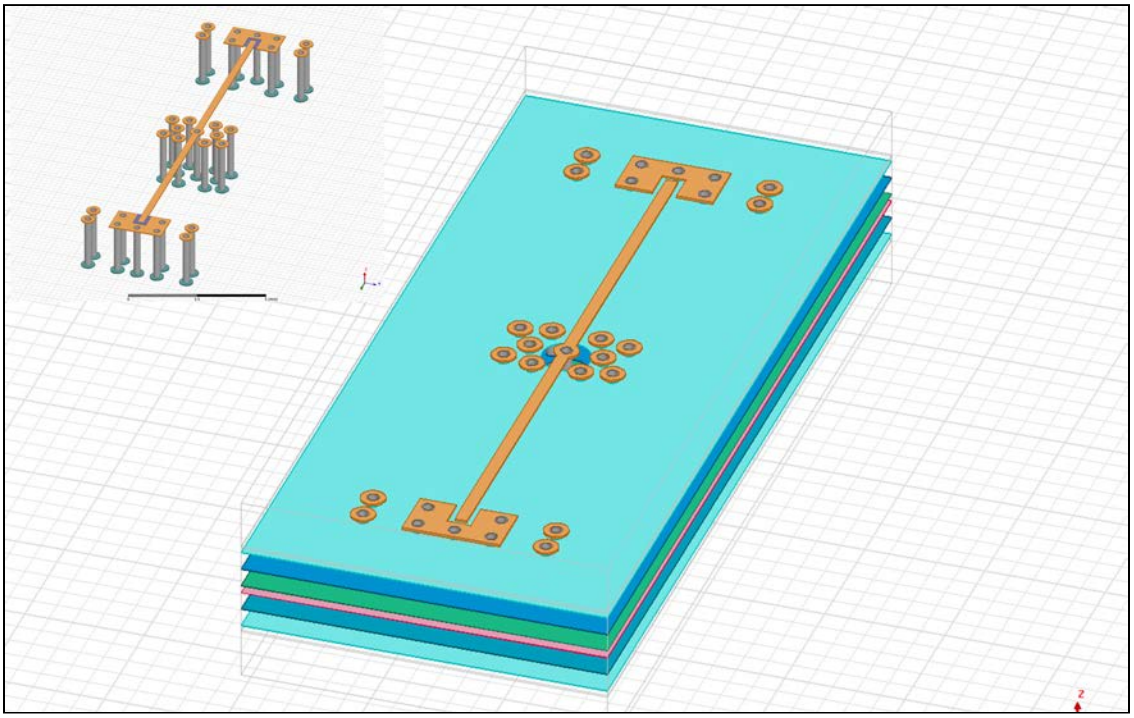


Figure 14 – Quarter Wave Stub Resonator Test Structure

Experimental Results

Current measurements of stub resonance on one Chronon test board (Figure 15) and one Tachyon test board (Figure 16) show resonant frequency of the stub structure. Figure 17 shows a comparison between two of the measurements. For the materials used, the measured dielectric constant for Chronon and Tachyon in the Z-axis is approximately 3.5 and 3.0 respectively. A ratio of the square root of the two Dk values will provide a relative indication of the ratio of propagation delay for the two materials and therefore the ratio of the stub resonant frequency of the test circuit, assuming that both materials have similar anisotropic characteristics and physical dimensions. This ratio is 1.08:1.

If both materials are anisotropic, and both have similar ratios of epoxy to resin Dk, then we would expect that the ratio of the stub resonant frequencies for both boards to be 1.08:1. However, if Chronon is effectively isotropic, due to matched Dk of epoxy and glass, then Dk (x/y-axis) and Dk(z-axis) are closer, resulting a smaller resonant frequency shift. We would then expect an offset between resonant frequencies for the Tachyon and Chronon materials.

Preliminary measurements show the Chronon boards to have a higher stub resonant frequency than the Tachyon boards, possibly indicating that Chronon has an effective Dk(Z-axis) that is lower than Tachyon. However, until mechanical measurements of the structures can be performed, this cannot be confirmed. Final measurement and simulation results for this paper were not available by publication time. Current work involves additional VNA and mechanical micro section measurements before rendering our final conclusions.

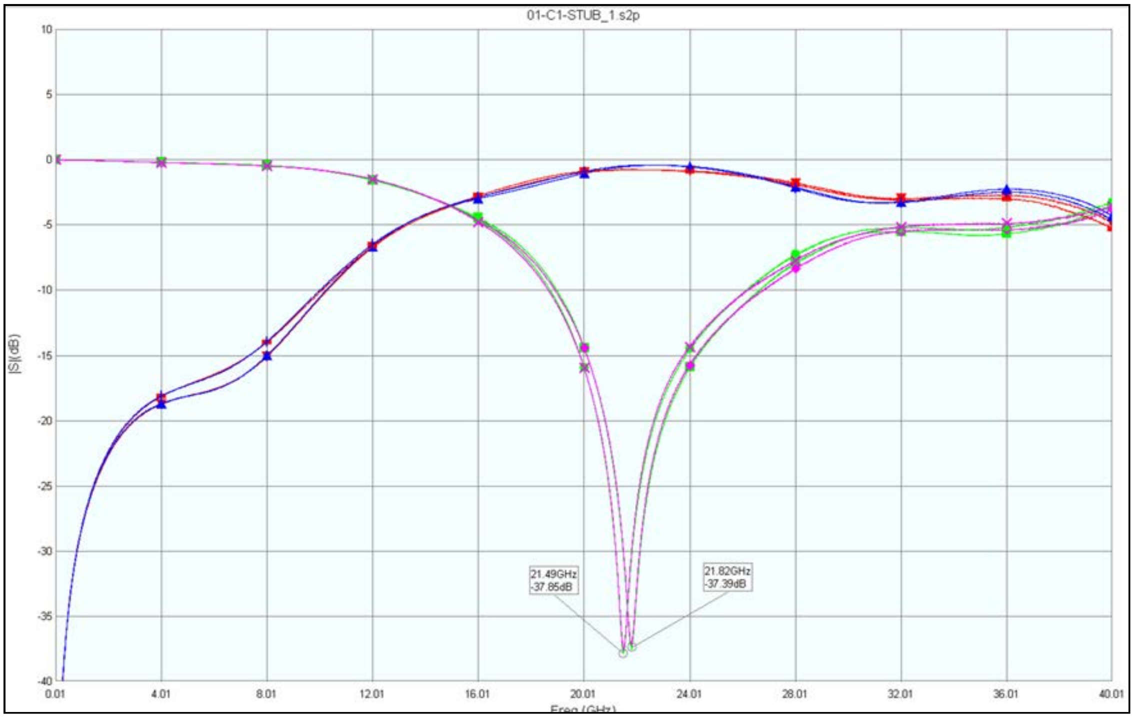


Figure 15 – Stub Resonant Frequency (Isola Chronon®)

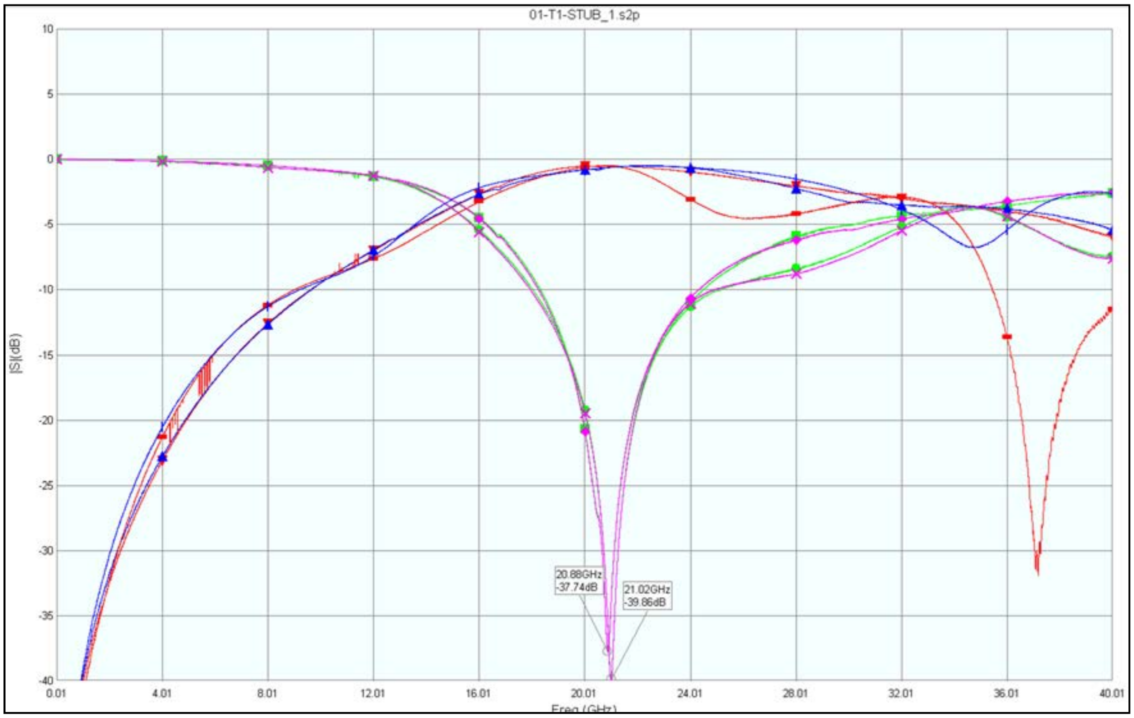


Figure 16 – Stub Resonant Frequency (Isola Tachyon®)