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A Practical Method to Model Effective Permittivity and Phase Delay Due to Conductor Surface Roughness

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Abstract

In the GB/s regime, accurate modeling of conductor loss and phase delay is a precursor to successful high-speed serial link designs. In this paper, a practical method to model effective permittivity and phase delay, due to conductor surface roughness, is presented. By obtaining the dielectric and roughness parameters, solely from manufacturers' data sheets, phase delay and effective permittivity can now be easily predicted. Detailed case studies and several examples test the model's accuracy.

Author(s) Biography

Lambert (Bert) Simonovich graduated in 1976 from Mohawk College of Applied Arts and Technology, Hamilton, Ontario Canada, as an Electronic Engineering Technologist. Over a 32-year career, working at Bell Northern Research/Nortel, in Ottawa, Canada, he helped pioneer several advanced technology solutions into products. He has held a variety of engineering, research and development positions, eventually specializing in high-speed signal integrity and backplane architectures. After leaving Nortel in 2009, he founded Lamsim Enterprises Inc., where he continues to provide innovative signal integrity and backplane solutions as a consultant. He has also authored and coauthored several publications, which are posted on his web site at www.lamsimenterprises.com. His current research interests include: high-speed signal integrity, modeling and characterization of high-speed serial link architectures.

Introduction

Permittivity is the ability of a dielectric material to store electrical energy in an electric field. In the PCB industry, relative permittivity (ϵ_r) and effective relative permittivity (ϵ_{reff}) are synonymous with dielectric constant (D_k) and effective dielectric constant (D_{keff}) respectively. Herein, D_k and D_{keff} are substituted accordingly.

By definition [6], D_{keff} is the ratio of the actual structure's capacitance to the capacitance when the dielectric is replaced by air. When modeling lossy transmission lines, using manufacturers' published dielectric and conductor material properties, often leads to a discrepancy in D_{keff} due to increased phase delay caused by surface roughness. This often leads to inaccuracy in simulated insertion loss (IL), as shown in the example of Figure 1 left. But when D_{keff} is tuned to measured value instead, the accuracy of IL is often improved, as shown on the right.

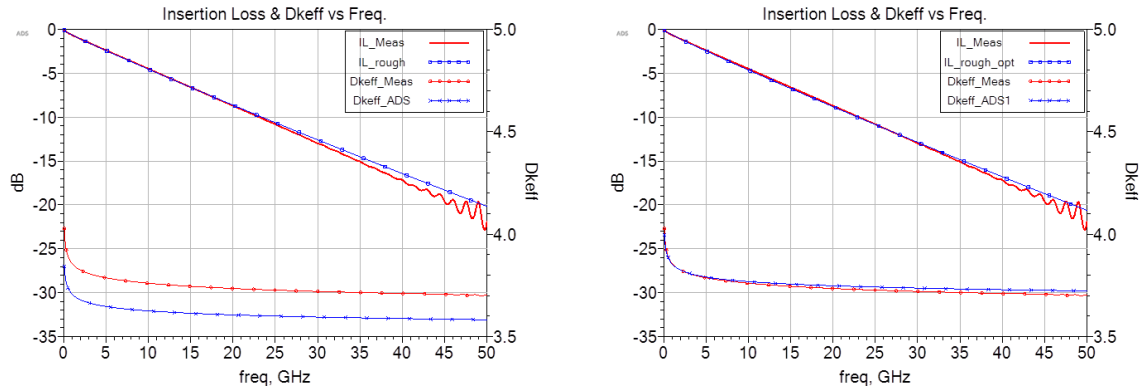


Figure 1 Simulated vs measured results for insertion loss and D_{keff} vs frequency using manufacturers' data sheet parameters (left) and when D_{keff} was tuned to measured value at 10 GHz (right). Modeled and simulated with Keysight EEsof EDA ADS [15].

Phase delay, also known as time delay (TD), is the time it takes for a signal to propagate from one end of a transmission line to the other. It can be derived from the transmission $S(2,1)$ phase angle of the S-parameter.

In an IEEE paper [3], the authors observed an increase in phase delay proportional to roughness profile and dielectric material thickness. This would explain why there is often difference between simulated and empirical results.

The motivation for this research work was to try and develop a method to accurately predict D_{keff} and phase delay due to conductor surface roughness profile, as published in manufacturers' data sheets, without relying on measured data for curve fitting.

Background

Effective D_k can be derived from TD , and is often used as a metric for simulation correlation accuracy instead. TD , as a function of frequency, in seconds, is calculated from the unwrapped measured transmission phase angle, and is given by [4]*:

Equation 1

$$TD(f) = -1 \left[\frac{\text{unwrap}(\text{phase}(S_{21}))}{360 \times \text{freq}} \right]$$

And:

D_{keff} , as a function of frequency, is then given by [4]:

Equation 2

$$D_{keff}(f) = \left(TD(f) \frac{c}{Length} \right)^2$$

Where:

c = speed of light (m/s);

$Length$ = length of conductor (m).

Since TD is proportional to relative permittivity of the material, my theory is the surface roughness profile decreases the separation between the reference plane(s) and conductor, thereby increasing the electric field (e-field) strength, resulting in additional capacitance, which accounts for an increase in effective D_k and phase delay.

The main focus of this paper is to prove the theory and to show a practical method to model effective D_k and phase delay due to surface roughness. By referencing Gauss's Law for charged parallel plates, I show mathematically, and through simulation, how the dielectric thickness and permittivity are interrelated to e-field and capacitance. I also reveal how the 10-point mean (R_z) roughness parameter is applied to finally determine effective D_k due to roughness, and then test the model via case studies.

* Keysight ADS equation syntax [15]

Application of Gauss' Law

Gauss' law relates the distribution of electric charge to resulting e-field, and can be used to determine the e-field between two large and oppositely charged parallel plates. Referring to Figure 2, the e-field in free space (E_0), is equal to the ratio of the charge density (σ), to the permittivity of free space (ϵ_0), and is given by [5]:

Equation 3

$$E_0 = \frac{\sigma}{\epsilon_0}$$

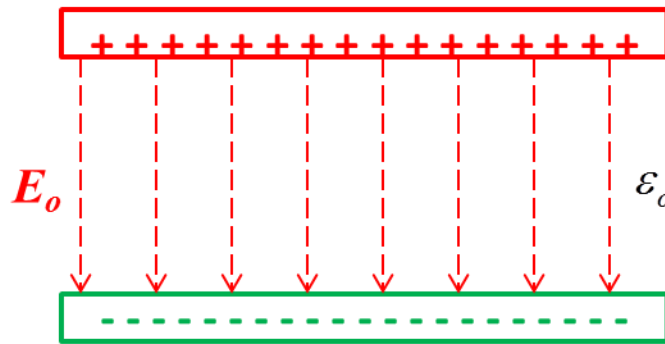


Figure 2 Electric field between two large and oppositely charged parallel plates in free space.

Dielectric materials are insulators often composed of polar molecules. These molecules look electrically like small dipoles with a negative charge on one end and positive charge on the other. In the absence of an external electric field, these molecules line up randomly as shown in Figure 3.

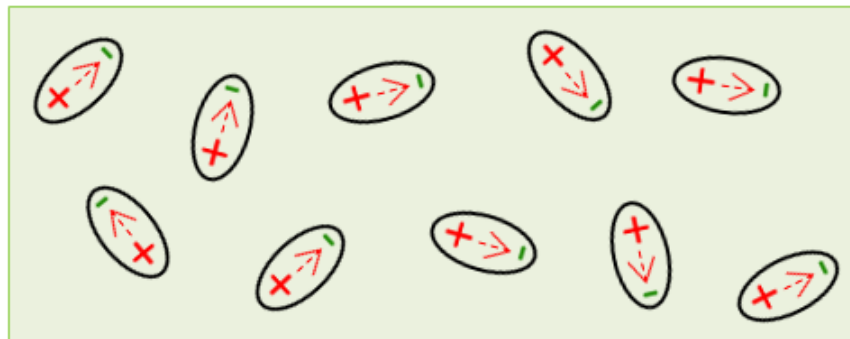


Figure 3 Random distribution of dipoles in the absence of an electric field.

When a dielectric material is placed between two, large and oppositely charged parallel plates, the dipoles align as shown in Figure 4. The collective e-field of the dipoles (E_D) opposes the e-field in the absence of any dielectric (E_0) to yield a net e-field intensity (E).

Equation 4

$$E = E_0 - E_D$$

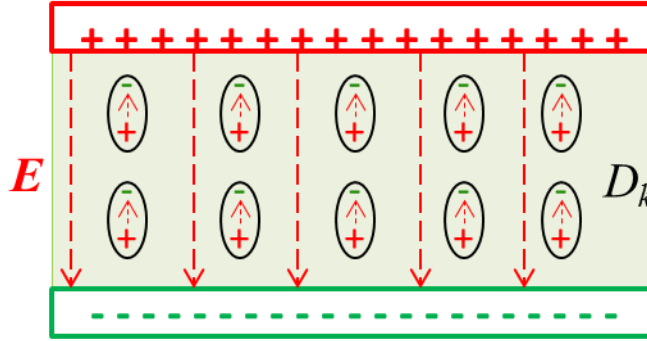


Figure 4 Polarization of dipoles in the presence of an electric field between two large and oppositely charged parallel plates.

Since the insertion of dielectric material reduces the e-field intensity inversely proportional to the D_k of the material, the e-field intensity E is given by [5]:

Equation 5

$$E = \frac{\sigma}{D_k \epsilon_0}$$

If charge density (σ) is defined as the charge (Q), per unit area (A), of a surface, then E is given by [5]:

Equation 6

$$E = \frac{Q}{D_k \epsilon_0 A}$$

Electric Field vs Parallel Plate Separation

Electric field intensity can also be expressed as the ratio of the potential difference in volts (V), to the distance (d) between two plates, and is given by [5]:

Equation 7

$$E = \frac{V}{d}$$

Referring to Figure 5, since electric field intensity is inversely proportional to the distance between two large parallel plates, with constant voltage, it can be shown that by applying Equation 7, the ratio of E_2 to E_1 is:

Equation 8

$$\frac{E_2}{E_1} = \frac{d_1}{d_2} = \frac{H_1}{H_2}$$

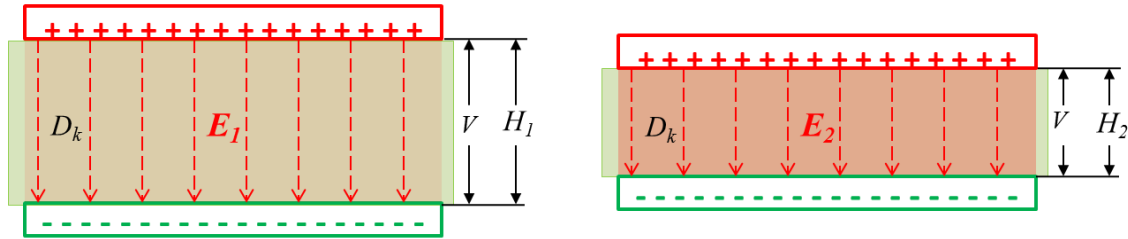


Figure 5 Illustration showing electric field intensity (E) is inversely proportional to the separation (H) between two oppositely charged parallel plates, with constant voltage.

Parallel Plate Capacitor

Any structure capable of storing an electric charge is called a capacitor. Figure 6 is an example of such a structure. The relationship between capacitance, voltage, separation and charge is given by [5]:

Equation 9

$$C = \frac{Q}{V} = \frac{D_k \epsilon_0 A}{H}$$

Where:

C is capacitance in farads (F)

Q is charge on either conductor in coulombs (C)

V is potential difference between charges in volts

D_k is the dielectric constant of the material

ϵ_0 is permittivity of free space ($\sim 8.85\text{pf/m}$)

A is the area of the plates (m^2)

H is the separation between plates (m)

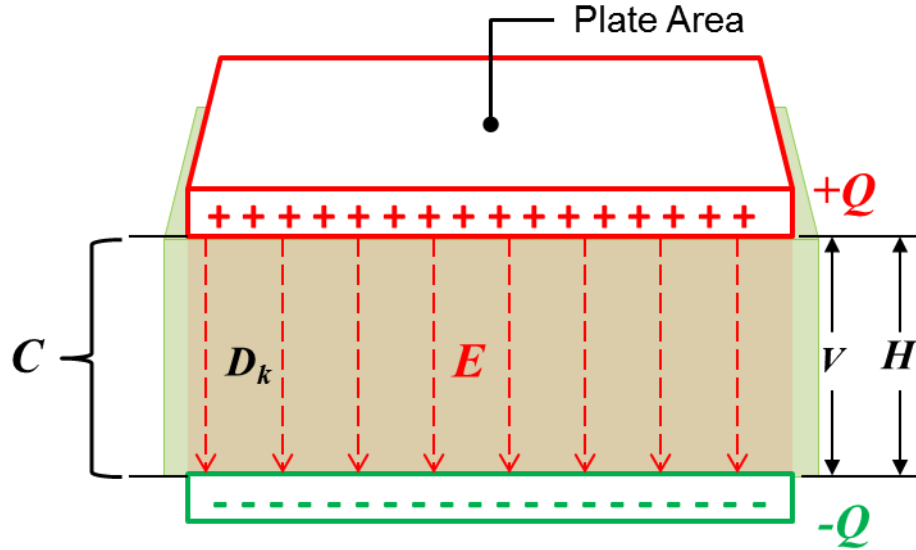


Figure 6 Two equally large and oppositely charged parallel plates, closely separated by a dielectric, forms a capacitor.

Since capacitance is inversely proportional to the separation between two, large and oppositely charged parallel plates, with constant voltage, it can be shown that by applying Equation 9, the ratio of C_2 to C_1 is:

Equation 10

$$\frac{C_2}{C_1} = \frac{H_1}{H_2} = \frac{E_2}{E_1}$$

Conductor Surface Roughness

Rolled and electro-deposited (ED) are two copper foil fabrication processes used in PCB laminate construction today. Of the two, rolled copper will always be smoother than standard ED copper.

ED copper is widely used in the printed circuit (PCB) industry. It is produced by electro-depositing copper, from a bath of copper sulfate solution, onto a large rotating drum made of stainless steel or titanium. The speed of the drum rotation determines the thickness of the foil.

A finished sheet of ED copper foil has a matte side and drum side. The matte side is the side facing the copper sulfate solution while the drum side faces the drum surface. The drum side is always smoother than the matte side.

The matte side is usually bonded to the core laminate. For high-speed boards, the drum side of the foil is sometimes laminated to the core instead. In that case it is referred to as reversed treated (RT) foil.

Profilometers are often used to quantify the roughness tooth profile of ED copper. Figure 7 shows an example profile of a rough conductor surface. Tooth profiles are typically reported in terms of 10-point mean roughness for both sides, but sometimes the drum side reports average roughness in manufacturers' data sheets if there is very little roughness. Some manufacturers may also report root-mean-square (RMS) roughness (R_q).

The 10-point mean (R_z), is the sum of the average of the five highest peaks and the five lowest valleys, of the rough conductor surface over the sample length. The average surface roughness parameter (R_a) is the arithmetic average of the roughness profile over the sample length.

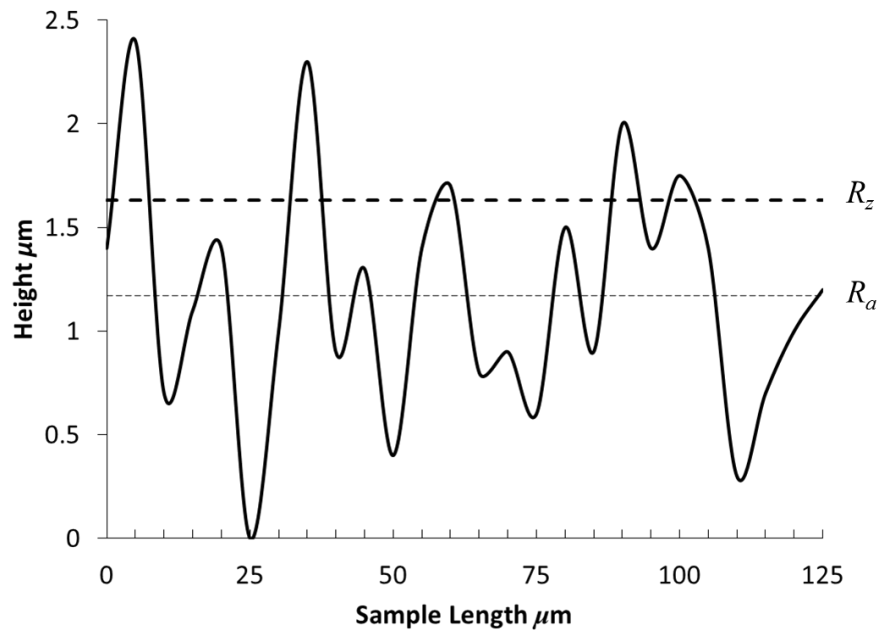


Figure 7 Schematic illustration of a rough conductor profile as measured with a profilometer.

Effective Dk Due to Roughness

In an IEEE paper [3], the authors observed an increase in D_{keff} proportional to the conductor roughness profile and inversely proportional to dielectric material thickness. Figure 8 plots D_{keff} vs dielectric height for Rogers LCP dielectric material with two foil roughness profiles.

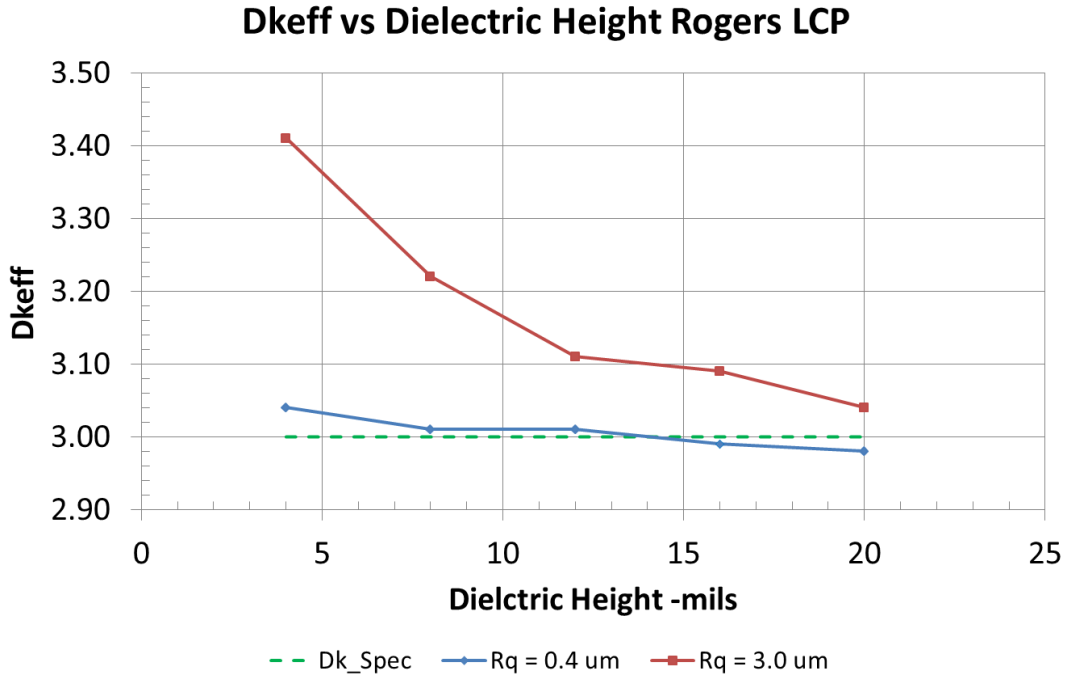


Figure 8 Extracted D_{keff} vs. thickness for 50 ohm transmission lines on LCP clad with 0.4 and 3.0 μm profile foils [3].

It was observed that for a relatively smooth copper profile with $R_q = 0.4\mu\text{m}$, D_{keff} pretty much matched the manufacturer's published value of 3. But when a rougher copper profile with $R_q = 3.0\mu\text{m}$ was used, it revealed two things:

1. As thickness of the dielectric increased from 5 mils to 20 mils, D_{keff} decreased.
2. The rougher the copper profile, the higher D_{keff} for the same dielectric thickness.

This supports the theory that the higher roughness profile adds additional capacitance, thereby increasing D_{keff} , due to reduced separation between the two large parallel plates, and can be explained with the aid of Figure 9.

The illustration on the left shows two smooth copper foil sheets bonded to each side of a dielectric material. The separation is denoted by H_{smooth} and is equal to thickness t_{diel} . On

the right shows two copper foil sheets with an exaggerated roughness profile, attached to the same thickness of dielectric material. Both copper sheets have the same thickness with roughness included, but now the effective separation is reduced, as denoted by H_{rough} .

This is because curing of the prepreg into a core, under heat and pressure, sees the rough copper tooth profile being pressed into the prepreg. As a result, the effective separation between copper sheets is less, compared to smooth copper.

In the PCB industry, prepreg is the term commonly used to describe a weave of glass fiber yarns pre-impregnated with resin which is only partially cured. Since R_z is a 10-point mean metric of the roughness profile, we can assume the effective separation reduces proportionally to a mean height of H_{rough} , and therefore the average capacitance will increase proportionally.

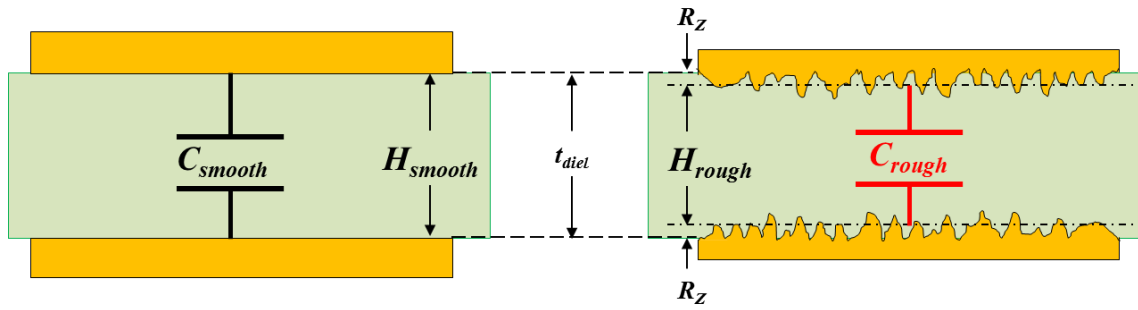


Figure 9 Smooth and rough copper foil sheets bonded to dielectric material. Capacitance increases in proportion to roughness profile R_z .

Quickfield modeling software [18] was used to simulate and verify the theory. The results are shown in Figure 10. The figure on the left shows two smooth copper foil sheets bonded to the top and bottom of a 2 cm thick dielectric material.

A D_k of 4.0 was used for the permittivity, and a +1.0 V potential was applied between the top and bottom plates respectively. As expected the e-field strength was uniform throughout. The capacitance reported by the software wizard was 141.67 pF/m.

On the right shows two copper foil sheets, with an exaggerated roughness profile, attached to the same thickness and properties of dielectric material. The peak-peak thickness of each plate is equal to the thickness of respective smooth plate.

When +1.0 V potential was applied, the e-field strength increased, or decreased in proportion to the roughness peaks and valleys of the roughness profile respectively. The average capacitance increased to 175.99 pF/m.

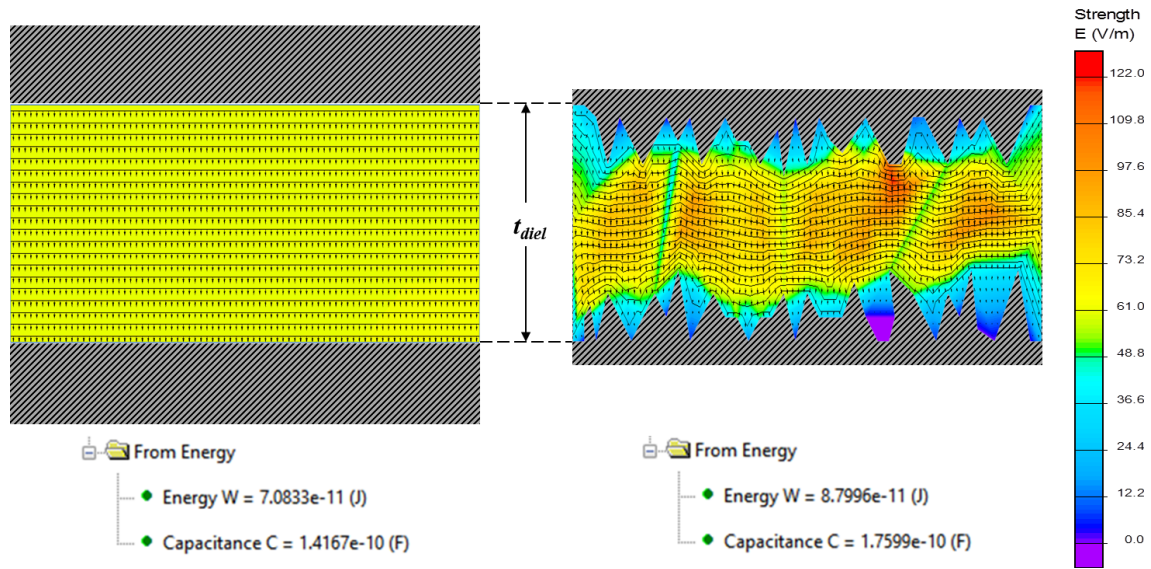


Figure 10 Quickfield [18] simulation of smooth vs rough conductor with same thickness of dielectric. With smooth plates, as shown on the left, the e-field strength is uniform, as expected. The roughness profile, as shown on the right, increases or decreases the e-field strength proportional to the peaks and valleys respectively. Average capacitance also increases proportionally to the roughness profile.

Modeling Effective Dk Due to Roughness

Wadell [6] defines D_{keff} as the ratio of the actual structure's capacitance to the capacitance when the dielectric is replaced by air.

Equation 11

$$D_{keff} = \frac{C_{actual}}{C_{air}}$$

D_{keff} is highly dependent on the test apparatus and conditions of how it is measured. There are several methods used in the industry, as referenced in [7]. One method, commonly used by many laminate suppliers, is a clamped stripline resonator test method, described by IPC-TM-650 Test Methods Manual [8].

IPC-TM-650, section 2.5.5.5, Rev C, defines test methods to rapidly test dielectric material for permittivity and loss tangent, over an X-band frequency range of 8-12.4 GHz, in a production environment.

The measurements are made under stripline conditions using a carefully designed resonant element pattern card, made out of the same dielectric material to be tested. The card is sandwiched between two sheets of unclad dielectric material under test. The

whole structure is then clamped between two large plates, lined with copper foils that are grounded. They act as reference planes for the stripline.

By measuring a resonant frequency of the cavity, the effective permittivity and loss tangent are determined, as outlined in [8]. The value of this method is to assure consistency of product, when used in fabricated boards. It does not guarantee the values directly correspond to design applications.

This is a key point to keep in mind, and here is why.

Since the resonant element pattern card and material under test are not physically bonded together, as it would be the case in real life, there are small air gaps between the various layers that affect measured results. These air gaps are caused, in part, by:

- Etching away the copper on material under test, leaving the bare substrate complete with the micro void imprint of the copper roughness.
- The air gap between resonant element pattern card and material under test due to the copper thickness of the etch pattern.
- The roughness profile of the copper, on the resonant element pattern card and fixture's grounded foil reference planes, are different than would likely be in practice. Empirical results from [3] would suggest that very smooth, copper foil was likely used for the test fixture.

If D_{keff} and R_z roughness parameters from the manufacturers' data sheets are known, then the effective D_k due to roughness of the fabricated core laminate can now be easily determined as follows[†]:

Given:

$$C_{smooth} = \frac{D_{keff} \epsilon_0 A}{H_{smooth}}; C_{rough} = \frac{D_{keff} \epsilon_0 A}{H_{rough}}$$

Where:

D_{keff} is the D_k of the dielectric material as published in manufacturer's data sheet.

H_{smooth} is the thickness of the dielectric as published in manufacturer's data sheet.

[†] See Appendix for full derivation

H_{rough} is the effective height between plates due to roughness profile. If R_z is used for the height of the roughness profile, then separation between copper plates H_{rough} is:

Equation 12

$$H_{rough} = H_{smooth} - 2R_z$$

Then from Equation 10:

Equation 13

$$\frac{C_{smooth}}{C_{rough}} = \frac{H_{rough}}{H_{smooth}}$$

Based on Equation 11, it can be shown that:

Equation 14

$$\frac{C_{rough}}{C_{smooth}} = \frac{D_{keff_rough}}{D_{keff}}$$

And therefore the effective D_k of the material due to roughness profile (D_{keff_rough}) is:

Equation 15

$$D_{keff_rough} = \frac{H_{smooth}}{(H_{smooth} - 2R_z)} \times D_{keff}$$

With reference to Figure 11, using D_{keff} with rough copper model, as shown on the left, is equivalent to using D_{keff_rough} with smooth copper model, as shown on the right. Therefore D_{keff_rough} would be used for impedance calculation and numerical simulations based on surface roughness, instead of effective D_k value published in manufacturers' data sheets.

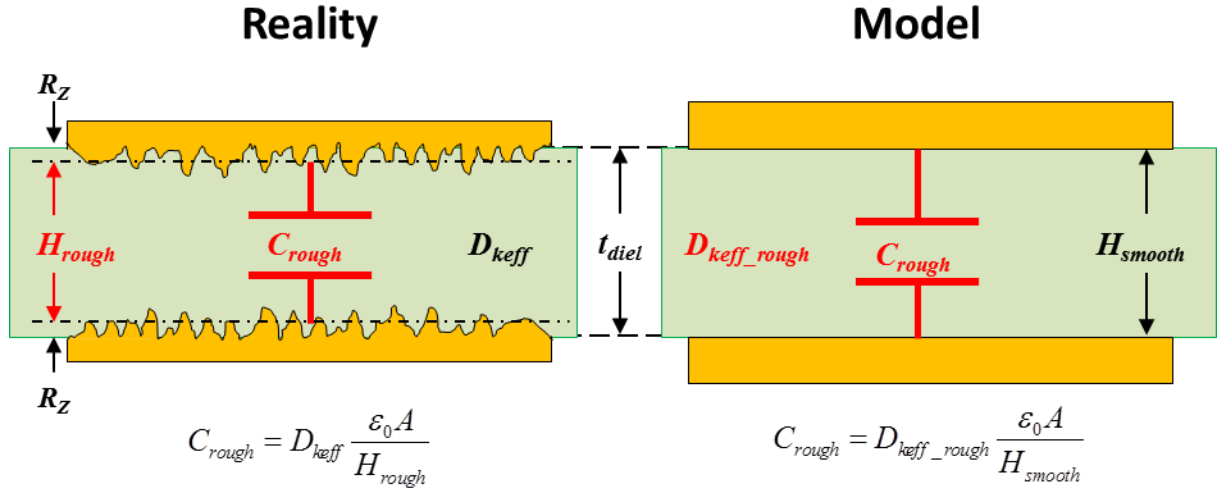


Figure 11 Effective D_k due to roughness model. Using D_{keff} with rough copper model (left) is equivalent to using D_{keff_rough} with smooth copper model (right).

Validating the Model over Dielectric Height

When applying Equation 15 to results of IEEE paper [3], and initially tuning R_z equal to $6.1 \mu m$ at 4 mil dielectric height, then using that value for the other dielectric heights, there is excellent correlation to measured D_{keff} , as shown in Figure 12.

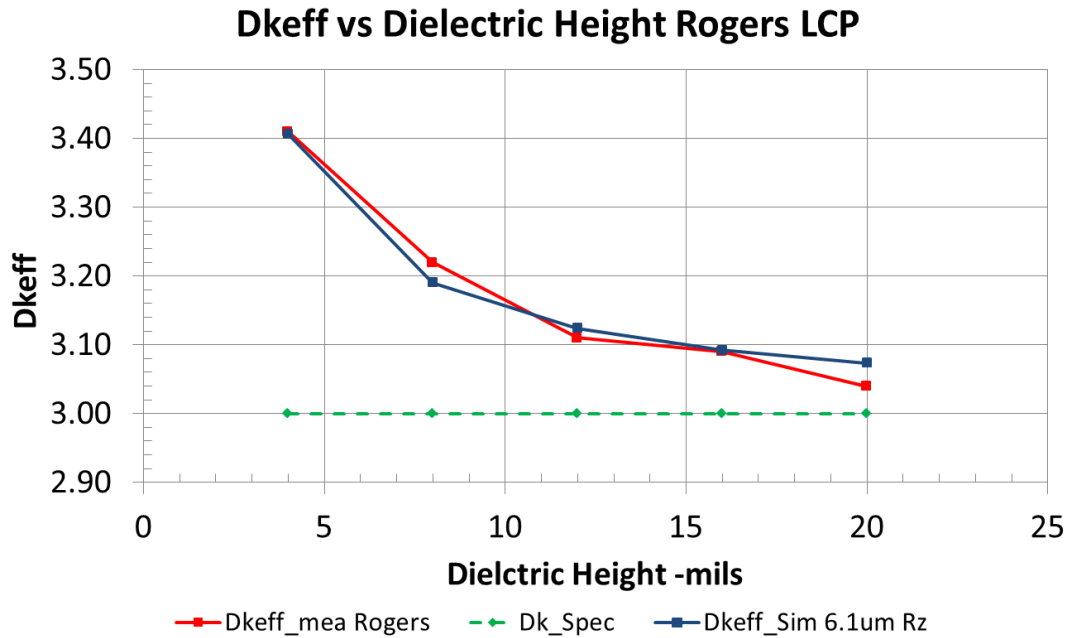


Figure 12 Measured [3]vs simulated D_{keff} of rough copper profile when dielectric height is varied from 4 mils to 20 mils.

FR408HR - RTF Case Study

To test the accuracy of the model, board parameters and measured data from [10] was used. The extracted de-embedded generalized modal S-parameter (GMS) data was computed from 2 inch and 8 inch single-ended stripline traces. They were originally measured from the CMP-28 40 GHz High-Speed Channel Modeling Platform [11], and provided by [14].

The PCB was fabricated with Isola FR408HR material. The default foil is MLS, Grade 3, controlled elongation RTF. Roughness R_z parameters for drum and matte sides are $120\mu\text{in}$ ($3.048\mu\text{m}$) and $225\mu\text{in}$ ($5.715\mu\text{m}$) respectively for 1 oz. copper [13].

An oxide or micro-etch treatment is usually applied to the copper surfaces prior to final lamination. The etch treatment creates a surface full of micro-voids which follows the underlying rough profile and allows the resin of the prepreg to squish in and fill the voids, providing a good anchor. Typically $50\mu\text{in}$ ($1.27\mu\text{m}$) of copper is removed when the treatment is completed, depending on the board shop's process control.

The PCB stripline geometry physical parameters are shown in Figure 13. H_1 , H_2 and t are thicknesses of core, prepreg and copper foil respectively, as published in manufacturers' data sheets. Widths w_1 and w_2 are the design specific parameters for the bottom and top surfaces of the PCB trace respectively.

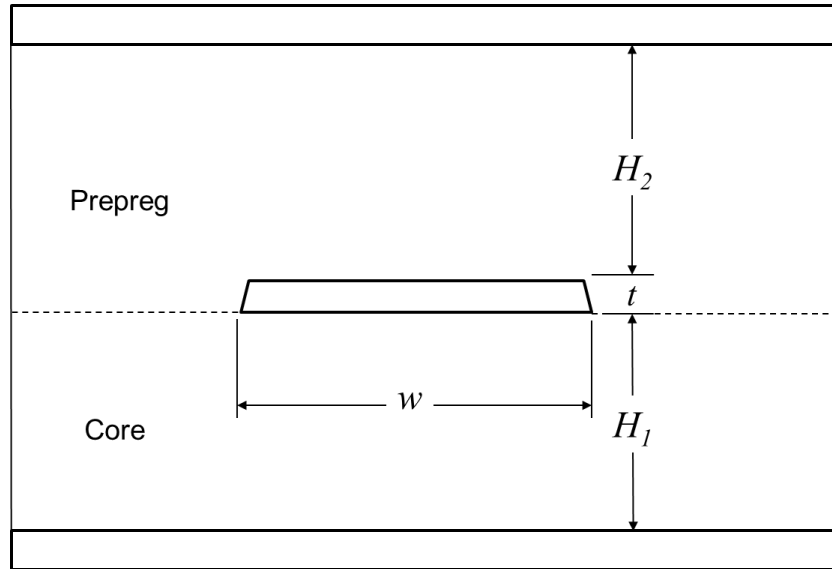


Figure 13 Generic PCB stripline geometry showing core, prepreg, dielectric heights and conductor parameters.

The data sheet and design parameters are summarized in Table 1. Respective D_k , D_f , core, prepreg and trace thickness were obtained from the isoStack® software [12]. Roughness

of the matte side after micro-etch treatment ($R_z = 4.445\mu\text{m}$) was used to determine D_{keff} of the prepreg.

Table 1 FR408HR test board parameters obtained from manufacturers' data sheets and design objective.

Parameter	FR408HR/RTF
D_k Core/Prepreg	3.65/3.59 @10GHz
D_f Core/Prepreg	0.0094/0.0095 @ 10GHz
R_z Drum side	3.048 μm
R_z Matte side before Micro-etch	5.715 μm
R_z Matte side after Micro-etch	4.445 μm
Trace Thickness, t	31.730 μm
Trace Etch Factor	2:1 (60 deg taper)
Trace Width, w	11 mils (279.20 μm)
Core thickness, H_1	12 mils (304.60 μm)
Prepreg thickness, H_2	10.6 mils (269.00 μm)
GMS trace length	6 in (15.23 cm)

By applying Equation 15, determine D_{keff} of core and prepreg due to roughness:

1. D_{keff_core} :

$$D_{keff_core} = \frac{H_{smooth}}{(H_{smooth} - 2R_z)} \times D_{k_core} = \frac{304.6\mu\text{m}}{(304.6\mu\text{m} - 2 \times 3.048\mu\text{m})} \times 3.65 = 3.725$$

2. $D_{keff_prepreg}$:

$$D_{keff_prepreg} = \frac{H_{smooth}}{(H_{smooth} - 2R_z)} \times D_{k_prepreg} = \frac{269\mu\text{m}}{(269\mu\text{m} - 2 \times 4.445\mu\text{m})} \times 3.59 = 3.713$$

Keysight EEsof EDA ADS software [15] was used for modeling and simulation analysis. The controlled impedance line (CIL) model allows modeling of trapezoidal traces.

Figure 14 is the general schematic used for analysis. There are three transmission line substrates; one for dielectric loss; one for conductor loss and the other for total loss without roughness.

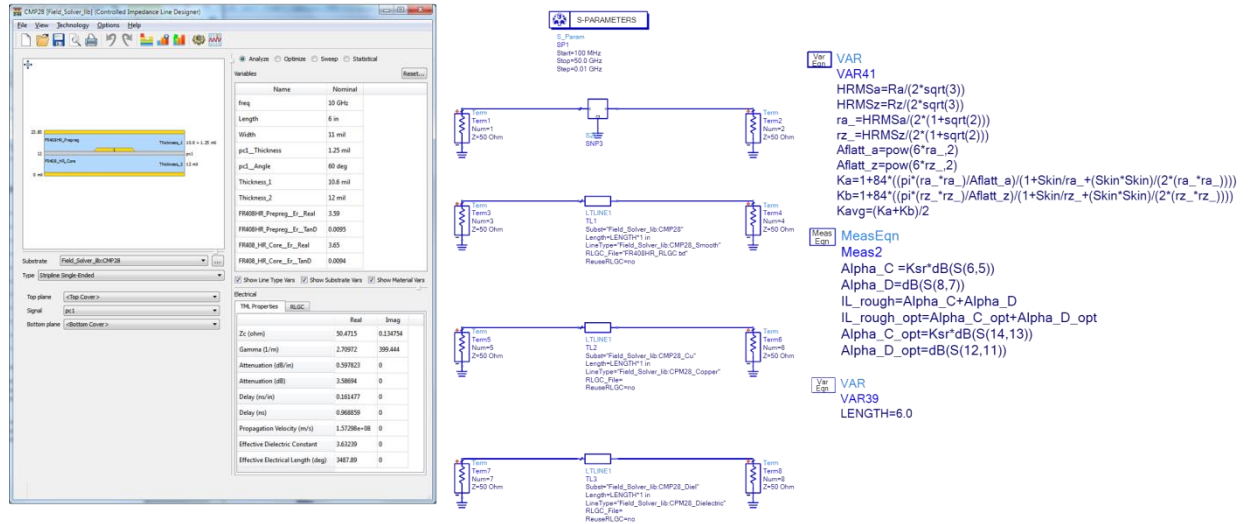


Figure 14 Keysight EEsof EDA ADS [15] generic schematic of controlled impedance line designer used in the modeling and simulation analysis.

Dielectric loss was modeled using the Svensson/Djordjevic wideband Debye model to ensure causality. By setting the conductivity parameter to a value much-much greater than the normal conductivity of copper ensures the conductor is lossless for the simulation. Similarly the conductor loss model sets the D_f to zero to ensure lossless dielectric.

Conductor loss due to roughness was modeled using cubic close-packing of equal spheres (CCPES) model, and total insertion loss was determined as described in [10].

Results

Results for effective permittivity due to roughness are shown in Figure 15. On the left graph, D_{keff} measured (red) was 3.761 compared to simulated D_{keff} (blue) of 3.626, at 10 GHz, when data sheet values for core and prepreg were used. This gave an error of - 3.6%.

But when the respective D_{keff_rough} was used for core and prepreg there was better correlation, $D_{keff}=3.727$ vs 3.761, for an error of only -0.9%, as shown on the right graph.

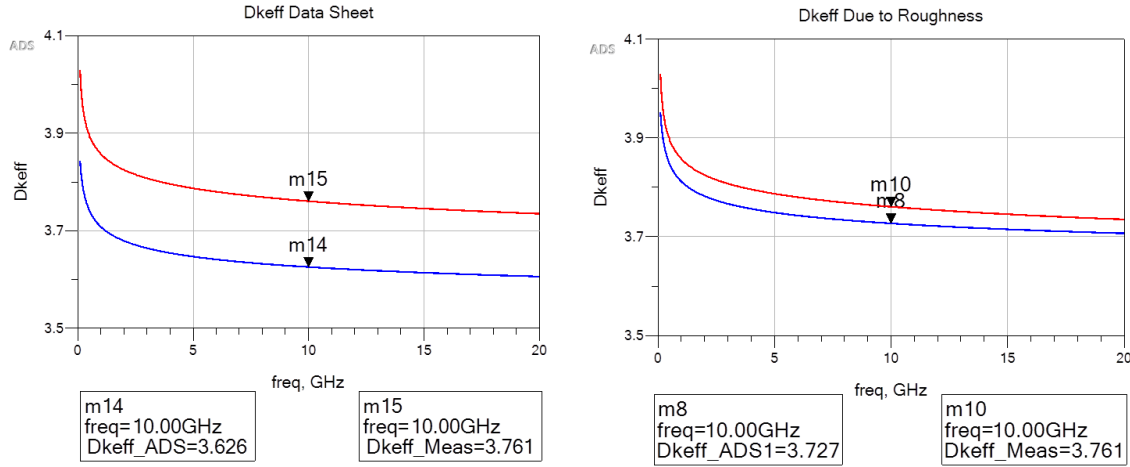


Figure 15 Measured vs simulated D_{keff} using FR408HR data sheet values for core and prepreg (left) and using D_{keff_rough} (right).

Simulated IL and phase delay, due to conductor roughness, are shown in Figure 16. The left graph compares measured IL and phase delay (red) vs simulated (blue) when data sheet parameters were used. IL are the top curves and phase delay are bottom curves. The right graph shows improved phase delay over the entire frequency range and IL improvement past 25GHz when respective D_{keff_rough} was used for core and prepreg.

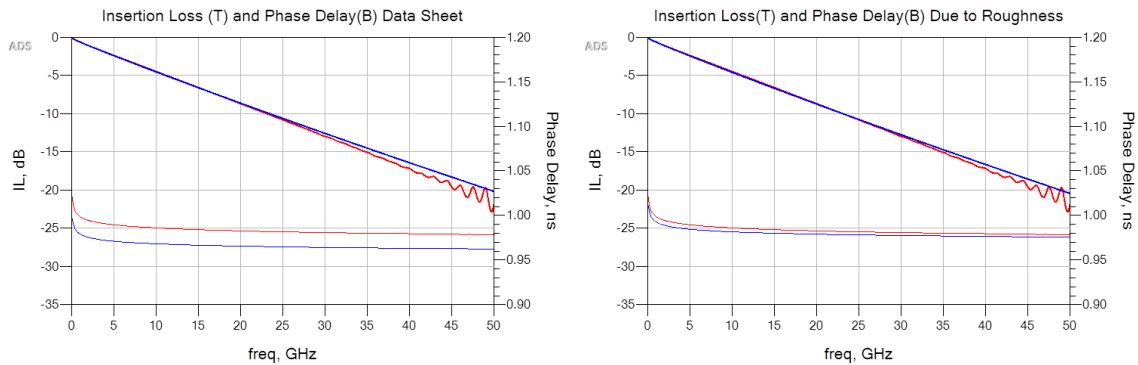


Figure 16 Simulated results for insertion loss (top curves) and phase delay (bottom curves) using FR408HR data sheet values for D_{keff} (left graph) and using D_{keff_rough} (right graph). Measured results are red curves and simulated are blue.

N4000-13EP/VLP Case Study

The PCB stripline geometry parameters are the same as shown in Figure 13. Table 2 summarizes parameters from DesignCon 2015 Paper [9] and material data sheets. Material was N4000-13EP with very low profile (VLP) foil. Respective D_k , D_f , core and prepreg values were obtained from Nelco dielectric calculator software [17].

Table 2 N4000-13EP test board parameters obtained from manufacturers' data sheets and design objective.

Parameter	N4000-13EP/RTF
D_k Core/Prepreg	3.83/3.72 @10GHz
D_f Core/Prepreg	0.0085/0.0085 @ 10GHz
R_z Matte side	2.50 μm
R_d Drum w/ Micro-etch	1.44 μm
Trace Thickness, t	15.23 μm
Trace Etch Factor	2:1 (60 deg taper)
Trace Width, w	9.9 mils (251 μm)
Core thickness, H_1	9.8 mils (249 μm)
Prepreg thickness, H_2	9.09 mils (231 μm)
GMS trace length	4 in (10.15cm)

Similar to CMP-28 case study, the same method using Keysight EEsof EDA ADS software [15] was followed for modeling and simulation analysis. Equation 15 was used to determine D_{keff} of core and prepreg due to roughness. Dielectric loss was modeled using the Svensson/Djordjevic wideband Debye model to ensure causality. Conductor loss due to roughness was modeled using hexagonal close-packing of equal spheres (HCPES) model, as described in [9].

Results

Results for effective permittivity due to roughness are shown in Figure 17. On the left graph, D_{keff} measured (red) was 3.867 compared to simulated D_{keff} (blue) of 3.792, at 10 GHz, when data sheet values for core and prepreg were used. This gave an error of - 1.9%.

But when the respective D_{keff_rough} was used for core and prepreg there was better correlation, D_{keff} = 3.829 vs 3.867, for an error of only -0.98%, as shown on the right graph.

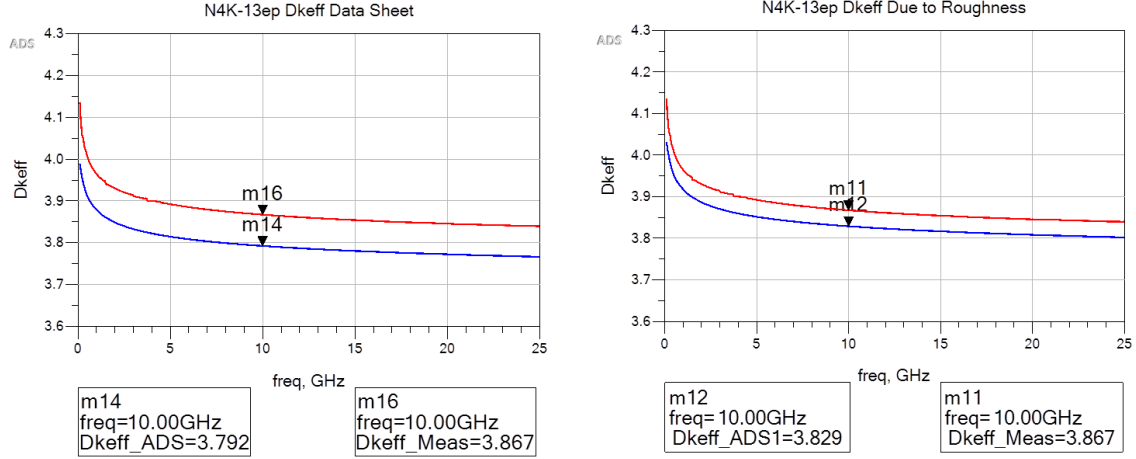


Figure 17 Measured vs simulated D_{keff} using N4000-13EP data sheet values for core and prepreg (left) and using D_{keff_rough} (right).

Simulated IL and phase delay, due to conductor roughness, are shown in Figure 18. The left graph compares measured IL and phase delay (red) vs simulated (blue) when data sheet parameters were used. IL are the top curves and phase delay are bottom curves. The right graph shows slight improvement in IL and phase delay when respective D_{keff_rough} was used for core and prepreg.

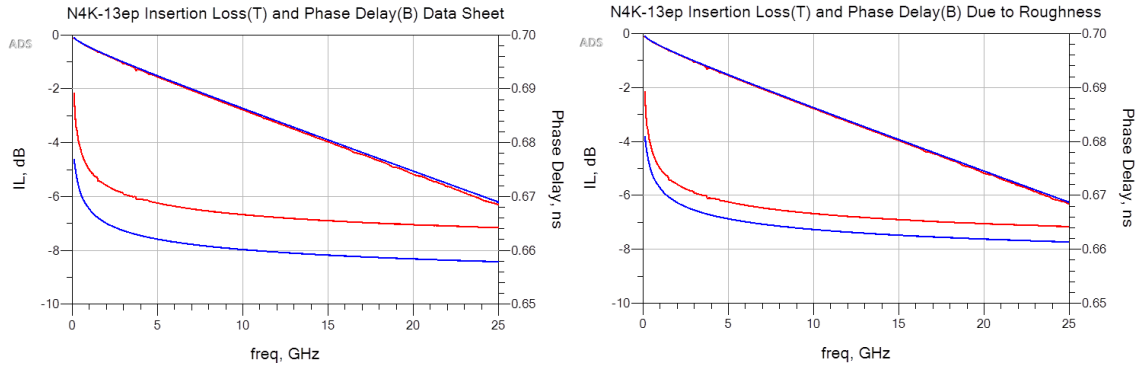


Figure 18 Simulated results for insertion loss (top curves) and phase delay (bottom curves) using N4000-13EP data sheet values for D_{keff} (left graph) and using D_{keff_rough} (right graph). Measured results are red curves and simulated are blue.

As expected, there was not a dramatic impact in either D_{keff} or phase delay, compared to FR408HR/RTF case study, because VLP foil is typically smoother than RTF foil and is consistent with the study done by[3].

Summary and Conclusions

1. Analysis done in this paper supports the theory that surface roughness profile decreases the separation between the reference plane(s) and conductor, thereby

increasing the e-field strength, resulting in additional capacitance, which accounts for increased D_{keff} and phase delay as summarized by:

$$\frac{E_{rough}}{E_{smooth}} = \frac{H_{smooth}}{H_{rough}} = \frac{C_{rough}}{C_{smooth}} = \frac{D_{keff_rough}}{D_{keff_smooth}} = \frac{TD_{rough}}{TD_{smooth}}$$

2. By using an effective D_k due to roughness, derived from Gauss' Law for parallel plate capacitors, instead of published D_k values from data sheets, excellent results were achieved, when compared to measured data without curve fitting.

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Appendix

Determining Effective Dk Due to Roughness

Given:

$$C_{smooth} = \frac{D_{keff} \varepsilon_0 A}{H_{smooth}}; C_{rough} = \frac{D_{keff} \varepsilon_0 A}{H_{rough}}$$

Then:

$$\begin{aligned} \frac{C_{smooth}}{C_{rough}} &= \frac{\frac{D_{keff} \varepsilon_0 A}{H_{smooth}}}{\frac{D_{keff} \varepsilon_0 A}{H_{rough}}} \\ &= \frac{H_{rough}}{H_{smooth}} \\ \therefore H_{rough} &= H_{smooth} \frac{C_{smooth}}{C_{rough}} \end{aligned}$$

$$C_{rough} = \frac{D_{keff} \varepsilon_0 A}{H_{rough}} = \frac{D_{keff} \varepsilon_0 A}{H_{smooth} \frac{C_{smooth}}{C_{rough}}} = \frac{\varepsilon_0 A}{H_{smooth}} \times D_{keff} \frac{C_{rough}}{C_{smooth}}$$

If :

$$D_{keff} \frac{C_{rough}}{C_{smooth}} = D_{keff_rough}$$

Then :

$$C_{rough} = D_{keff_rough} \frac{\varepsilon_0 A}{H_{smooth}}$$

$$\frac{C_{rough}}{C_{smooth}} = \frac{H_{smooth}}{H_{rough}} = \frac{D_{keff_rough} \frac{\varepsilon_0 A}{H_{smooth}}}{D_{keff} \frac{\varepsilon_0 A}{H_{smooth}}} = \frac{D_{keff_rough}}{D_{keff}}$$

$$\therefore D_{keff_rough} = \frac{H_{smooth}}{H_{rough}} \times D_{keff} = \frac{H_{smooth}}{(H_{smooth} - 2R_z)} \times D_{keff}$$