8^{th} Annual Symposium on Signal Integrity

PENN STATE, Harrisburg
Center for Signal Integrity

Practical Measurements of Dielectric Constant and Loss for PCB Materials at High Frequency

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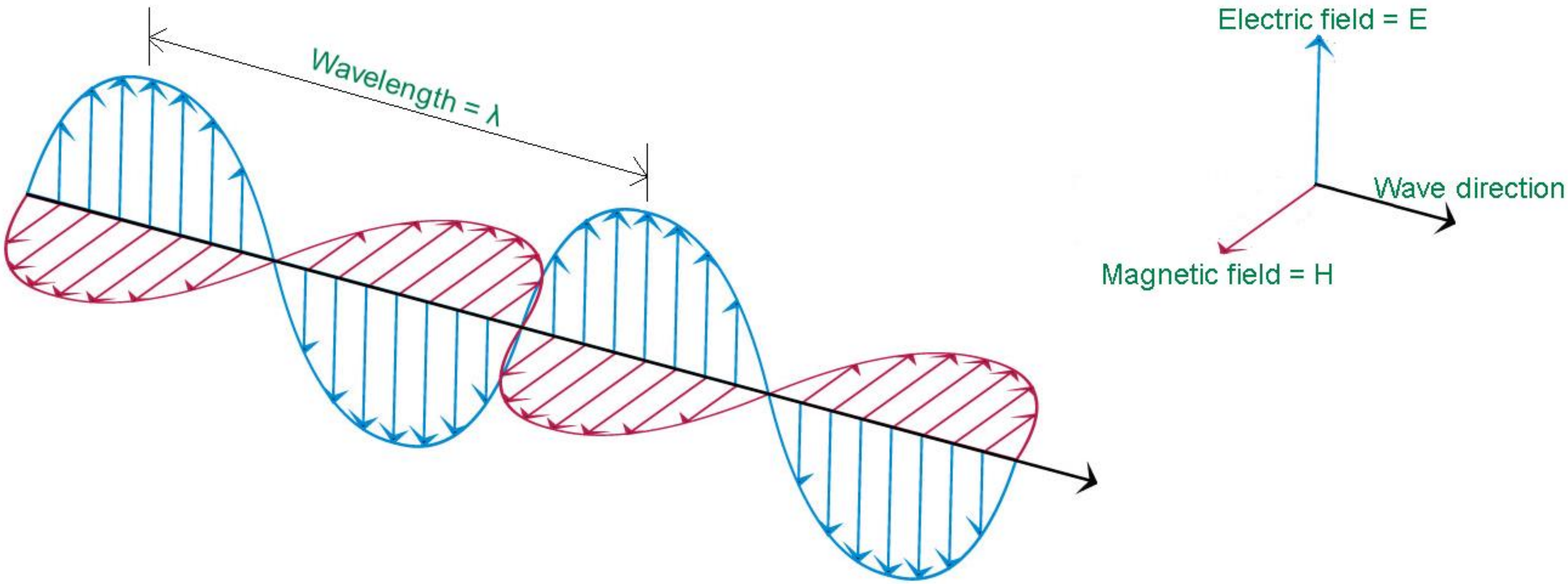
Practical Measurements of Dielectric Constant and Loss for PCB Materials at High Frequency

Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

Common Test Methods for Material Electrical Characterization

Circuit Evaluation Techniques for Material Characterization

Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)



Wavelength (λ) is the physical length from one point of a wave to the same point on the next wave

Long wavelength = low frequency and the opposite is true

Short wavelength = more waves in the same time frame so higher frequency

Amplitude is the height of the wave and often related to power

High electric field = High magnetic field = High amplitude = High power

Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

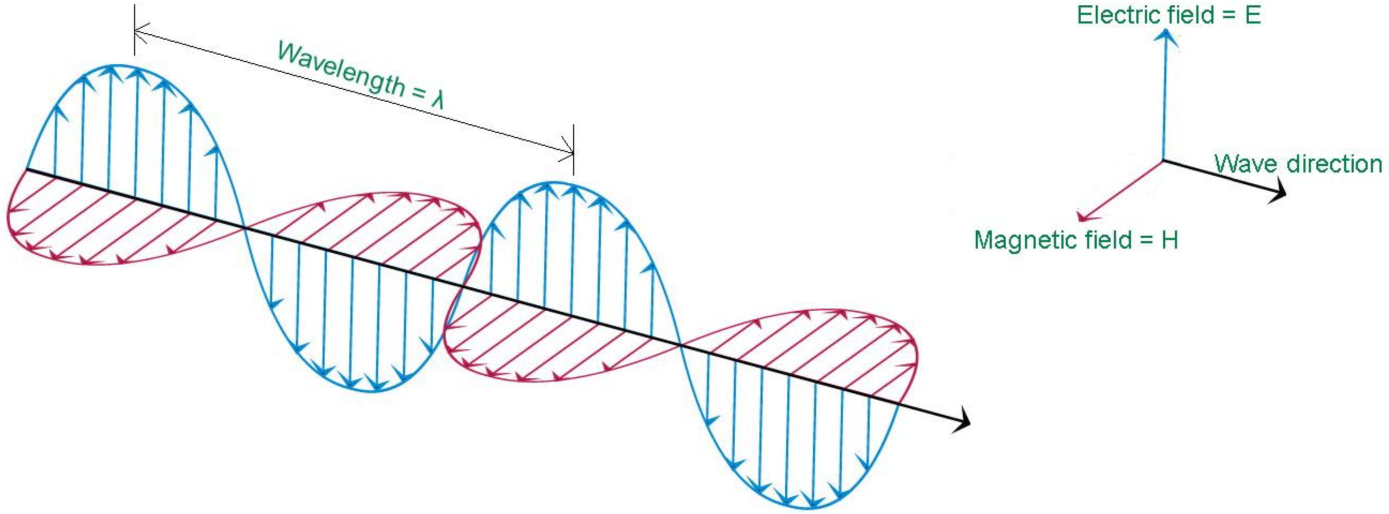
- Transverse ElectroMagnetic (TEM) wave

  Electric field varies in z axis

  Magnetic field varies in x axis

  Wave propagation is in y axis

- TEM wave propagation is most common in PCB technology, but there are other waves



Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

Other wave propagation modes are:

TE (transverse-Electric) or H wave; magnetic field travels along with wave

TM (transverse-Magnetic) or E wave; electric field travels along with wave

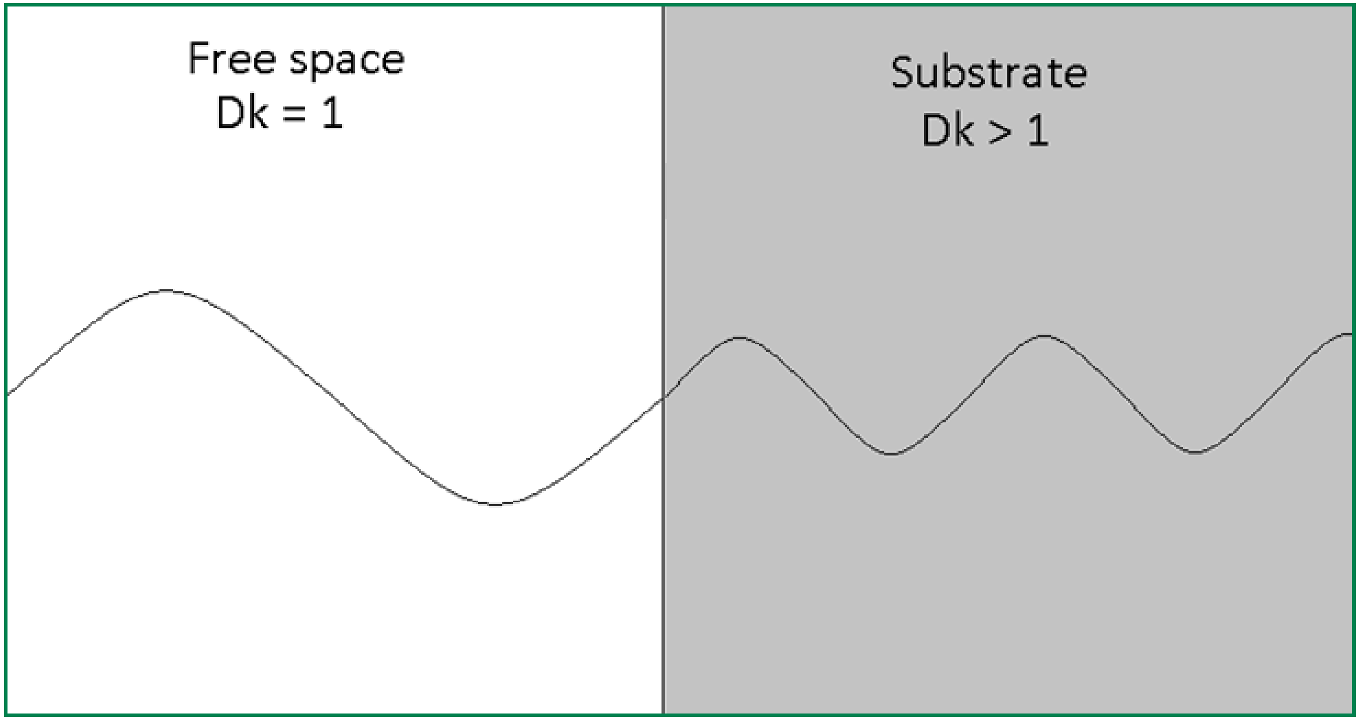
TEM or quasi TEM waves are typically the intended wave for a transmission line

Some PCB design scenarios will have problems with “modes” or “moding”

Moding issues are when the intended TEM wave is interfered with another wave mode such as TE or TM modes; this is a spurious parasitic wave or unwanted wave

Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

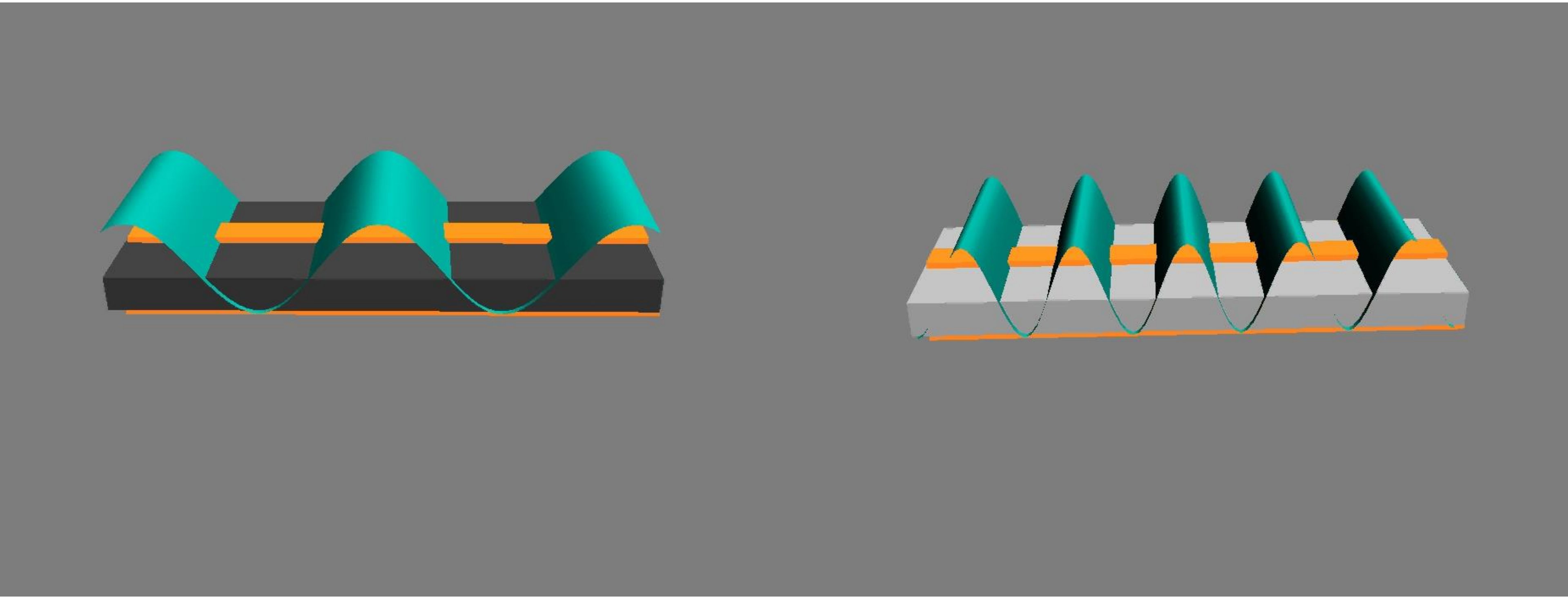
- When an EM wave transitions from free space to a medium of higher relative permittivity (ε_r or dielectric constant or Dk) it will:
  - have slower velocity
  - have a shorter wavelength
  - and the amplitude is reduced



Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

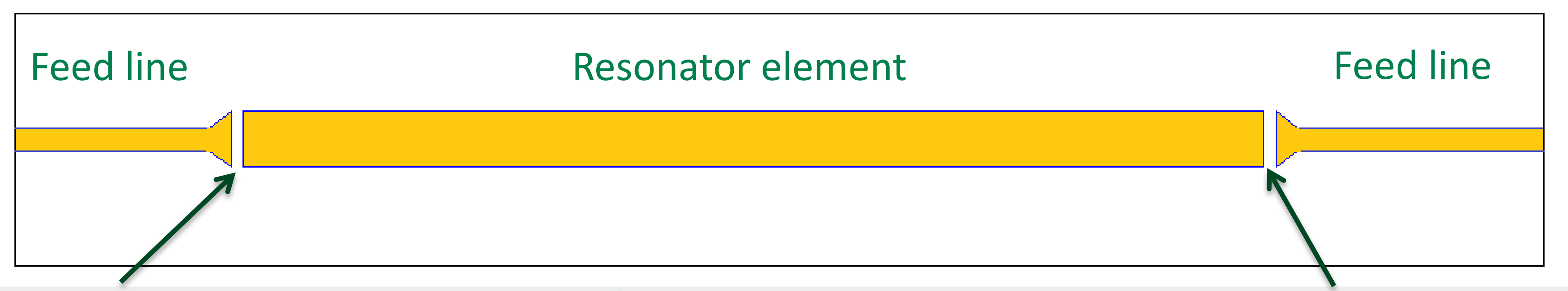
Circuit with low Dk

Circuit with high Dk



Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

Resonators used in PCB technology are often based on ½ wavelength



Top view of gap coupled resonator

The resonator element has the physical length of ½ wavelength for the 1st resonant frequency node

Basically a standing wave is established and a lot of energy is generated at the "resonant" frequency

Relative permittivity defined, by electric field and dipole moments

$$\mathbf{D} = \varepsilon\mathbf{E}$$

D is electric displacement vector, **E** is electric field intensity, ε is complex permittivity

- When an electric field is applied to a dielectric material, electric dipole moments are created
- The dipole moments augment the total displacement flux
- Additional polarization (**P**) is due to the material and its’ related dipole moments

$$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P}$$

ε_0 is free space permittivity

Relative permittivity defined, by electric field and dipole moments

- Dielectrics used in the high frequency PCB industry are typically a “linear dielectric”
  - Or **P** is linear with an applied **E so:**

$$\mathbf{P} = \varepsilon_0 \chi \mathbf{E}$$

χ is electric susceptibility of the material

Relative permittivity defined, by electric field and dipole moments

- Finally, the displacement flux, including material effects:

$$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P} = \varepsilon_0\,(1+\chi)\,\mathbf{E} = \varepsilon E$$

$$\varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon_0\,(1+\chi)$$

- ε' is the real (storage) and ε" is the imaginary (dissipative)
- ε' is associated with dielectric constant and ε" is associated with dissipation factor (Df) of the material

$$Dk = \varepsilon_r = \varepsilon'/\varepsilon_0$$

$$Df = \mathrm{Tan}(\delta) = \varepsilon''/\varepsilon'$$

Relative permittivity defined, by electric field and dipole moments

- From about 100 MHz to 300 GHz most interaction between electric fields and the substrate material is due to displacement and rotation of the dipoles

- The dipole displacement contributes to the Dk (ε_r)

- Molecular friction due to dipole rotation contributes to tan(δ) or Df

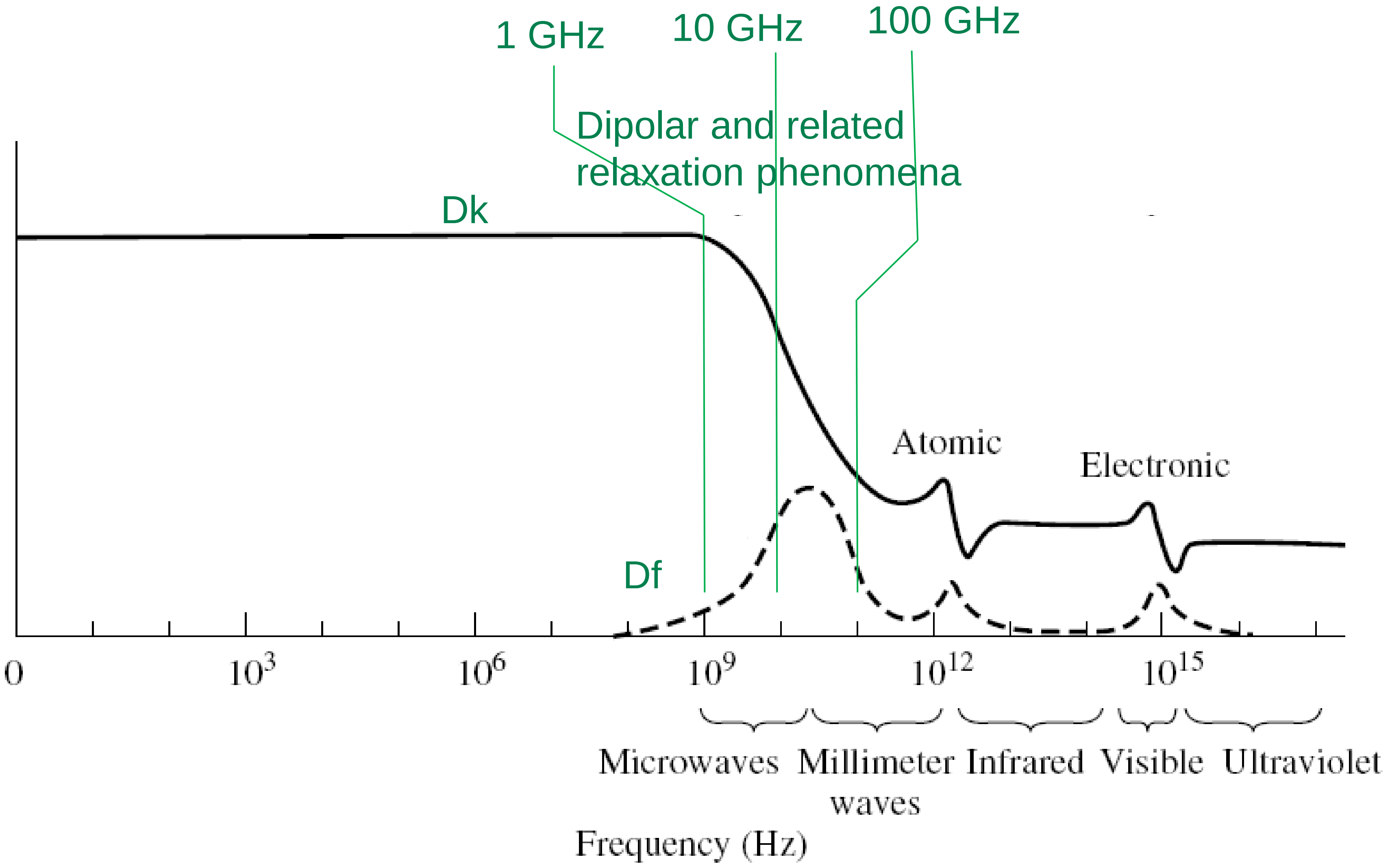
Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

- Dispersion is how much the Dk will change with a change in frequency
- Dipole moment relaxation is another issue which contributes to dispersion
  - At low frequencies the dipole relaxation has little affect on Dk dispersion
  - At microwave frequencies dipole relaxation has more affect on dispersion

Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

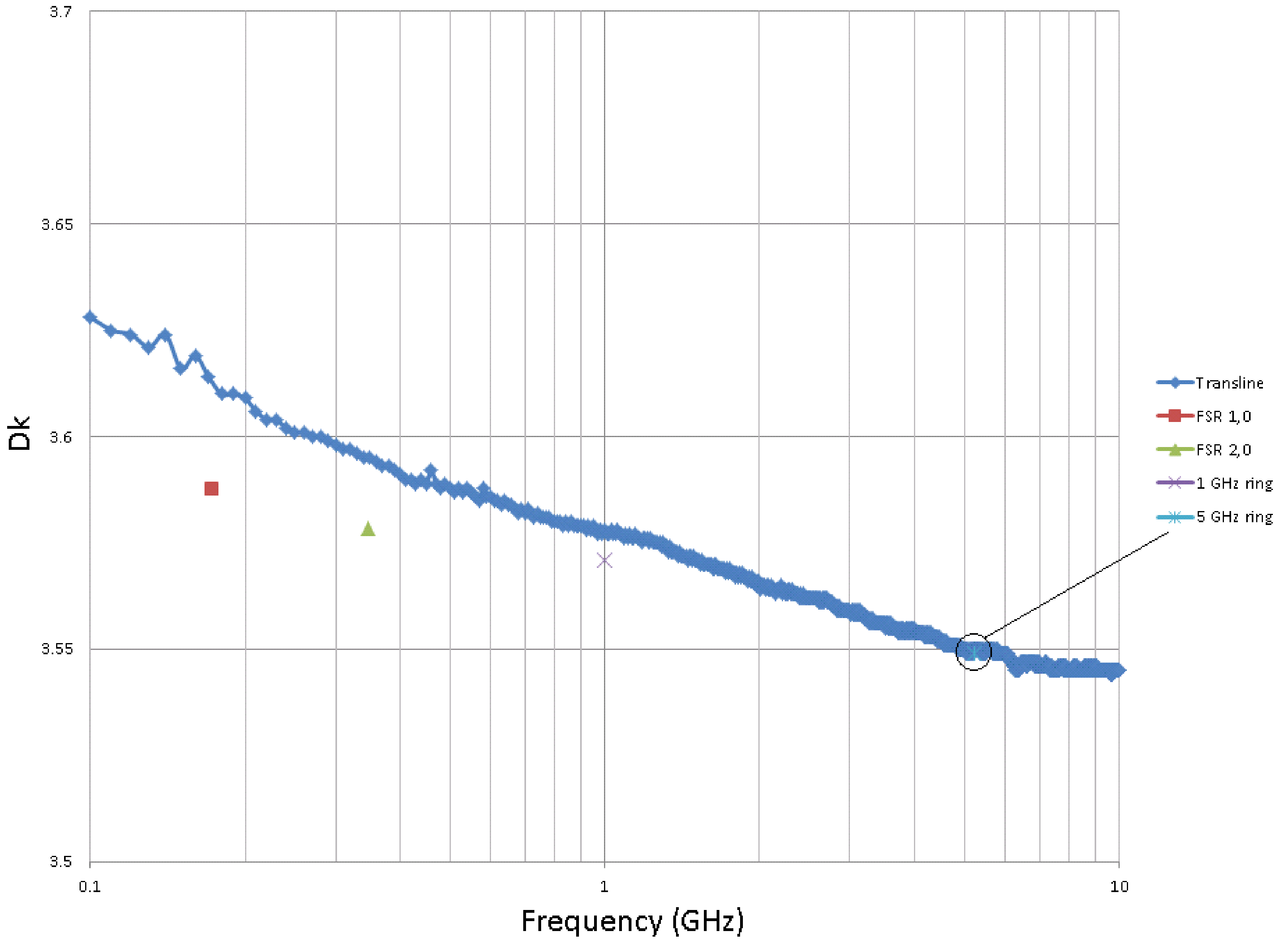
Frequency vs. Dk curve for a **generic** dielectric material

Low loss materials have much less Dk-Frequency slope



Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

Comparison of the same sheet of copper clad laminate with different test methods, Dk vs. Frequency using 20mil thick RO4003C^{TM} laminate



Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

PCB Losses

- Insertion loss is the total loss of a high frequency PCB
- There are 4 components of insertion loss

α_T is total insertion loss
α_C is conductor loss
α_D is dielectric loss
α_R is radiation loss
α_L is leakage loss

$$\alpha_T = \alpha_C + \alpha_D + \alpha_R + \alpha_L$$

- Typically RF leakage loss is considered insignificant for PCB, but there are exceptions
- Microwave engineering puts a lot of emphasis on conductor and dielectric loss
- mmWave engineering focuses on conductor, dielectric and radiation loss

Microwave is ≅ 300 MHz to 30 GHz
Millimeter-wave (mmWave) is ≅ 30 GHz to 300 GHz

Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

PCB Losses

Dielectric Losses

Attenuation (reduction) of the signal energy due to the substrate

Mostly due to the Tanδ or dissipation factor (Df) of the substrate

Conductor Losses

Conductor losses are due to several factors:

- Copper surface roughness
- DC and AC resistance of the conductor
- Ground return path resistance
- Skin effects
- Permeability of the conductor

A rougher surface is a longer path for a wave to propagate.

Besides the resistance of the copper, due to skin effects, it may be the copper treatment that is used.

The ground return path narrows with higher frequency. Less copper area used, so more resistance.

This is unusual but some metal finish or copper treatment have ferromagnetic properties with increased loss due to the equivalent of high Df in regards to permeability

Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

PCB Losses

- There are many variables regarding radiation loss
- Radiation loss is:
  - Frequency dependent
  - Circuit thickness dependent
  - Dielectric constant (Dk) dependent
- Radiation loss can vary intensity due to:
  - Circuit configuration (microstrip, coplanar, stripline)
  - Signal launch
  - Spurious wave mode propagation
  - Impedance transitions and discontinuities

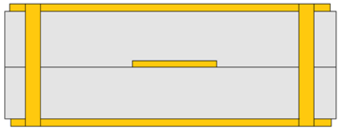
↑ frequency ↑ radiation loss

↑ thickness ↑ radiation loss

↑ Dk ↓ radiation loss

Microstrip

Coplanar



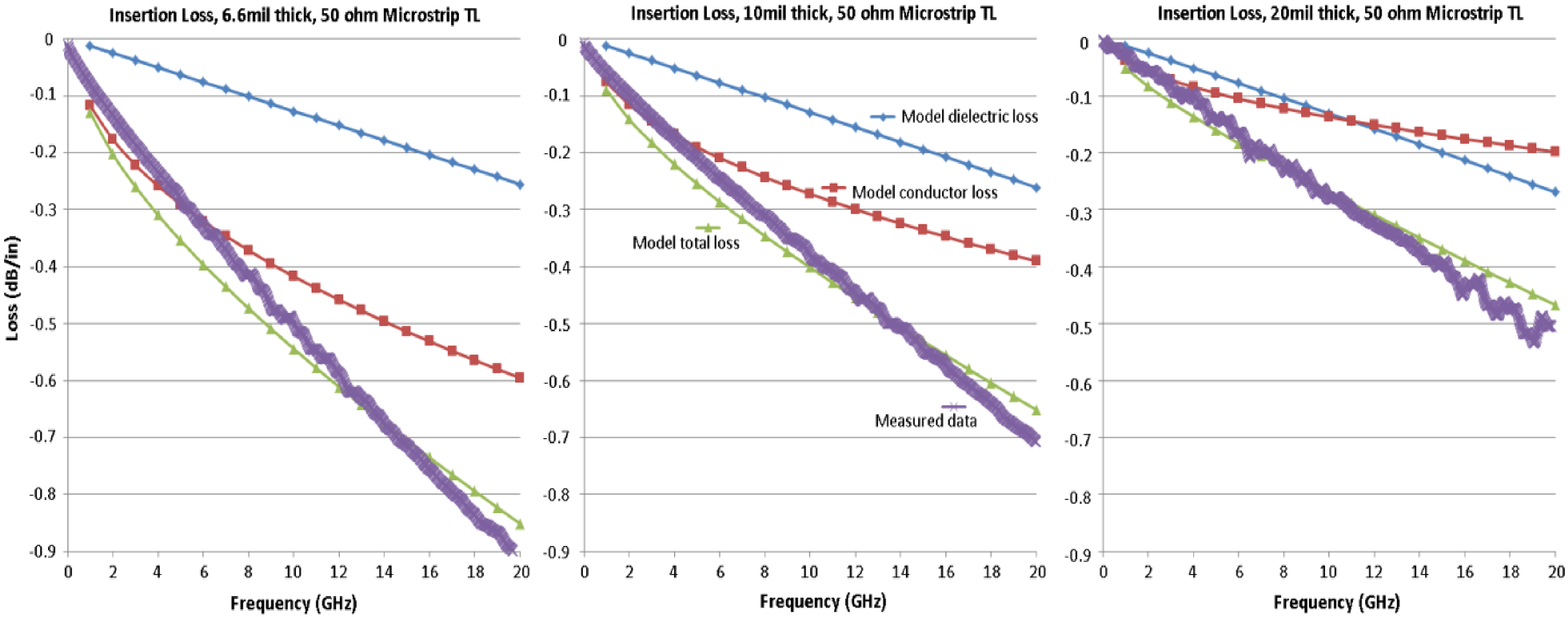
Stripline

Basic ElectroMagnetic Concepts for PCB (Printed Circuit Board)

PCB Losses

Different components of loss in regards to thickness for a microstrip PCB

Dissecting losses when using the same material at different thickness for microstrip TL



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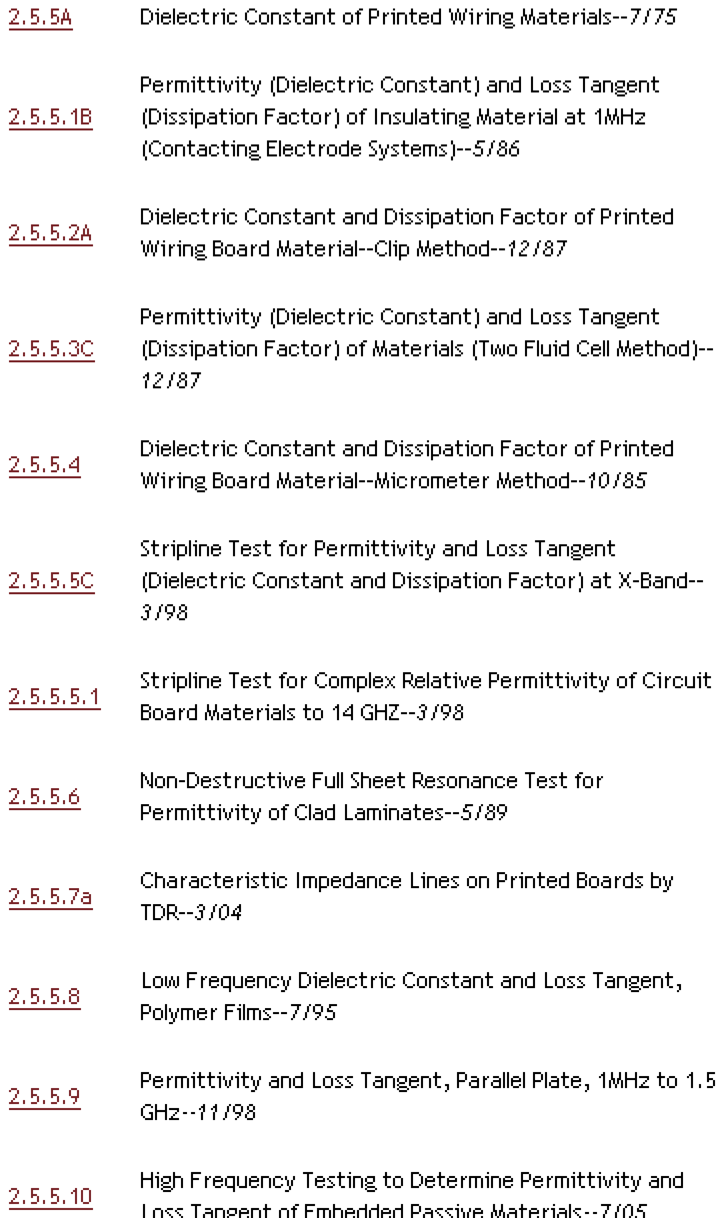
Common Test Methods for Material Electrical Characterization

- IPC has 13 different test methods to determine Dk and / or Df
- ASTM and NIST have several test methods
- Many OEM’s and Universities have their own test methods
- Each test method has its own pro's and con's
- The results of one test may not correlate well to the results of another method, when using the exact same material
- There is No Perfect test method



2.5.5A	Dielectric Constant of Printed Wiring Materials--*7/75*
2.5.5.1B	Permittivity (Dielectric Constant) and Loss Tangent (Dissipation Factor) of Insulating Material at 1MHz (Contacting Electrode Systems)--*5/86*
2.5.5.2A	Dielectric Constant and Dissipation Factor of Printed Wiring Board Material--Clip Method--*12/87*
2.5.5.3C	Permittivity (Dielectric Constant) and Loss Tangent (Dissipation Factor) of Materials (Two Fluid Cell Method)--*12/87*
2.5.5.4	Dielectric Constant and Dissipation Factor of Printed Wiring Board Material--Micrometer Method--*10/85*
2.5.5.5C	Stripline Test for Permittivity and Loss Tangent (Dielectric Constant and Dissipation Factor) at X-Band--*3/98*
2.5.5.5.1	Stripline Test for Complex Relative Permittivity of Circuit Board Materials to 14 GHZ--*3/98*
2.5.5.6	Non-Destructive Full Sheet Resonance Test for Permittivity of Clad Laminates--*5/89*
2.5.5.7a	Characteristic Impedance Lines on Printed Boards by TDR--*3/04*
2.5.5.8	Low Frequency Dielectric Constant and Loss Tangent, Polymer Films--*7/95*
2.5.5.9	Permittivity and Loss Tangent, Parallel Plate, 1MHz to 1.5 GHz--*11/98*
2.5.5.10	High Frequency Testing to Determine Permittivity and Loss Tangent of Embedded Passive Materials--*7/05*

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Common Test Methods for Material Electrical Characterization

Common material test methods:

Full Sheet Resonance (FSR) test

Clamped Stripline Resonator test

Split Post Dielectric Resonator (SPDR) test

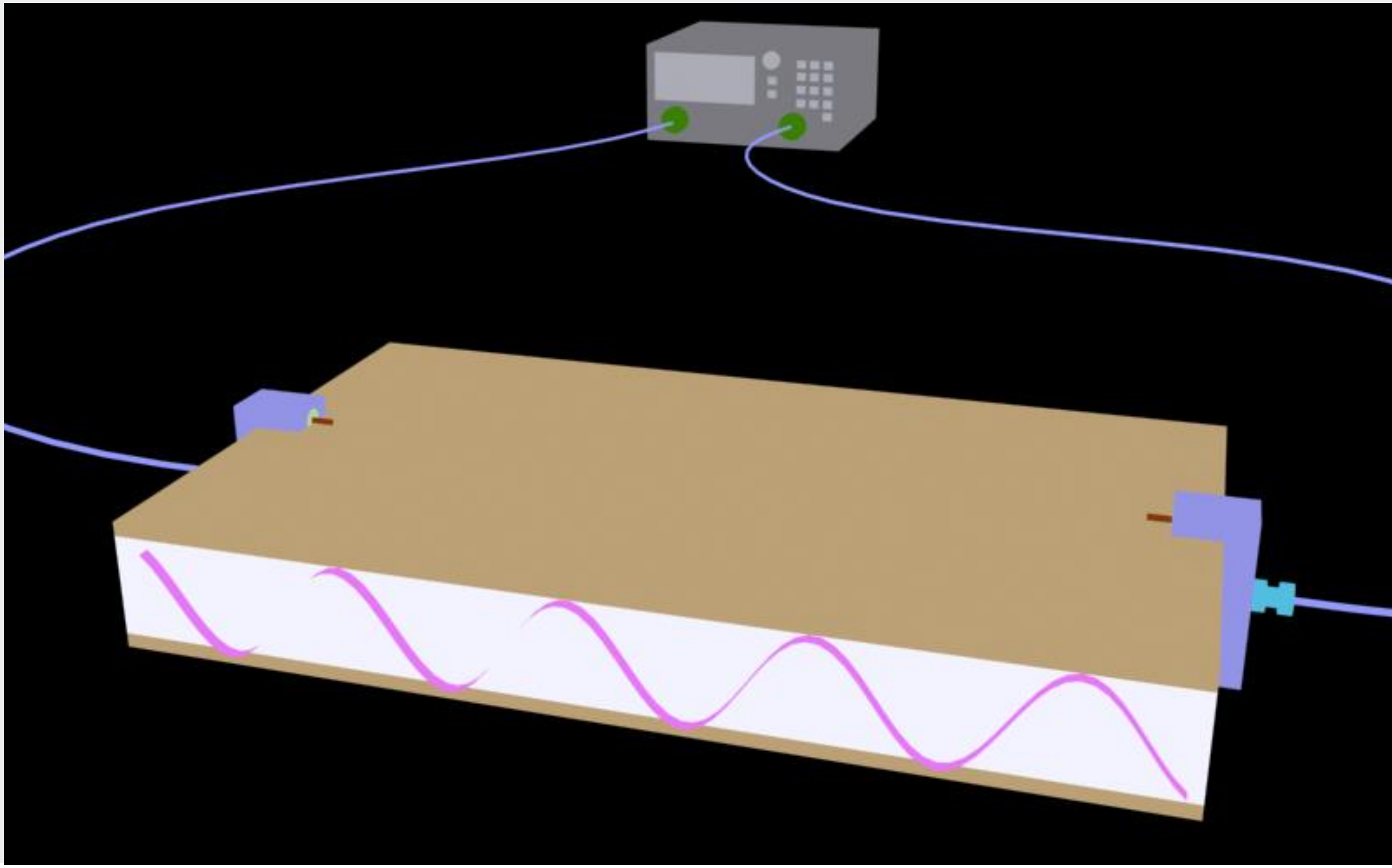
Split Cylinder Resonator test

Rectangular Waveguide resonator test

Full Sheet Resonance (FSR) test, IPC-TM-650 2.5.5.6

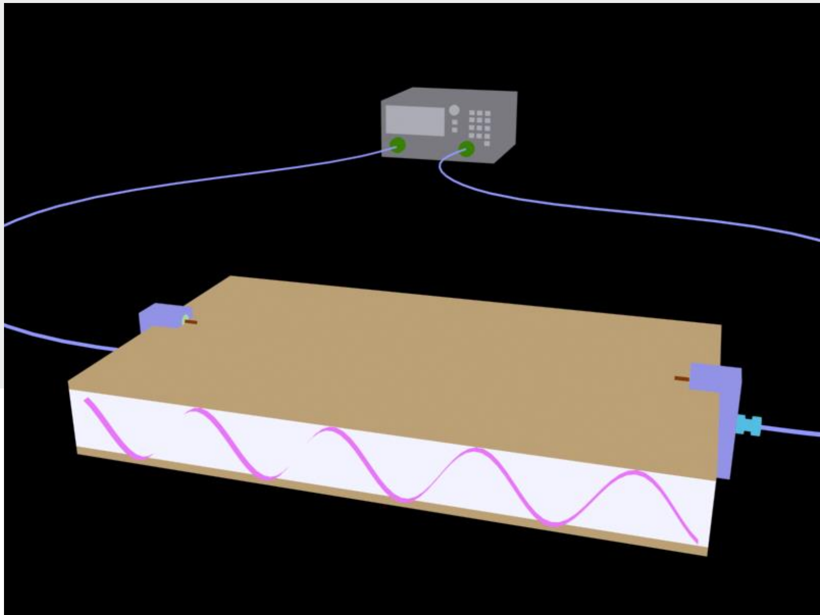
Network Analyzer sweeps a range of frequencies and evaluates at what frequency there are standing waves or resonant peaks

Knowing the exact length of the panel, and the resonant frequency peak the Dk is calculated

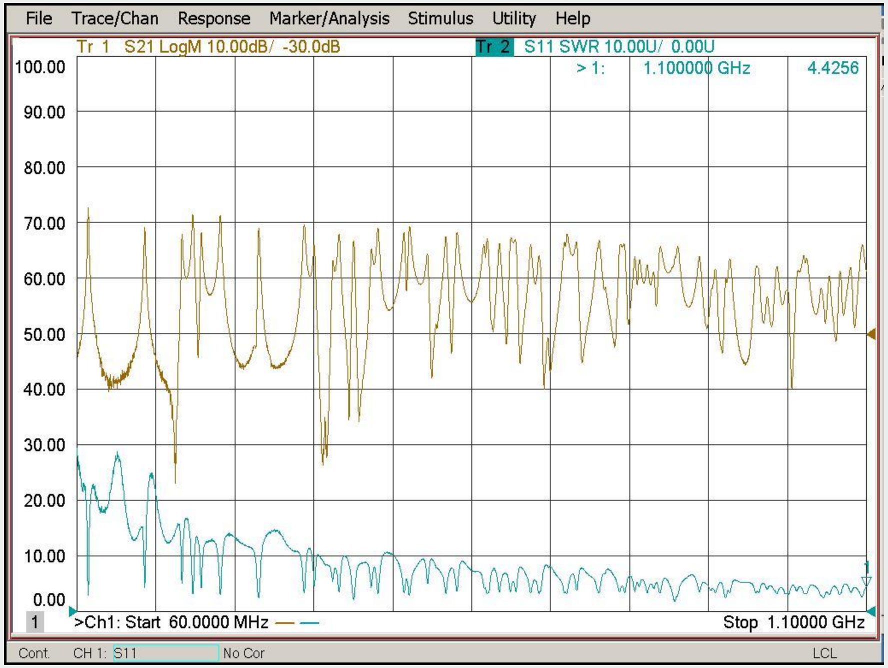


Full Sheet Resonance (FSR) test, IPC-TM-650 2.5.5.6

- The panel is acting like a parallel plate waveguide
- FSR can only determine Dk and not Df
- This is because we can not accurately account for radiation loss
- The open sides of the panel allow radiation losses

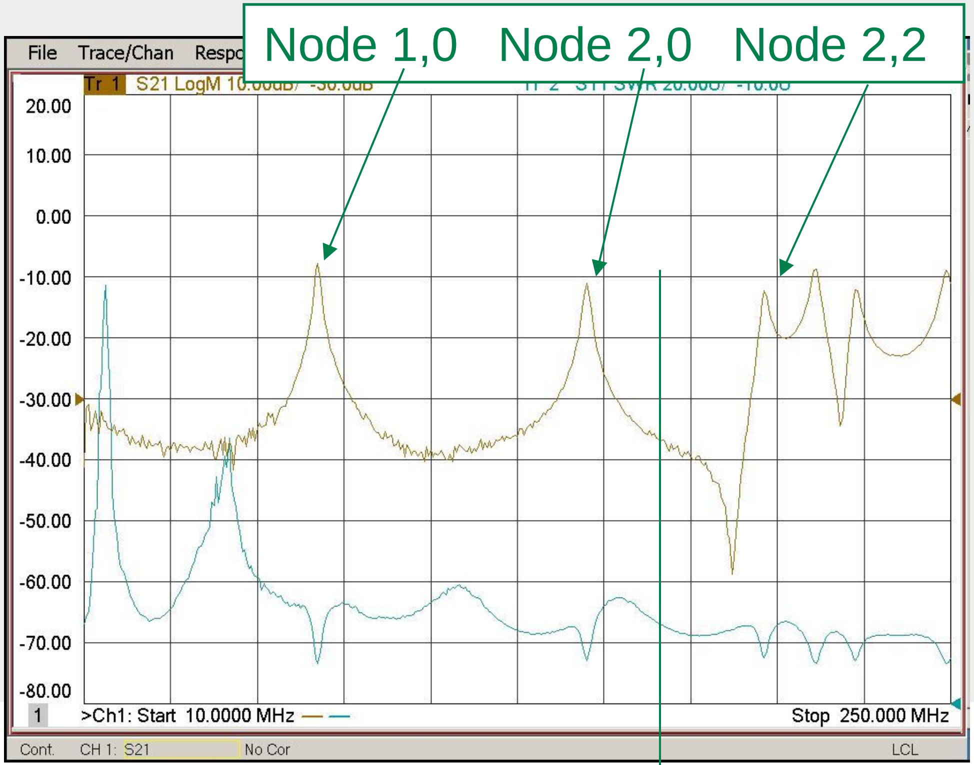


Full Sheet Resonance (FSR) test, IPC-TM-650 2.5.5.6



Multiple nodes (resonant peaks) over wider range of frequencies

Isolated nodes over short range of frequencies



Node 1,0 Node 2,0 Node 2,2

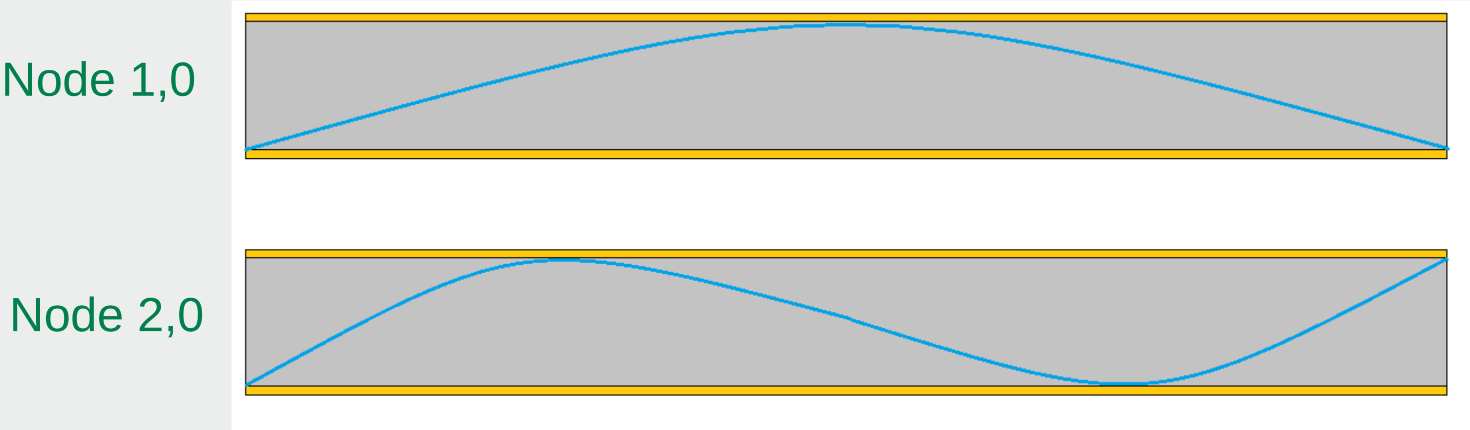
Length axis nodes only | Both axes nodes

Full Sheet Resonance (FSR) test, IPC-TM-650 2.5.5.6

A “node” is based on the number of ½ wavelengths in a direction on the panel

Node 1,0 is 1 half wavelength in the length direction and No wave in the width

Node 1,2 is 1 half wavelength in the length direction and 2 half wavelengths in the width direction (not shown)



Side view of the panel under test in the length axis

Full Sheet Resonance (FSR) test, IPC-TM-650 2.5.5.6

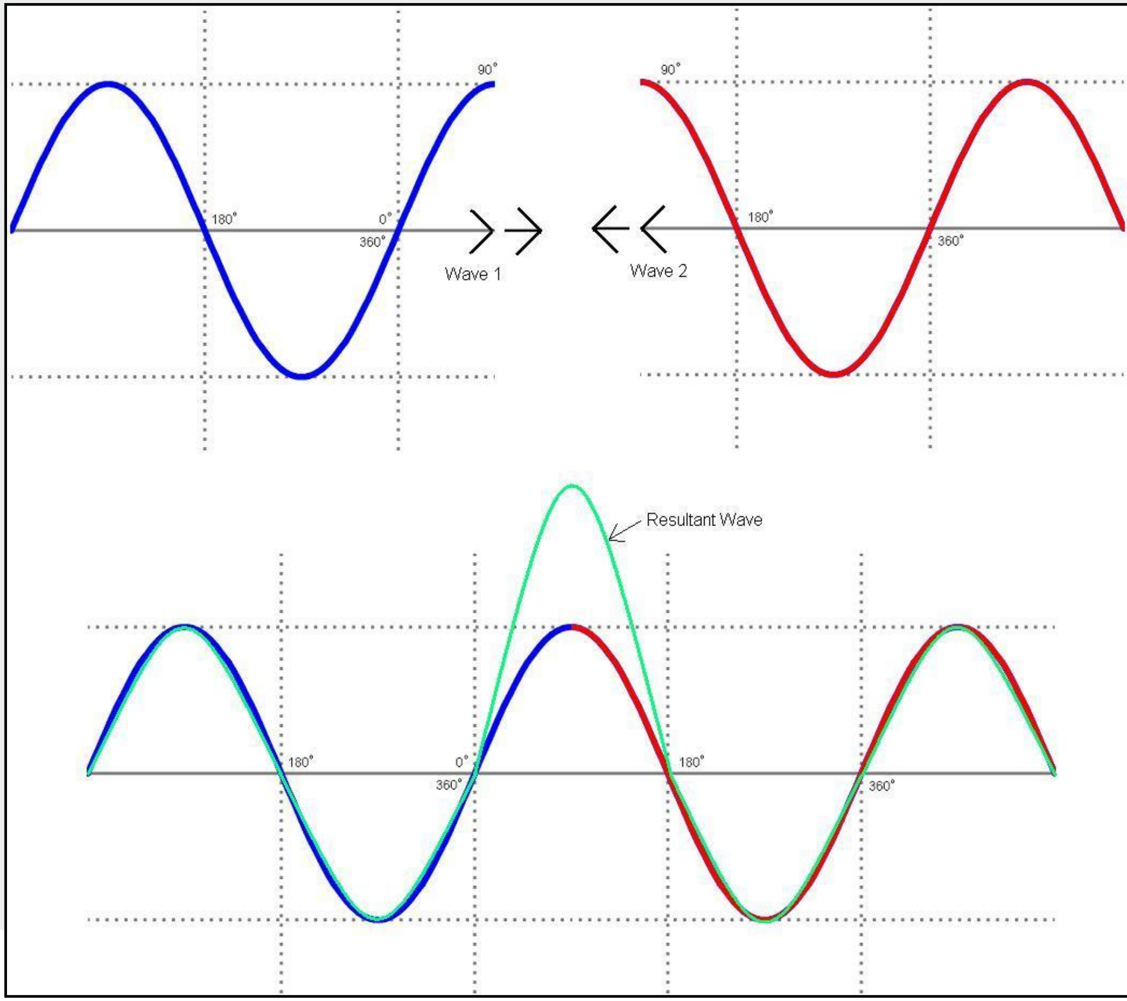
Wave Interference patterns

Constructive:

When two waves collide of the same wavelength and at the same phase angle, the resultant wave has a significantly increased amplitude (shown)

Destructive:

When two waves collide of the same wavelength and are 180 degrees out of phase (1/2 wavelength), both waves are nullified (not shown)



Example of Constructive Interference shown

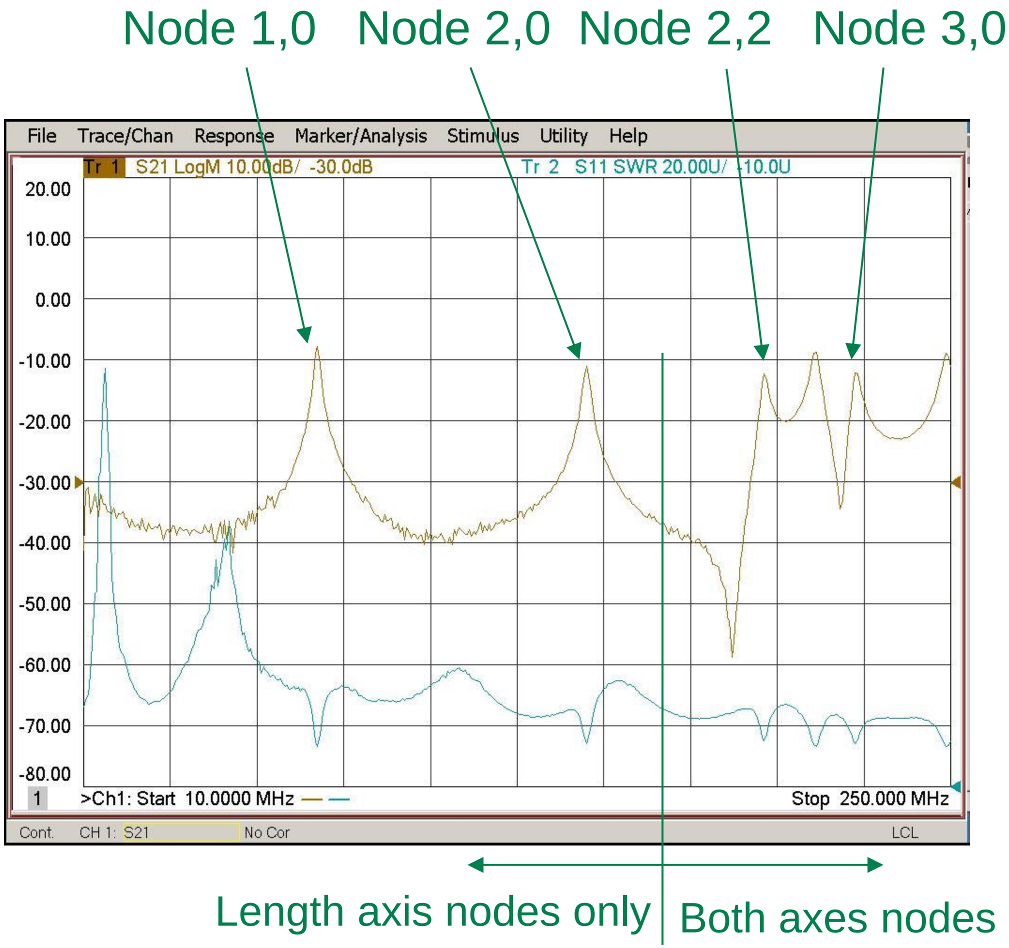
Full Sheet Resonance (FSR) test, IPC-TM-650 2.5.5.6

For a rectangular panel it is best to measure nodes 1,0 and 2,0

These nodes are in the range of frequency where only the length axis has standing waves

The nodes above 2,0 can have interference due to wave propagating in both axes

Example: node 3,0 can have interference due to the other waves near its frequency. It can be seen that node 3,0 is not a well defined peak as nodes 1,0 and 2,0.

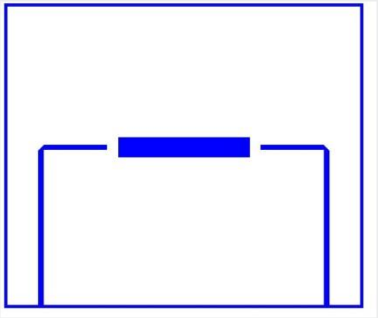


Full Sheet Resonance (FSR) test, IPC-TM-650 2.5.5.6

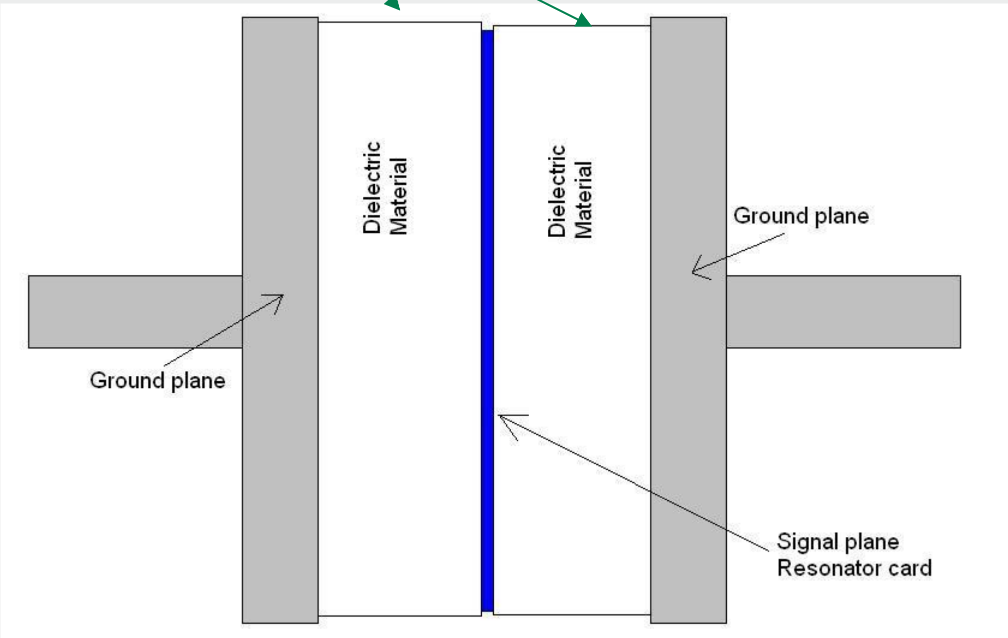
- Pro's
  - Quick and simple test
  - Accurate determination of Dk
  - Minimal operator dependencies
  - Non-destructive test
- Con's
  - Can not test for dissipation factor
  - Thin materials may have Dk accuracy concerns
  - Measurements are at a lower frequency (typ. < 1 GHz)

X-Band Clamped Stripline Resonator test, IPC-TM-650 2.5.5.5c

- Raw material is clamped together with resonator card in between
- The outside metal clamps act as the ground planes for the stripline



Top view of resonator card

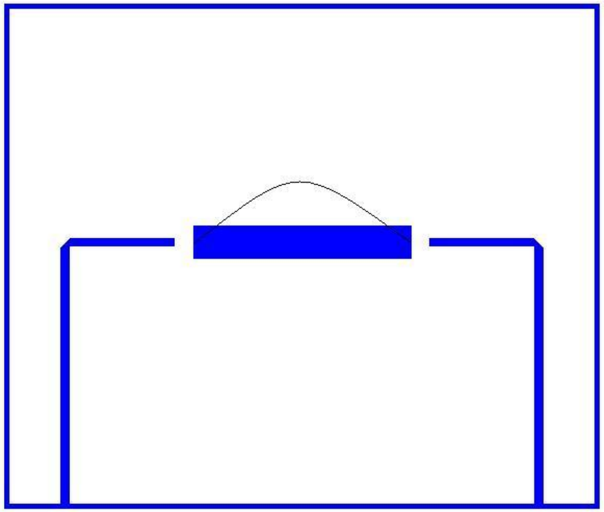


Side view of resonator card clamped into test fixture

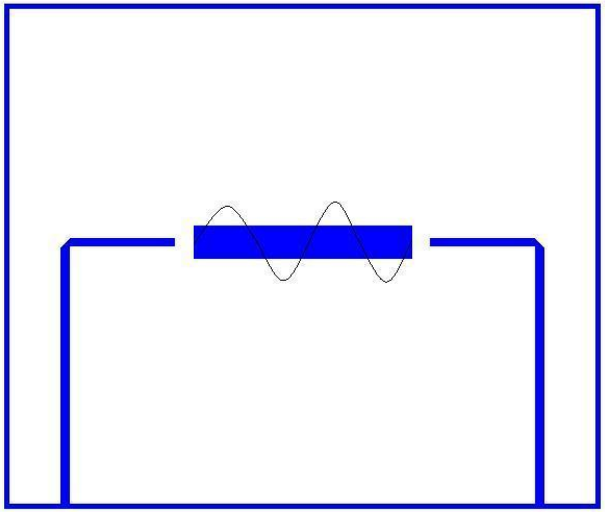
Common Test Methods for Material Electrical Characterization

X-Band Clamped Stripline Resonator test,
IPC-TM-650 2.5.5.5c

- We test at 10 GHz, per IPC, but since the resonator will resonate at 1/2 wavelengths, some other frequencies can be tested
- What can be tested accurately, with our default equipment is:
  - 2.5 GHz
  - 5.0 GHz
  - 7.5 GHz
  - 10.0 GHz
  - 12.5 GHz
- Any frequency above this we would need to change the cables, fixture and connectors that we use



2.5 GHz testing with 1/2 a wavelength or node 1



10 GHz testing with four ½ wavelengths, 4 half wavelengths or node 4

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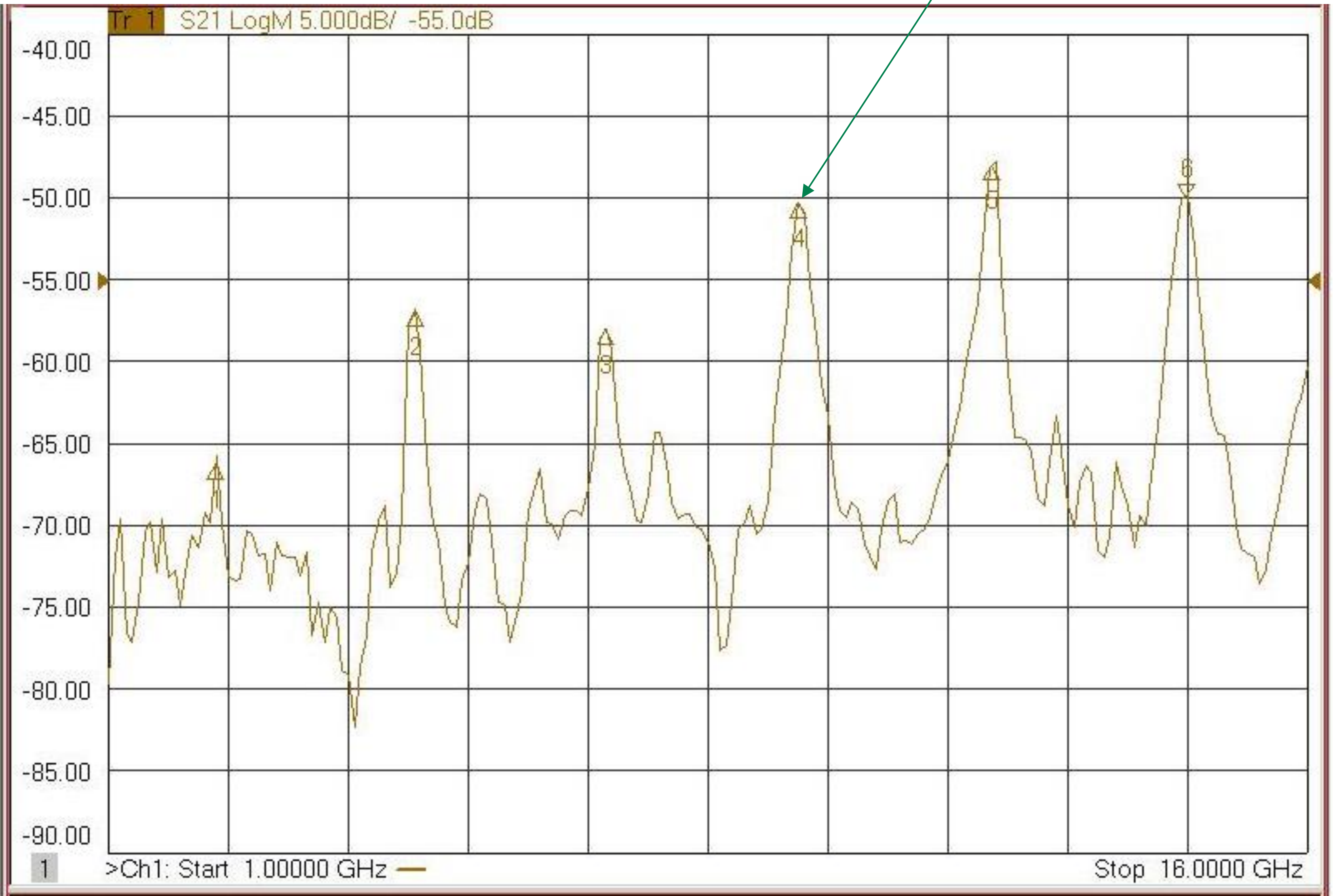
Common Test Methods for Material Electrical Characterization

X-Band Clamped Stripline Resonator test,
IPC-TM-650 2.5.5.5c

Node 4, 10 GHz

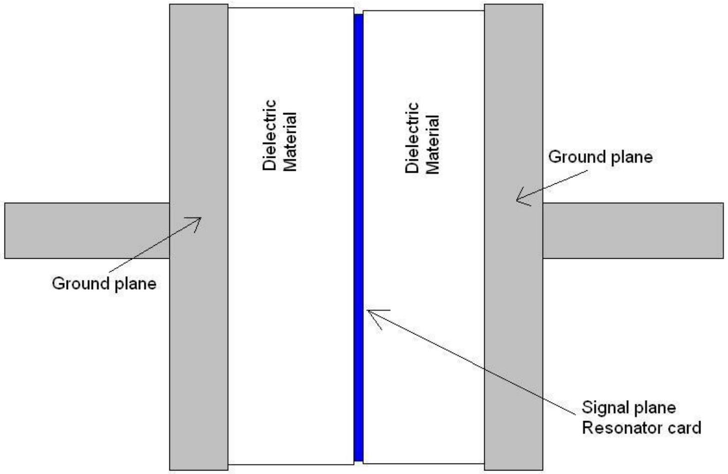


Common Test Methods for Material Electrical Characterization

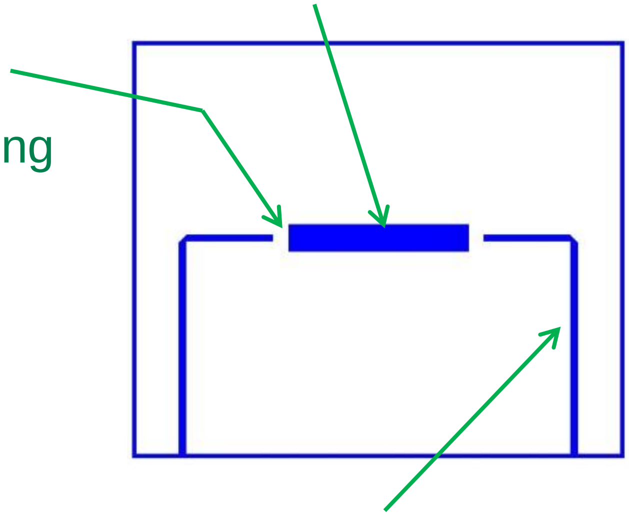
X-Band Clamped Stripline Resonator test,
IPC-TM-650 2.5.5.5c

- There is some amount of entrapped air
- Certain materials with rougher surface will have more air entrapped
- The entrapped air will cause the test to report a lower Dk

- Material with a high degree of anisotropy can accuracy concerns



Side view of resonator card clamped into test fixture



Resonator element

Gap coupling (2X)

Feed lines (2X)

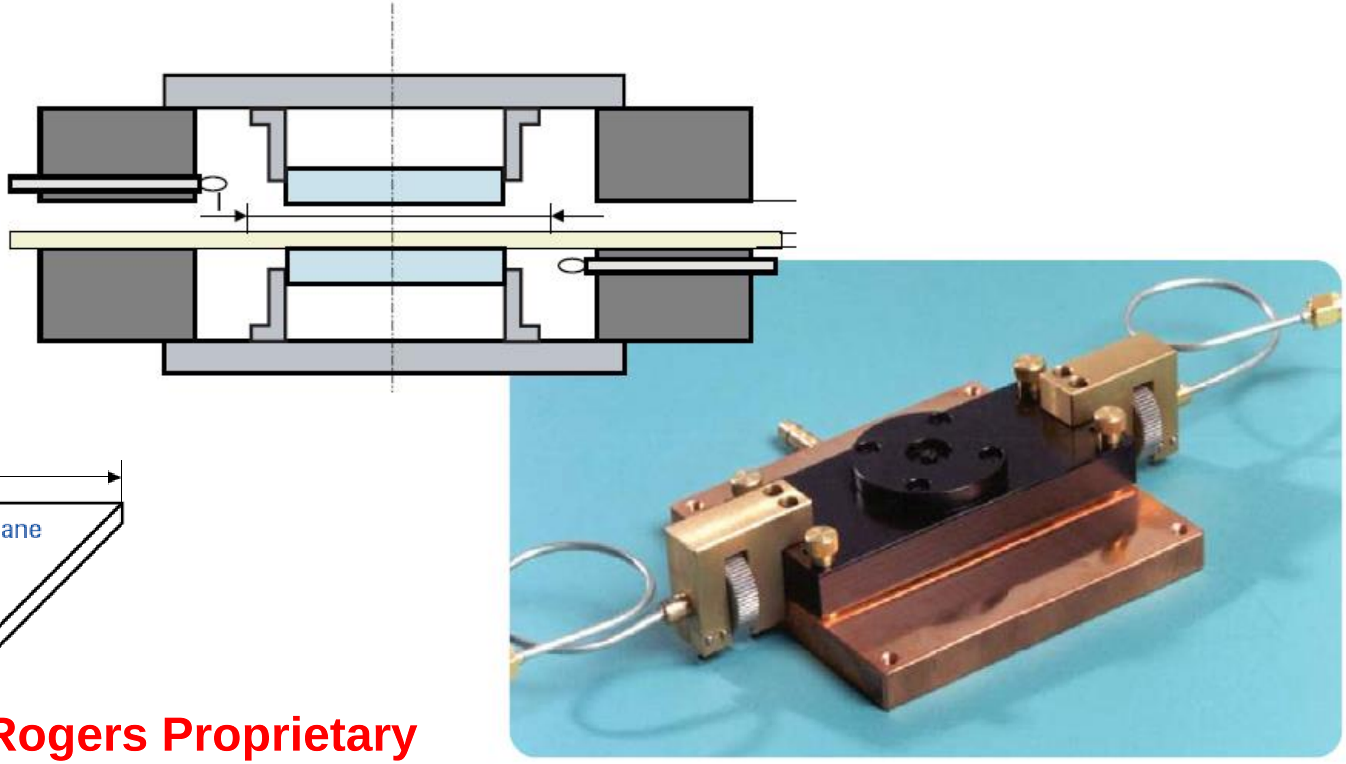
X-Band Clamped Stripline Resonator test, IPC-TM-650 2.5.5.5c

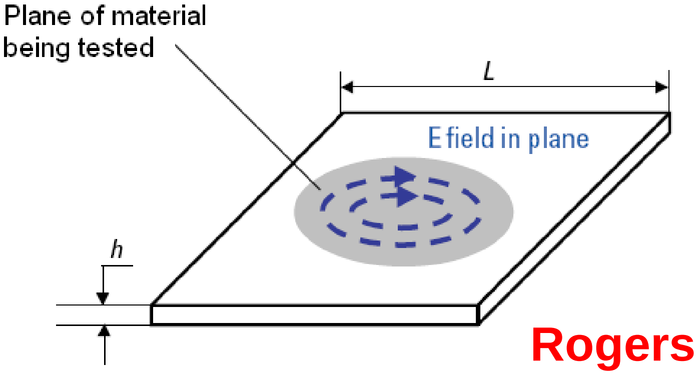
- Pro's:
  - Reports Dk and Df (no radiation losses)
  - Very good for a fast test, high frequency Dk / Df test
  - Simple structure allows simple calculations
  - Good accuracy for Dk and moderately good for Df
  - Minimal operator dependencies
  - Testing is done in the range of many user applications (2-10 GHz)
- Con's:
  - Dk can be reported lower than actual circuits with some materials
  - Destructive test
  - Limited material configurations
  - Some resonator cards may change over time

Common Test Methods for Material Electrical Characterization

Split Post Dielectric Resonator (SPDR) test

- A resonator that compares the baseline measurement of an empty cavity (air) to a cavity with material
- There is an electric field established between the two resonators (top and bottom)
- The associated wave pattern is a right hand circular polarized TE mode
- The electrical properties of the material is evaluated in the x-y plane only





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Common Test Methods for Material Electrical Characterization

Split Post Dielectric Resonator (SPDR) test

- SPDR testing is sample thickness dependent
    - SPDR fixture that is tuned to 10 GHz can test material that is 12mils or less
    - SPDR tuned to 20 GHz can test material that is 25mils or less
- There is no minimum thickness, in theory
- Sample can not sag and it must remain planar with no bow or twist
- A very accurate thickness measurement is critical for Dk and less critical for Df
- Since it only evaluates materials in the x-y plane there can be significantly different Dk numbers of some materials compared to FSR and stripline testing

Common Test Methods for Material Electrical Characterization

Split Post Dielectric Resonator (SPDR) test

- Pro's
    - Very fast and user friendly test
    - Assuming an accurate and repeatable thickness measurement method, then SPDR is accurate and repeatable
    - Can stack samples of different material in SPDR for evaluating composite Dk and Df
    - SPDR is sometimes used with FSR or clamped stripline to evaluate anisotropy
- Con's
    - Doesn't test the z-axis
    - Glass reinforced or filled materials that are polarized will report significantly different Dk values compared to results from FSR and stripline test methods
    - Accuracy of the thickness measurement is extremely critical for Dk values

Circuit Evaluation Techniques for Material Characterization

Microstrip transmission line testing

Microstrip gap coupled strip resonators

Microstrip ring resonators

Microstrip couplers

Microstrip 180° Hybrids

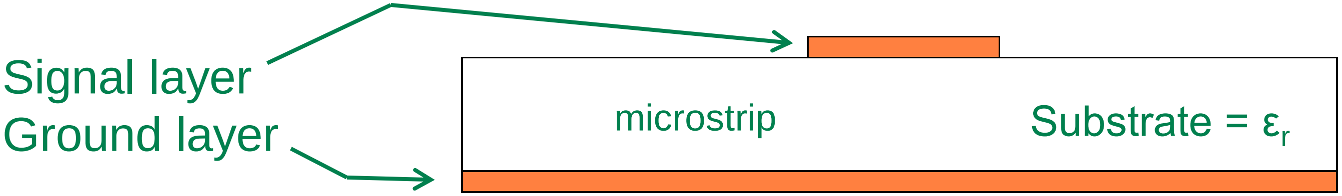
Microstrip stub tuning networks

Microstrip delay lines

Many of these circuits can use other circuit configurations such as grounded coplanar or stripline, however there are less circuit fabrication variables with non-pth microstrip

Circuit Evaluation Techniques for Material Characterization

Microstrip differential phase length method, transmission line testing

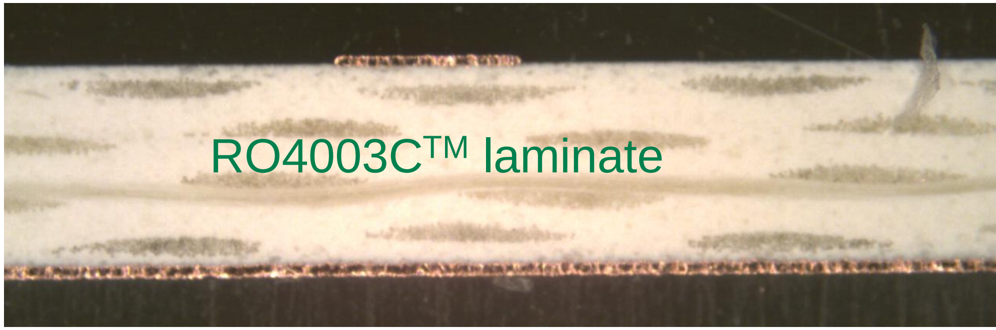

Signal layer
Ground layer
microstrip
Substrate = ε_r

Cross-sectional view

Uses microstrip transmission line circuits of different length; typically 3:1 length ratio

Circuits are:

- identical in everywhere except for length
- are made in very near proximity of each other on the same panel
- 50 ohm characteristic impedance



Circuit Evaluation Techniques for Material Characterization

Microstrip differential phase length method, transmission line testing

Measurements are taken of the phase angle at a specific frequency for each circuit.

The microstrip phase angle formula is used and altered to accommodate two circuits of different length:

$$\Phi = 2\pi f \frac{\sqrt{\varepsilon_{eff}}}{c} L$$

(Φ) phase angle for single circuit of length (L) at a specific frequency (f)

$$\Delta\Phi = 2\pi f \frac{\sqrt{\varepsilon_{eff}}}{c} \Delta L$$

(ΔΦ) difference of phase angle for two circuits at a specific frequency (f) with a difference of circuit length (ΔL)

$$\varepsilon_{eff} = \left(\frac{\Delta\Phi c}{2\pi f \Delta L} \right)^2$$

Formula rearranged to solve for effective dielectric constant (ε_{eff})

Once ε_{eff} is solved, MWI-2010 or a EM field solver is used to calculate the Dk of the material at that specific frequency. This procedure is repeated by increasing to the next frequency and recalculating the ε_{eff} and solving for the Dk.

Circuit Evaluation Techniques for Material Characterization

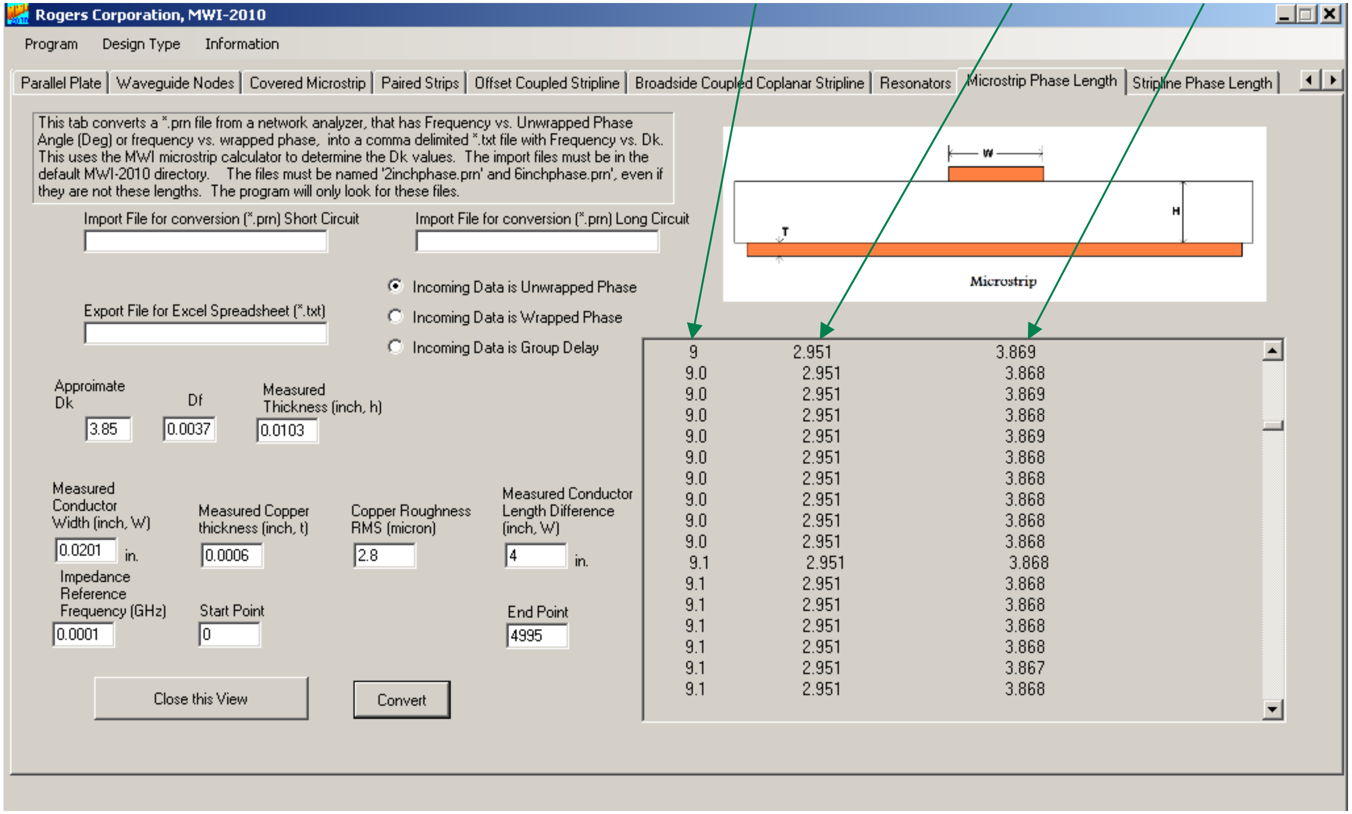
Microstrip differential phase length method, transmission line testing

- Example of data collected for the 2” transmission line circuits, for frequency (Hz) vs. Unwrapped Phase angle shown the left; saved in *.prn format.

```
"S21 Phase"
"Frequency (Hz)","Deg",
10000000, -6.415483e+000,
20000000, -5.809750e+000,
30000000, -6.611060e+000,
40000000, -7.710355e+000,
50000000, -8.156395e+000,
60000000, -9.462810e+000,
70000000, -1.081575e+001,
80000000, -1.216637e+001,
90000000, -1.353176e+001,
100000000, -1.492709e+001,
110000000, -1.630360e+001,
120000000, -1.770339e+001,
130000000, -1.908737e+001,
140000000, -2.050327e+001,
150000000, -2.189041e+001,
160000000, -2.326334e+001,
170000000, -2.468114e+001,
180000000, -2.607940e+001,
190000000, -2.749413e+001
```

- Once the *.prn file with the frequency-phase data for both the 2” and 6” circuit is read into MWI-2010 and the details of the circuit construction are entered then the software outputs a *.txt file which can be read into Excel.

Freq. (GHz) Effective Dk Dk



This tab converts a *.prn file from a network analyzer, that has Frequency vs. Unwrapped Phase Angle (Deg) or frequency vs. wrapped phase, into a comma delimited *.txt file with Frequency vs. Dk. This uses the MWI microstrip calculator to determine the Dk values. The import files must be in the default MWI-2010 directory. The files must be named '2inchphase.prn' and 6inchphase.prn', even if they are not these lengths. The program will only look for these files.

Import File for conversion (*.prn) Short Circuit

Import File for conversion (*.prn) Long Circuit

Export File for Excel Spreadsheet (*.txt)

● Incoming Data is Unwrapped Phase

○ Incoming Data is Wrapped Phase

○ Incoming Data is Group Delay

Approimate Dk: 3.85

Df: 0.0037

Measured Thickness (inch, h): 0.0103

Measured Conductor Width (inch, W): 0.0201 in.

Measured Copper thickness (inch, t): 0.0006

Copper Roughness RMS (micron): 2.8

Measured Conductor Length Difference (inch, W): 4 in.

Impedance Reference Frequency (GHz): 0.0001

Start Point: 0

End Point: 4995

```
9       2.951     3.869
9.0     2.951     3.868
9.0     2.951     3.869
9.0     2.951     3.868
9.0     2.951     3.869
9.0     2.951     3.868
9.0     2.951     3.868
9.0     2.951     3.868
9.0     2.951     3.868
9.0     2.951     3.868
9.1     2.951     3.868
9.1     2.951     3.868
9.1     2.951     3.868
9.1     2.951     3.868
9.1     2.951     3.868
9.1     2.951     3.867
9.1     2.951     3.868
```

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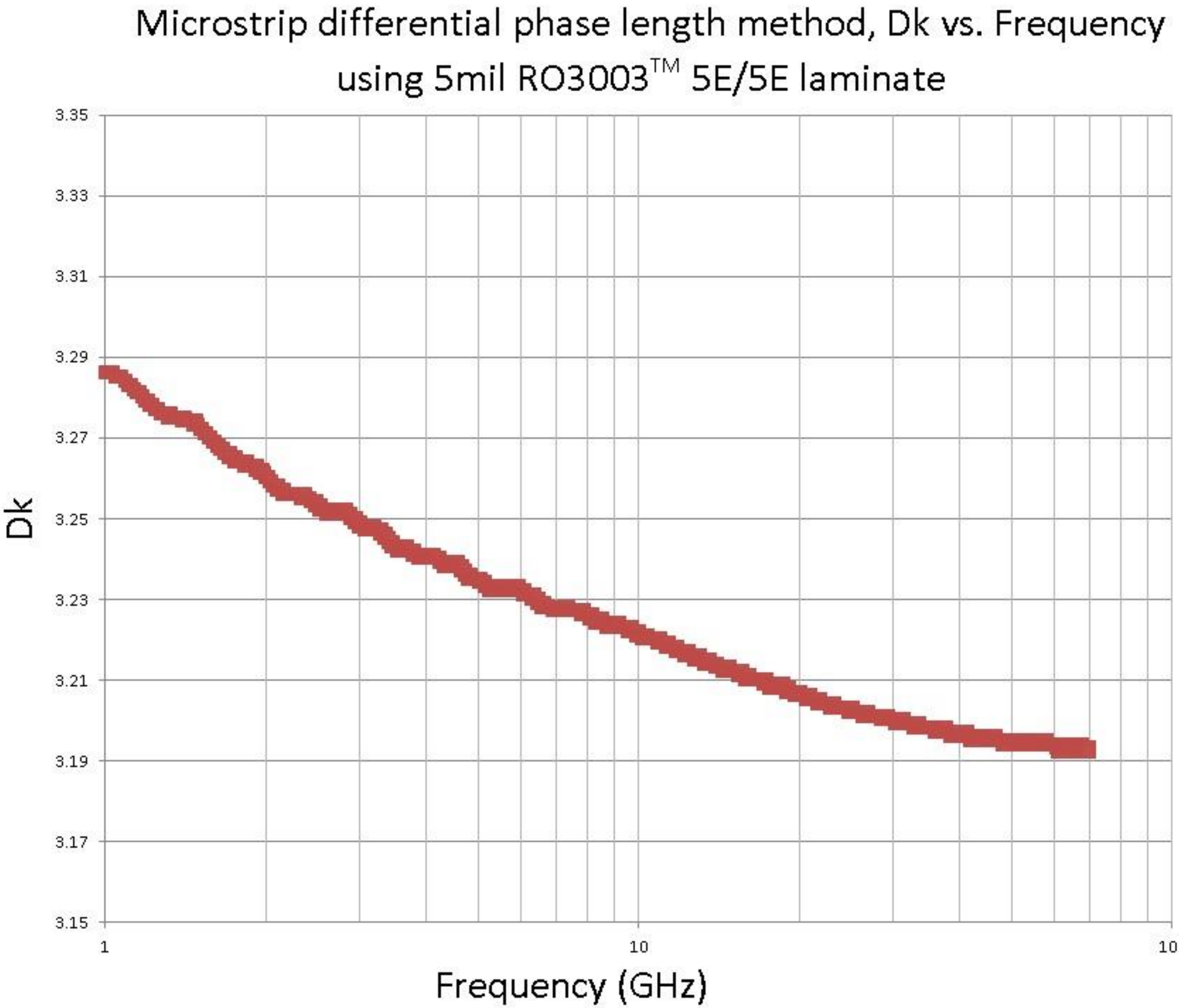
Circuit Evaluation Techniques for Material Characterization

Microstrip differential phase length method, transmission line testing



Circuit Evaluation Techniques for Material Characterization

Microstrip differential phase length method, transmission line testing

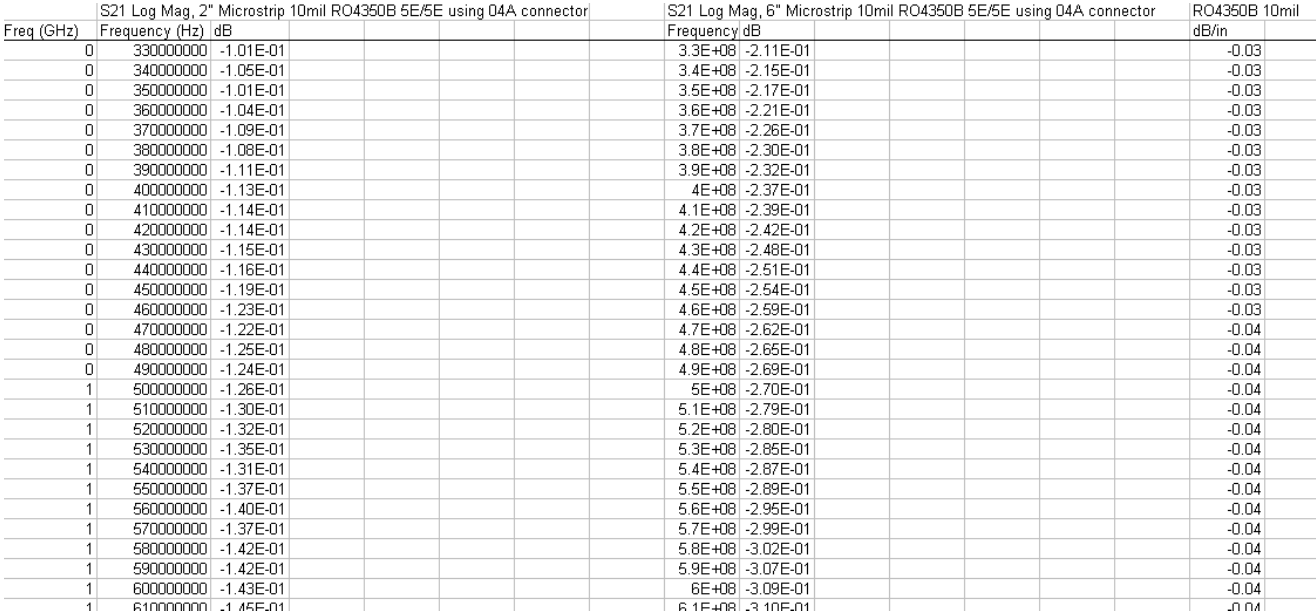
- Pro's
  - Copper surface roughness affects are captured
    - Copper surface roughness has an impact on the phase constant

      Allen Horn, III*, John Reynolds*, and James Rautio$^+$; *Rogers Corporation, $^+$Sonnet software, "Conductor Profile Effects on the Propagation Constant of Microstrip Transmission Lines, IEEE MTT-S, 2010.
  - Wideband Dk vs. Frequency data
  - Results are from actual circuit testing and not a fixture or raw material sampling
- Con's
  - Time consuming to design, make circuits and evaluate them
  - This method is a transmission / reflection technique which is typically not as accurate as a resonator technique
  - Wideband signal launch can be an issue
  - Wideband mode suppression can be an issue

Circuit Evaluation Techniques for Material Characterization

Microstrip differential length method, transmission line insertion loss testing

- This method uses the same principle as the Differential Phase Length method
- Except this method is using the S21 magnitude values from the short and long circuits
- The same pressure contact connectors are used and oriented to the same ports during testing
- The loss of the short circuit is subtracted from the long circuit, leaving loss as dB/unit_length
- The subtraction of the loss of the two circuits is intended to eliminate the loss of the connectors and the signal launch

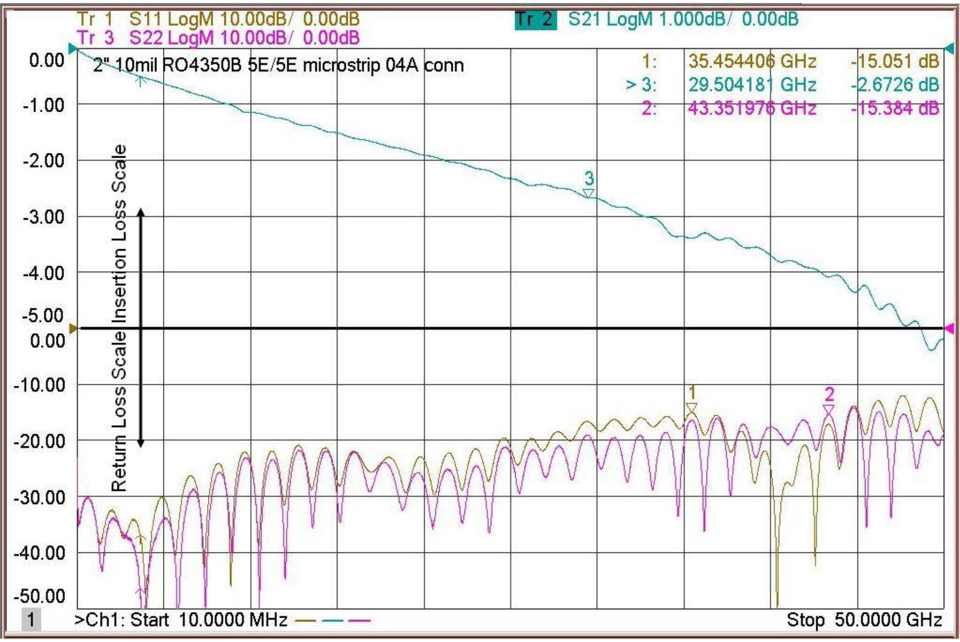


	S21 Log Mag, 2" Microstrip 10mil RO4350B 5E/5E using 04A connector		S21 Log Mag, 6" Microstrip 10mil RO4350B 5E/5E using 04A connector		RO4350B 10mil
Freq (GHz)	Frequency (Hz)	dB	Frequency	dB	dB/in
0	330000000	-1.01E-01	3.3E+08	-2.11E-01	-0.03
0	340000000	-1.05E-01	3.4E+08	-2.15E-01	-0.03
0	350000000	-1.01E-01	3.5E+08	-2.17E-01	-0.03
0	360000000	-1.04E-01	3.6E+08	-2.21E-01	-0.03
0	370000000	-1.09E-01	3.7E+08	-2.26E-01	-0.03
0	380000000	-1.08E-01	3.8E+08	-2.30E-01	-0.03
0	390000000	-1.11E-01	3.9E+08	-2.32E-01	-0.03
0	400000000	-1.13E-01	4E+08	-2.37E-01	-0.03
0	410000000	-1.14E-01	4.1E+08	-2.39E-01	-0.03
0	420000000	-1.14E-01	4.2E+08	-2.42E-01	-0.03
0	430000000	-1.15E-01	4.3E+08	-2.48E-01	-0.03
0	440000000	-1.16E-01	4.4E+08	-2.51E-01	-0.03
0	450000000	-1.19E-01	4.5E+08	-2.54E-01	-0.03
0	460000000	-1.23E-01	4.6E+08	-2.59E-01	-0.03
0	470000000	-1.22E-01	4.7E+08	-2.62E-01	-0.04
0	480000000	-1.25E-01	4.8E+08	-2.65E-01	-0.04
0	490000000	-1.24E-01	4.9E+08	-2.69E-01	-0.04
1	500000000	-1.26E-01	5E+08	-2.70E-01	-0.04
1	510000000	-1.30E-01	5.1E+08	-2.79E-01	-0.04
1	520000000	-1.32E-01	5.2E+08	-2.80E-01	-0.04
1	530000000	-1.35E-01	5.3E+08	-2.85E-01	-0.04
1	540000000	-1.31E-01	5.4E+08	-2.87E-01	-0.04
1	550000000	-1.37E-01	5.5E+08	-2.89E-01	-0.04
1	560000000	-1.40E-01	5.6E+08	-2.95E-01	-0.04
1	570000000	-1.37E-01	5.7E+08	-2.99E-01	-0.04
1	580000000	-1.42E-01	5.8E+08	-3.02E-01	-0.04
1	590000000	-1.42E-01	5.9E+08	-3.07E-01	-0.04
1	600000000	-1.43E-01	6E+08	-3.09E-01	-0.04
1	610000000	-1.45E-01	6.1E+08	-3.10E-01	-0.04

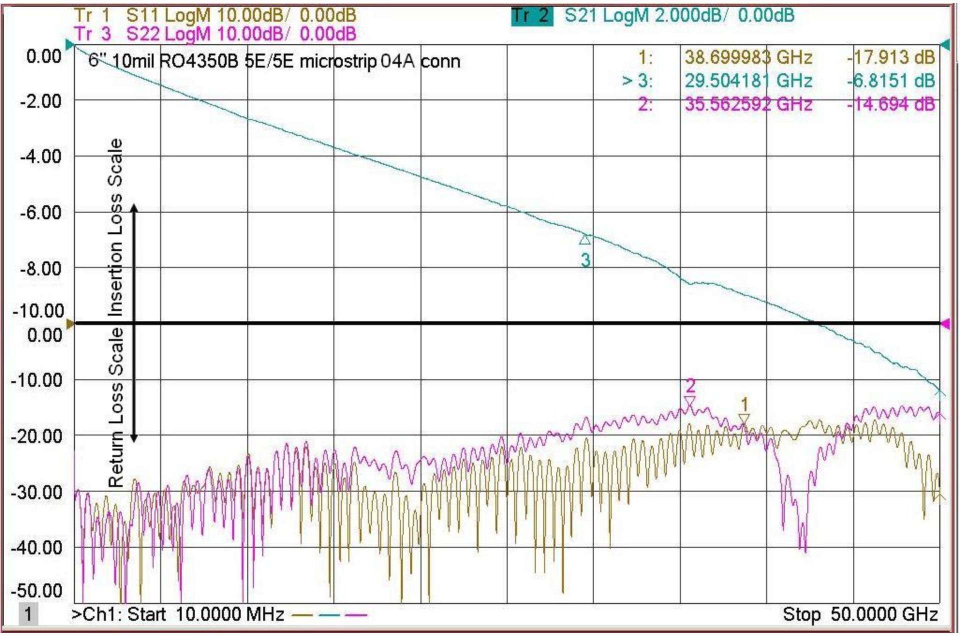
Circuit Evaluation Techniques for Material Characterization

Microstrip differential length method, transmission line insertion loss testing

Screen shots from PNA while testing two circuits of the same material which are different length only



2” microstrip transmission line



6” microstrip transmission line

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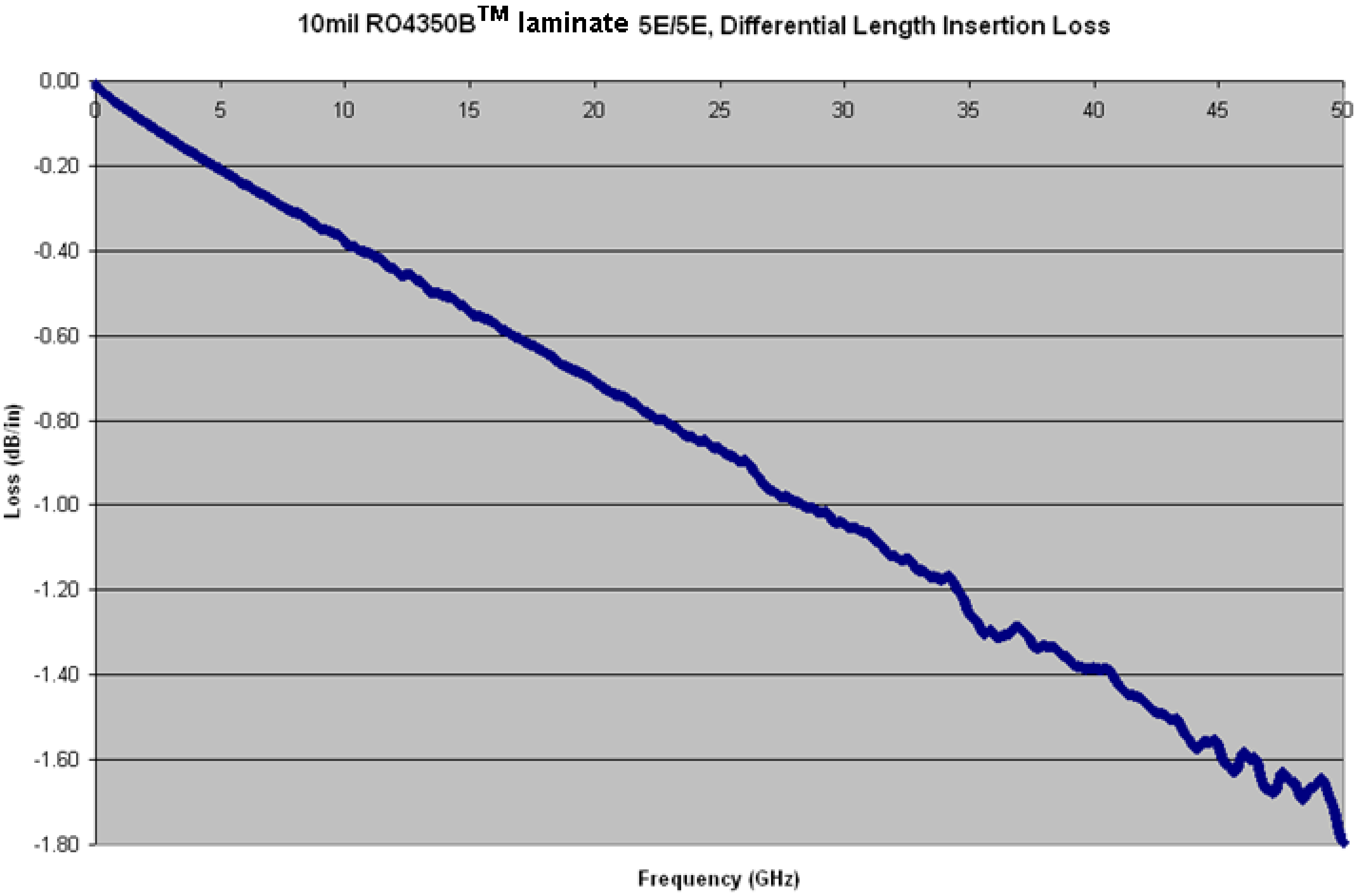
Circuit material used is 10mil thick RO4350B^{TM} laminate

The world runs better with Rogers.®

Circuit Evaluation Techniques for Material Characterization

Microstrip differential length method, transmission line insertion loss testing

Insertion loss results:



Circuit Evaluation Techniques for Material Characterization

Microstrip differential length method, transmission line insertion loss testing

- Pro's
  - Copper surface roughness affects are captured
    - Copper surface roughness has an impact on insertion loss

      J. W. Reynolds, P. A. LaFrance, J. C. Rautio, A. F. Horn III, “Effect of conductor profile on the insertion loss, propagation constant, and dispersion in thin high frequency transmission lines,” DesignCon 2010.
  - Wideband Insertion loss vs. Frequency data
  - Results are from actual circuit testing and not a fixture or raw material sampling
- Con's
  - Time consuming to design, make circuits and evaluate them
  - Wideband signal launch can be an issue
  - Wideband mode suppression can be an issue

Circuit Evaluation Techniques for Material Characterization

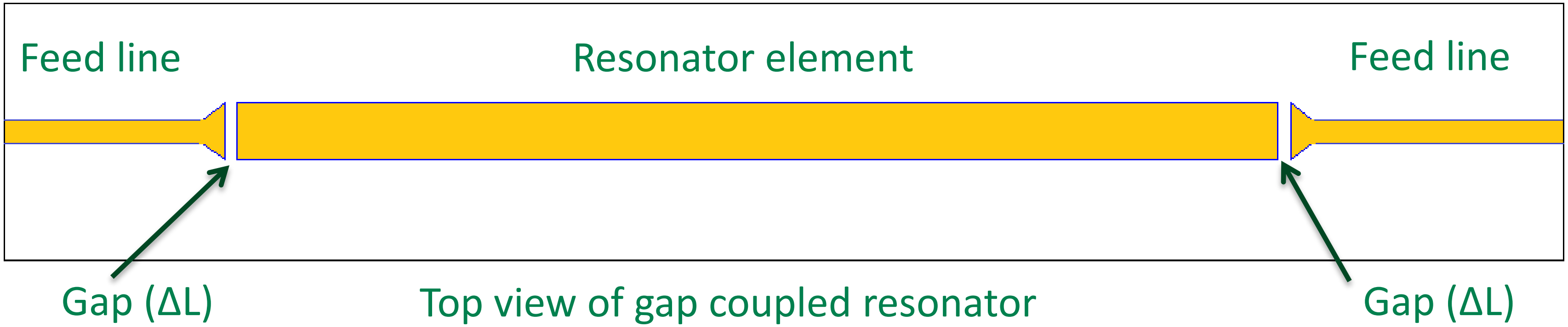
Side note: Microstrip transmission line testing to obtain Df (dissipation factor)

- Some companies will use microstrip transmission line testing to back calculate the Df
- Typically the Df of the material is not accurately found from transmission line testing
- Many times the reported Df has the conductor loss included as wells as radiation loss
- It is recommended not to extrapolate Df from transmission line S21 measurements due to many variables which impact the accuracy:
    - To calculate the Df, the conductor loss and radiation loss must be subtracted
    - Conductor loss is affected by copper surface roughness
    - The impact of copper surface roughness on loss is frequency dependent
    - There are many different methods for calculating surface roughness affect on conductor loss and each method has its own set of limits and capabilities
    - Radiation loss can be difficult to accurately account due to the wideband measurements as well as differences in signal launch impacting radiation loss
    - Varying levels of return loss or mismatch loss may not be well captured
- Df calculation is better done on resonant structures than transmission / reflection

Circuit Evaluation Techniques for Material Characterization

Microstrip gap coupled strip resonators and ring resonators

- Gap coupled strip resonators are used to evaluate materials for Dk and Df
- These structures do have some amount of radiation loss
- Sometimes they are tested in a grounded metal enclosure to capture the radiation losses
- The gap coupling should be loosely coupled to realize the Q of the dielectric more than the conductor Q
- The gap coupling can affect the center frequency and cause inaccuracies in determining Dk and Df



Top view of gap coupled resonator

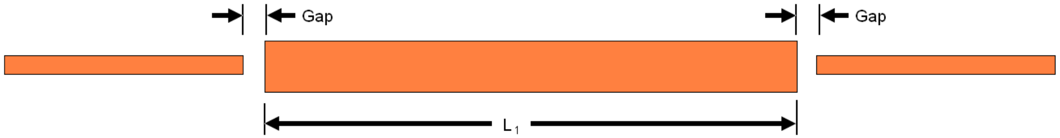
$$\mathrm{Eff\_}\varepsilon_r = \left[\frac{n\ c}{2\ f_r\left(L + \Delta L\right)}\right]^2$$

Circuit Evaluation Techniques for Material Characterization

Microstrip gap coupled strip resonators and ring resonators

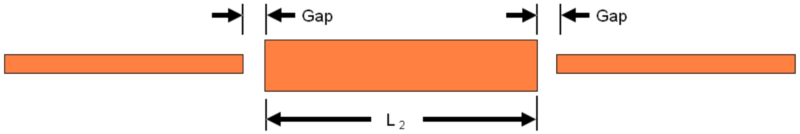
- A method was developed to eliminate the potential impact of the gaps
- Again, a differential length method is used

$$Eff\_\varepsilon_r = \left[\frac{n\,c}{2\,f_r\,(L+\Delta L)}\right]^2$$



Eq. For long resonator

$$L_1 + \Delta L = \frac{n_1\,c}{2\,f_{r1}\sqrt{Eff\_\varepsilon_r}}$$



Eq. For short resonator

$$L_2 + \Delta L = \frac{n_2\,c}{2\,f_{r2}\sqrt{Eff\_\varepsilon_r}}$$

Simultaneously solve to eliminate ΔL

$$Eff\_\varepsilon_r = \left[\frac{c\,(n_1 f_{r2} - n_2 f_{r1})}{2\,f_{r1}\,f_{r2}\,(L_2 - L_1)}\right]^2$$

ΔL is the added length of the resonator due to fringing and is dependent on the gap size

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Circuit Evaluation Techniques for Material Characterization

Microstrip gap coupled strip resonators and ring resonators

- Taking the differential length method of resonators to the next step was to use ring resonators

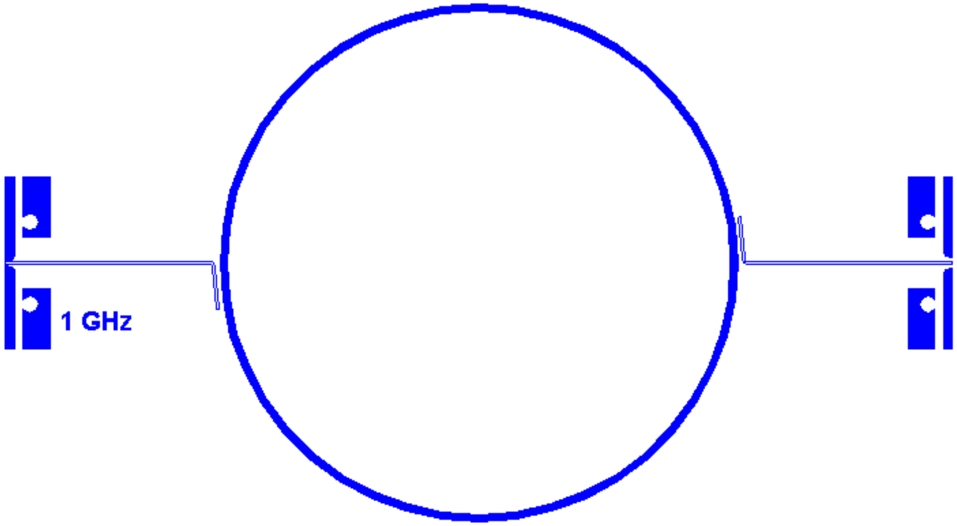
- Ring resonators, when designed correctly, have minimal or no radiation loss

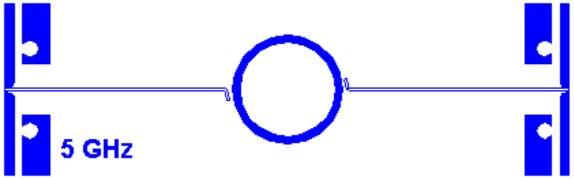
- The gap coupling can impact the resonant frequency and the calculations of Dk and Df

- Using the previous method, the impact of the gaps can be minimized

- Ring resonators can be designed with the exact same feed line, gaps and other dimensions, with the only difference being the circumference

- The two circumferences needs to be a multiple of common resonant nodes



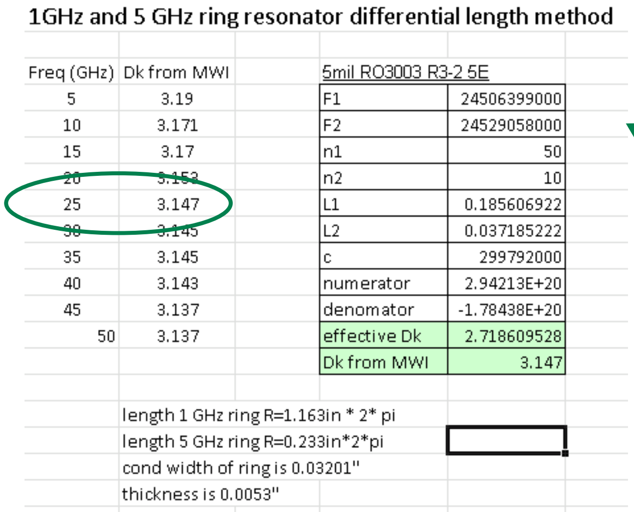


Circuit Evaluation Techniques for Material Characterization

Microstrip gap coupled strip resonators and ring resonators

example using a 1 GHz and 5 GHz ring resonators built on 5mil RO3003

Screen shot of Excel worksheet for the ring resonator nodes at 25 GHz



1GHz and 5 GHz ring resonator differential length method

Freq (GHz)	Dk from MWI	5mil RO3003 R3-2 5E	
5	3.19	F1	24506399000
10	3.171	F2	24529058000
15	3.17	n1	50
20	3.153	n2	10
25	3.147	L1	0.185606922
30	3.145	L2	0.037185222
35	3.145	c	299792000
40	3.143	numerator	2.94213E+20
45	3.137	denomator	-1.78438E+20
50	3.137	effective Dk	2.718609528
		Dk from MWI	3.147

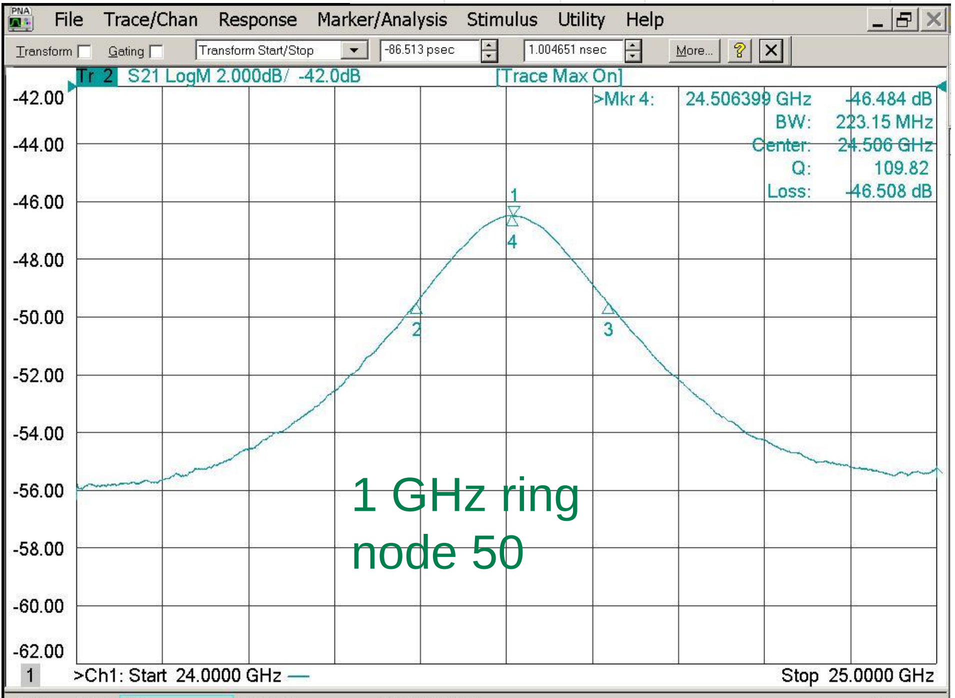
length 1 GHz ring R=1.163in * 2* pi

length 5 GHz ring R=0.233in*2*pi

cond width of ring is 0.03201"

thickness is 0.0053"

Below are screen shots from the PNA for the ring resonators at 25 GHz



Tr 2 S21 LogM 2.000dB/ -42.0dB [Trace Max On]

>Mkr 4: 24.506399 GHz -46.484 dB

BW: 223.15 MHz

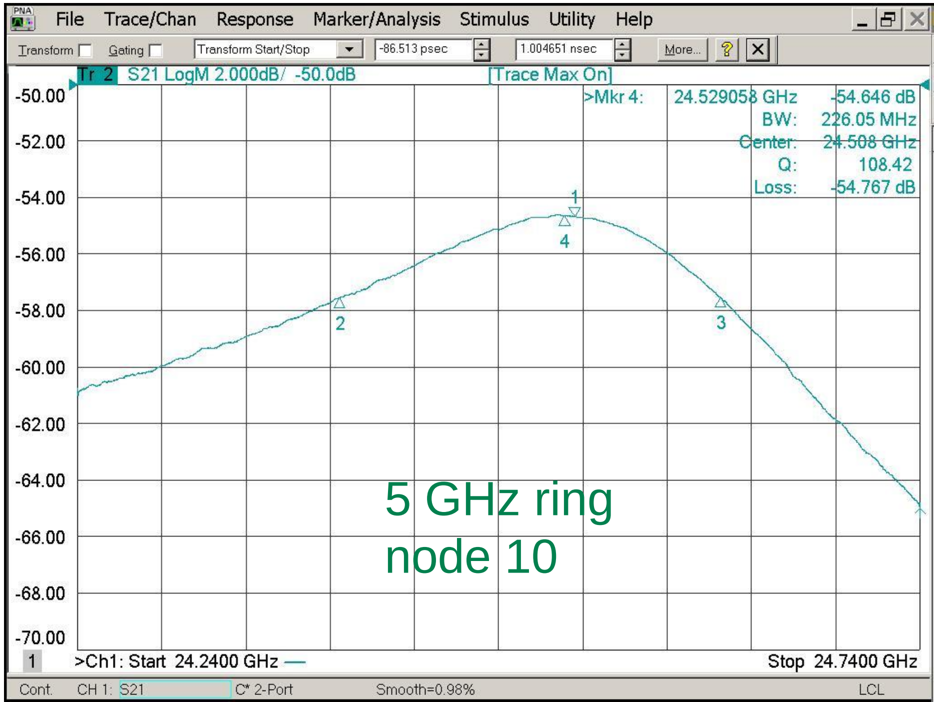
Center: 24.506 GHz

Q: 109.82

Loss: -46.508 dB

>Ch1: Start 24.0000 GHz — Stop 25.0000 GHz

1 GHz ring node 50



Tr 2 S21 LogM 2.000dB/ -50.0dB [Trace Max On]

>Mkr 4: 24.529058 GHz -54.646 dB

BW: 226.05 MHz

Center: 24.508 GHz

Q: 108.42

Loss: -54.767 dB

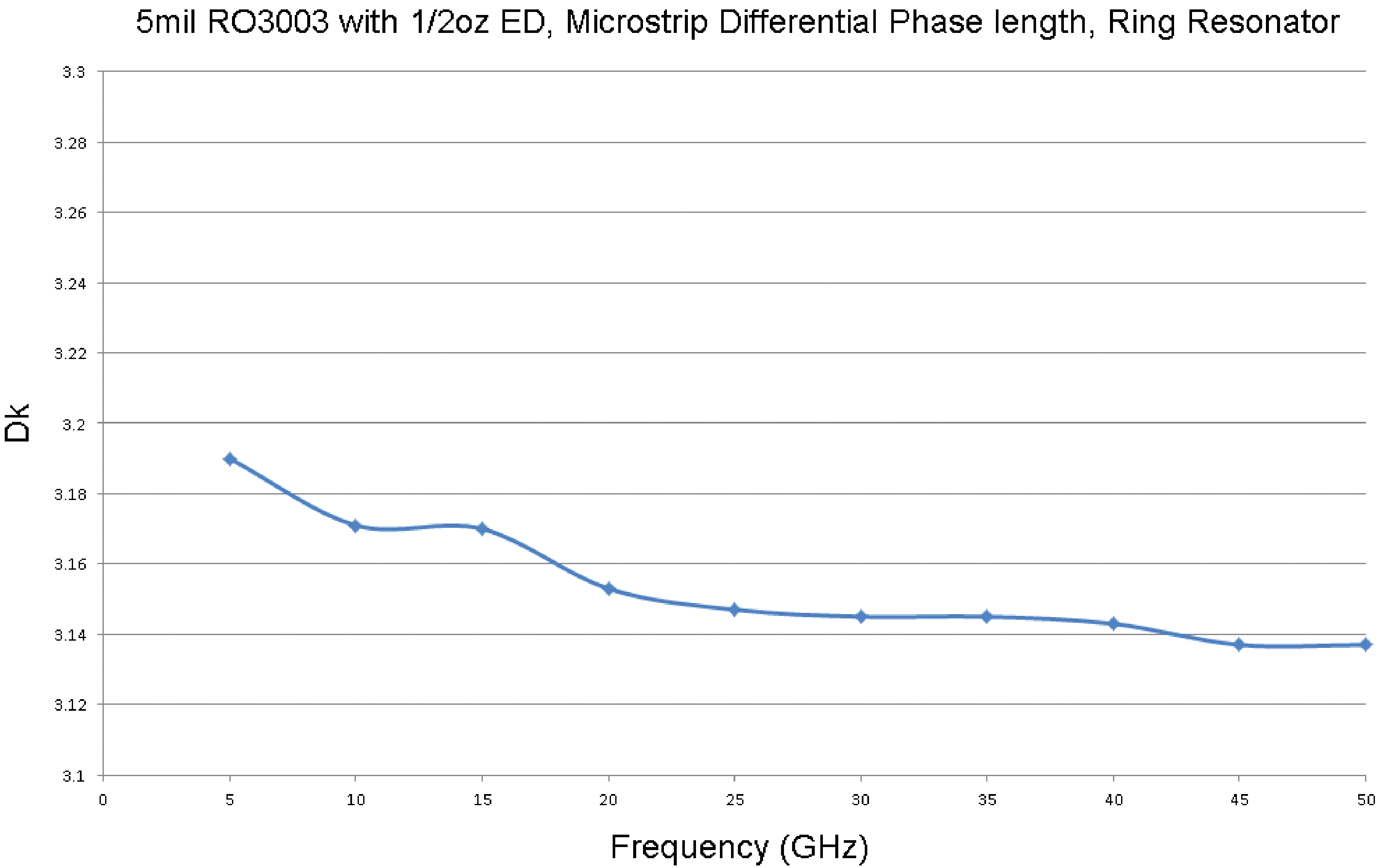
>Ch1: Start 24.2400 GHz — Stop 24.7400 GHz

Cont. CH 1: S21 C* 2-Port Smooth=0.98% LCL

5 GHz ring node 10

Circuit Evaluation Techniques for Material Characterization

Microstrip gap coupled strip resonators and ring resonators



5mil RO3003 with 1/2oz ED, Microstrip Differential Phase length, Ring Resonator

Circuit Evaluation Techniques for Material Characterization

Microstrip differential circumference ring resonator testing

- Pro's
    - Ring resonators have minimal or no radiation loss so calculated Df can be more accurate
    - There is more freedom in designing the gap coupling so it will not impact the accuracy of the calculated Dk values
    - The is a lot of literature and references for using ring resonators regarding material characterization
    - Results are narrowband; less issue with signal launch and spurious modes
- Con's
    - Time consuming to design, make circuits and evaluate them
    - Results are narrowband and limited information for wideband applications