Determining Dielectric Properties of High Frequency PCB Laminate Materials

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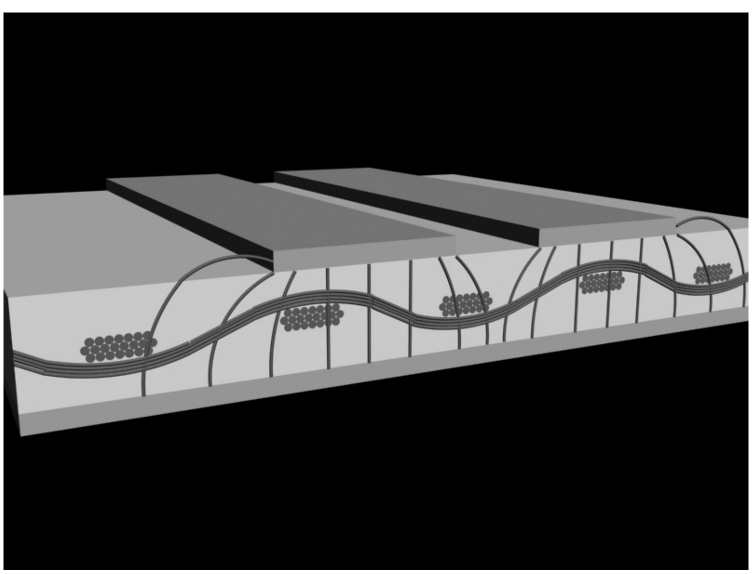
Abstract
This paper will focus on understanding the dielectric constant (dk) of high frequency laminate materials. The dissipation factor (df) and other electrical properties will be discussed as well, however in less detail. There are many different methods that can be used to determine these properties and each of them have their own capabilities and potential shortcomings. And if a very accurate dk value is found, by the nature of the high frequency circuit design, it may experience a slightly different value. This paper is formatted in three sections. The first is discussion on the effects of circuit design, as it relates to variation of dk. Next is test methods used for testing the high frequency laminate materials. And third will be discussion on the substrate construction and how that can affect dk values. Two of the most common test methods will be discussed, as well as their capabilities and results on varying types of materials. Also some variation of these test methods will be shown in order to have enhanced testing capabilities. The test methods discussed will be from IPC-TM-650 and they are the clamped stripline resonator and the full sheet resonator (FSR) test. Microstrip transmission line testing will be discussed as well.

Circuit design: With different microwave or high frequency circuit designs, the electromagnetic fields can use the substrate differently. This combined with the properties of some laminates can make the circuit behave as if it has a different dk value than what may have been assumed. Two simple microwave circuits will be used as examples to demonstrate the dk difference that can be experienced when using the exact same laminate.

The two circuits discussed will be a microstrip bandpass edge coupled filter and a microstrip transmission line. The laminate used will be a high frequency substrate with a woven glass reinforcement layer and a reported dk value of 3.5. The woven glass layer will use glass that is a standard in the PCB industry, which is E-glass and this example, will assume the glass to have dk value of 6.2. So the reported dk value of the laminate at 3.5 is a composite dk number. And the substrate material that is not glass must have a dk that is less than 3.5.

The microstrip edge coupled filter circuit will be discussed first. Two drawings of this circuit are shown in figure 1. It can be seen in figure 1a that the substrate between the two copper planes has one layer of glass weave embedded in the laminate material (blue layer).

1a



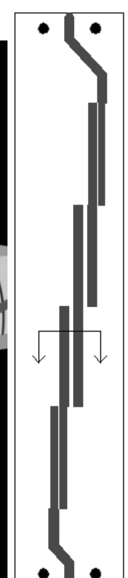


Figure 1a. Three-dimensional cross-sectional view of a segment of an edge coupled filter operating in even mode.
Figure 1b. Top view of edge coupled filter.

The normal operation of this filter will utilize the even and odd modes of the electric field excitation as shown in figure 1 and 2 respectively; electrical fields (E-fields) are symbolized by the red lines in the figures.

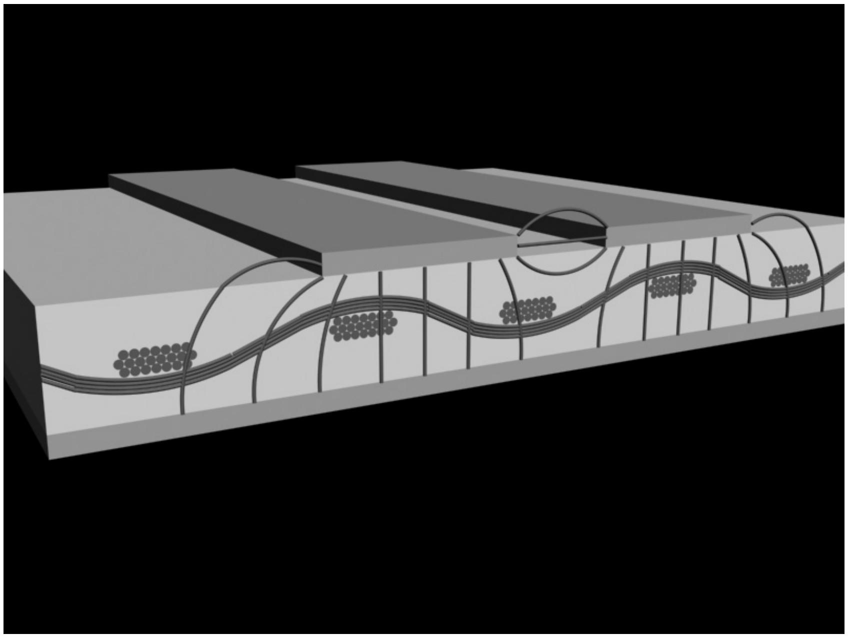


Figure 2. Segment of an edge coupled filter operating in odd mode.

The associated magnetic field lines are not shown. It can be seen that in the even mode, the E-fields are mostly employing the z-axis properties of the laminate. While operating in the odd mode, it can be seen that the x-y plane properties of the substrate are more utilized than in the even mode. During normal operation of this filter, it can be seen that all three axes of the laminate are being used efficiently. Also if one would imagine an anomaly within the x-y plane, it may be readily detected by the interaction of the E-fields in the odd mode.

Depending on the location of the glass weave in regards to the conductor routing, the filter may experience a different dk value. In figure 3 the filter segments are shown operating in odd mode and with a difference in the location of the glass weave as compared to figure 2, which is also shown in odd mode operation. In figure 2 it can be seen that the coupling E-fields are within the air and the resin part of the laminate only. In figure 3 some of the E-fields will be in the air, resin and the glass, which will have a different dk value than in figure 2. A scenario that may exaggerate this effect would be if the glass layer is very large and course and near the copper layers.

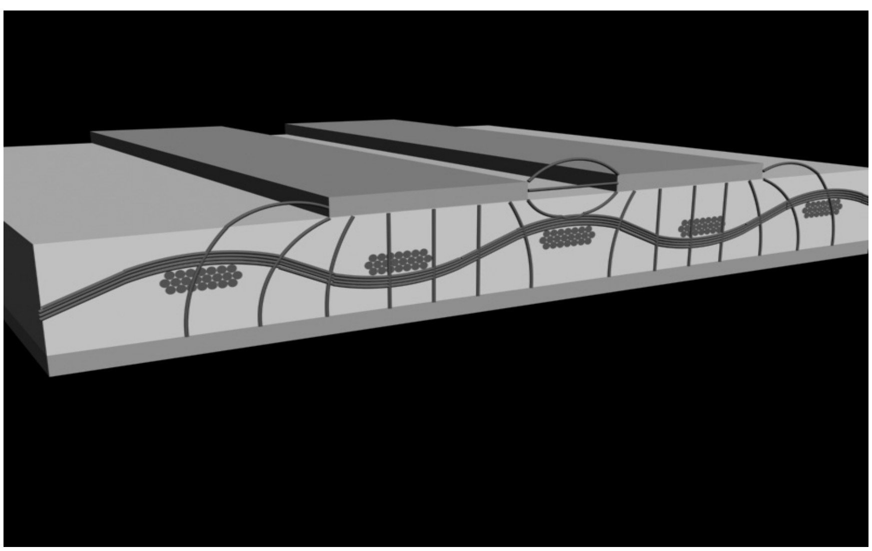


Figure 3. Segment of an edge coupled filter operating in odd mode, with a different location in regards to the glass wave as compared to figure 2.

These filters that operate at higher frequencies may be even more sensitive to this effect due to several issues. At higher frequencies the filter conductor segments will be shorter in length and an averaging effect over a longer conductor will be less beneficial. Also at higher frequencies the E-fields will be more concentrated and a composite substrate may have a more obvious dk difference. The manner in which this filter is stair-stepped (figure 1b, top view) would make this design more prone to having some of the filter segments having more glass interaction than others. Many laminates will have multiple layers of glass weave which can help to average the glass effect. However at higher frequencies the laminate is typically thinner so the potential benefit of having multiple glass layers may not be true. The thinner laminates may have just one glass layer as shown in the previous figures.

In the second example of the microstrip transmission line, there are some of the same concerns as the filter. However the transmission line is typically much less sensitive to the dk anomalies. The transmission line is usually operating in a TEM (transverse electromagnetic) mode; however other modes can be supported. A picture of the microstrip transmission line is shown in figure 4, with the associated E-field lines.

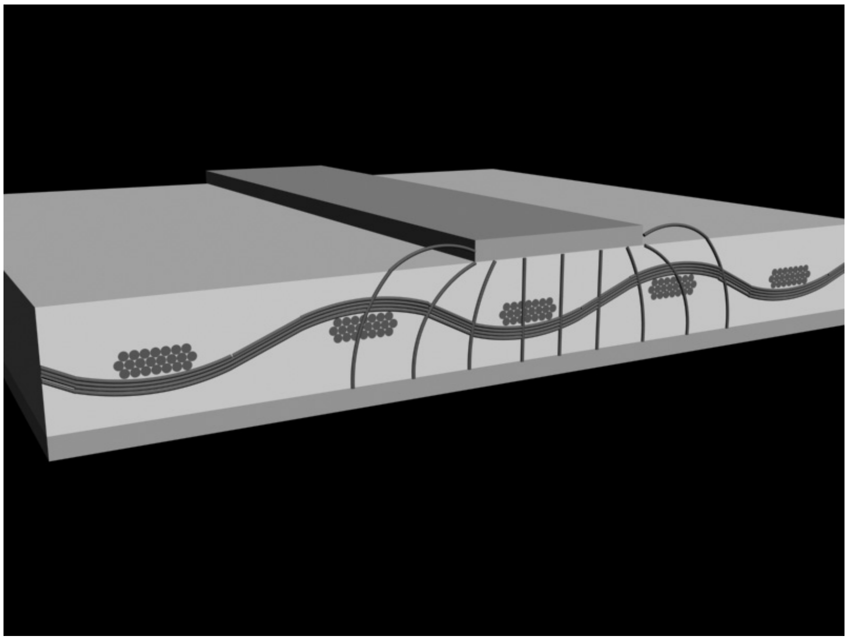


Figure 4. Microstrip transmission line

This circuit does not operate with the even and odd mode and it is typically much longer than the segments of the filter. So the averaging of the non-homogenous dk over a longer distance is very beneficial to where the circuit experiences a dk that is much closer to the composite dk of the material. The composite dk is mostly in regards to the z-axis or thickness axis of the material and using a material that is anisotropic may not have much effect on the transmission line as it could on the filter.

Of course there are some high frequency laminates that are not glass reinforced, so the potential electrical differences in these two circuits may be minimal or non-existent when using these materials. Rogers Corporation does have high frequency laminates that are non-glass reinforced, however also supplied are glass reinforced substrates that are constructed with several glass concerns in mind. The glass layer is purposely moved deeper into the laminate and away from the surface, as much as possible. Also the most fine and dense glass is typically used and as few layers of glass as possible. These different attributes help minimize the potential affect of the glass. In figure 5 a cross section is shown for one of these materials and it is the Rogers RO3206™ laminate.

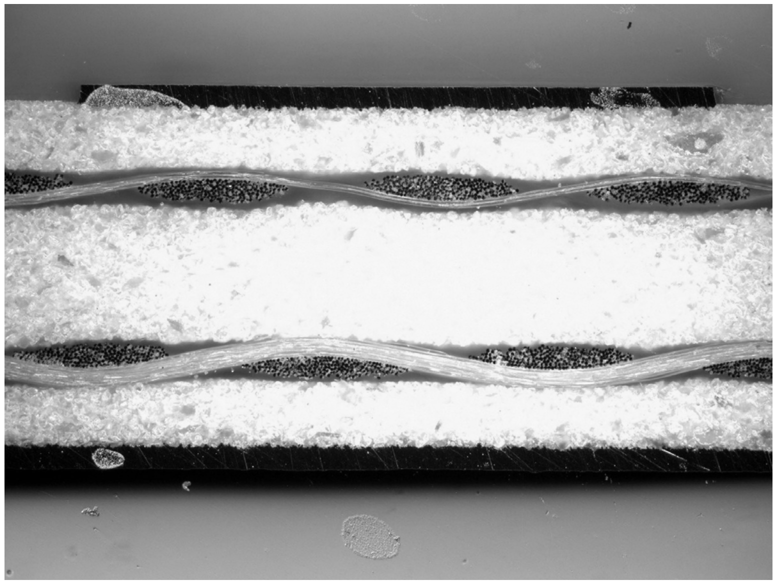


Figure 5. Cross section of a PTFE based laminate with optimum glass reinforcement.

Test methods: There are many different methods that can be used to test a laminate for the dk value. Most laminate suppliers use the standard IPC test methods; per IPC-TM-650.2.5. When looking specifically at the test methods for determining dk the most commonly used are the IPC-TM-650.2.5.5.5c (X Band, Clamped Stripline Resonator test) and IPC-TM-650.2.5.5.6 (FSR, Full Sheet Resonator test). Like any methodology each of these has good capabilities and some challenges, when looking at the test methods in detail.

The stripline resonator test method will be discussed first. This is a very good test method for a laminate supplier that needs to test large a volume of materials on a routine basis. However this method may yield a dk number that is slightly different than if a true multilayer PCB was made as the same resonator and using the same material. There are several reasons for this; although this is a good test method for a laminate supplier to use for process and quality control. A simple picture depicting the stripline test is shown in figure 6.

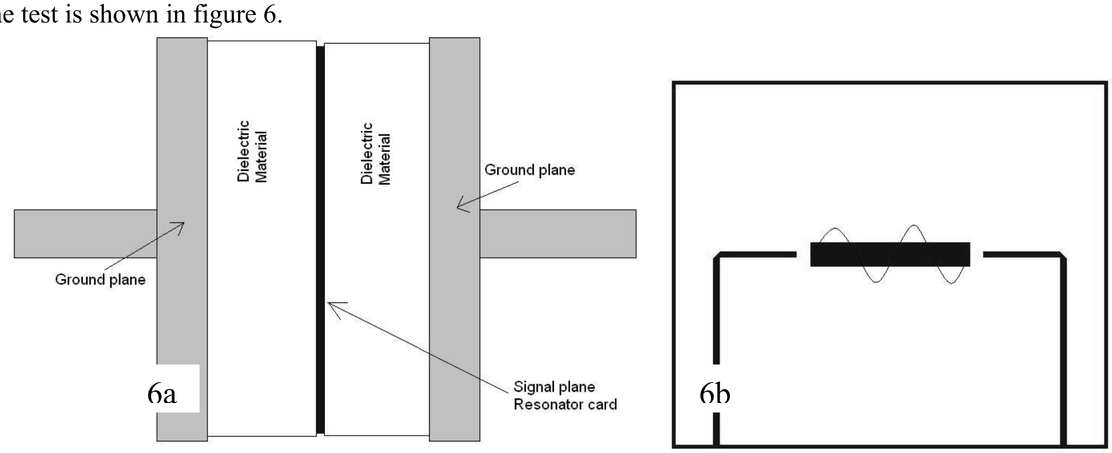


Figure 6. Clamped stripline resonator methodology. Figure 6a is the side view of the clamped stripline resonator. Figure 6b is the top view of the stripline resonator circuit that is sandwiched between the two ground planes.

The plates of the clamping mechanism are used as the ground planes. The signal plane, between the two ground planes, is a thin circuit that is designed as a good resonator at 10 GHz and using a length of 2 wavelengths. The substrate to be tested is then etched to be free of copper and placed between the resonator and ground planes. In doing this, it is inevitable to have some amount of entrapped air within these layers of the clamped stripline resonator. The entrapped air will lower the reported dk value. With some materials this is more significant than with others.

A material that uses a copper, which is relatively high profile (rough copper surface), will have the mirror image of the copper roughness on the substrate surface after the copper is etched away. This rougher substrate surface will increase the amount of surface area and potentially increase the amount of entrapped air during the stripline test.

Another potential issue is that the material under test should have intimate contact with the resonator circuit geometry. When the material being tested is a very rigid substrate then it will not allow much conformance around the etched copper pattern of the resonator. Whereas some PTFE materials are very soft and they will conform around the resonator geometry and minimize this concern.

As can be seen in figure 6b, the resonator is edge coupled and it is purposely loosely coupled. This is done to better realize the Q of the material as opposed to the Q of the circuit design. The Q is related to the loss of the resonator, which is related to the dissipation factor. Also the edge coupling will have some fringing electric fields which will make the resonator appear longer in length. This additional length is referred to as the ΔL in the formulas which relate to the calculation of the dk and df. The ΔL can also alter the dk values somewhat when testing material that is rigid and not conforming well in the gap area. The following formulas are from IPC-TM-650 2.5.5.5c as seen in equations 1 and 2 and pertain to the stripline resonator test method.

$$dk = \varepsilon_r = [n\ C\ /\ (2\ f_r\ (L + \Delta L))]^2 \qquad (1)$$

$$df = \tan\delta = [(f_1 - f_2)\ /\ f_r] - 1/Q_c \qquad (2)$$

C is the speed of light, f_r is the resonant center peak frequency, L is the resonator length, f_1 and f_2 are the 3dB frequencies associated with the bandwidth of the resonant peak. The $1/Q_c$ is the approximate conductor loss and is subtracted out in order to get the dielectric losses. The IPC test method defines this number per equation 3. If the copper that is used for the resonator circuit has a smooth surface as compared to the same resonator circuit using a rough copper surface, then the $1/Q_c$ value should vary from these two resonators due to the copper surface roughness difference. Equation 3 may not account for these differences adequately and could over estimate the df value of the material under test.

$$\frac{1}{Q_c} = \frac{\alpha_c\ C}{\pi f \sqrt{\varepsilon_r}} \qquad (3)$$

Another loss associated with a PCB resonator would be radiation losses and they are not accounted for here, which makes sense due to stripline structures having negligible radiation losses.

Two screenshots of a material under test are shown in figures 7 and 8. In figure 7 one can see several resonant peaks and are labeled nodes 1 through 5. The different resonant peaks are a difference in frequency of ½ wavelengths. With the lowest frequency being node 1 and is typically around 2.5 GHz and the highest at node 5 is 12.5 GHz, per the IPC resonator design specifications. Typically node 4 is the peak that is measured for determining dk and df and is design nominally at 10 GHz. The reason node 4 is not closer to the 10 GHz number in the figures, is because the resonator was designed for a product that has a 3.5 dk and the product under test has a dk that is slightly higher. Thus all of the nodes will shift down in frequency somewhat due to the increase in dk. The limit for obtaining the higher nodes is due to the type of connectors, cabling, fixture and the resonator design.

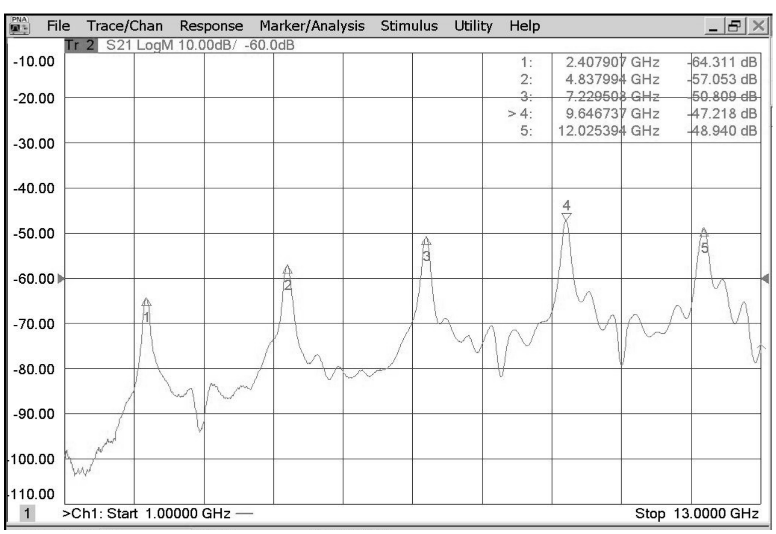


Figure 7. Five resonant peaks of a material under test with the stripline resonator

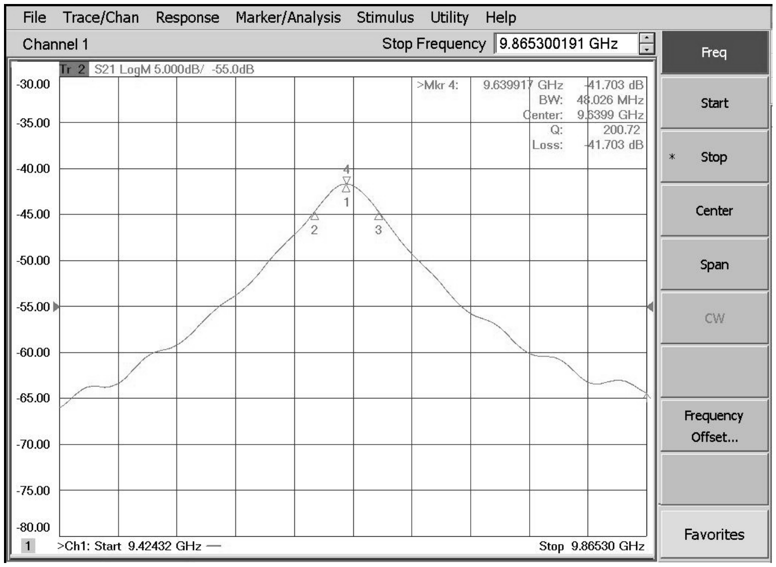


Figure 8. Node 4 resonant peak, nominally designed at 10 GHz. Markers 3 and 2 are f_1 and f_2 respectively and in regards to equation 2. Marker 4 is the center frequency of the resonant peak.

Some limited amount of experiments has been done in an effort to account for the entrapped air in the stripline test. With rigid material it was found that the dk number reported by the stripline test (while accounting for entrapped air) was within 0.016 of the dk number reported by an FSR test. The FSR test does not have entrapped air and will be discussed later. Considering the material that was tested, there is usually about a 0.26 difference in dk with these two different test methods.

When testing PTFE and trying to account for entrapped air, these materials are relatively soft so some assumptions had to be made about how much conformance was taking place around the resonator circuit pattern. The conformance assumption was twofold. First an assumption of a 50% deflection at the knee of the resonator conductor going down to the substrate surface in the gap areas and around the peripheral of the resonator conductor structures were made. Next the amount of surface area due to the copper roughness on the substrate being tested was assumed to be less than found on a laser profilometer by 20%. This was an effort to consider some compression of the soft material when clamped and under test. The output that was used from the laser profilometer was surface roughness as R_q (RMS) value of the substrate surface after the copper was etched off. In this case for the soft PTFE materials the dk numbers, when accounting for entrapped air, was within 0.012 of the dk numbers reported by the FSR test method. The FSR test method is typically at a lower frequency, so node 1 on the stripline test was used and a special panel size was used for the FSR test in order to have both tests operating at approximately the same frequency.

The FSR test is another test that is commonly used by high frequency circuit material manufacturers. This test is a quick test that is non-destructive, as opposed to the destructive test of the stripline resonator. This test is per IPC-TM-650 2.5.5.6 and FSR is the abbreviation for Full Sheet Resonator. It can determine a relatively accurate dk at a specific frequency, however due to the size of the panels tested (and some other reasons) the test is done at a relatively low frequency. The test is usually done at less than 1 GHz and for most high frequency laminates that is acceptable. However some materials are more sensitive than others to the dk value as it relates to frequency and that will be discussed later. Another issue with the FSR test is that the df is not determined and thinner laminates may be more challenging for accurate dk testing.

The FSR test method uses the actual laminate panel under test as a parallel plate waveguide. A network analyzer launches signals across some frequency range on one side of the panel and the transmitted power is monitored on the other side. The various maxima of resonant peaks of the transmission scattering parameter (S_{21}) are noted. The center frequency of a resonant peak is related to the physical length and / or width of the panel as it relates to wavelength. Usually a relatively large sample is tested which translates to a longer wavelength or in other words a lower frequency. A simple drawing of a panel under test, using the FSR method is shown in figure 9.

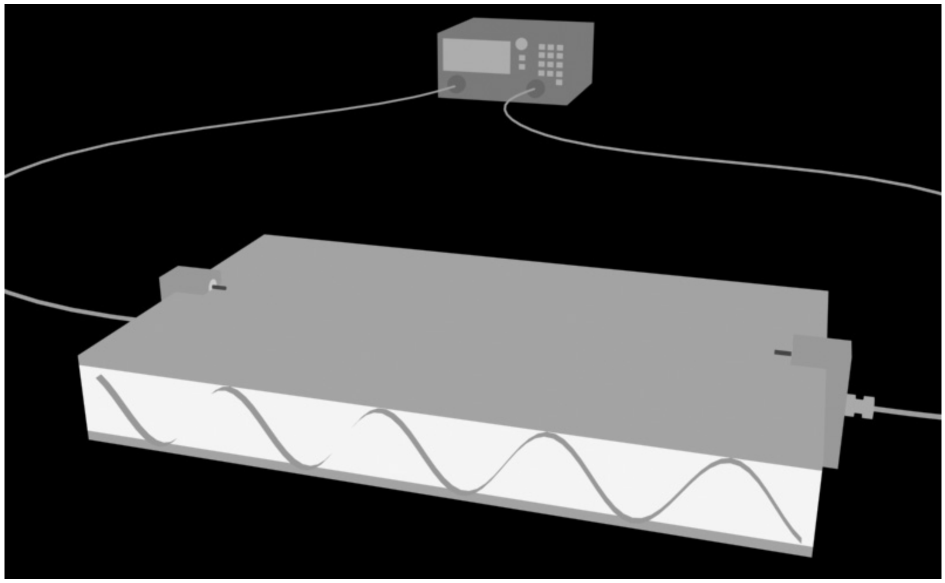


Figure 9. Panel being tested with the FSR test method.

The dissipation factor is not determined by this test method due to radiation losses not being accounted for with the open wall waveguide format. Per [1] it is possible to do FSR testing and account for the conductor and radiation losses in order to obtain df. This is done by calculating the conductor losses and radiation losses, subtracting them out, which will leave just the dielectric losses. With the dielectric loss known, then the df can be determined. This method uses finite difference method to perform field solving and appears to be relatively accurate; there are some assumptions that would need to be made. Another more practical manner of doing this may be to enclose the material under test and capture all radiation losses. This method will be described in more detail later in this paper.

A screenshot of a panel under test is shown in figure 10 with some notation.

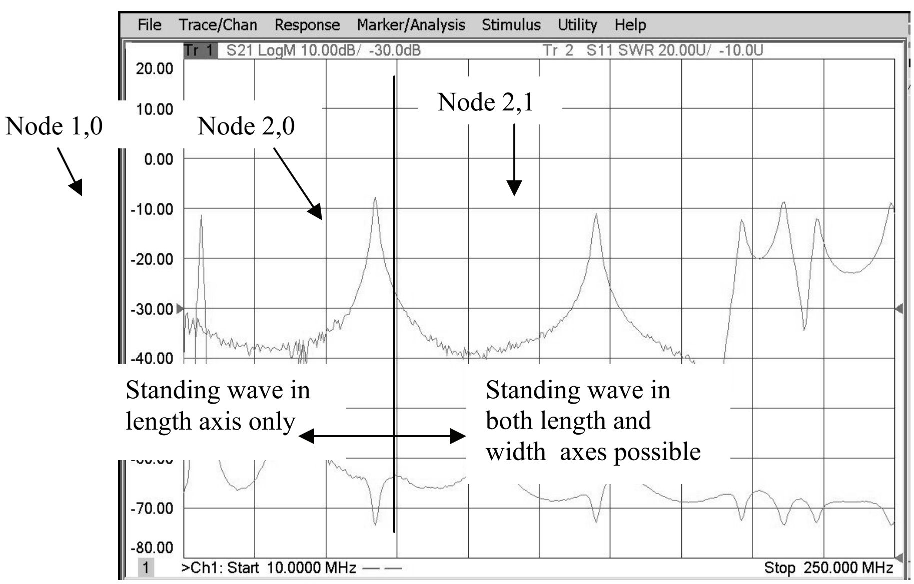


Figure 10. Screenshot of a panel under test for the FSR testing.

The different resonant peaks are identified with node connotation. In this case node 1,0 is referring a resonant peak where a maxima has occurred along the length axis only. Also it could be thought of as a standing wave established with a ½ wavelength along the length axis and no standing waves along the width axis. And of course if node 2,1 is considered, then there is a standing wave set up in the length direction of the panel which has 2 ½ wavelengths (1 full wavelength) and 1 ½ wavelength in the width direction.

It can be seen in figure 10 that there is a vertical line drawn on the chart that separates the range of frequencies to where only resonant nodes would occur on one axis (length) and the range where nodes could occur on both the width and length axes.

This is important to note because the nodes that are in the frequency range were standing waves can be set up on both axes may be susceptible to distortion of the resonant peaks due to wave interference patterns. And it is theorized this is the reason nodes 1,0 and 2,0 in figure 10 are well defined and the nodes above that may have some skew. In general, it is safer to measure the nodes in the frequency range where there are standing waves along one axis only.

A method to get more nodes along the length axis only, is by making the panel a dimension that is much longer that it is wide. With the width axis narrower that means the first standing wave will need to be at a higher frequency (shorter wavelength) and therefore you will get more resonant peaks in the range of frequencies that are related to the length axis only. This is a way to do FSR testing at higher frequencies safely. There is a risk of having a panel with such a small area that the fringing effects become significant and falsely alter the dk values. How small of an area would need to be determined experimentally using a material with a vast database of known good dk values. The reason why is the fringing effects will be more dominate on a thin material as compared to the same material that is thicker. Also the fringe effects will be more obvious at higher frequencies and then the nominal dk value of the material can alter this as well. A very high dk material will have fewer issues with the fringe effects, since the E-fields are more contained in the substrate as compared to a lower dk material. In general testing a panel that is thicker and with a large area will help minimize fringe effects concern.

The formulas used to determine the dk values for FSR testing are from IPC-TM-650 2.5.5.6 and are shown in equation 4 and 5.

$$f_r := \frac{c}{2}\cdot\sqrt{\frac{\left(\frac{m}{L}\right)^2+\left(\frac{n}{W}\right)^2}{dk}} \qquad (4)$$

$$dk := \left(\frac{c}{2\cdot f_r}\right)^2\cdot\left[\left(\frac{m}{L}\right)^2+\left(\frac{n}{W}\right)^2\right] \qquad (5)$$

The f_r is the resonant peak center frequency, c is the speed of light, m is the node in the length direction, n is the node in the width direction, L is the physical length of the panel and W is the width.

There is an experimental FSR test method that has shown promise for a very quick test that could be done by the laminate suppliers that appears to yield a relatively accurate dk and df values. This test method is the FSR testing within a grounded enclosed container. When configured correctly the radiation losses are contained and only the conductor losses are necessary to subtract out in order to obtain the dielectric loss; which is true of the stripline resonator test that many laminate suppliers already employ. Once the dielectric losses are understood then the df of the material is easily found. Admittedly this test will need to be fine tuned to compensate for some anomalies that are pretty well understood theoretically but would need validation.

A screenshot of a sample being tested in an enclosed FSR structure is shown in figure 11.

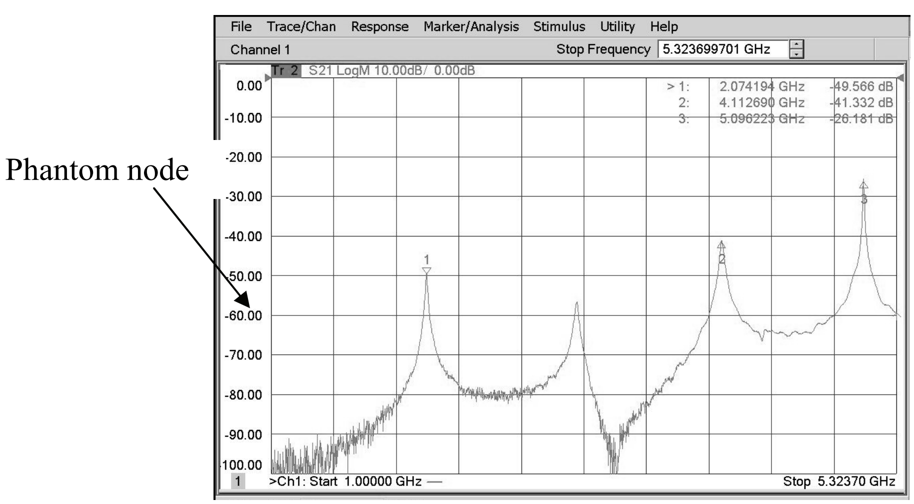


Figure 11. Screenshot of FSR nodes within an enclosed FSR

In figure 11 it can be seen that there are several resonant nodes. The noted markers of 1, 2, and 3 are node 1,0 and node 2,0 and node 2,1 respectively. There is another significant peak between nodes 1,0 and 2,0 that should not be there. It has been labeled a phantom node and it appears to be from a dimensional relationship between the signal launch probe and the enclosed housing distance. If this node was measured for resonant frequency and bandwidth, the reported dk and df would be significantly incorrect. The sample under test in figure 11 was a 30mil thick laminate with a substrate dk of 3.6 and was approximately 38.1mm (1.5”) by 25.4mm (1”).

A screenshot of node 1,0 is shown in figure 12.

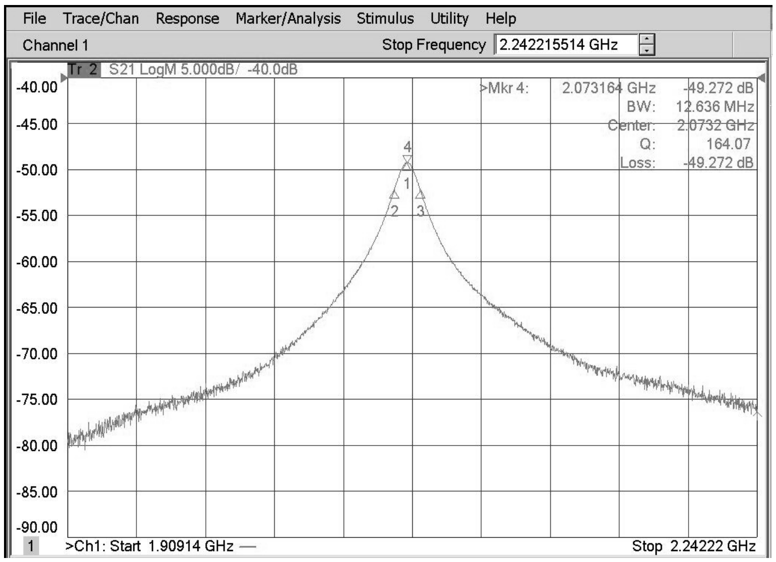


Figure 12. Node 1,0 shown in the enclosed FSR test configuration

Node 1,0 shown in figure 12 is very well defined. Obtaining the center frequency will determine the dk value per equation 5. The df value will need to account for and subtract out the conductor loss values. The same method for doing this will be done according to equation 2. Again radiation losses will not need to be considered with the enclosed FSR test. Determining the value for conductor losses would be done according to a popular microwave engineering text [2] and that follows:

$$\alpha_c = \frac{2\, k_c R_s}{\omega \mu \beta d} \qquad (6)$$

And determining the conductor losses due to equation 6 with a supplement to consider the affects of surface roughness of the copper is using the same reference, however a different page number [3] and that follows:

$$\alpha'_c = \alpha_c \left[1 + \frac{2}{\pi} \tan^{-1}(1.4) \left(\frac{RMS}{\delta_s} \right)^2 \right] \qquad (7)$$

The variables are: α'_c is the adjusted conductor loss due to copper roughness and α_c is the conductor loss without this consideration; k_c is the cut off frequency wavenumber, R_s is the surface resistance, ω is the angular frequency, μ is the permeability of the conductor and in the case of copper it is typically assumed to be $1^* \mu_0$, however in [4] a more accurate number is referenced for this property of copper to be $0.999991^*\mu_0$. β is the phase constant and d is the thickness of the conductor. In equation 7 the RMS value is the surface roughness of the conductor on the side which is in contact with the substrate (treated side of copper) and the δ_s the skin depth of the conductor. There is still some concern that the R_s may be somewhat erroneous due to the metallization that is used on the treated side of the copper. The conductivity of that metal and how it relates to the skin effects would need to be better understood to minimize this concern.

A manufacturer of high frequency laminates could then use a simple process flow model for testing dk and df of laminate materials in high volume using the enclosed FSR procedure as follows:

1. excise out a very precise double copper clad sample of the substrate.
2. the sample size dimensions must be very accurately known for the area.

3. the samples are loaded into an appropriate enclosed signal launch fixture
4. the fixture, network analyzer and supporting regiment adequately samples the response of the enclosed copper clad substrates
5. the dk and df are reported.

In practice this procedure could be very fast and as simple as stamping out an accurately controlled dimension of a substrate sample (hard die or routed), put it into a simple clamping fixture, close the fixture, measure the dominate resonant peak and report the values. The operator of this procedure would only stamp out the sample put it into a clamping fixture, press a button and the fixture would close, sample measured and results displayed. Extremely little human error could be introduced, with very minimal test error introduced assuming proper good engineering considerations are applied. At this point the enclosed FSR is considered experimental and those interested would need to do some optimization of this potential test procedure.

Substrate Construction: As it was seen in the case of the edge-coupled filter, the substrate construction can have a varying affect on the electrical performance of a microwave circuit. There are several other substrate related issues, which can have an affect as well.

Some materials have more anisotropic properties than others. Typically the woven glass materials have more anisotropy, but there are some exceptions. And some non-woven glass substrates can have nearly isotropic behavior, but that may not always be a good assumption. If a material has some anisotropic dk behavior then it may or may not be apparent depending on the circuit design and the same applies to the results of a test method. A paper was recently written [5] and it details how to better understand the affects of isotropic behave due to PCB materials.

The substrate thickness can also have an affect on the apparent dk value. There are several reasons for this phenomenon. In some cases the laminate supplier will use different styles of glass cloth for different thicknesses of the same product. This means that some thickness of laminate may have more glass as a percentage, than a different thickness, considering the same material. Then there is a capacitive affect as the same material is evaluated at different thickness. Also the issue of coupling could be involved as well and thinner laminates are much tighter coupled. And the surface resistance and copper surface roughness may become more dominate on thinner laminates. The thin laminates may be influenced by fringe effects as well. FSR testing was done on the same high frequency material at different thickness and shown in figure 13.

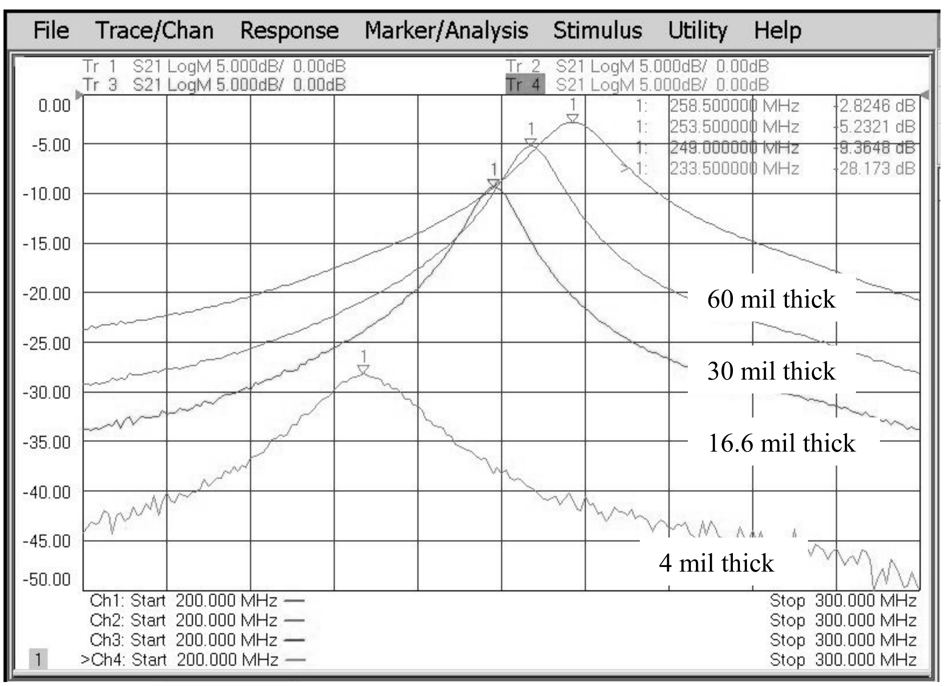


Figure 13. FSR testing and looking at node 1,0 for different thickness of the same material.

In figure 13 node 1,0 was tested by FSR on the same material with different thickness and it can be seen that the center resonant peak frequency decreases as the laminate is thinner. A decrease in center frequency for FSR testing is indicative of an increase in dk. Also the material that was tested here used the same building blocks to construct these thicknesses. Or in other words the same type of glass was used and the ratio of resin, filler and glass were the same.

A study done at Rogers Corporation [6] was done using several different test methods. In this study one of the testing procedures was using microstrip transmission lines on different thickness of the same material and the trend of thinner laminates having a higher dk was also revealed. A summary of this test method is shown in figure 14.

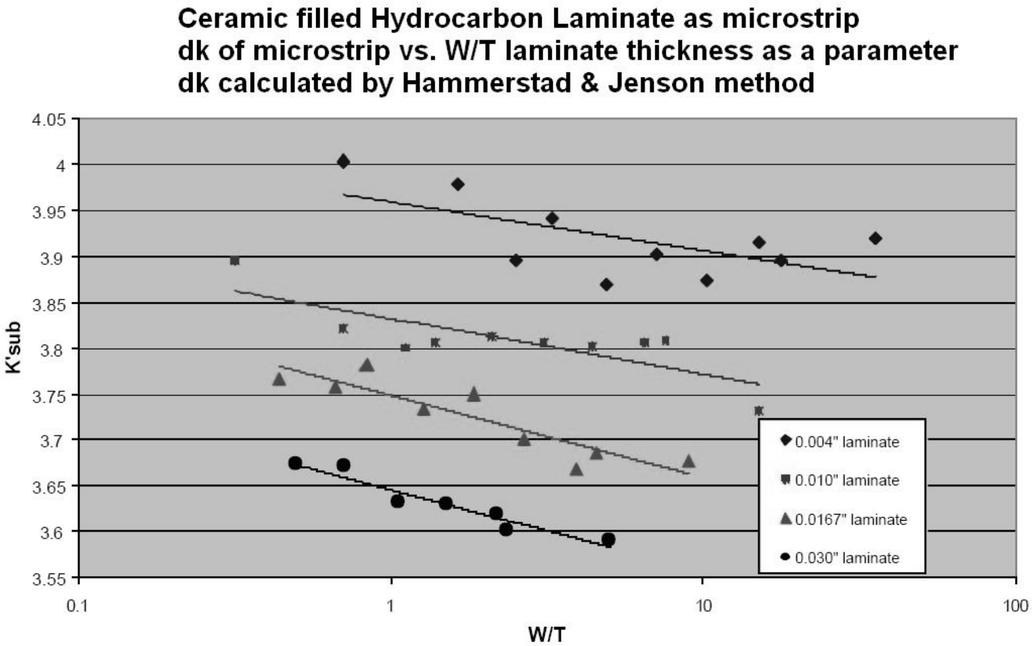


Figure 14. Summary results of microstrip circuit testing, evaluating dk and laminate thickness. The W/T ratio is the conductor width (W) to the substrate thickness (T). The reference to Hammerstad & Jenson is given here [7].

Another paper recently written [8] discusses the effects of copper roughness regarding the dk of the material. It is noted that the losses associated with the copper roughness will impact the complex phase constant and therefore can alter the dk. Essentially the exact same substrate using a smooth copper as compared to using a rougher copper surface will have a different dk value. Also there is a consideration [9] regarding the microstrip structure having the dk value altered due to phase velocity differences. A smoother copper will have a slightly faster phase velocity as compared to a rough copper surface. In general the smooth copper will have lower dk values. From the study mentioned in [8] is a chart given in figure 15.

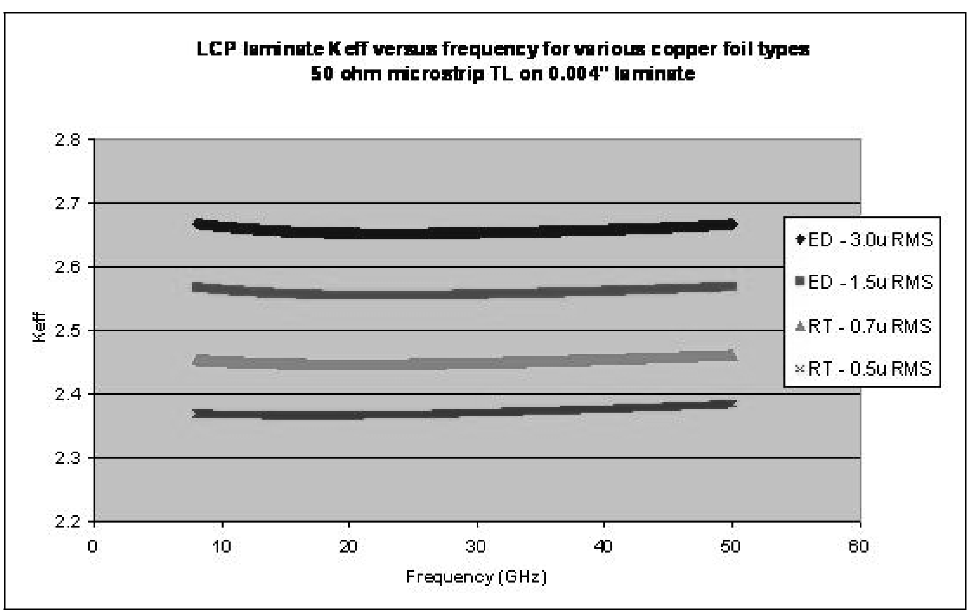


Figure 15. dk vs. copper roughness using the same substrate and different coppers with different surface roughness.

There are other issues regarding substrates and the dk values. The type of filler used to adjust the dk in a substrate can have some affect regarding dielectric dispersion and that will give the material a propensity to have a dk that varies with frequency. So the material could have a different dk at 1 GHz as compared to 10 GHz. Typically many materials have this attribute somewhat and some materials are more prone to dispersion than others.

Conclusion: Microwave circuit designs can experience different dk values of the substrate due to how the circuit is operating. Some designs will have electromagnetic fields that utilize the substrate different than other designs and thus a dk value of the same material may appear different.

There is no perfect test method. The test methods that laminate suppliers have used over many years are good for internal process control. These are industry standard IPC test methods and depending on an actual circuit design, the reported dk numbers from the laminate supplier may or may not have some variance for a particular design.

There are several inherent substrate properties that can cause a circuit to demonstrate a different dk than one may expect, such as dk varying with thickness or copper roughness. As a general statement the dk values found on laminate supplier datasheets is an average number, taken on a specific thickness of material with a defined test method. These numbers should be regarded as a good baseline or guide, however due to how the electromagnetic fields utilize the material in a particular design these numbers may or may not be slightly different than what the circuit will experience.

Acknowledgment
The author would like to express his gratitude to the diligent work, guidance and assistance of Dr. Al Horn, Art Aguayo, John Reynolds, Pat Larrow (LaFrance) and Semra Bekele.

[1] Jyh Sheen, “Conductor and Radiation Losses of the Parallel-Plate Dielectric Resonator”, IMTC 2005 – Instrumentation and Measurement Technology Conference, pp. 78-81, May 2005

[2] David M. Pozar, “Microwave Engineering, Third Edition”, John Wiley & Sons, Inc, pp 98-104, 2005

[3] David M. Pozar, “Microwave Engineering, Third Edition”, John Wiley & Sons, Inc, pp 86, 2005

[4] Brian C. Wadell, “Transmission Line Design Handbook”, Artech House, Inc., p.446, 1991

[5] James C. Rautio, “Measurement of Uniaxial Anisotropy in Rogers RO3010™ Substrate Material”, Submitted for review to COMCAS 2009, 2009

[6] John Reynolds, Pat Larrow, Al Horn, “Design Dielectric Constants for RO4003C™ and RO4350B™ High Frequency Circuit Substrates”, Technical Report 6006, 2006

[7] E. Hammerstad and O. Jenson, “Accurate models for microstrip computer aided design”, 1980 MTT-S Int. Microwave symp. Dig. pp. 407-409, May 1980

[8] J.W. Reynolds, P.A. LaFrance, J.C. Ratio, A.F. Horn III, “Effect of conductor profile on the insertion loss, propagation constant, and dispersion in thin high frequency transmission lines”, Rogers Corporation and Sonnet Software

[9] James D. Woermbke, “Soft Substrates Conquer Hard Designs”, Defense and Space Center, Systems Development Div. Westinghouse Electric Corp., 1982

Determining Dielectric Properties of High Frequency PCB Laminate Materials

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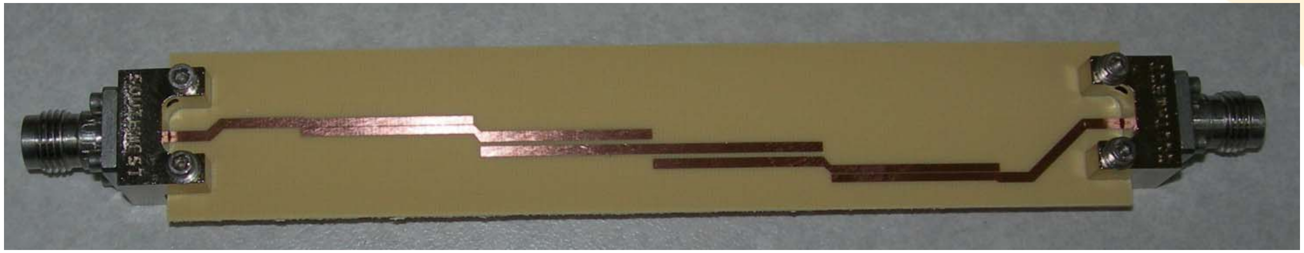
Several aspects explored related to understanding the dielectric constant (dk) value of high frequency materials

- Circuit Design
- Test Methods
- Material Construction

Determining Dielectric Properties of High Frequency PCB Materials – <u>Circuit Design</u>

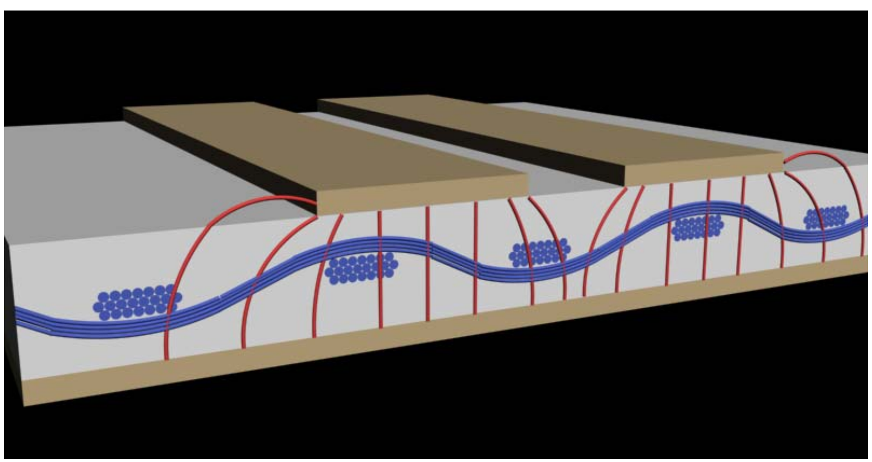
- Different high frequency circuit designs will use the material differently
- The electromagnetic fields can be different for different designs
- When the fields use the material differently, according to design, then a different dk value may be experienced when two different designs use the same material
- Two simple circuit design examples will be given
    - Microstrip edge coupled bandpass filter
    - Microstrip transmission line

Determining Dielectric Properties of High Frequency PCB Materials – Circuit Design

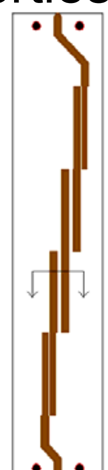


Microstrip edge coupled filter, operating in even and odd mode

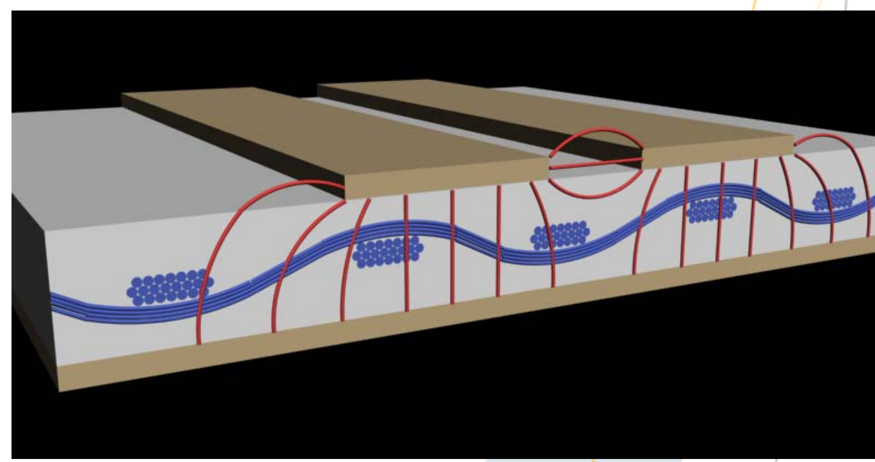
- Assuming a glass reinforced laminate, with a composite dk of 3.5
- dk of glass is assumed to be 6.2 and the resin must be lower than 3.5
- In even mode the E-fields mostly uses z-axis properties of the laminate
- Odd mode uses some z-axis properties as well as x-y axis properties



Operating in even mode



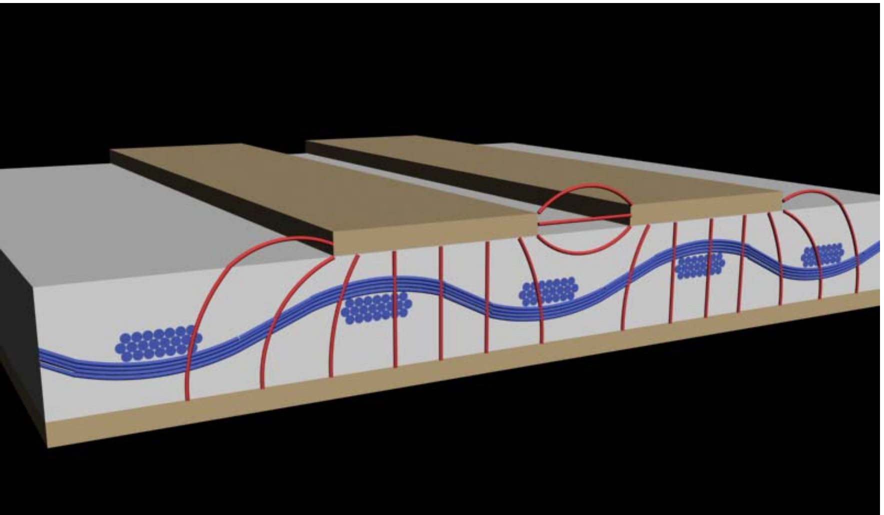
Top view

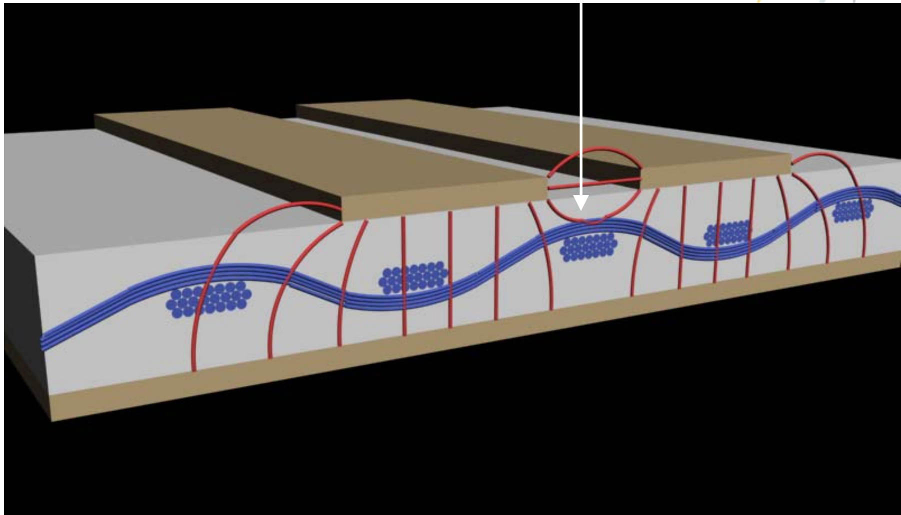


Operating in odd mode

Determining Dielectric Properties of High Frequency PCB Materials – Circuit Design

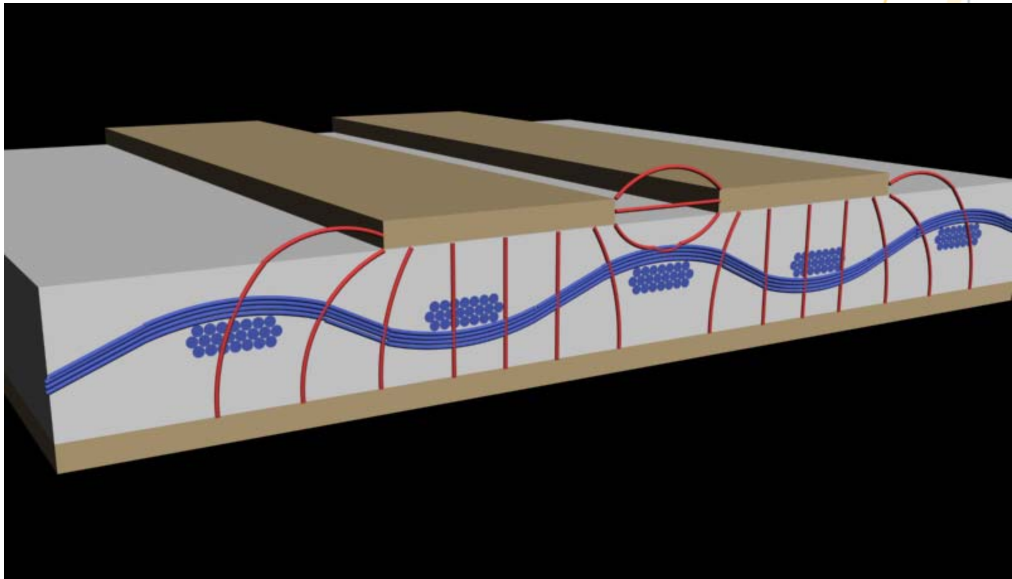
- With the stepped design of the filter, some filter segments may align to the glass weave features differently
- Both pictures below are operating in odd mode and are the same filter, but just looking at different segments
- Picture on the right has filter segments in different location as compared to the glass
- Edge coupled E-fields in right picture use glass, but not in the left picture
- Glass dk much higher than the resin system
- Circuit on the right should experience a higher dk due to the glass location





Determining Dielectric Properties of High Frequency PCB Materials – Circuit Design

- The glass-to-circuit pattern effect is more significant when using one glass layer that is a large course glass style and near the copper layers
- The effect could be more pronounced at higher frequencies
- Higher Frequencies:
  - will have shorter filter segments and the averaging affect is minimal
  - E-fields are more concentrated and the coupling fields are stronger
  - thinner laminates are used at higher frequency, so single glass layers are more likely (as shown). If the laminate had more glass layers, then there may be some beneficial averaging affects



Determining Dielectric Properties of High Frequency PCB Materials – Circuit Design

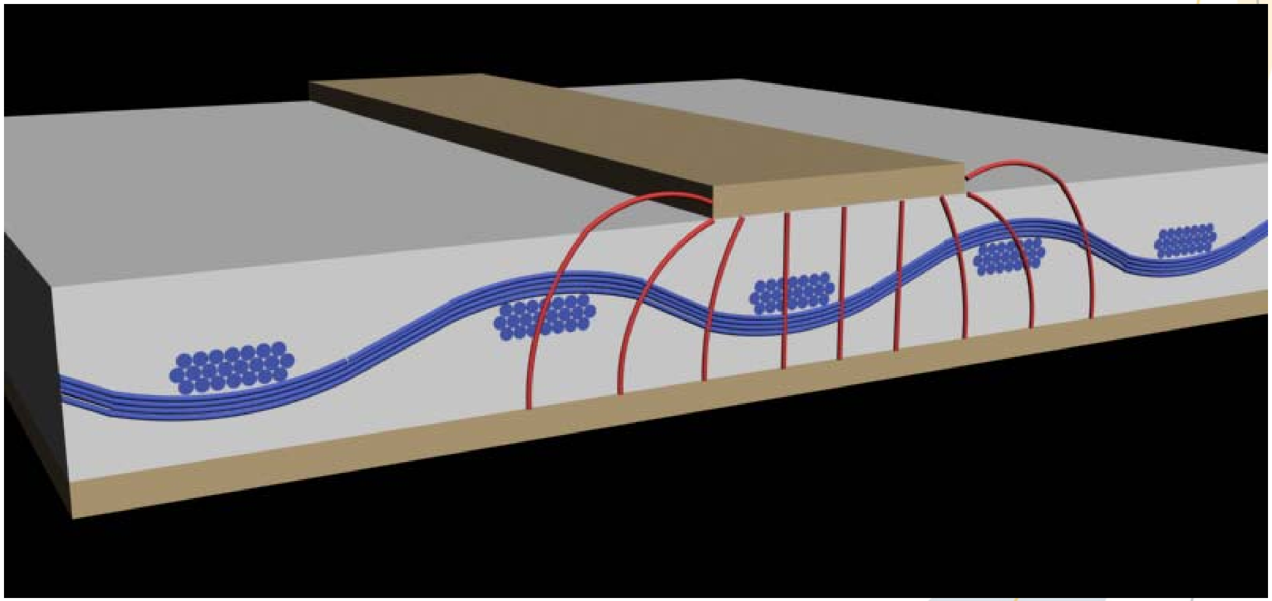
- Microstrip Transmission Line circuit
  - Less sensitive to the glass-to-circuit pattern effect because:
    - typically much longer conductors so there is a beneficial averaging effect over the distance
    - operates in the TEM mode usually and does not have the even-odd mode operation

TEM mode (Transverse Electromagnetic)

Red lines are symbolic of electric field lines

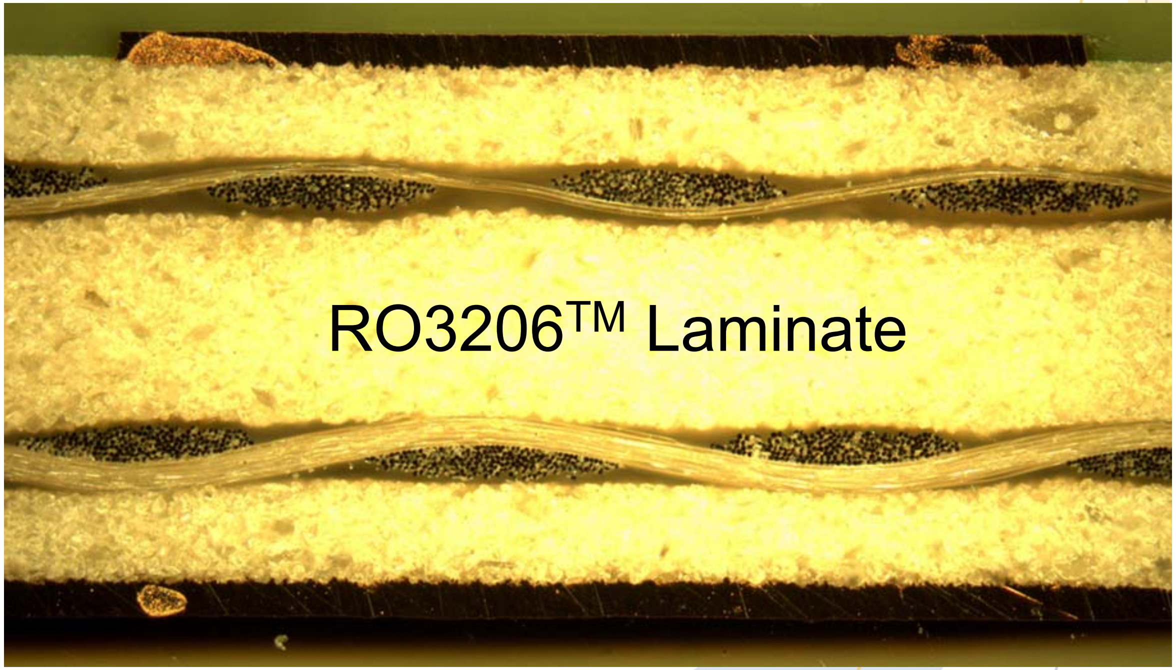
Magnetic field lines are not shown, however would encircle the signal conductor

Wave propagation would be out of the page



Determining Dielectric Properties of High Frequency PCB Materials – Circuit Design

- Some high frequency laminates do not have glass layers, such as Rogers RO3000® laminate series
- With these laminates the glass-to-circuit pattern is not a concern
- Some high frequency laminates with glass reinforcement, are designed optimum for glass concerns
- Having the glass deeper into the substrate, as few glass layers as possible and fine-dense glass is optimum as shown in the picture below

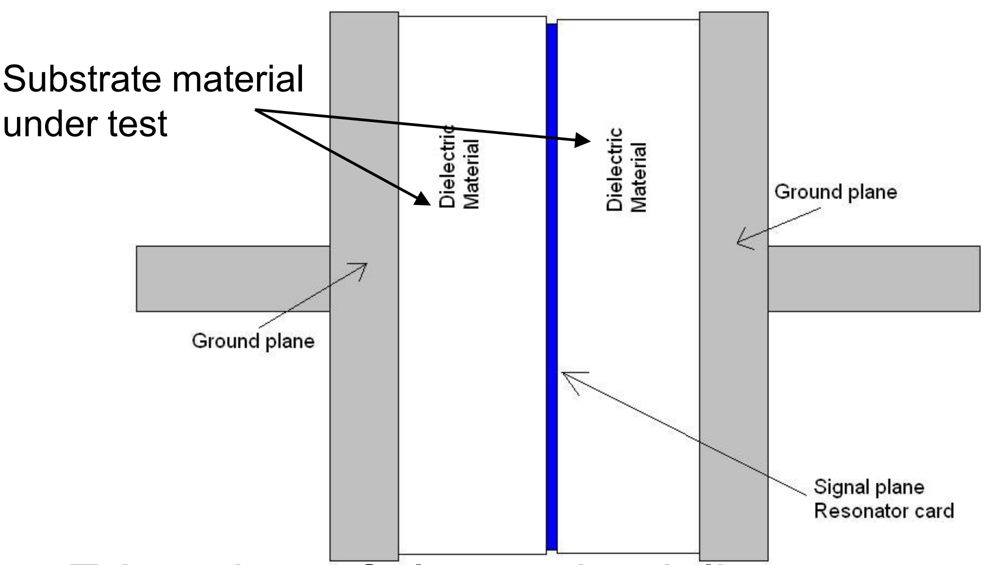


Determining Dielectric Properties of High Frequency PCB Materials – Test Methods

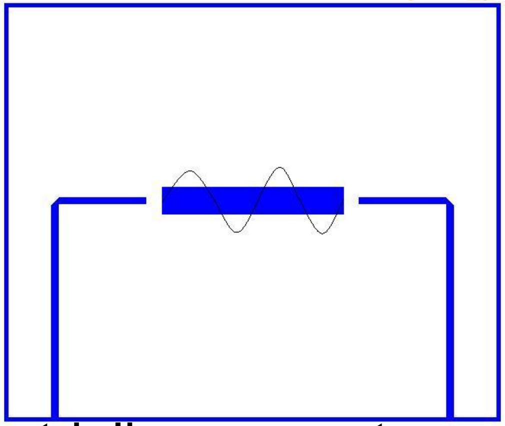
- There are a multitude of test methods to determine dk and dissipation factor (df) of a high frequency PCB material
- Each test method has it's own good capabilities and challenges
- There is no perfect test method
- The determined dk value from one test method may vary as compared to another, when testing the exact same material
- Two common IPC test methods will be discussed in detail
    - X-Band Clamped Stripline Resonator per IPC-TM-650 2.5.5.5c
    - Full Sheet Resonator (FSR) per IPC-TM-650 2.5.5.6

Determining Dielectric Properties of High Frequency PCB Materials – <u>Test Methods</u>

- Clamp stripline resonator test method:
  - Excellent method for a laminate supplier needing to test high volume of samples quickly
  - Very good repeatability and reliability
  - Excellent test for Process Control or QA
  - The reported dk results may or may not be similar to a “real” stripline resonator PCB made of the exact same material and same design



Edge view of clamped stripline



Top view of stripline resonator circuit sandwiched between ground planes

Determining Dielectric Properties of High Frequency PCB Materials – Test Methods

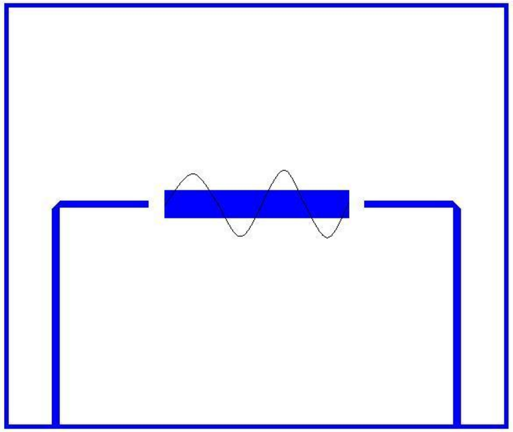
- Clamp stripline resonator test method:
  - Resonator designed to have two wavelengths at 10 GHz
  - Design is loosely gap coupled to better realize the Q of the material
  - Q is related to losses and dielectric losses related to df
  - Standard IPC formulas may overestimate the df value of a material
    - Conductor losses subtracted out to get the dielectric losses (df) may not adequately account for losses due to copper surface roughness

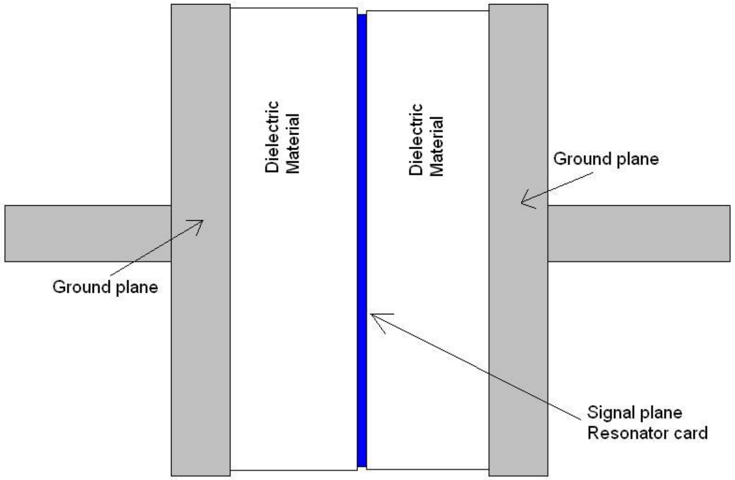
$$df = \tan\delta = [(f_1 - f_2) / f_r] - 1/Q_c \qquad \frac{1}{Q_c} = \frac{\alpha_c C}{\pi f \sqrt{\varepsilon_r}}$$

  - The ΔL value is the added electrical length of the resonator to account for fringe effects at the gaps $dk = \varepsilon_r = [n\,C / (2 f_r (L + \Delta L))]^2$
    - This may cause more variance in dk values with some rigid materials that do not conform to the resonator circuit geometry well

Determining Dielectric Properties of High Frequency PCB Materials – <u>Test Methods</u>

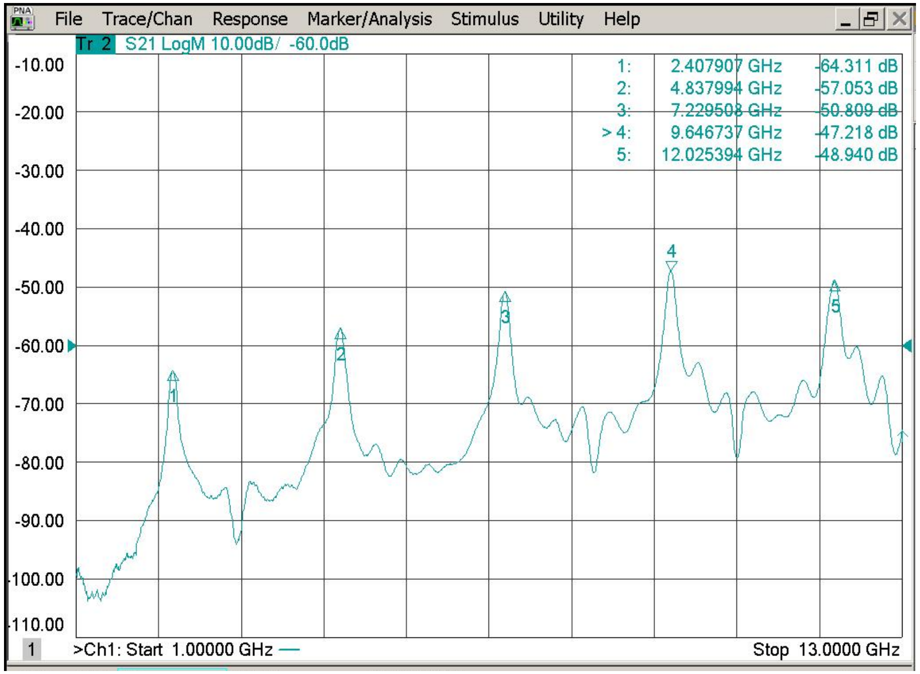
- Clamp stripline resonator test method:
  - Material for testing is etched free of copper, placed between the resonator circuit and ground planes
  - Entrapped air will lower the reported dk value
  - Some materials will have more entrapped air than others
    - Rigid materials with minimal conformance to the resonator circuit pattern
    - Materials that use a rough copper will increase the surface area of the sample under test



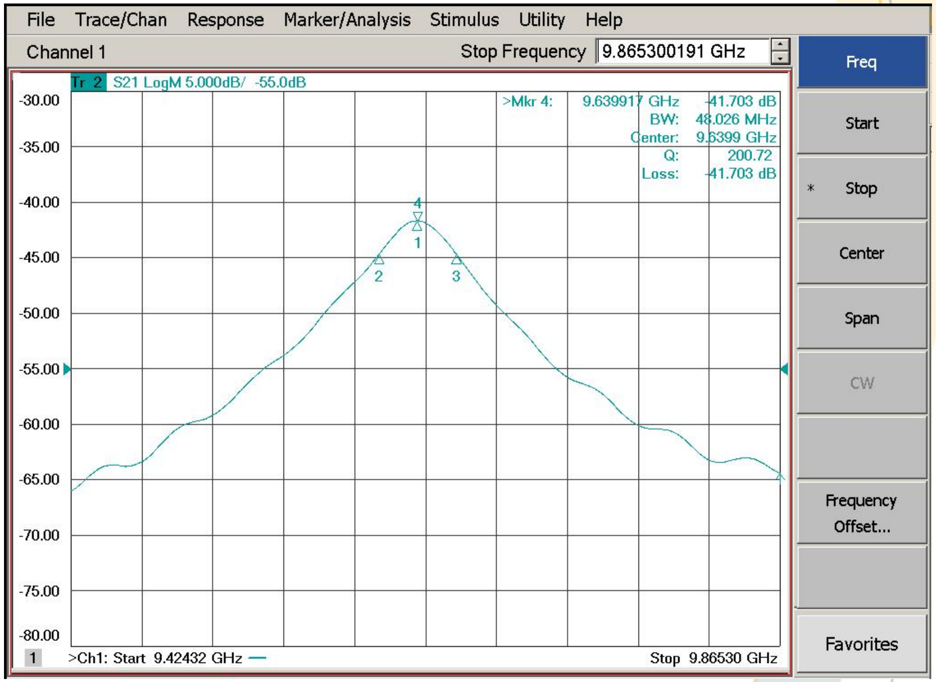


Determining Dielectric Properties of High Frequency PCB Materials – Test Methods

- Clamp stripline resonator test method:
  - Screen shots of stripline resonator nodes



Nodes 1 - 5

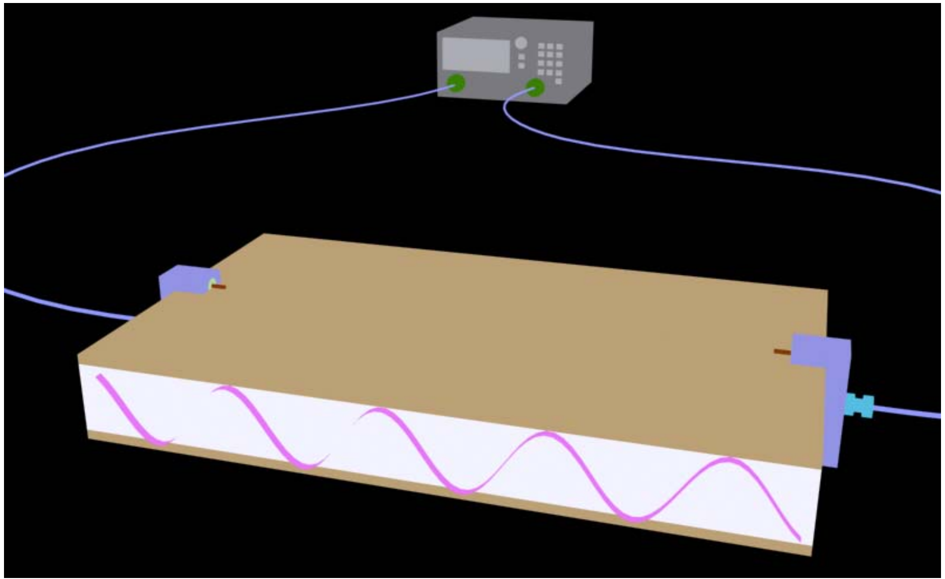


Node 4, 10 GHz, dk and df testing

Using a laserprofilometer, it has been found that the entrapped air can be approximated relatively well, to increase the accuracy of this test

Determining Dielectric Properties of High Frequency PCB Materials – <u>Test Methods</u>

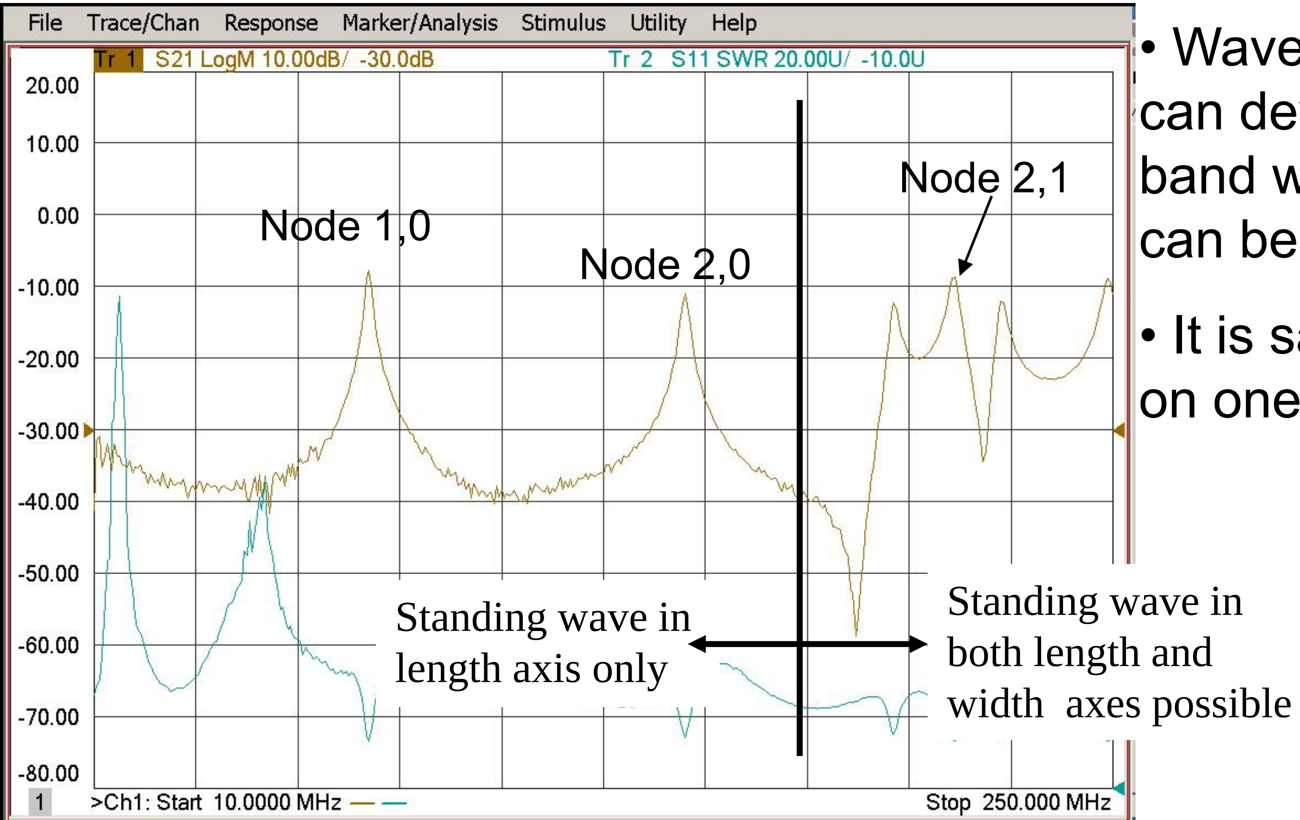
- Full Sheet Resonator (FSR):
  - Non-destructive test, unlike the stripline resonator test
  - Uses the actual panel under test as a parallel plate waveguide
  - Resonant peaks found where ½ wavelength standing waves are established or maxima peaks from the transmission parameter S_{21}
  - Since the panel sizes are relatively large, so is the wavelength; therefore this testing is done at lower frequencies



  - dk values only are reported
  - Radiation losses not accounted for, so can not report df

Determining Dielectric Properties of High Frequency PCB Materials – <u>Test Methods</u>

- Full Sheet Resonator (FSR):
  - Node 1,0 is 1, ½ wavelength in the length direction and 0 in the width
  - Node 2,1 is 2, ½ wavelengths in length axis and 1, ½ wavelength in width



- Wave interference patterns can develop in the frequency band where standing waves can be in both length and width
- It is safer to measure nodes on one axis only (length)

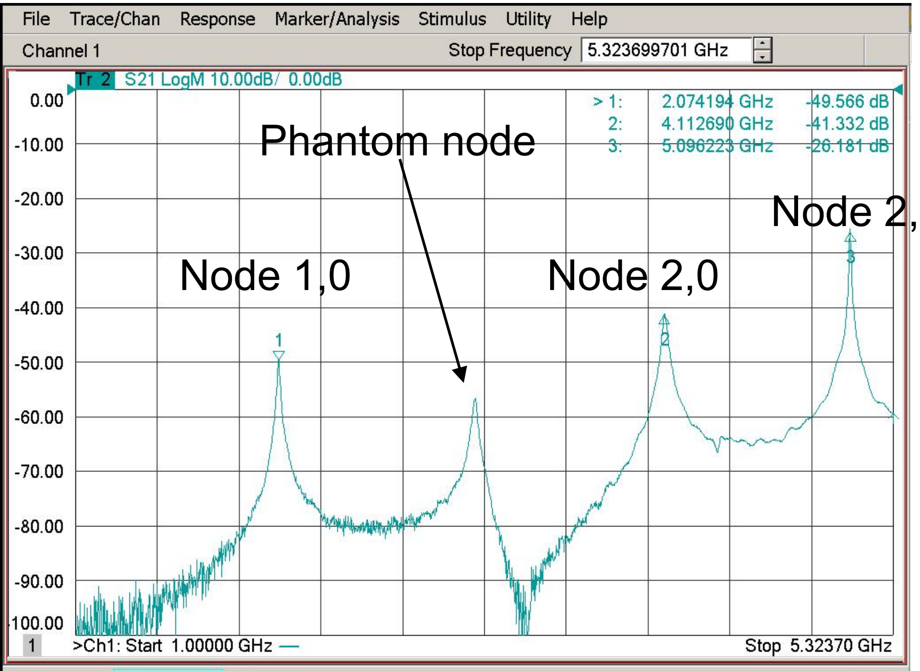
Determining Dielectric Properties of High Frequency PCB Materials – Test Methods

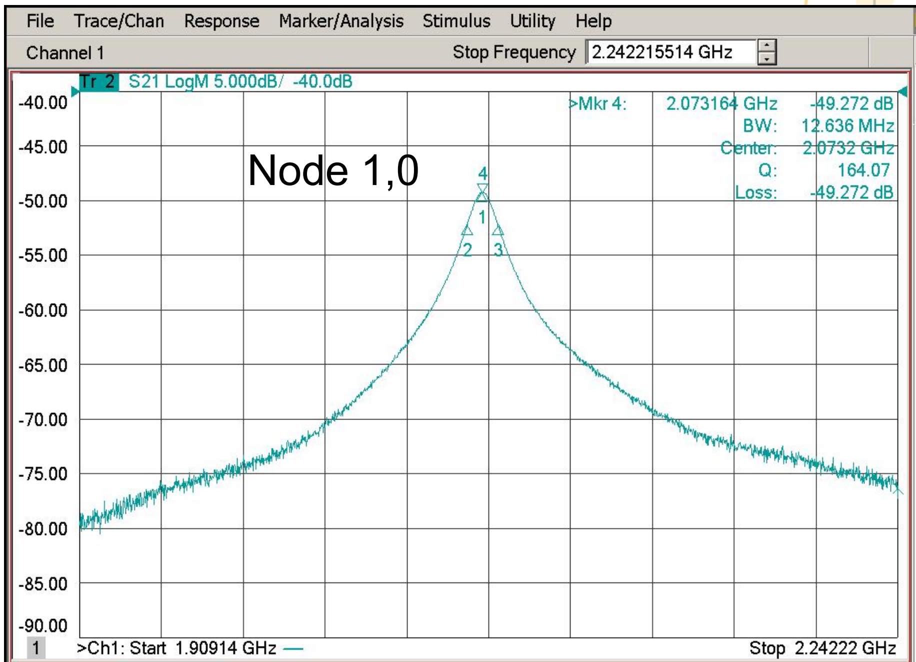
- Full Sheet Resonator (FSR):
  - More resonant peaks can be accomplished in the length axis if the length:width ratio is altered to have a relatively narrow panel
    - A more narrow width means a higher frequency is needed to establish the first node in the region of length-width standing waves
    - This allows higher frequency testing with safe nodes (length only)
    - Too narrow can cause the fringe effects to become troublesome
  - Field solving techniques [1] have been used to account for radiation losses and therefore can find df values from FSR
  - A more practical approach may be using a grounded enclosed fixture for the FSR test
    - This will encapsulate the radiation losses and then only the conductor losses need to be accounted for in order to calculate the df

$$\alpha_c = \frac{2\,k_c R_s}{\omega \mu \beta d} \qquad \alpha'_c = \alpha_c \left[1 + \frac{2}{\pi} \tan^{-1}(1.4) \left(\frac{RMS}{\delta_s} \right)^2 \right]$$

Determining Dielectric Properties of High Frequency PCB Materials – <u>Test Methods</u>

- Full Sheet Resonator (FSR):
  - Experimental Enclosed FSR test method
  - Phantom node is due to probe-to-enclosure wall distance
  - This could be an extremely fast test for high volume dk and df testing
  - Accuracy of sample dimensions is critical
  - Test method needs optimization, experimental only at this time





Determining Dielectric Properties of High Frequency PCB Materials – Material Construction

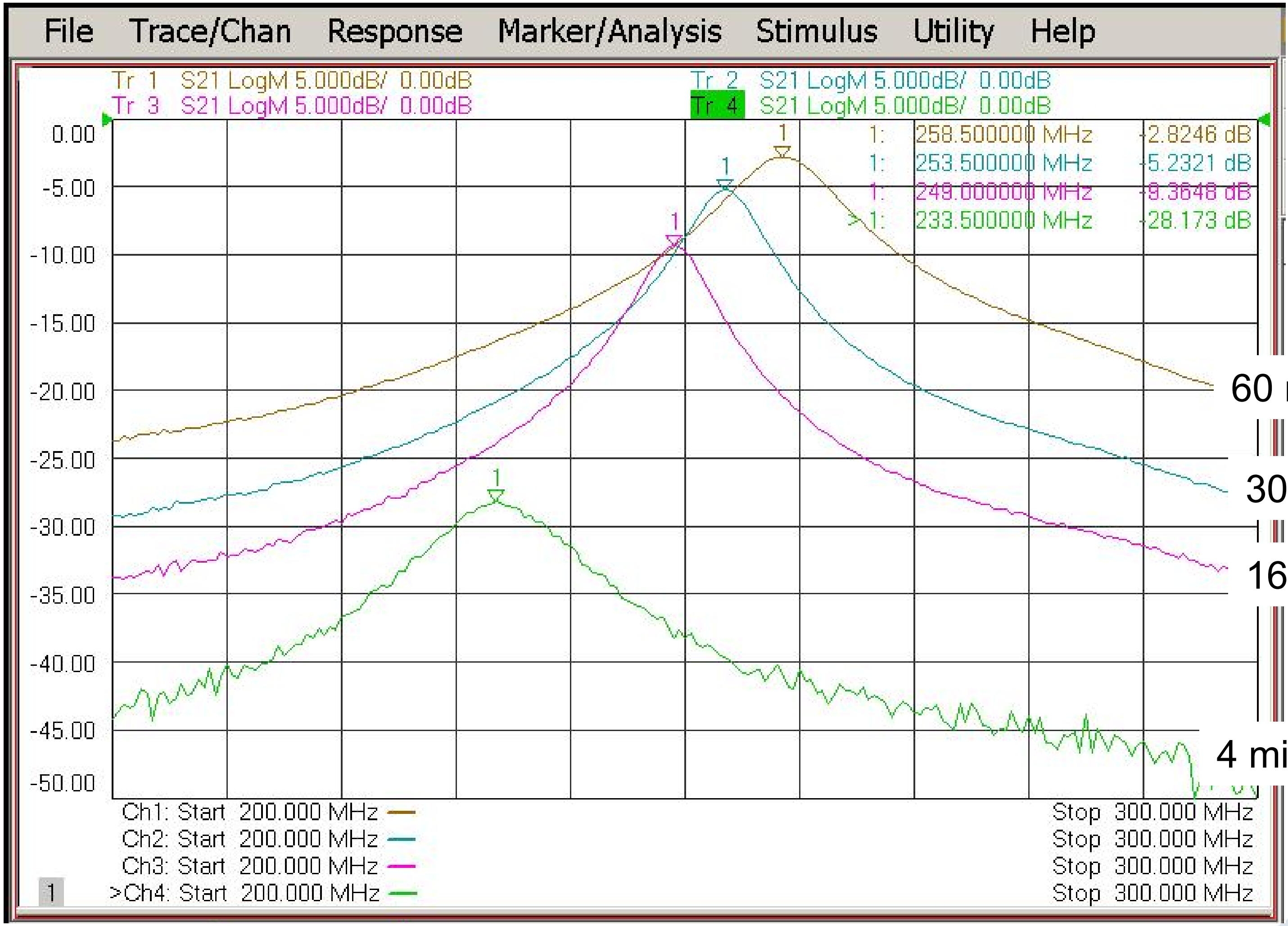
- There are several issues where the material construction can alter the assumed dk value
    - A laminate supplier may use a different glass ratio when making the same laminate, however in different thicknesses
    - Anisotropic dk behavior
        - Most times due to glass reinforcement
        - Sometimes non-glass reinforced filled materials can be anisotropic
    - dk that varies with thickness (not due to glass ratio)
    - dk that varies with copper losses due to variation in surface roughness

Determining Dielectric Properties of High Frequency PCB Materials – Material Construction

- dk that varies with thickness (not due to glass ratio). Three reasons are hypothesized:
    - Parallel plate capacitance effect
    - Coupling gets tighter as the copper planes get closer (thinner laminate). Coupling can effect the center resonant frequency for most resonators
    - As the material gets thinner, copper losses begin to dominate.
        - A material with rougher copper may adjust the dk more than the same material using a smooth copper
        - Surface resistance values may induce some error depending on the metallization used on the treated side of the copper
        - Skin effects more dominate a lower frequency and thin laminates

Determining Dielectric Properties of High Frequency PCB Materials – <u>Material Construction</u>

• dk that varies with thickness; shown is node FSR node 1,0 for various thickness of the same material

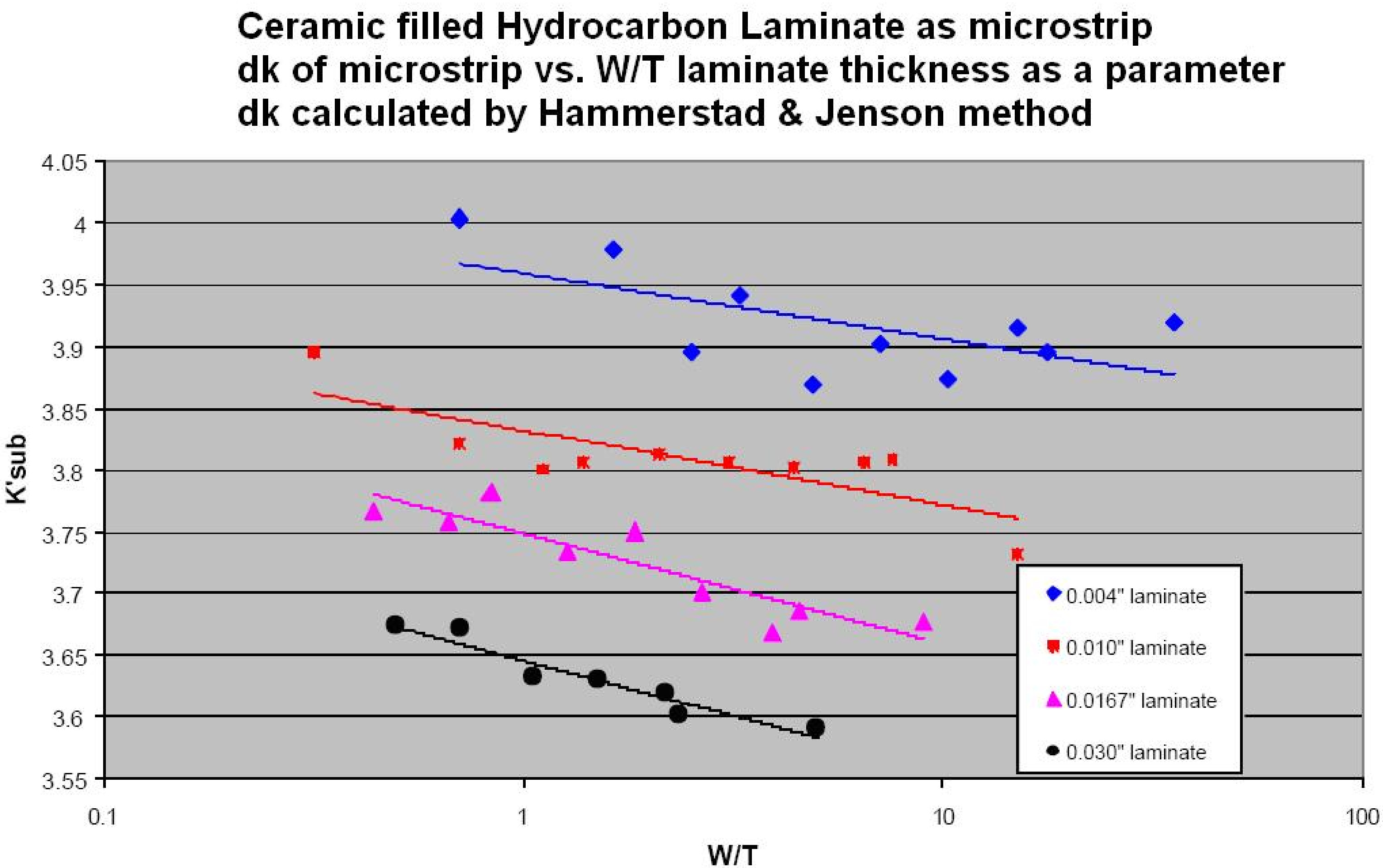


A decrease in center frequency is an increase in dk

Thinner laminates have higher dk

Determining Dielectric Properties of High Frequency PCB Materials – Material Construction

• dk that varies with thickness; A study [2] using microstrip transmission lines on same material with different thickness

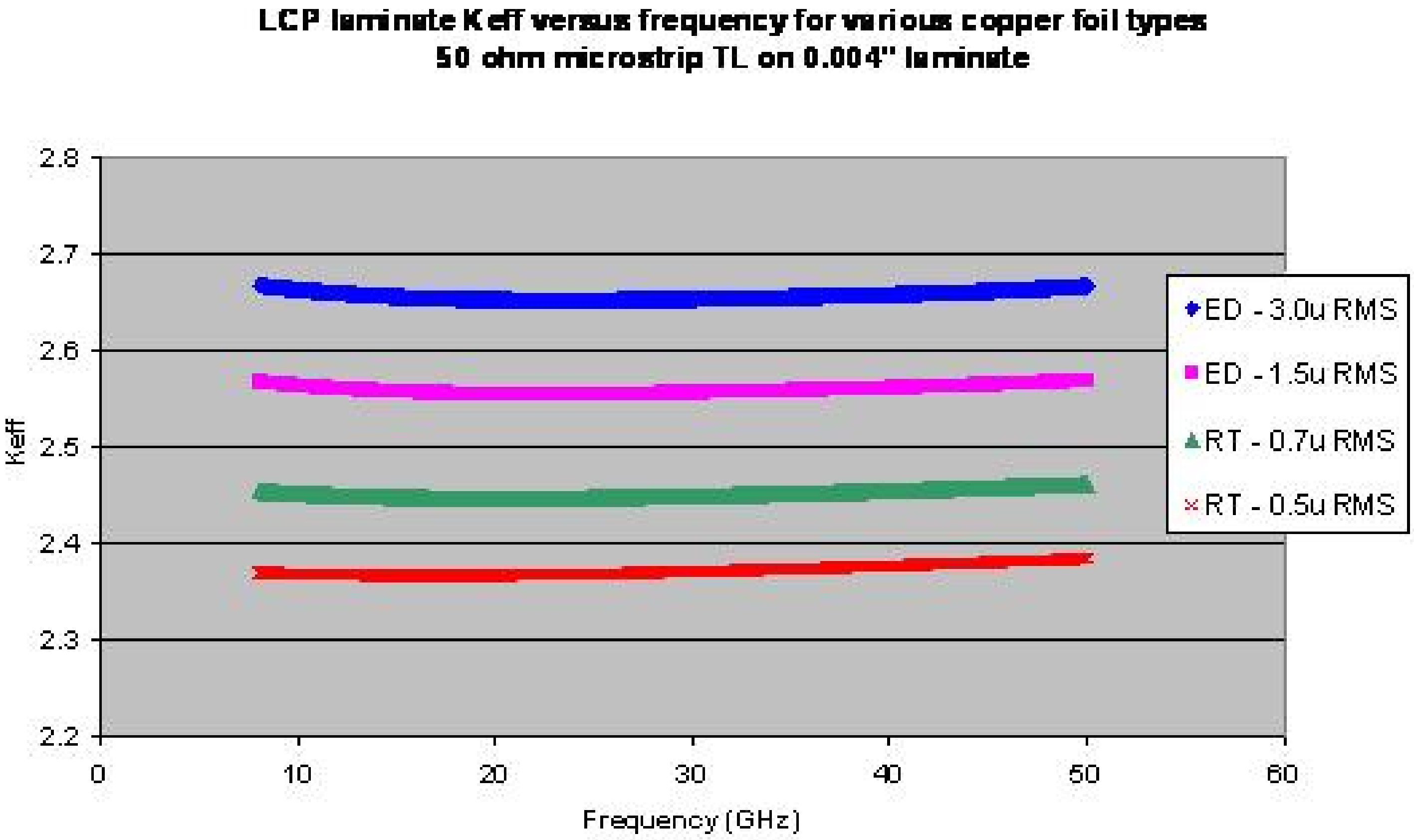


W is Width and T is thickness

Hammerstad & Jenson reference [3]

Determining Dielectric Properties of High Frequency PCB Materials – Material Construction

• dk that varies with copper roughness; Rogers Corporation study [4] showing the effects of dk with regards to only changing the copper roughness on a homogenous laminate material



Determining Dielectric Properties of High Frequency PCB Materials – Conclusion

- Conclusion
  - Due to the electromagnetic fields of a specific circuit design, the circuit can experience a different dk on one design as compared to another when using the exact same material
  - IPC test methods are intended to give the material supplier a good system for process and quality control
  - IPC test methods are intended to give the circuit designer a good approximation of the dk and df values
  - There are several inherent material properties with any laminate, that can alter the assumed dk to be a slightly different value
  - Good news is that the laminate supplier test methods (specifically Clamped stripline resonator and FSR) are good for maintaining a consistent product

Determining Dielectric Properties of High Frequency PCB Materials – Conclusion

• References

[1] Jyh Sheen, “Conductor and Radiation Losses of the Parallel-Plate Dielectric Resonator”, IMTC 2005 – Instrumentation and Measurement Technology Conference, pp. 78-81, May 2005

[2] John Reynolds, Pat Larrow, Al Horn, “Design Dielectric Constants for RO4003CTM and RO4350BTM High Frequency Circuit Substrates”, Technical Report 6006, 2006

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[4] J.W. Reynolds, P.A. LaFrance, J.C. Ratio, A.F. Horn III, “Effect of conductor profile on the insertion loss, propagation constant, and dispersion in thin high frequency transmission lines”, Rogers Corporation and Sonnet Software