Design Right the First Time: Understanding how Dielectric Constant (Dk) Test Methods Affect Time to Market

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ROGERS CORPORATION

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Design Right the First Time: Understanding how Dielectric Constant (Dk) Test Methods Affect Time to Market

Agenda

- Optimum Design Dk values and the potential variation
- Normal variations of high frequency circuit materials
- PCB fabrication influences which impact RF performance
- End-use environmental conditions and potential impact on PCB RF performance

Design Right the First Time: Understanding how Dielectric Constant (Dk) Test Methods Affect Time to Market

Optimum Design Dk values and the potential variation

Commercial Grade Materials

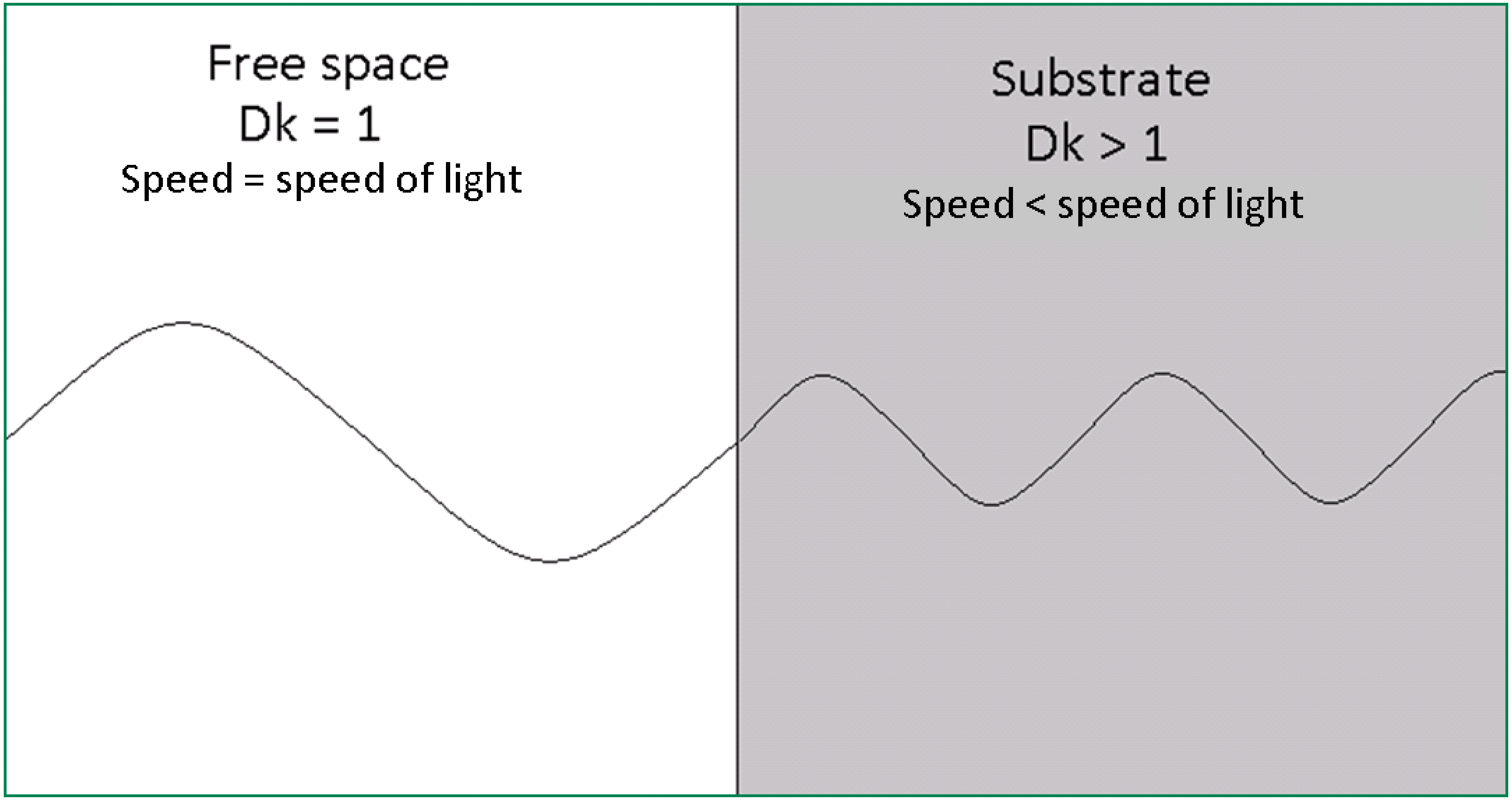
RO3000® series, RO3200™ series, RO4000® series
High Frequency Laminates

Product	Dielectric Constant, ε_r @ 10 GHz (Typical) Process[1]	Dielectric Constant, ε_r @ 10 GHz (Typical) Design[11]	Dissipation[1] Factor TAN δ @ 10 GHz (Typical)	Thermal[2] Coefficient of ε_r -50°C to 150°C ppm/°C (Typical)	Volume Resistivity Mohm • cm (Typical)	Surface Resistivity Mohm (Typical)	Moisture[4] Absorption D48/50 % (Typical)
RO3003™ PTFE Ceramic	[7] 3.00 ± 0.04	3.00	0.0013	13	1×10^7	1×10^7	0.04
RO3035™ PTFE Ceramic	3.50± 0.05	3.60	0.0017	-50° to 10°C: -34 10°C to 150°C: -11	1×10^7	1×10^7	0.04
RO3006™ PTFE Ceramic	6.15 ± 0.15	6.5	0.0020	-262	1×10^5	1×10^5	0.02
RO3010™ PTFE Ceramic	10.20 ± 0.30	11.2	0.0022	-280	1×10^5	1×10^5	0.05
RO3203™ PTFE Ceramic	[7] 3.02 ± 0.04	3.02	0.0016	-13	1×10^7	1×10^7	0.03

- Terminology:
  - Design Dk – The Dk value that is suggested for circuit design and modeling. The number given here is the intrinsic Dk (ε_r) value of the substrate and there is some frequency and thickness dependencies which will be discussed
  - Process Dk – The Dk value for raw material testing to a specific industry standard test method (IPC-TM-250 2.5.5.5c)

Optimum Design Dk values and the potential variation

- A higher Dk material will slow an electromagnetic wave



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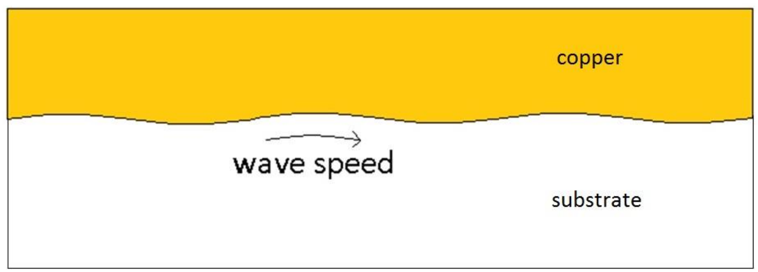
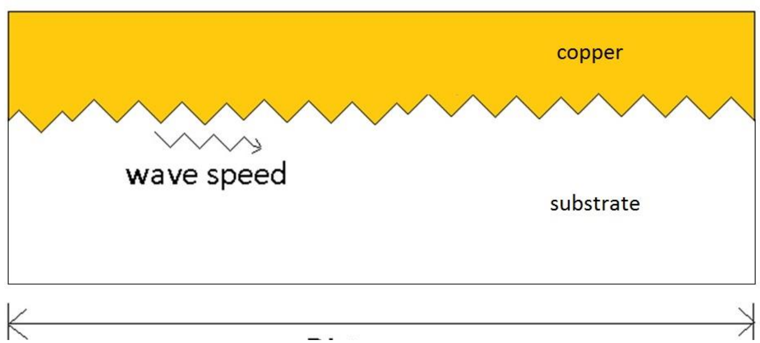
Optimum Design Dk values and the potential variation

- There are other things that can slow the wave besides a substrate with higher Dk
- A rough copper surface can slow the wave propagation
- Again, a slower wave translates into higher Dk even if the substrate is unchanged





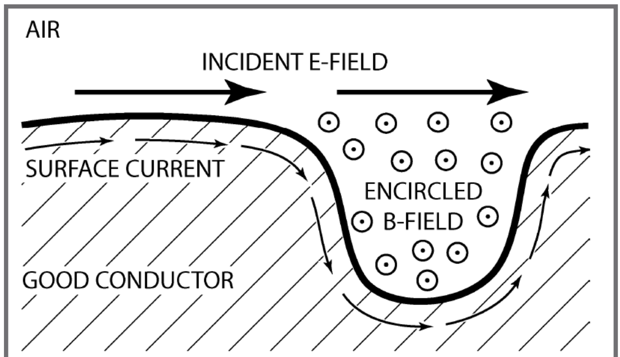
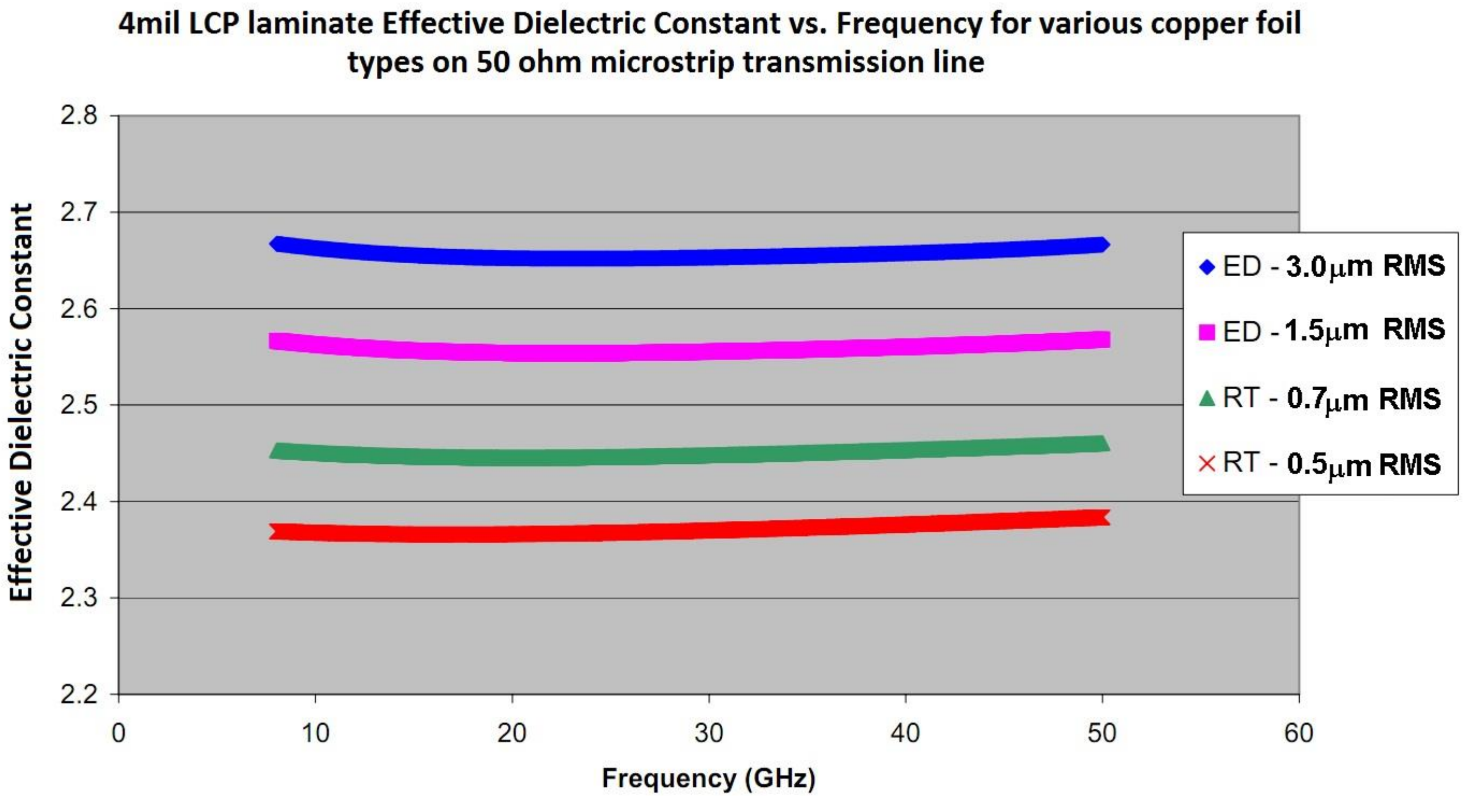


Fig. 7. Magnetic field encircled by the surface current flowing on a rough conductor and excited by the incident electric field results in substantial surface inductance, above and beyond that generated by the smooth surface skin effect.

Excerpt at the far right is from:
"Conductor Profile Effects on the Propagation Constant of Microstrip Transmission Lines", Allen F. Horn, III, * John W. Reynolds* and James Rautio[+]
***Rogers Corporation, Lurie R&D Center, Rogers, CT 06259-0157 USA**
[+]Sonnet Software, North Syracuse, NY 13212 USA

Optimum Design Dk values and the potential variation



- Shown are circuits with the same substrate, but using different copper types with different surface roughness
- Circuits with rougher copper surface (higher RMS) have higher effective Dk
- Again, the material is unchanged and it is only the copper roughness differences which are impacting the effective Dk of the circuits

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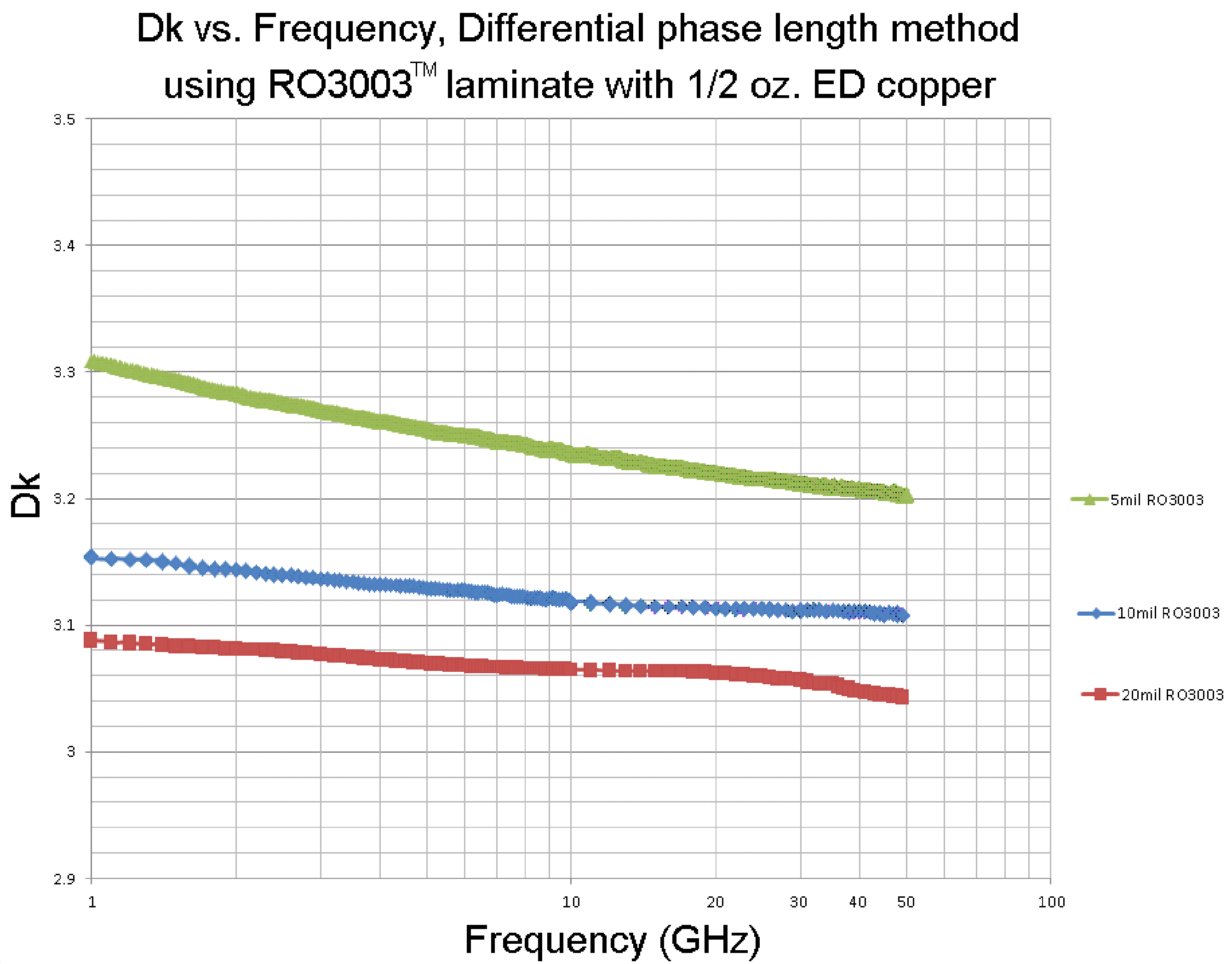
Optimum Design Dk values and the potential variation

This data shows results from circuit testing, using the same substrate (RO3003 laminate) and same copper type, however the circuits use different thicknesses of the substrate

All circuits were 50 ohm microstrip transmission lines

The Dk values shown here are the calculated Dk values from circuit testing



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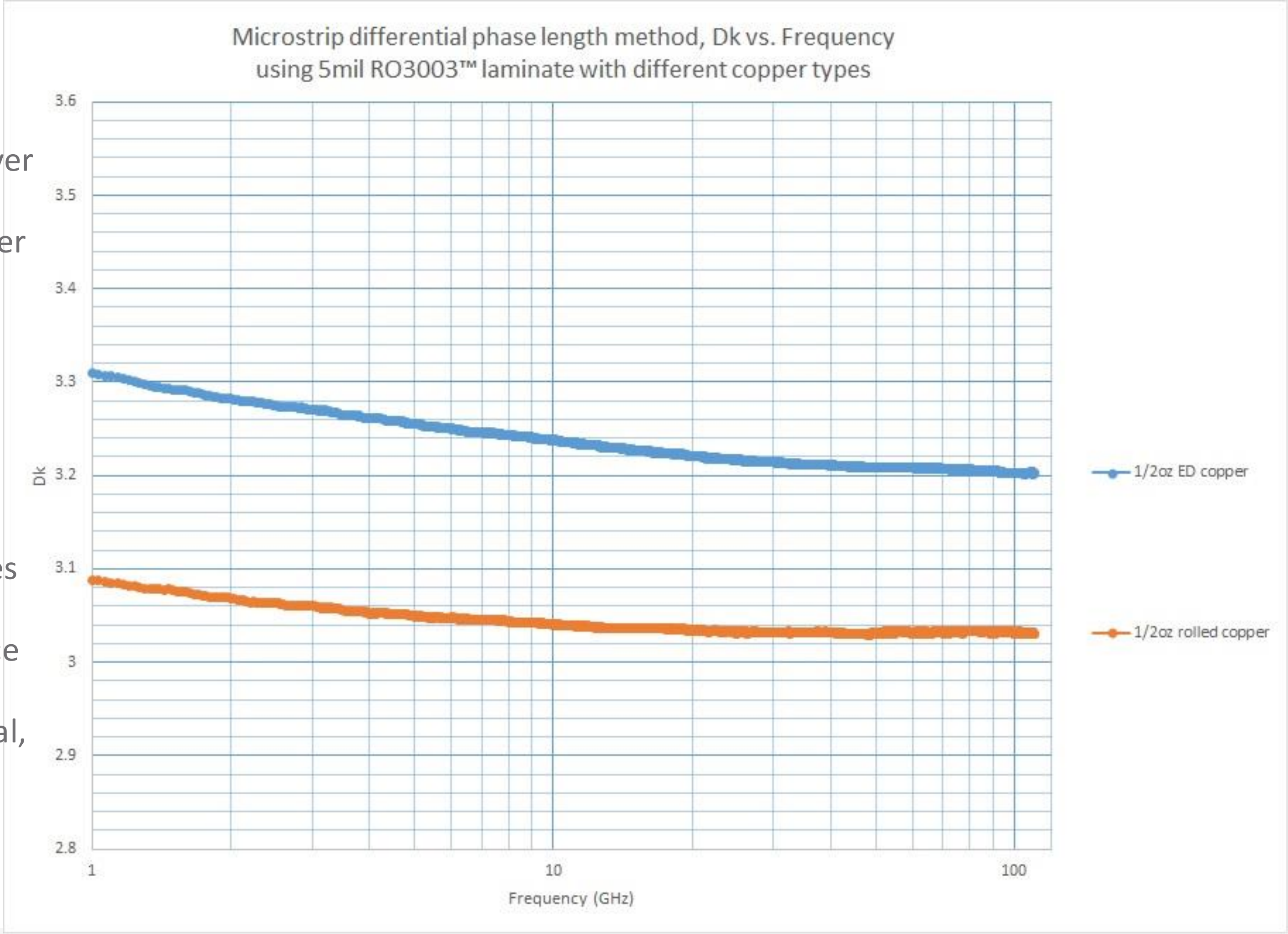
Optimum Design Dk values and the potential variation

This data shows results from circuit testing, using the same substrate and same thickness (5mil RO3003 laminate), however using different copper types which have very different copper surface roughness

This type of ED copper has a roughness of 1.8 microns RMS and the rolled copper is 0.3 microns RMS

The smooth copper (rolled) does not impact the phase velocity much so the circuit performance is showing Dk values near the intrinsic Dk value of the material, which is 3.0

All circuits were 50 ohm microstrip transmission lines



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Optimum Design Dk values and the potential variation

Dispersion is the term regarding a change in Dk, with a change in frequency

All circuit materials have dispersion

The Dk vs. Frequency curve for most dielectrics should have a slight negative slope

A curve with an increased slope is a material with more dispersion (not desired)

Our high frequency materials have minimal dispersion

Dispersion varies from one material to another based on:

- material polarization
- loss characteristics

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Optimum Design Dk values and the potential variation

- When an electric field is applied to dielectric material, dipole moments are established
- The dipole moments augment the electric flux, which has a relationship to Dk
- Dipole moments are created / relax as electric fields turn on / off or vary as sine wave
- 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

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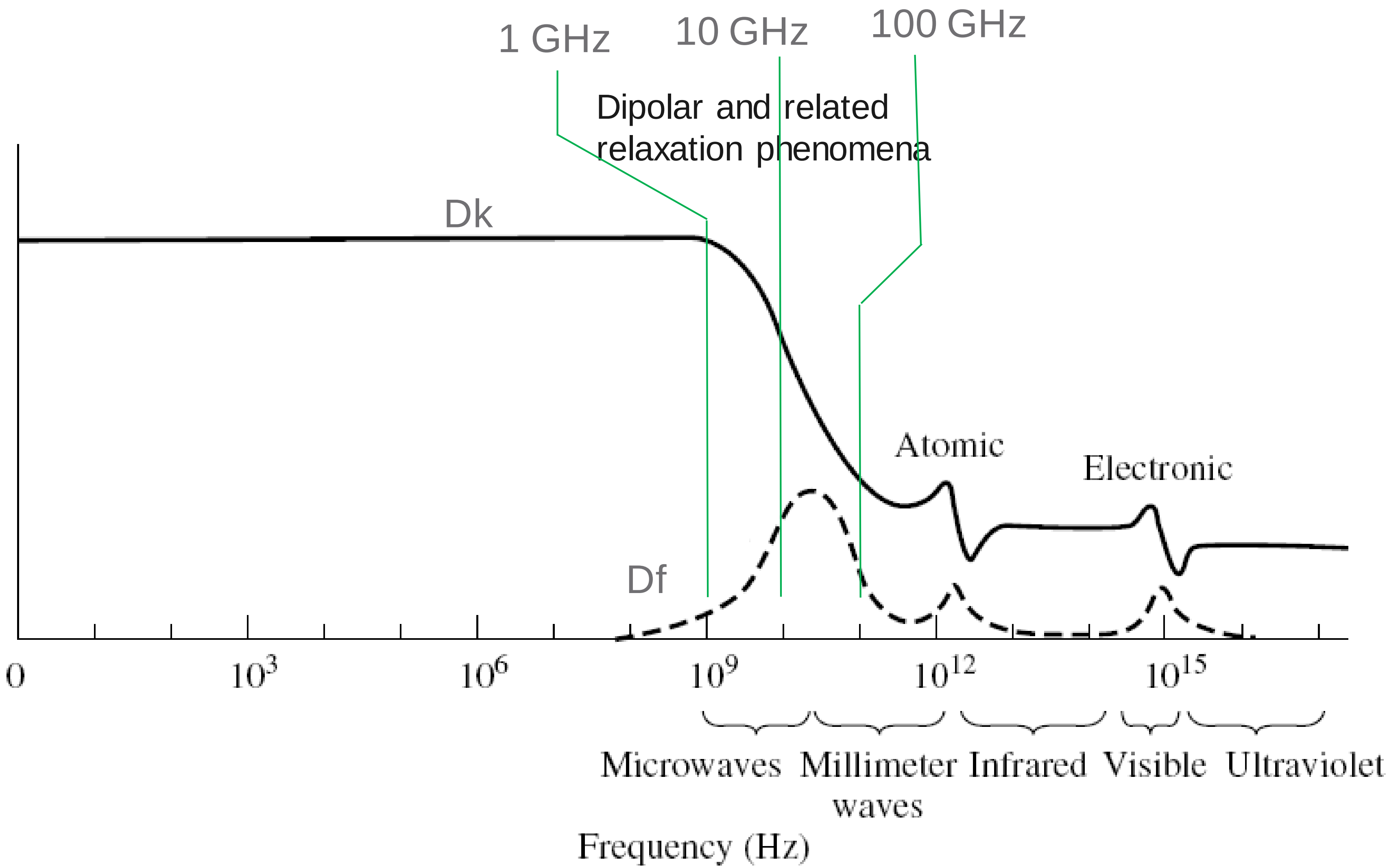
Dk vs. Frequency curve for a **generic** dielectric material is shown below

Low loss materials have much less Dk-Frequency slope



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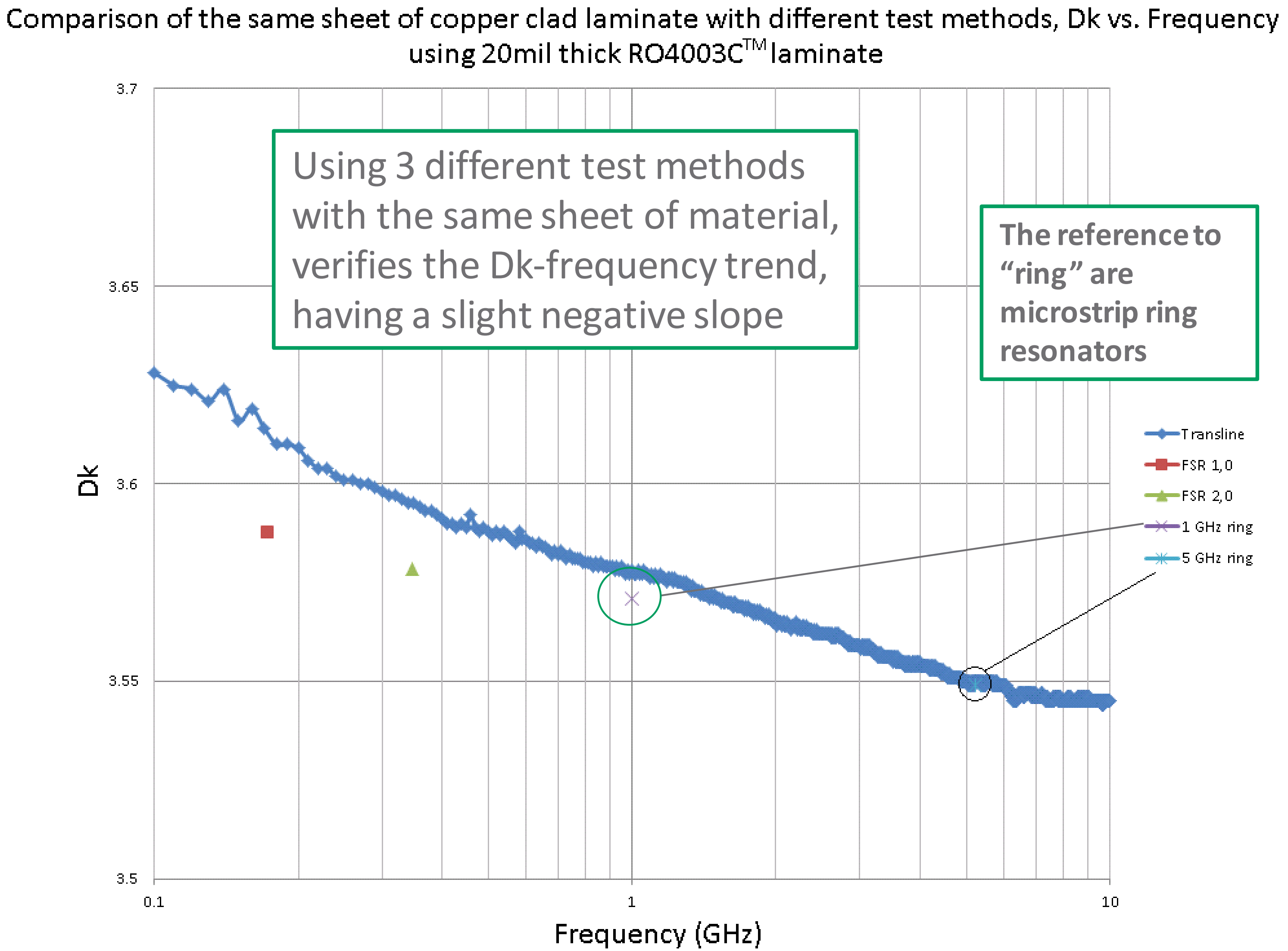
Optimum Design Dk values and the potential variation

FSR 1,0 is at ~ 175 MHz

FSR 2,0 is at ~ 350 MHz

Thick blue curve is microstrip transmission line testing using differential phase length method



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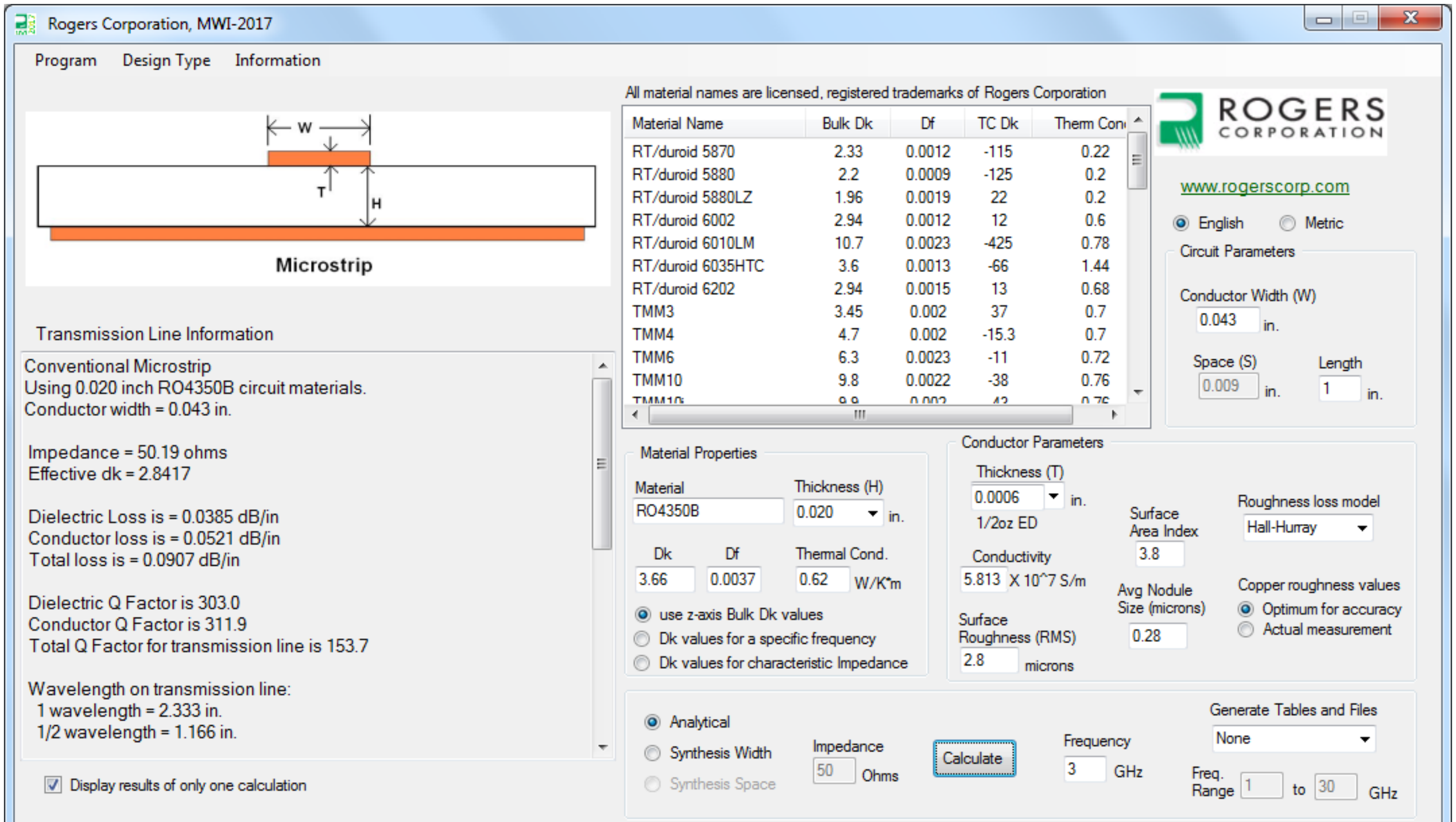
Optimum Design Dk values and the potential variation

- The free downloadable version of MWI-2017 has the Design Dk built into it
- In the future, other versions of MWI apps and on-line calculators will have Design Dk



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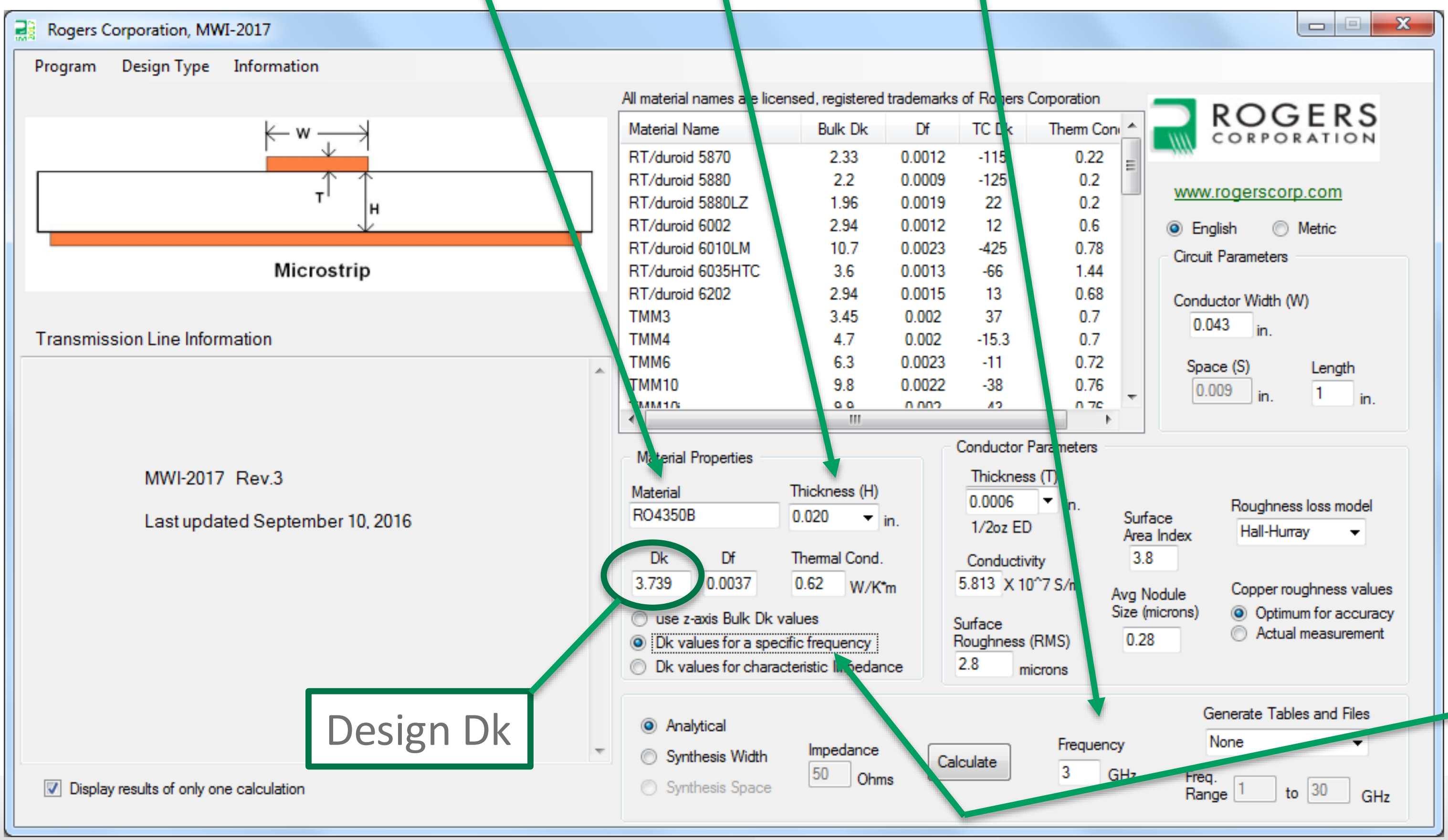
Optimum Design Dk values and the potential variation

- Select the desired material, thickness and frequency, then the Design Dk will be shown



This is an example of Design Dk for a frequency dependent application at 3 GHz

Use RF Design Dk values

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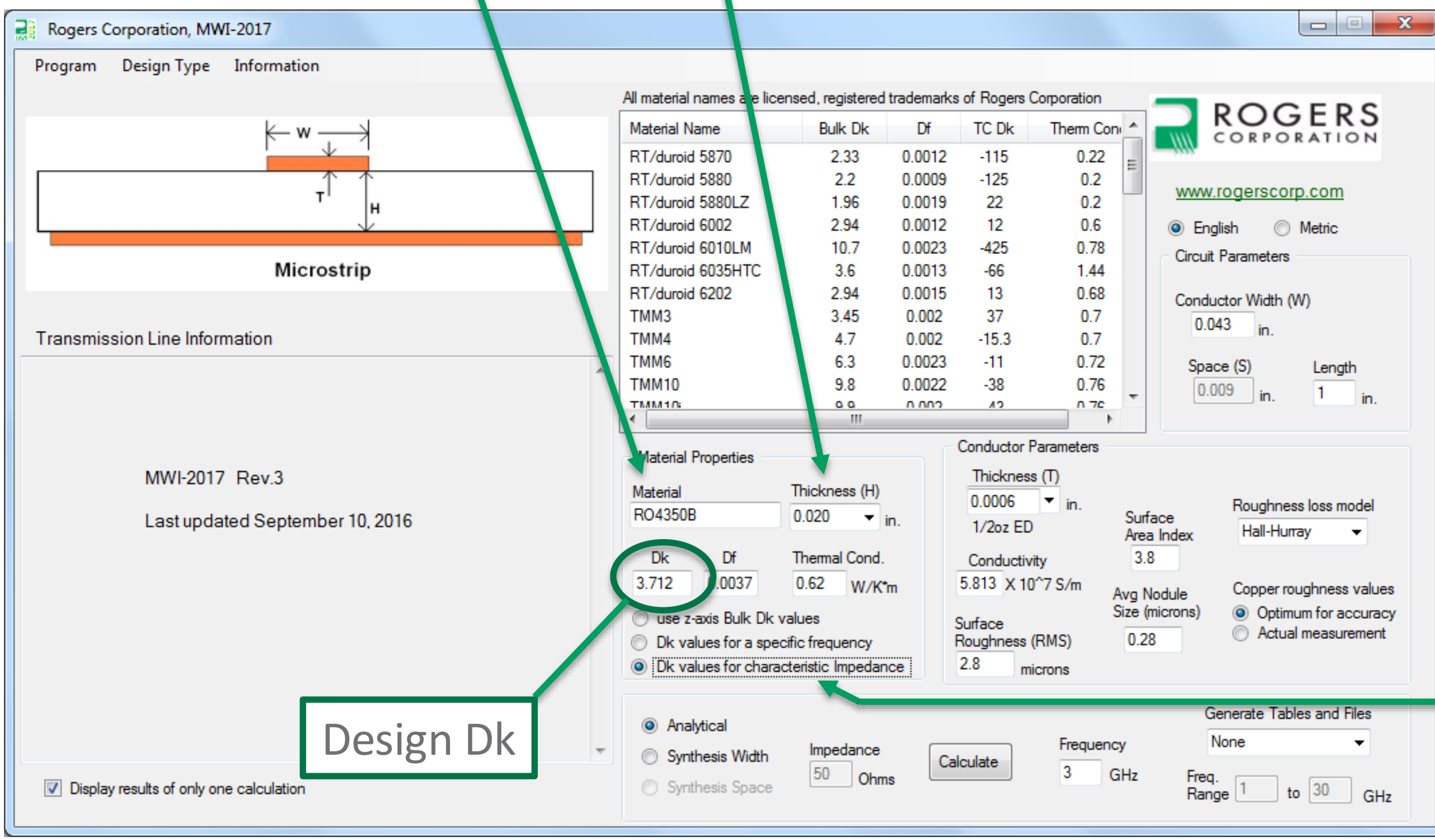
Optimum Design Dk values and the potential variation

- Select the desired material and thickness, then the Design Dk will be shown



This is an example of Design Dk for determining characteristic impedance or for a digital or wideband application

Use Digital Dk values

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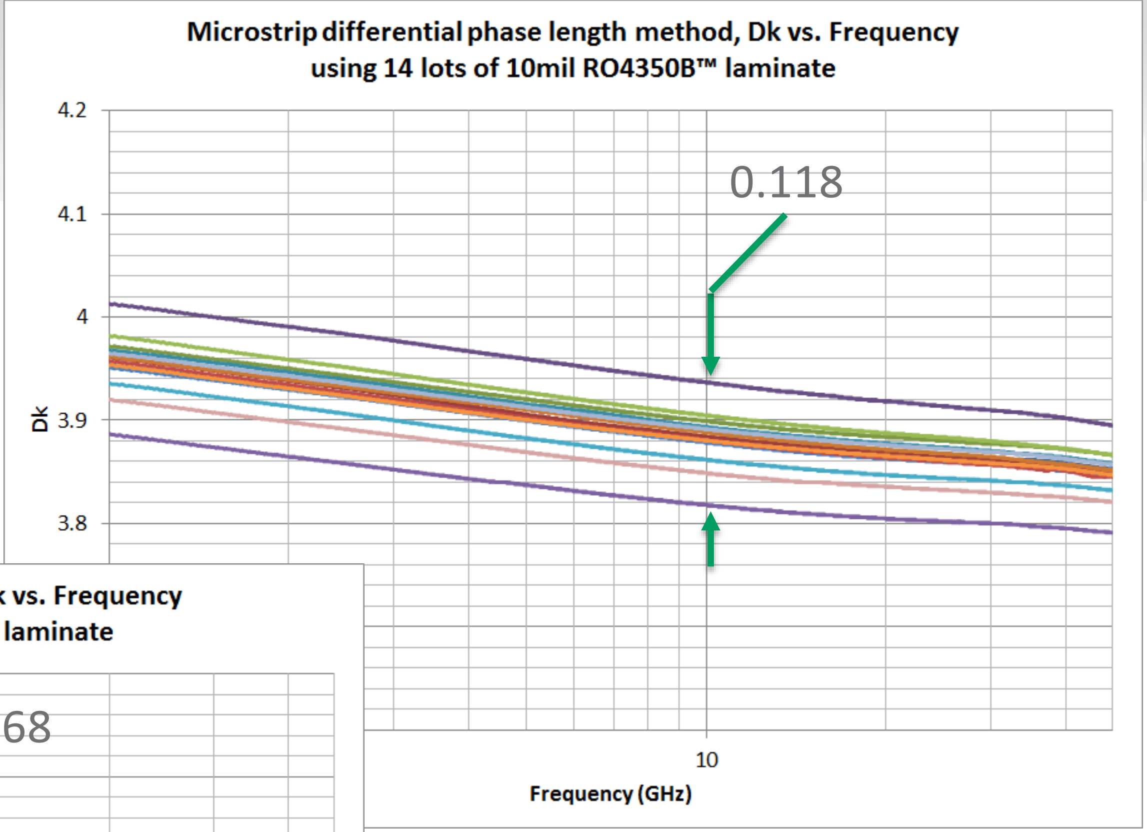
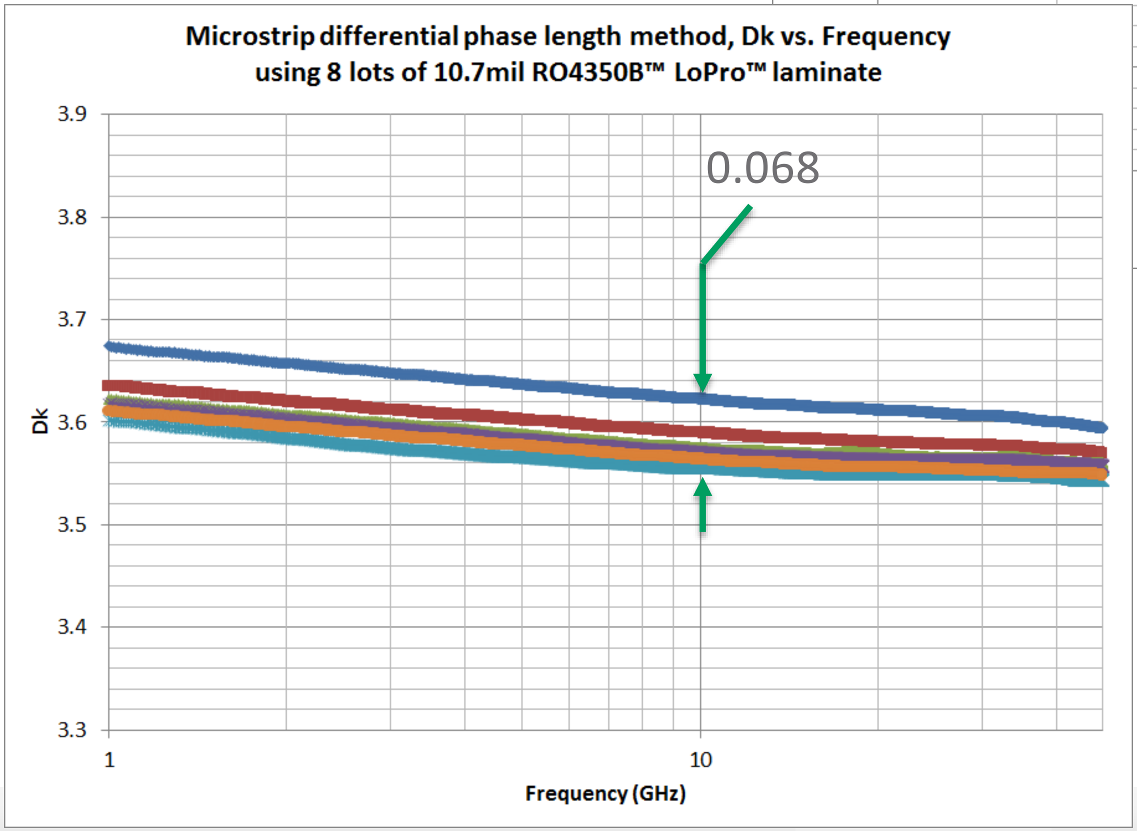
- Design Dk is not a material property
- Design Dk is a circuit property
- There is no tolerance for Design Dk because it is dependent on thickness, copper type or surface roughness, frequency and some PCB fabrication tolerances
- Design Dk variables:
    - Substrate Dk tolerance
    - Copper surface roughness tolerance
    - Accuracy of test method, microstrip differential phase length method
    - Accuracy of circuit dimension measurements
    - Conductor width variation on a single conductor from PCB fabrication
    - Plated finish and circuit design type

Copper roughness variation

- All copper foil has normal variation for surface roughness
- There is within-sheet variation and lot-to-lot variation of roughness





- RO4350B laminate uses a high profile copper with an average RMS roughness of 2.8 microns
- RO4350B LoPro laminate uses low profile copper with an average RMS roughness of 0.8 microns
- In general, smoother copper has less roughness variation and less Design Dk variation

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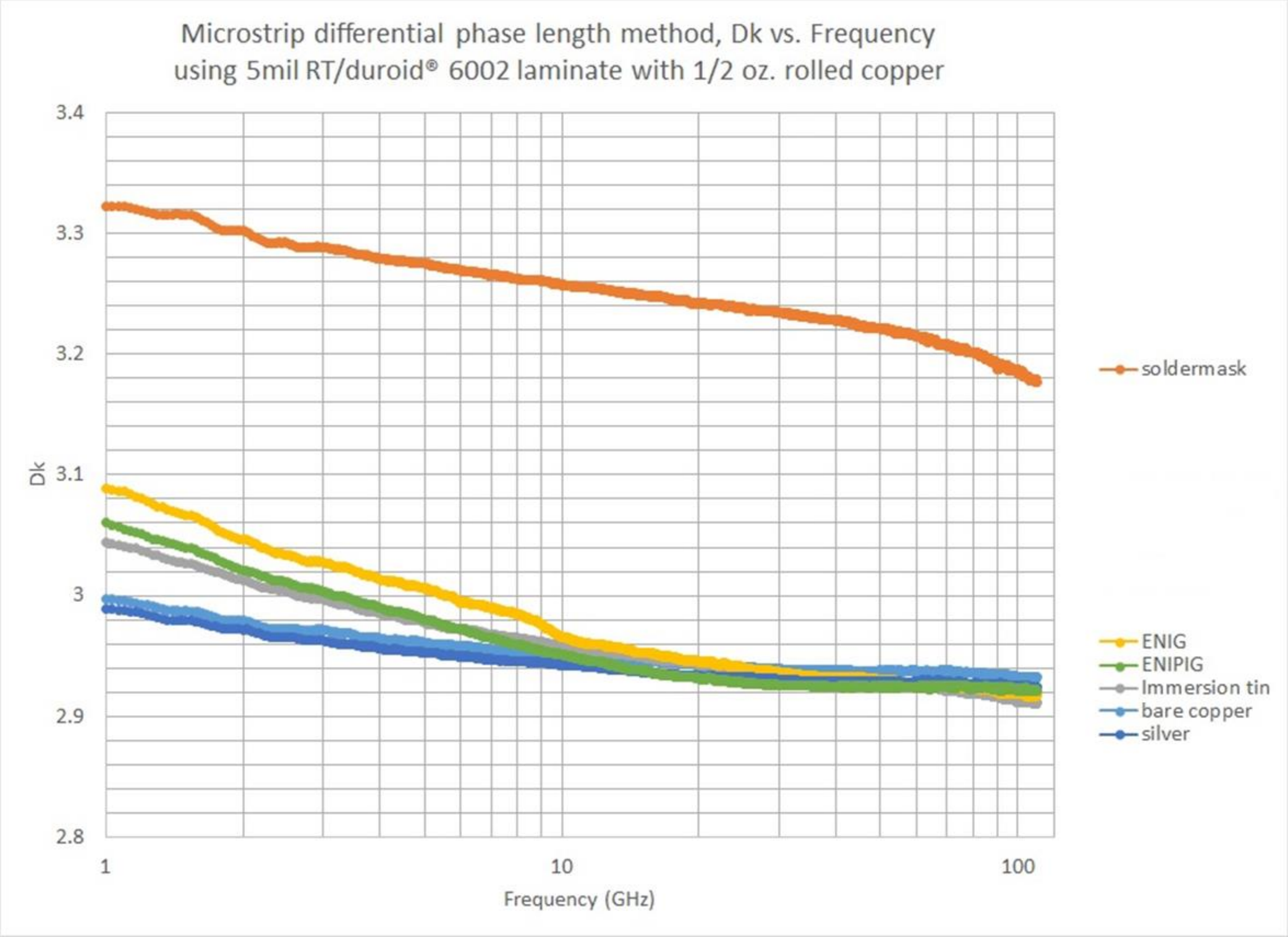
Optimum Design Dk values and the potential variation

Plated finishes have impact in frequency region where skin depth of the composite metal is changing quickly with a change in frequency

At low microwave frequencies the impact of plated finish is in order of plated finish composite conductivity

When this same study is done on thicker substrate the Dk differences are reduced

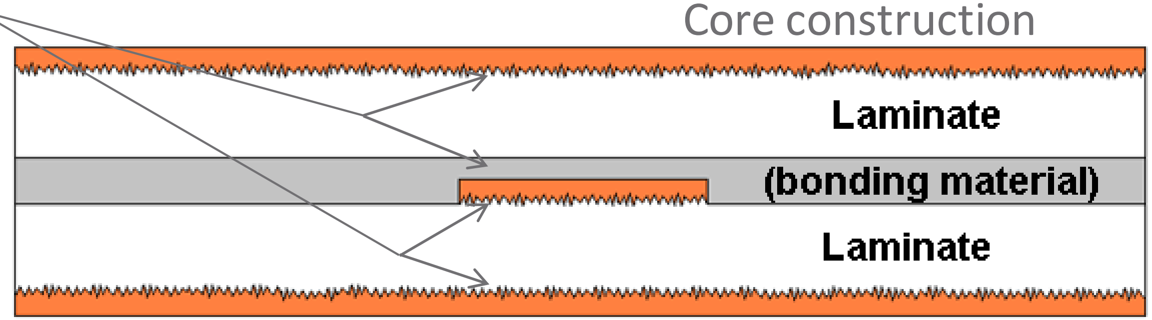


Optimum Design Dk values and the potential variation

A core construction will be different than a foil lam construction

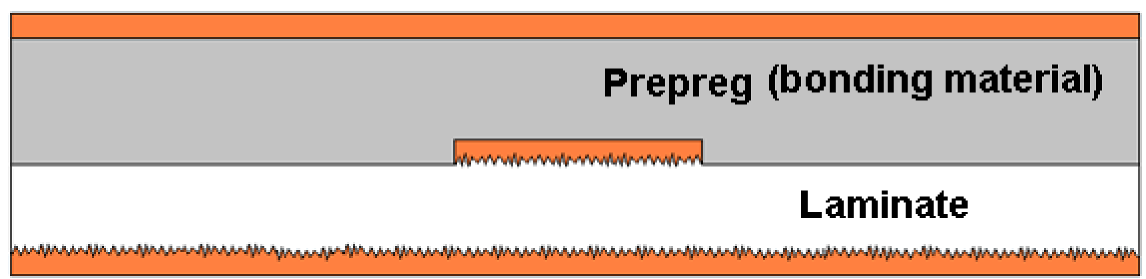
4 copper-substrate interfaces

Core construction



Core construction can have 3 of 4 copper-substrate the same

Foil lam construction



The foil lam construction will only have 2 of the 4 copper-substrate interfaces the same

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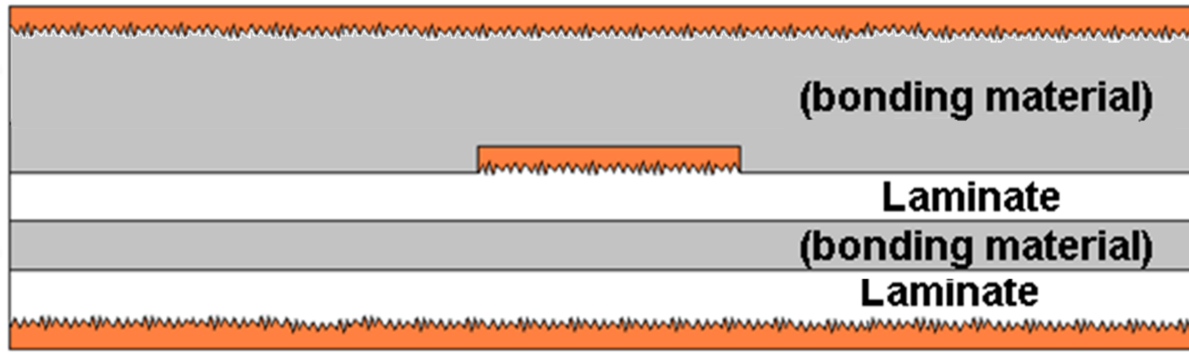
Optimum Design Dk values and the potential variation

- Bonding material, prepreg, can be very difficult to estimate Design Dk

This prepreg layer has two copper effects; a smooth copper and rough copper surface



This prepreg layer has no copper effect

The same prepreg, will need to have 2 different Design Dk values for this construction

	Design Dk			
How RO4450F prepreg is used:	4mil	8mil	12mil	20mil
Between blank cores (no copper)	3.70	3.70	3.70	3.70
Blank core 1 side of prepreg, copper other side	3.95	3.80	3.77	3.75
copper on both sides of prepreg	4.20	3.90	3.83	3.80

Assuming ED copper with relative high profile, or surface roughness of about 2.2 microns RMS (Rq)

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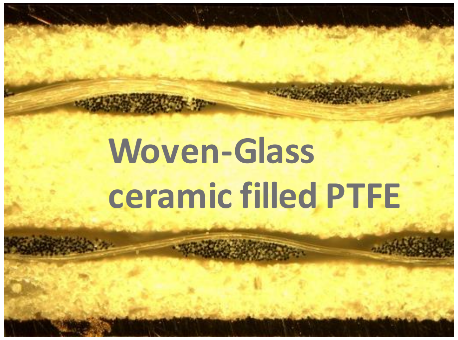
Normal variations of high frequency circuit materials

- Common types of copper clad laminates used in Microwave PCB (Printed Circuit Board) applications:
  - PTFE based
    - Woven-glass
    - Non-Woven-glass
    - Filled PTFE woven or non-woven-glass
  - Hydrocarbon based
    - Ceramic filled
    - Woven-glass
    - Non-woven-glass



Pictures are magnified cross-sectional views of different laminate

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Normal variations of high frequency circuit materials

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High Frequency Laminates

Product	Dielectric Constant, ε_r @ 10 GHz (Typical)		Dissipation[1] Factor TAN δ @ 10 GHz (Typical)	Thermal[2] Coefficient of ε_r -50°C to 150°C ppm/°C (Typical)	Volume Resistivity Mohm • cm (Typical)	Surface Resistivity Mohm (Typical)	Moisture[4] Absorption D48/50 % (Typical)
	Process[1]	Design[11]					
RO3003™ PTFE Ceramic	[7] 3.00 ± 0.04	3.00	0.0013	13	1 X 10^7	1 X 10^7	0.04
RO3035™ PTFE Ceramic	3.50± 0.05	3.60	0.0017	-50° to 10°C: -34 10°C to 150°C: -11	1 X 10^7	1 X 10^7	0.04
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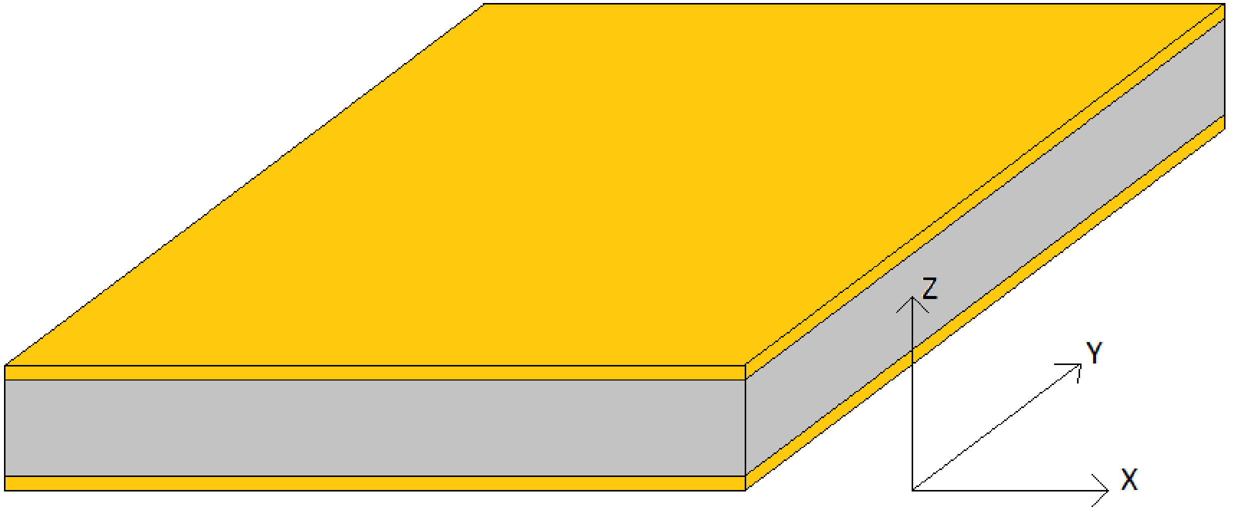
- Key electrical parameters: Dielectric constant (Dk), Dissipation factor (Df, loss)
- Other critical electrical parameters include: Thermal Coefficient of Dk, moisture absorption

Design Right the First Time: Understanding how Dielectric Constant (Dk) Test Methods Affect Time to Market

Normal variations of high frequency circuit materials

- Dielectric constant (also called: Dk or ε_r or E_r or K_{sub} or relative permittivity)

- Most materials used in the PCB industry are anisotropic (Dk is not the same on all three axes of the material) $Dk_X \neq Dk_Y \neq Dk_Z$



- Anisotropy is due to:
  - Unbalanced woven glass
  - Filler particles that naturally orient more along one axis
  - Normal directional characteristic of some manufactured material

Normal variations of high frequency circuit materials

- Anisotropy is related to electric displacement flux:

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

- As a practical point, the non-diagonal elements are typically not significant and ignored

$$\begin{pmatrix} D_x \\ D_y \\ D_z \end{pmatrix} = \begin{pmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$$

- Additionally, the ε_{xx} and ε_{yy} typically have little difference and for modeling (and for material measurement) purposes it is the ε_r of the x-y plane which is used in conjunction with the ε_r of the z-axis

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Normal variations of high frequency circuit materials

- For circuit design and modeling, anisotropy is typically not considered in transmission lines, stubs and other non-edge-coupled components
- Anisotropy should be considered for edge-coupled features
- As general rules:
  - Material with woven-glass reinforcement has more anisotropy
  - Material with high Dk (>5) has more anisotropy
- A few examples of some materials regarding anisotropy:

Material	Z-axis Design Dk	SPDR (X-Y Plane) Average Dk
RO3003	3.00	3.07
RO3006	6.40	7.18
RO3010	11.20	12.40
RO3203	2.99	3.14
RO3206	6.61	8.17
RO4350B	3.66	3.75

Normal variations of high frequency circuit materials

- Moisture absorption is a variable sometimes not considered for circuit performance variation in the field
  - All PCB materials absorb some amount of moisture; some less than others
  - The absorbed moisture is typically from humidity in the environment
  - Moisture (water vapor) absorbed in the material will increase the Dk and increase the Df
  - Rule of thumb, a good high frequency material will have < 0.3% moisture absorption

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Normal variations of high frequency circuit materials

- TCDk (Thermal Coefficient of Dielectric Constant) is another issue which is often overlooked in the design phase, for applications in a varying environment
  - TCDk is a property that all PCB materials have
  - TCDk is how much the Dk will change with a change in temperature
  - TCDk can be positive or negative and has units of ppm/°C
  - Rule of thumb, a good TCDk is less than |50| ppm/°C and ideal is 0 ppm/°C

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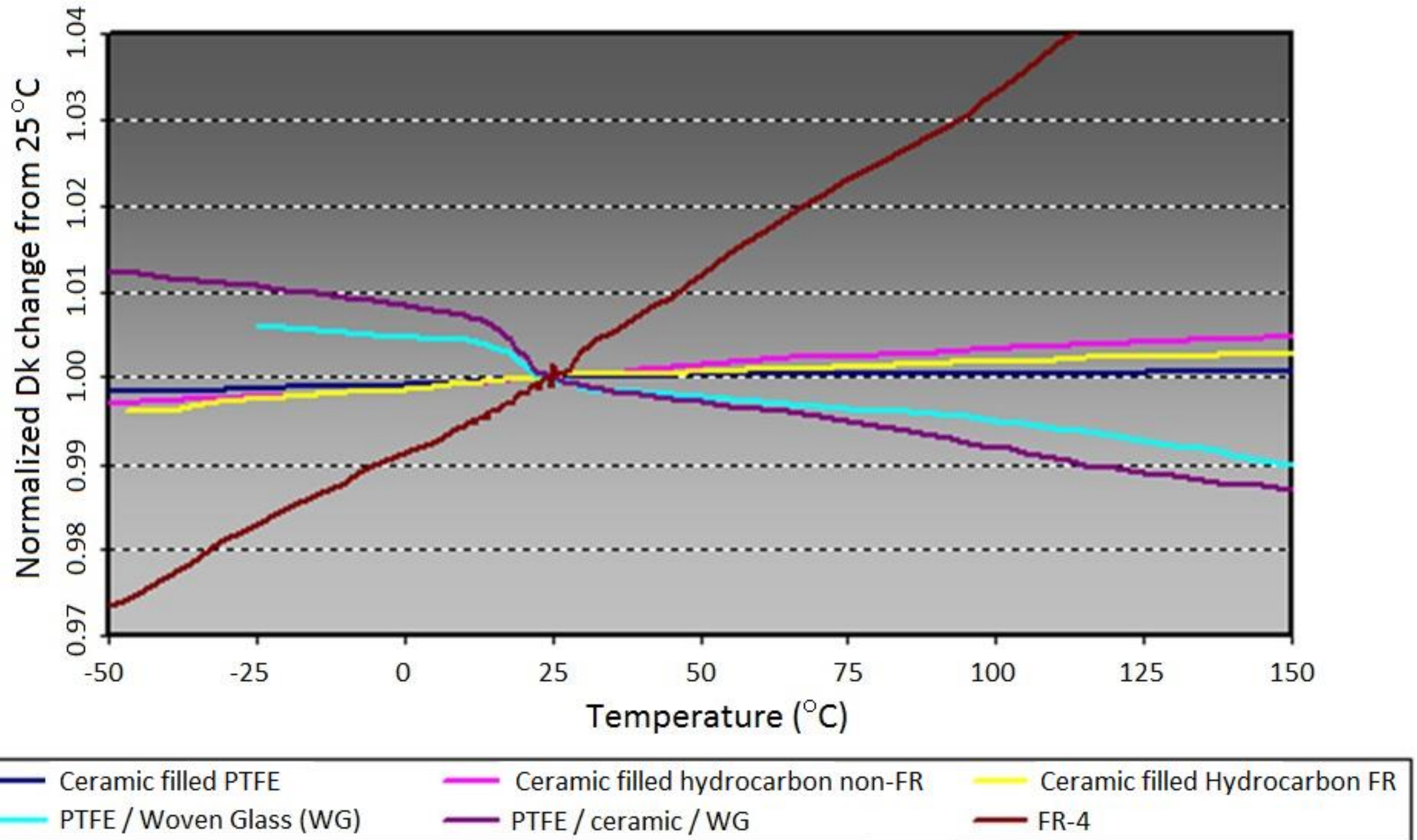
Normal variations of high frequency circuit materials



PCB fabrication influences which impact RF performance

- Most metal finishes used in the PCB industry are less conductive than copper
- A lower conductivity will cause higher conductor losses, which increases insertion loss
- Silver is the exception and does not increase conductor loss or insertion loss

Copper	5.817×10^7 S/m
Silver	6.301×10^7 S/m
Gold	4.52×10^7 S/m
Nickel	1.5×10^7 S/m
Aluminum	3.5×10^7 S/m
Brass	2.56×10^7 S/m
Solder	0.70×10^7 S/m
Tin	0.87×10^7 S/m

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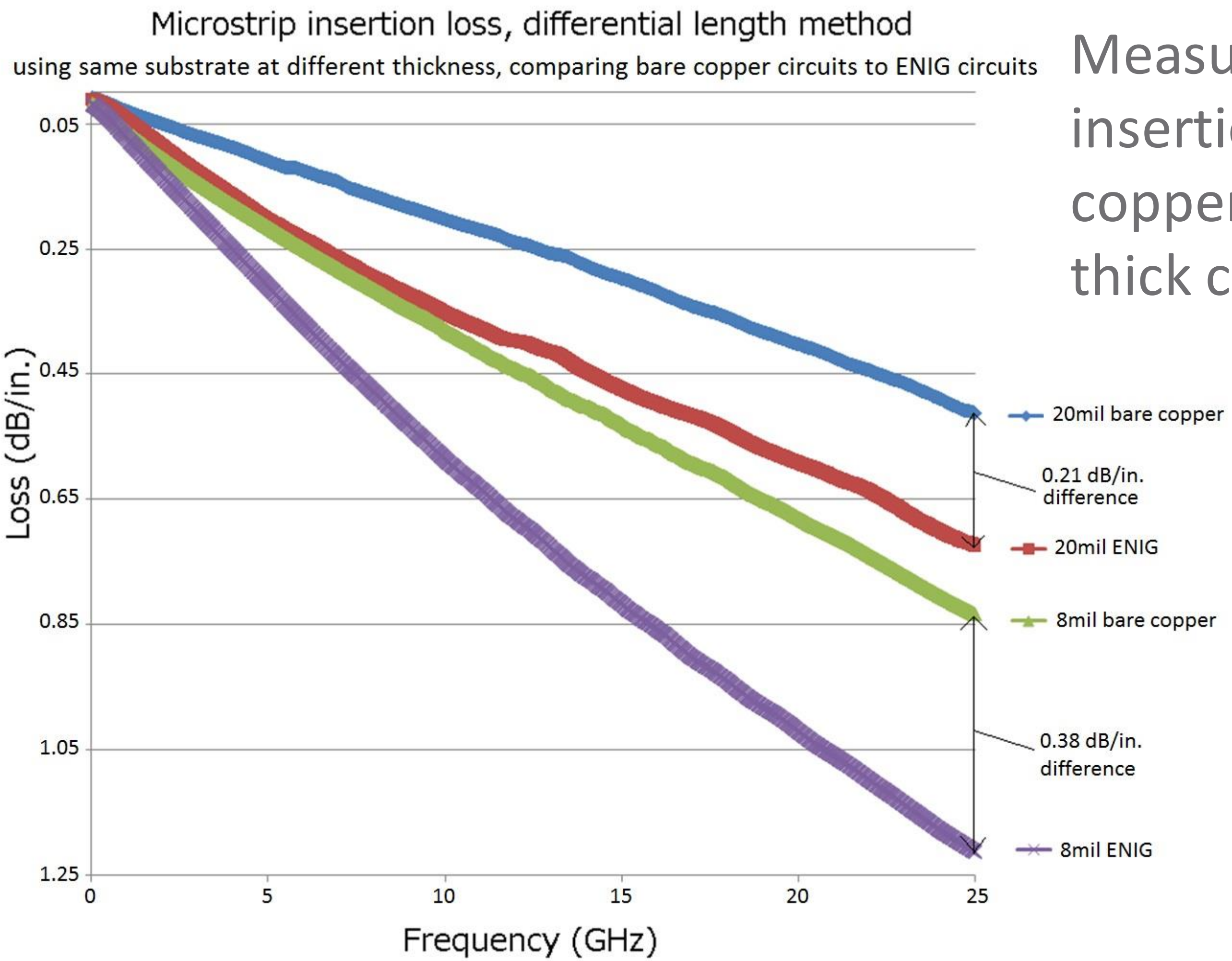
PCB fabrication influences which impact RF performance



Measured differences of insertion loss using bare copper vs. ENIG for thin and thick circuits

Difference of insertion loss for thick circuit

Difference of insertion loss for thin circuit

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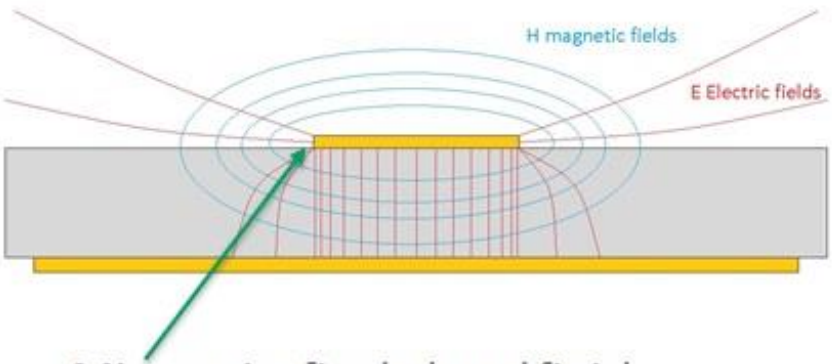
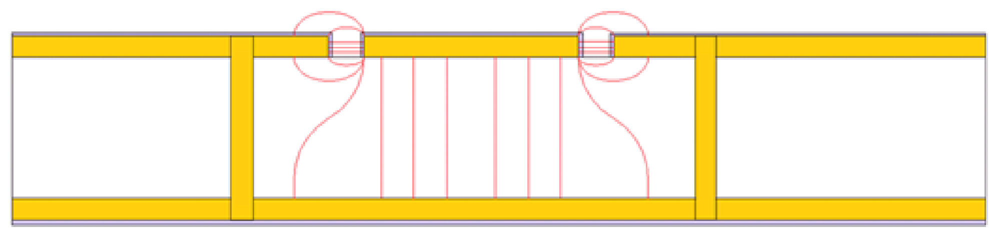
PCB fabrication influences which impact RF performance



Microstrip, final plated finish impacts the conductor loss due to high current density at the edge of the conductor



Grounded coplanar waveguide (GCPW) has fields and current densities using 4 edges of the ground-signal-ground configuration

Typically insertion loss for GCPW is more affected by final plated finish than microstrip

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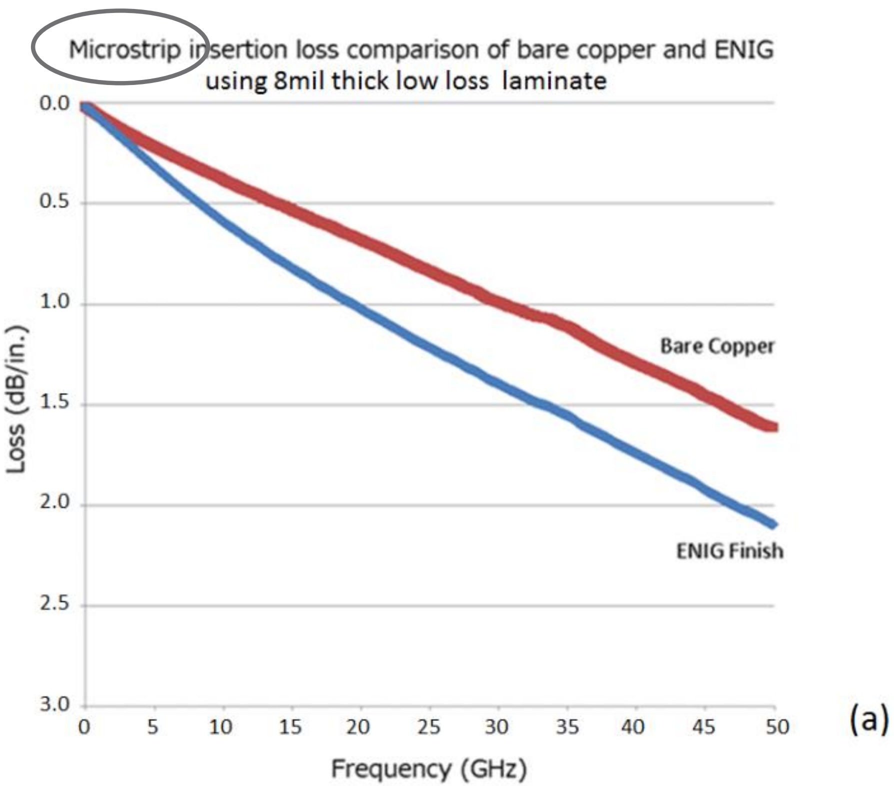
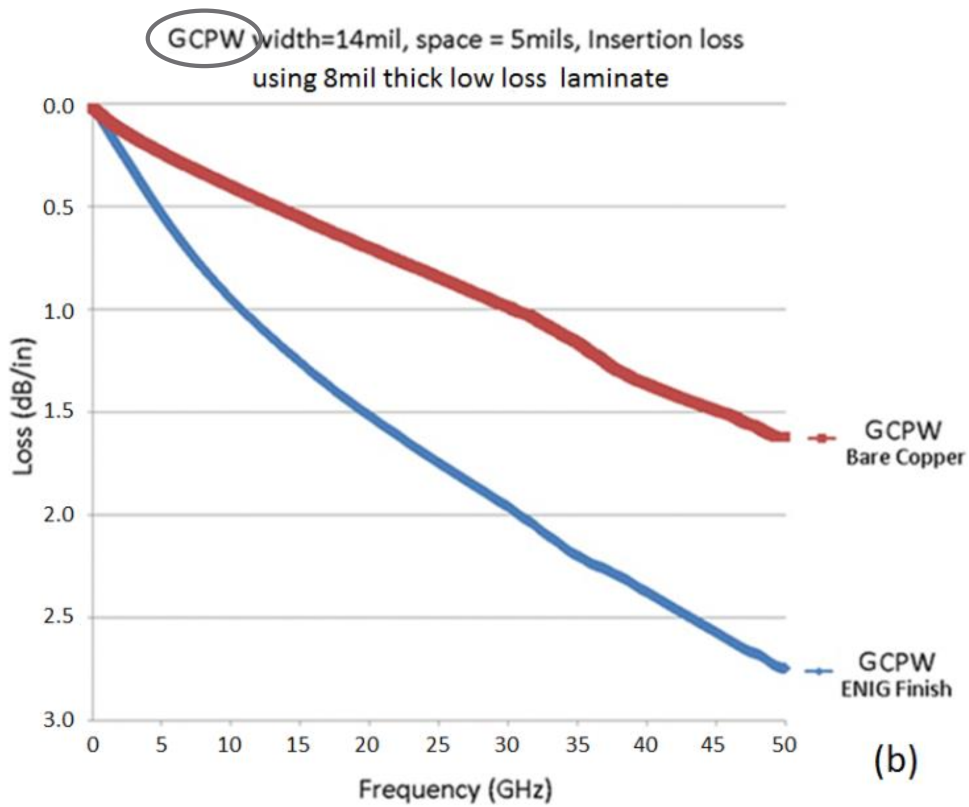
PCB fabrication influences which impact RF performance





PCB fabrication influences which impact RF performance

- A study was done to evaluate the effect of several different finishes on insertion loss

- The test vehicle:

  - is a set of 50 ohm microstrip transmission line circuits

  - insertion loss measurement uses differential length method

  - circuit material:
    - thin substrate (5mil) to exaggerate the conductor effects
    - very smooth copper (rolled copper) to minimize copper surface roughness effects and variations
    - very low loss (Df=0.0012) to minimize dielectric losses and again, allow conductor losses to dominate

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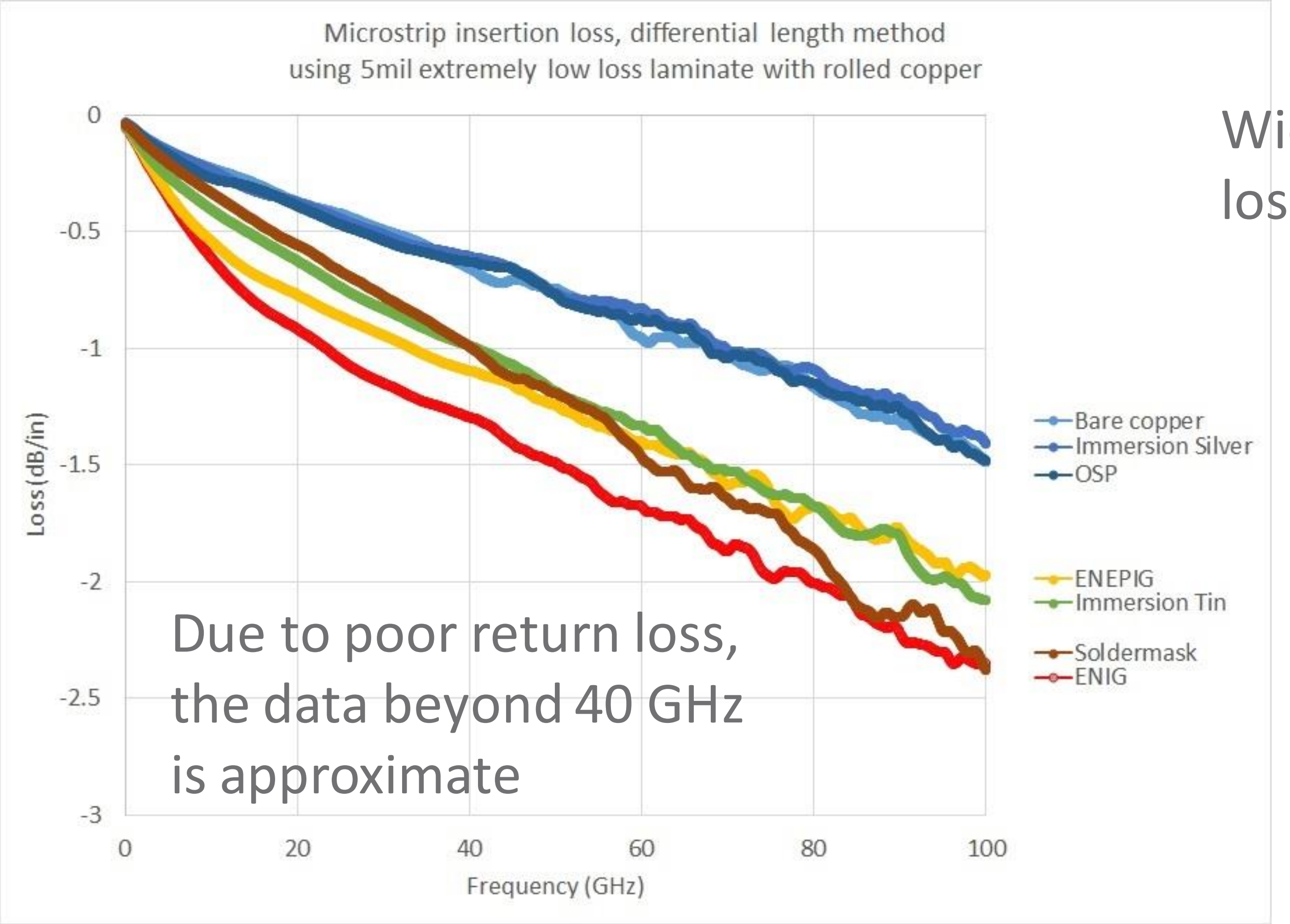
PCB fabrication influences which impact RF performance



Wideband insertion loss results

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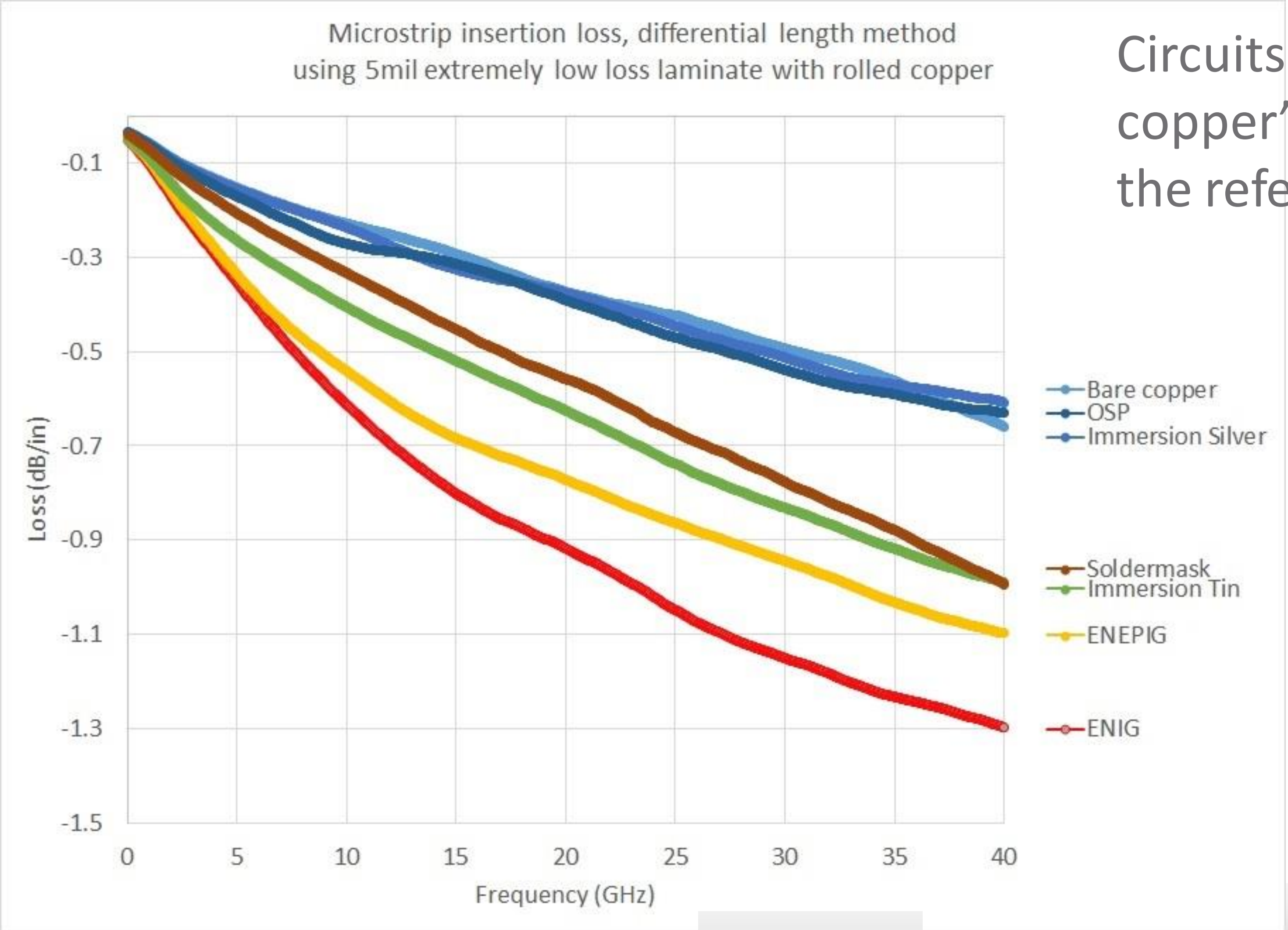
PCB fabrication influences which impact RF performance



Circuits with "bare copper" are considered the reference

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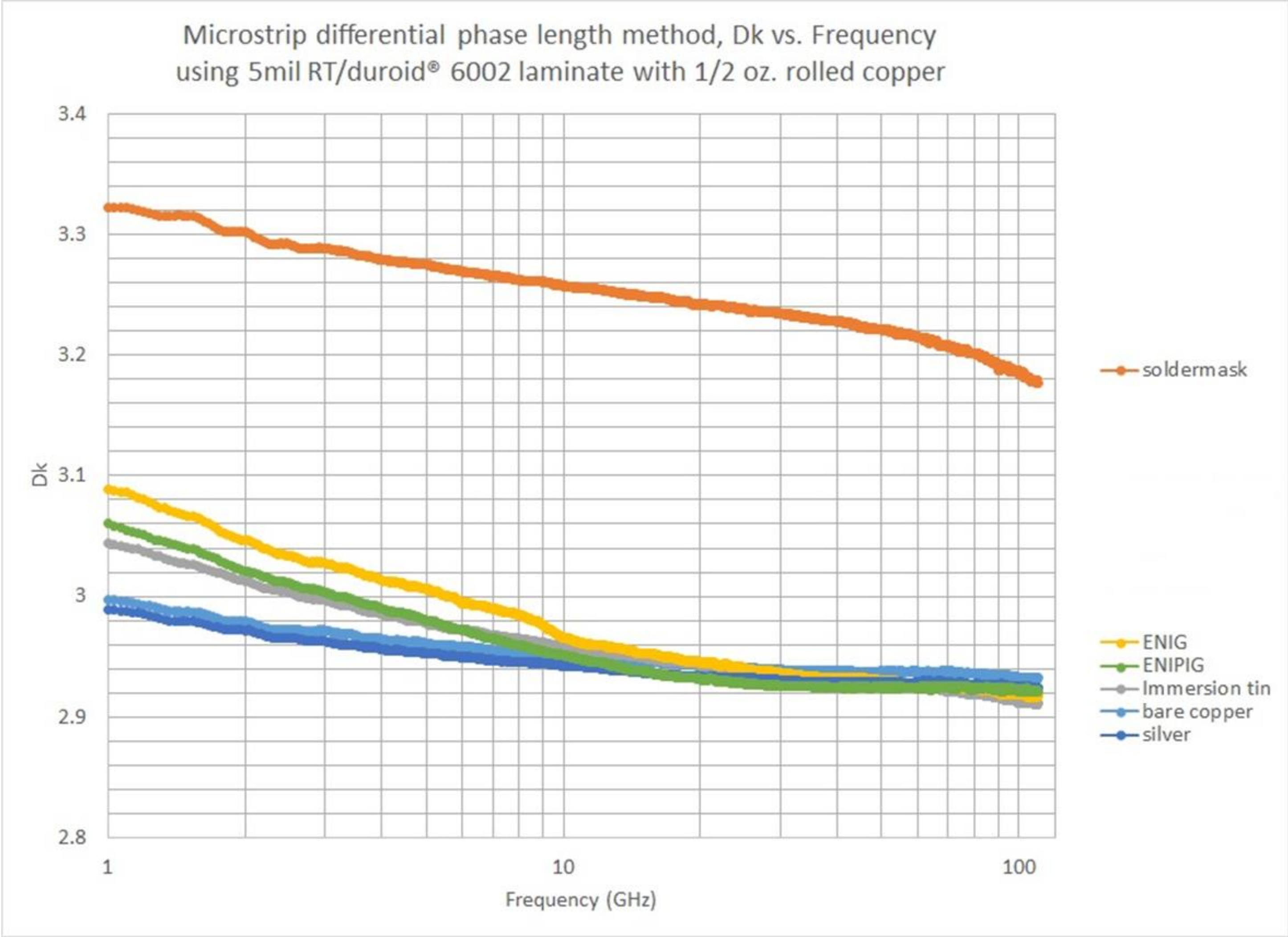
PCB fabrication influences which impact RF performance

Plated finishes have impact in frequency region where skin depth of the composite metal is changing quickly with a change in frequency

At low microwave frequencies the impact of plated finish is in order of plated finish composite conductivity

When this same study is done on thicker substrate the Dk differences are reduced



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PCB fabrication influences which impact RF performance

- Copper plating is a standard process to make a PCB
- Drilled through holes are plated with copper to make via connections between the various copper layers
- The additional copper of the signal conductor can influence RF performance
- The copper plating does have variation
  - there is copper thickness variation within a panel of circuits
  - and variation from batch-to-batch of circuits
- This copper thickness variation can have more impact on RF performance for certain designs

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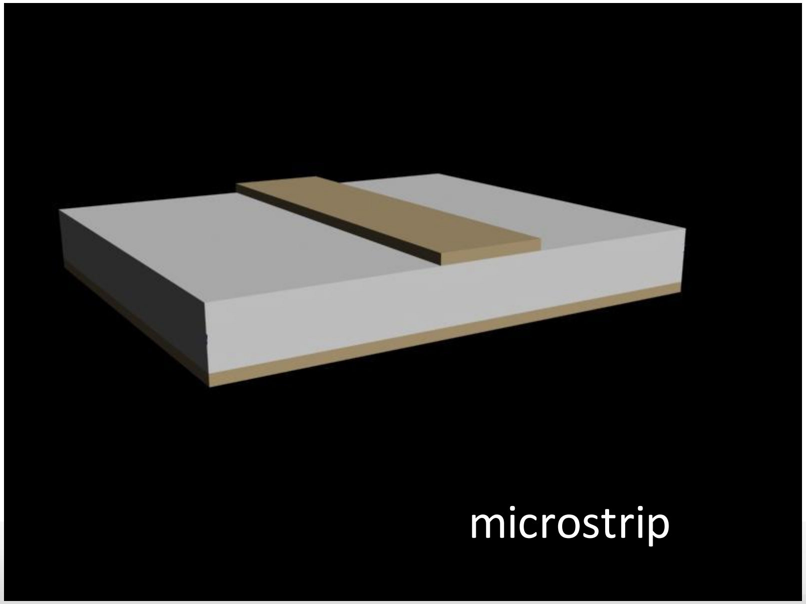
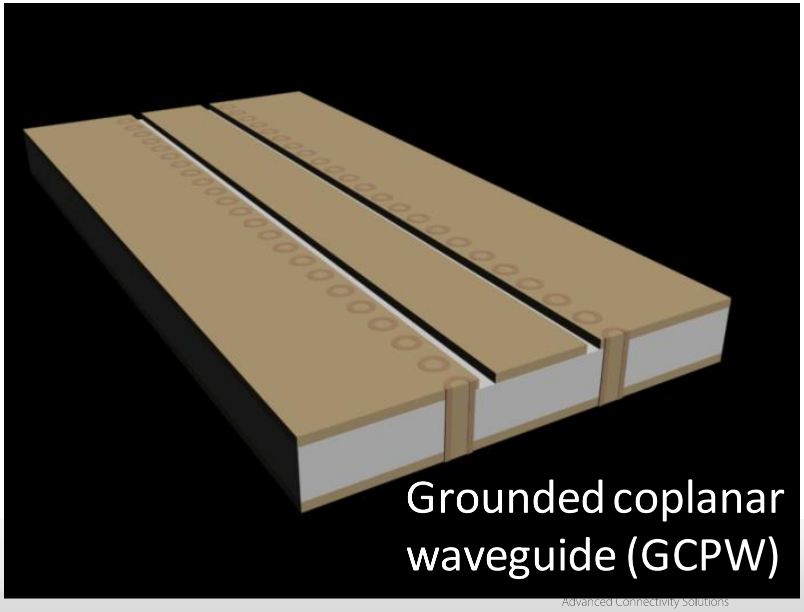
PCB fabrication influences which impact RF performance

- The copper plating variation has a larger impact on coupled features
- Grounded Coplanar Waveguide (GCPW) or differential pair
- A study was done which had a very controlled plating thickness and used the same material
    - Same sheet of material was used; it was cut in half and one half was used to make circuits with thin copper plating and the other half had circuits with thick plating

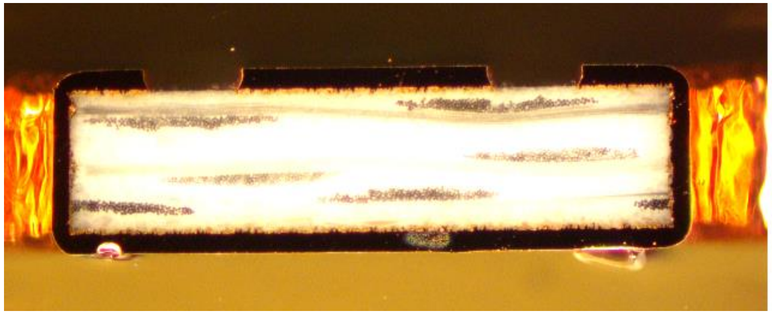


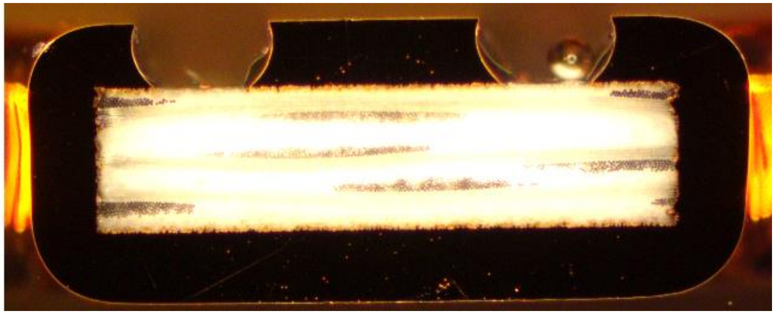


Design Right the First Time: Understanding how Dielectric Constant (Dk) Test Methods Affect Time to Market

PCB fabrication influences which impact RF performance

- In this study 2 different 50 ohm GCPW transmission line circuit designs were used
    - Tightly coupled GCPW; small space between coplanar Ground-Signal-Ground
    - Loosely coupled GCPW; wide space
- Additionally circuits were purposely made to have significantly different copper thickness
    - Thin copper plated, overall conductor was 1mil thick
    - Thick copper plated, overall conductor was 3mils thick


Tightly coupled GCPW with thin copper


Tightly coupled GCPW with thick copper

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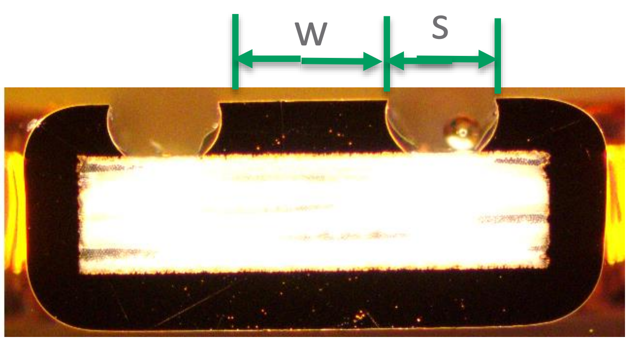
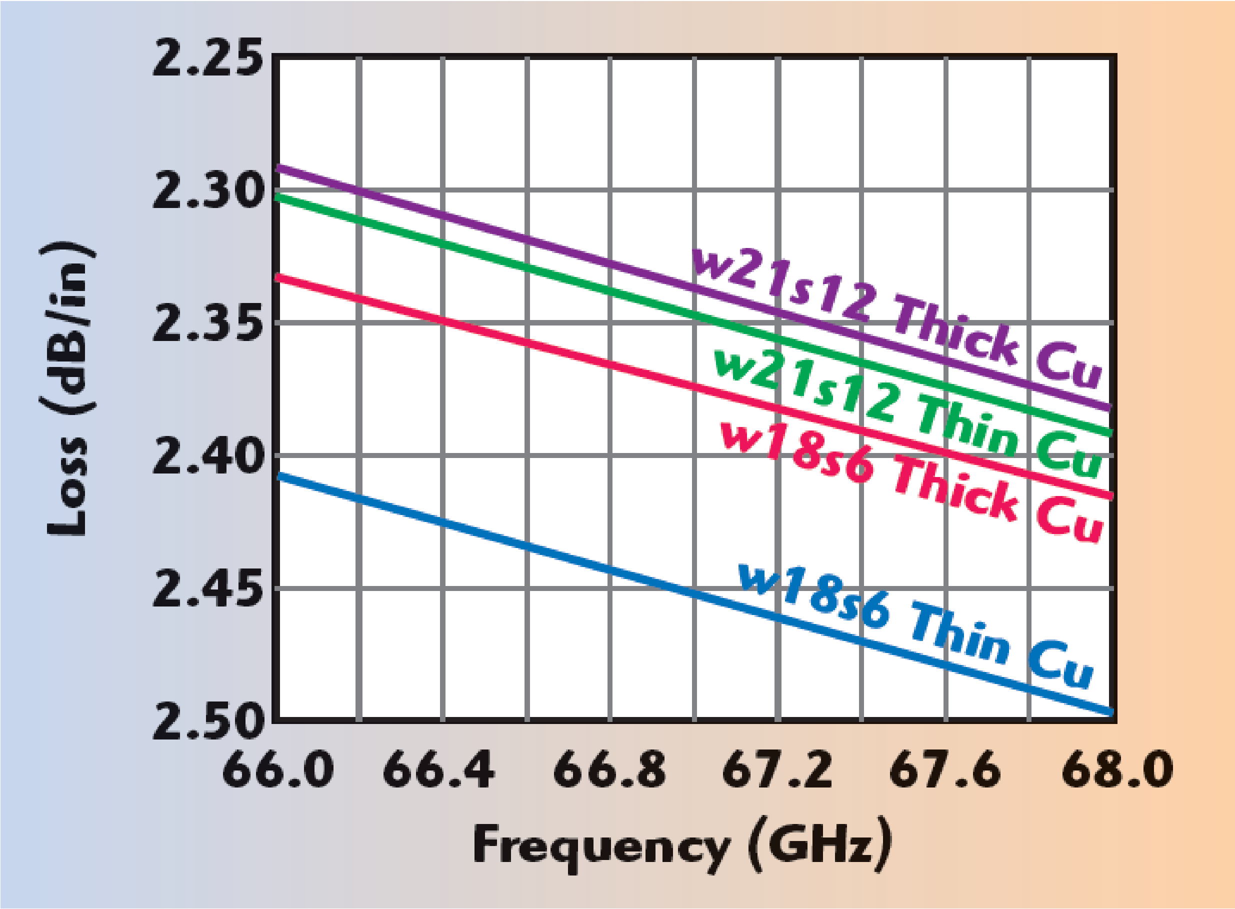
PCB fabrication influences which impact RF performance

- Using same sheet of laminate, there is a significant difference in loss based on copper plating thickness variation and /or design

- The circuit with the widest conductor and thickest copper had lowest loss, which was w21s12 thick cu





Legend example: w21s12 is a loosely coupled GCPW with a 21mil wide conductor and a 12mil space

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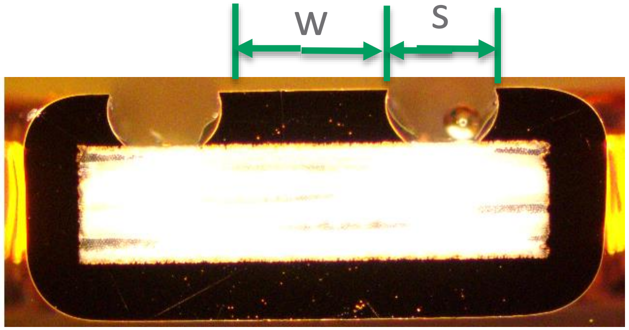
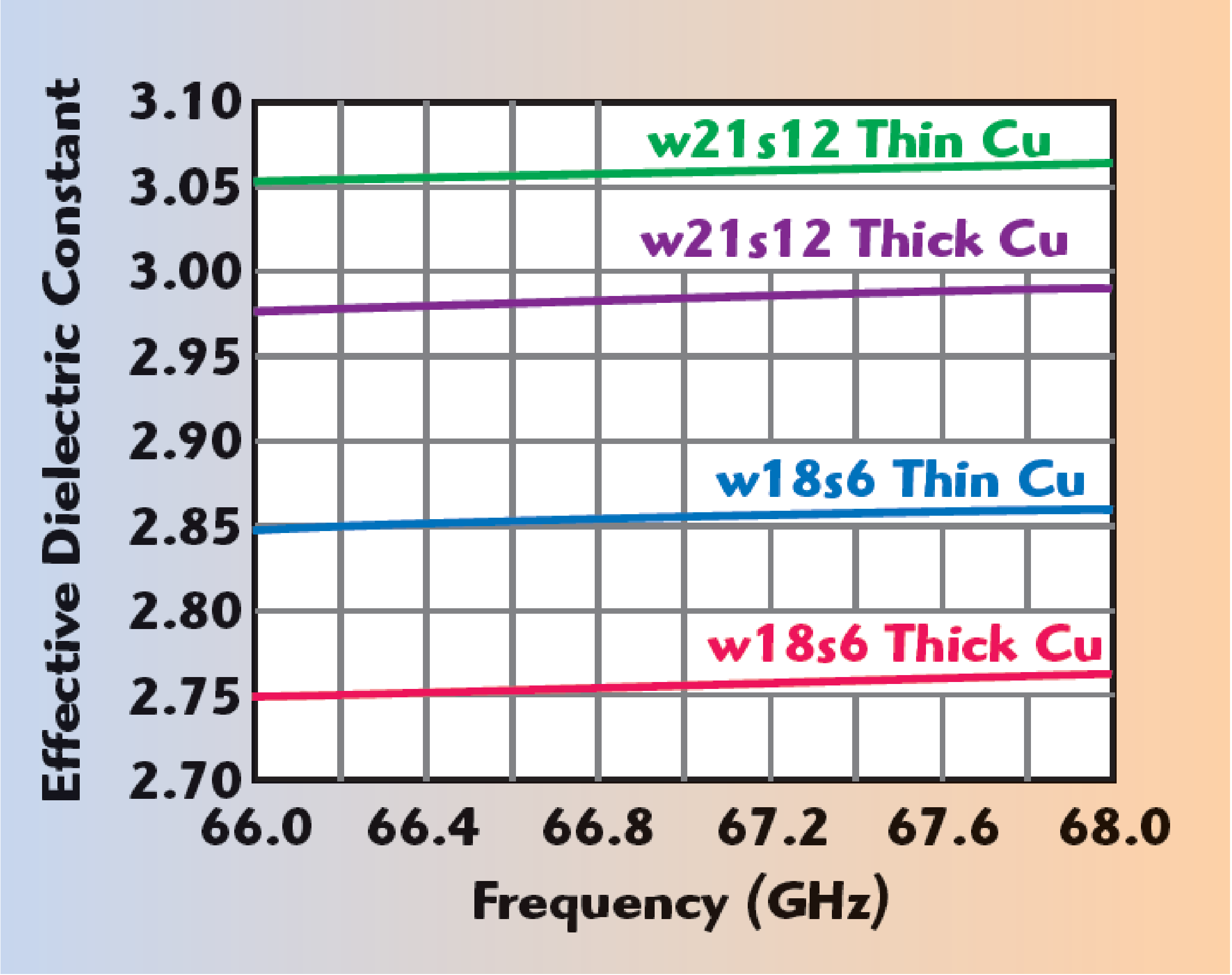
PCB fabrication influences which impact RF performance

- Continuing….
- There was a significant difference in phase response based on copper thickness variation and / or design
- The circuit with the lowest effective Dk had the tightest coupling and thickest copper (w18s6 thick cu)





Legend example: w18s6 is a tightly coupled GCPW with a 18mil wide conductor and a 6mil space

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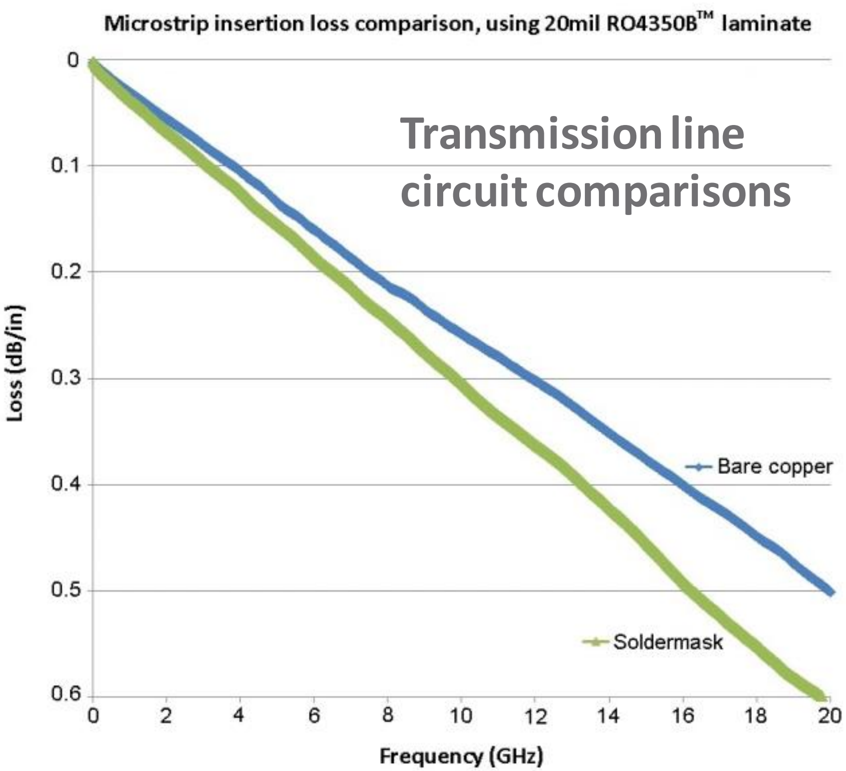
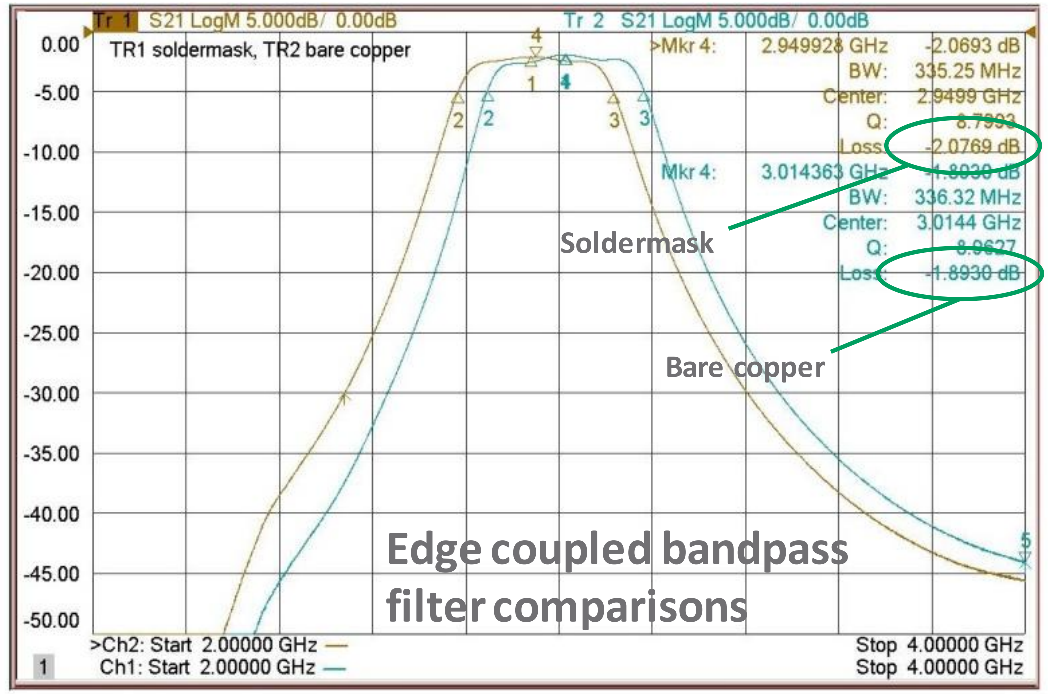
PCB fabrication influences which impact RF performance

- The addition of soldermask increases dielectric loss, which increase insertion loss
- The loss difference between circuits using bare copper and covered with soldermask is:
  - frequency dependent
  - substrate thickness dependent
  - circuit design configuration dependent





Total length of filer is ~ 4”

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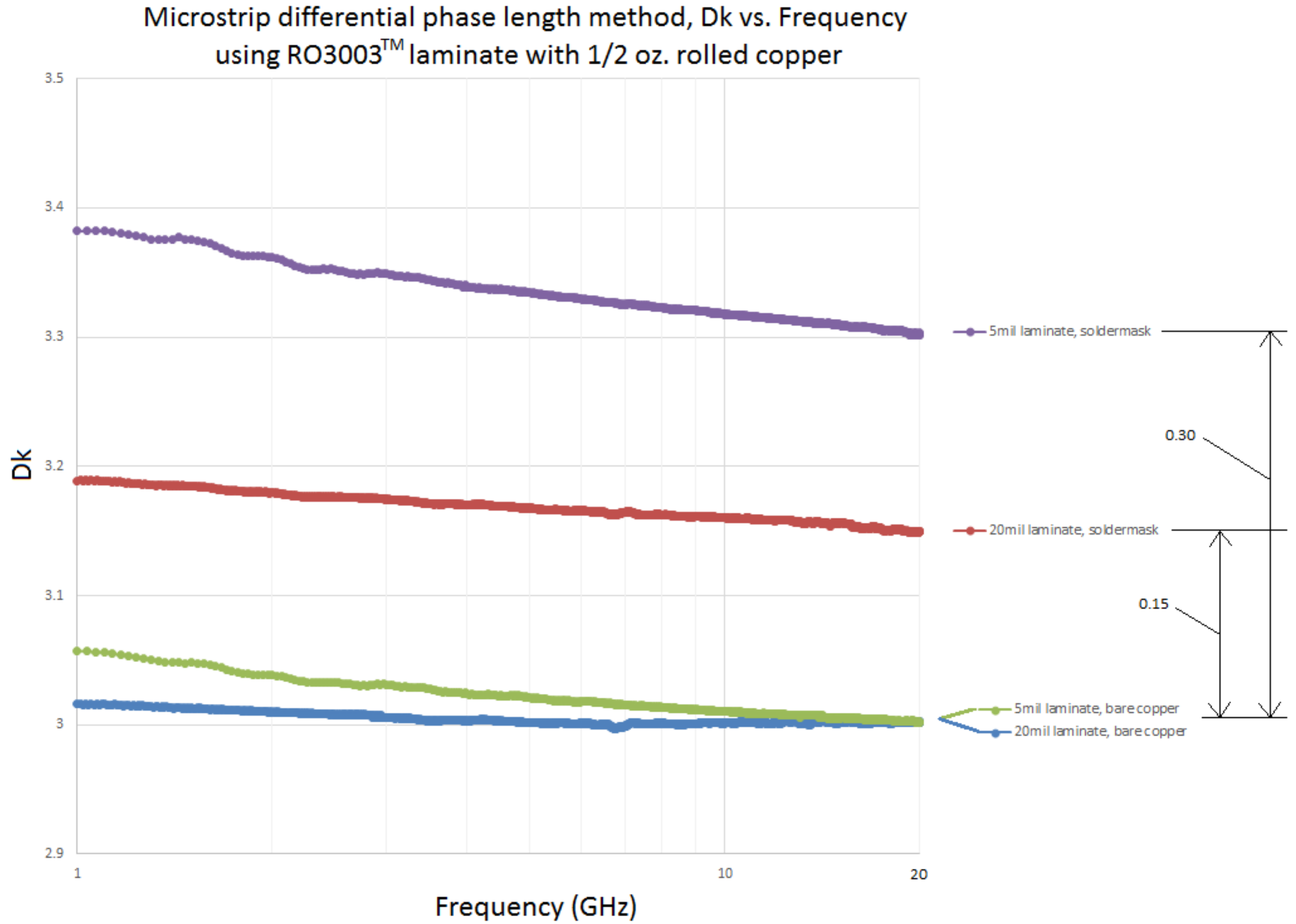
PCB fabrication influences which impact RF performance

The impact of soldermask on the Design Dk (circuit-perceived-Dk) will be different for circuits of different thickness



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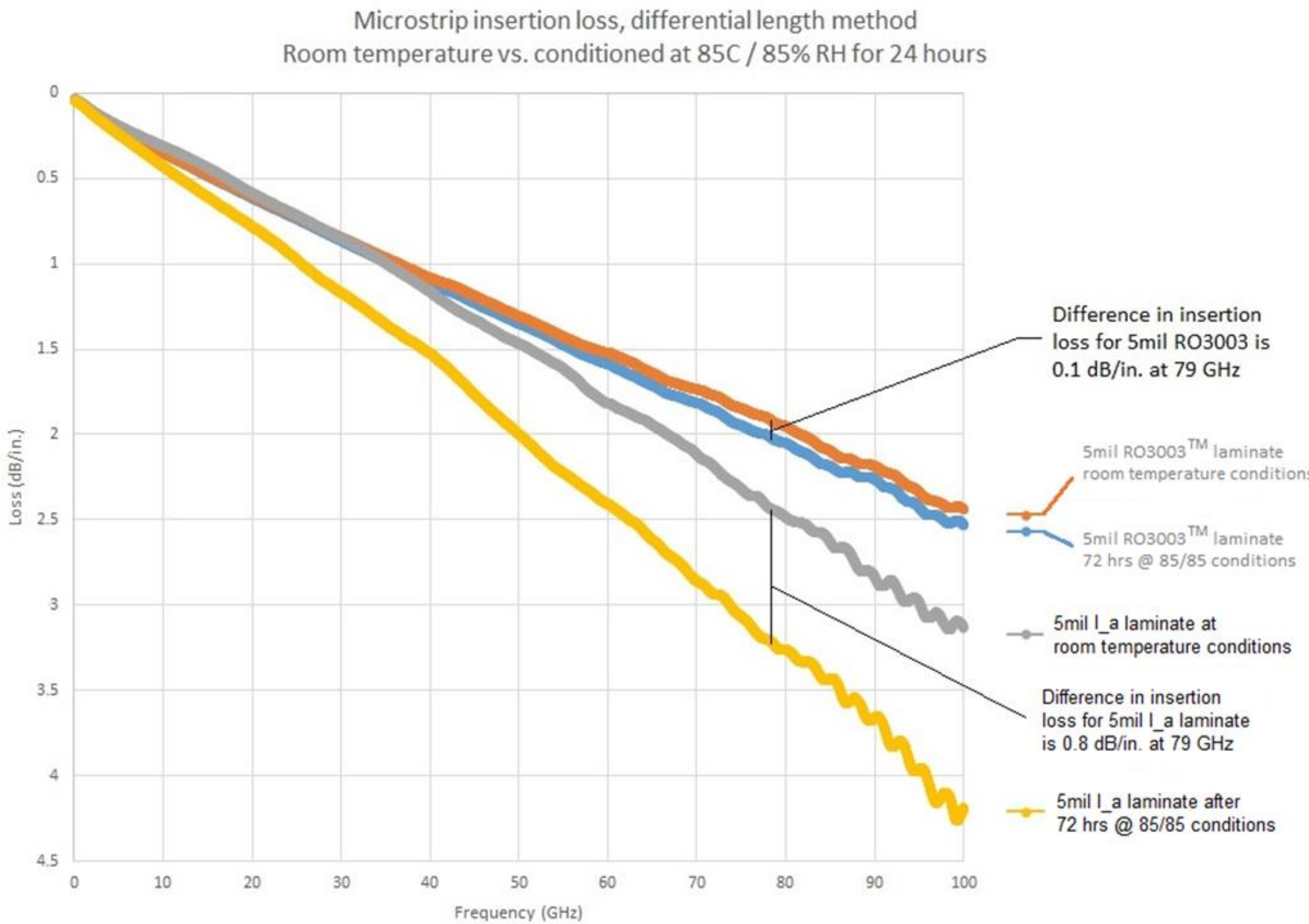
End-use environmental conditions and potential impact on PCB RF performance

The I a is a competitive thermoset material, which has a moisture absorption of approximately 0.3 %



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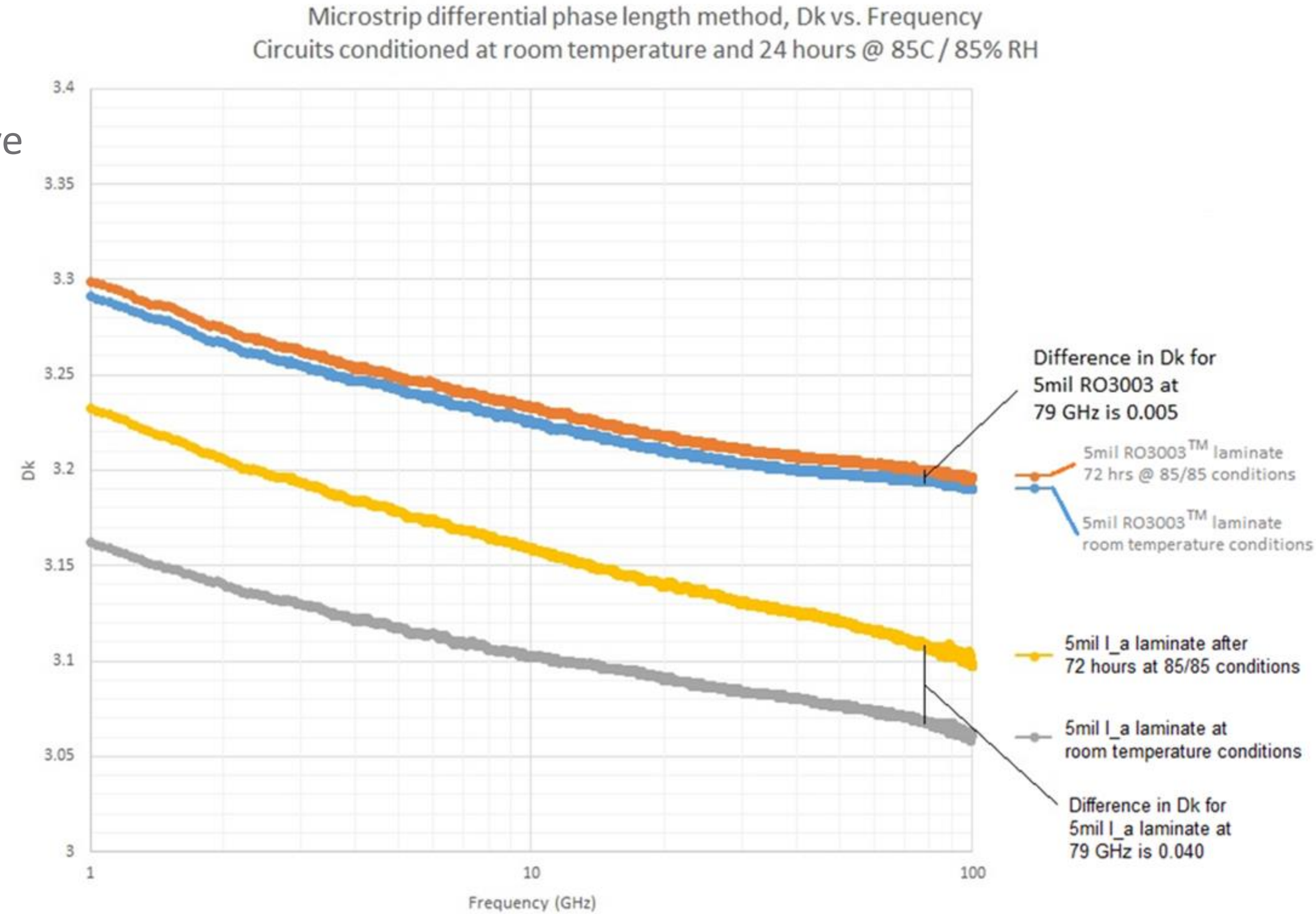
End-use environmental conditions and potential impact on PCB RF performance

The I a is a competitive thermoset material, which has a moisture absorption of approximately 0.3 %



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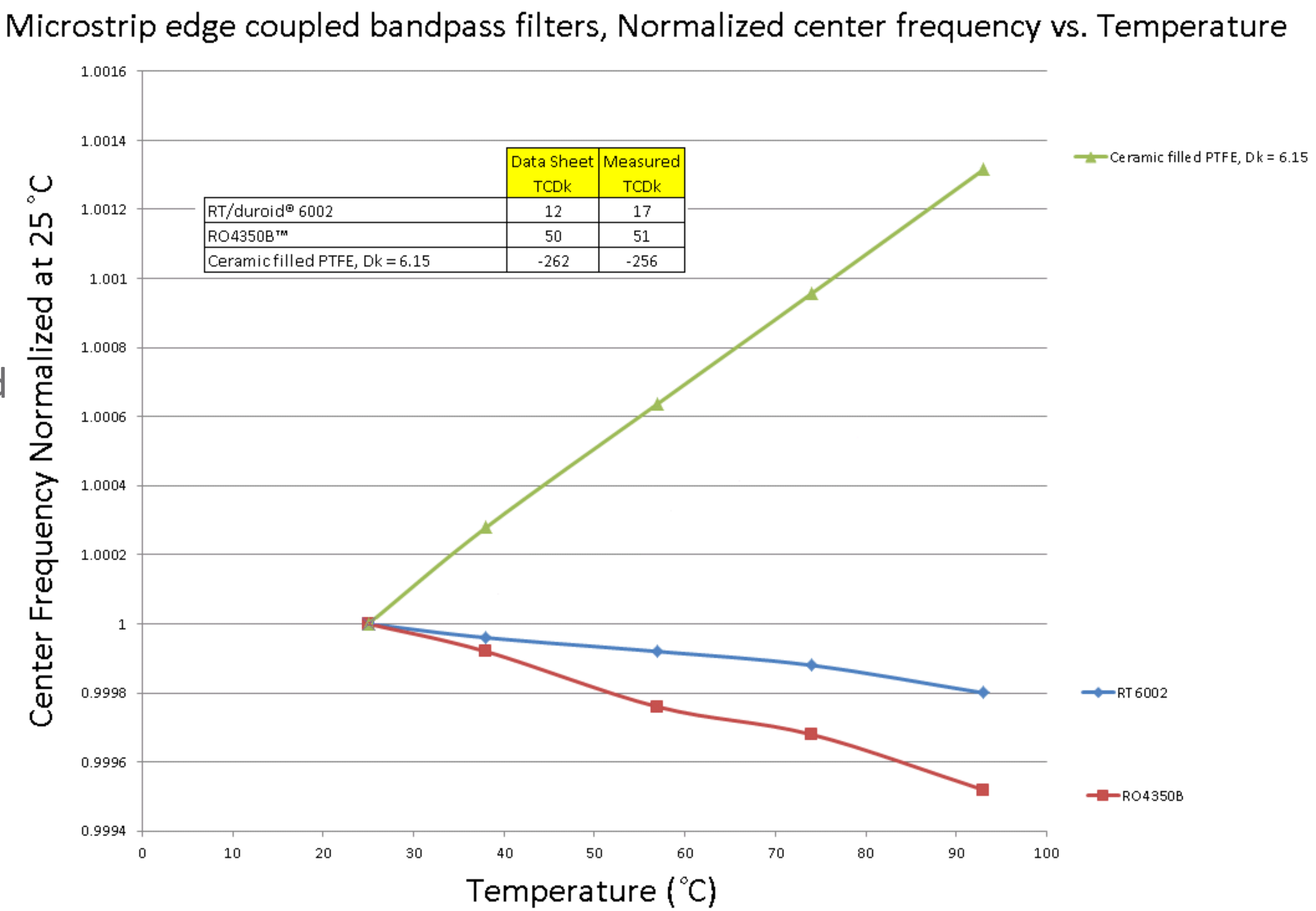
End-use environmental conditions and potential impact on PCB RF performance

Example of TCDk influence on filter performance

There can be another influence, which is typically more significant on wideband edge coupled circuits and that is related to CTE

If a laminate is used with a high CTE, the physical dimensions of the circuit can change with a change in temperature



	Data Sheet TCDk	Measured TCDk
RT/duroid® 6002	12	17
RO4350B™	50	51
Ceramic filled PTFE, Dk = 6.15	-262	-256

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