EXTRACTION OF DIELECTRIC PROPERTIES OF PCB LAMINATE DIELECTRICS ON PCB STRIPLINES TAKING INTO ACCOUNT CONDUCTOR SURFACE ROUGHNESS

Santa Clara Valley CHAPTER

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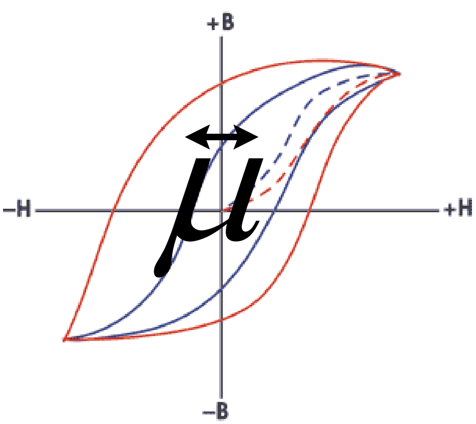
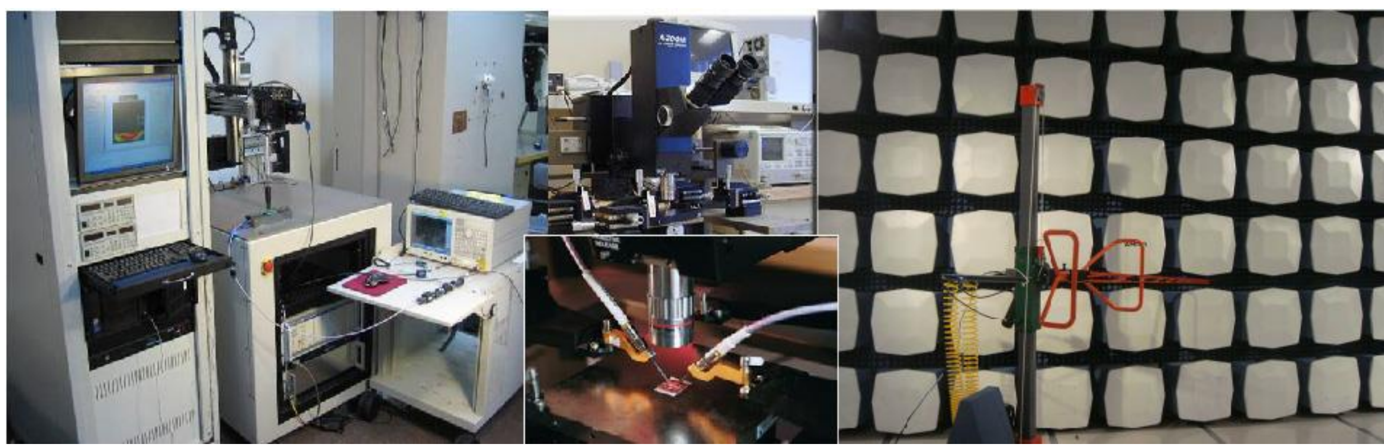
(THE WORK IS DONE IN EMC LAB OF MISSOURI S&T, SPONSORED BY CISCO AND NSF)





Tuesday, May 13, 2014

Outline

I. Introduction – motivation, objectives, and state-of-the-art

II. Idea of an "effective roughness dielectric" (ERD)

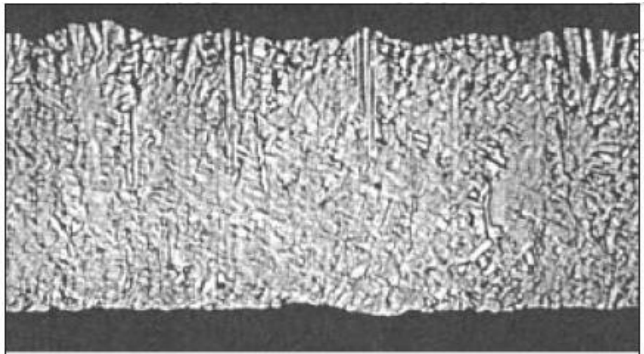
III. PCB stripline cross-sectional analysis and roughness profile quantification

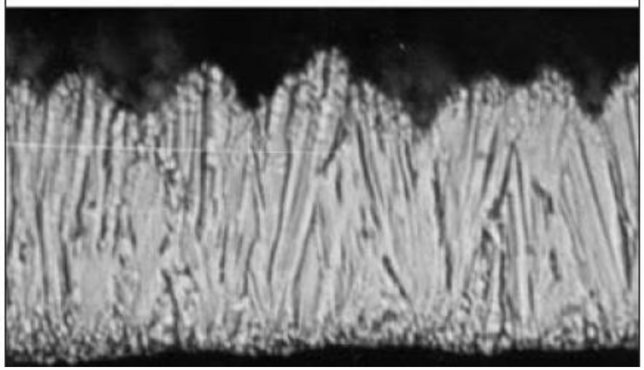
IV. Experiment-based input data for numerical electromagnetic modeling

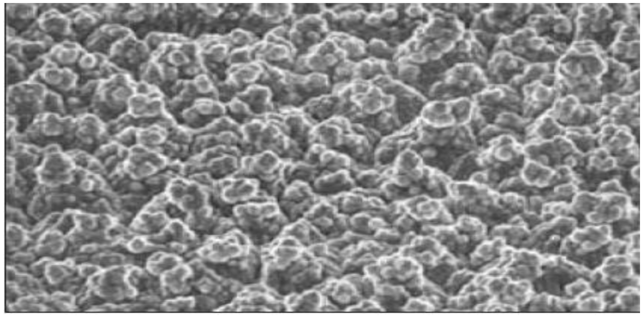
V. Modeling results & validation

VI. Building of "design curves" regarding conductor surface roughness

VII. Conclusions

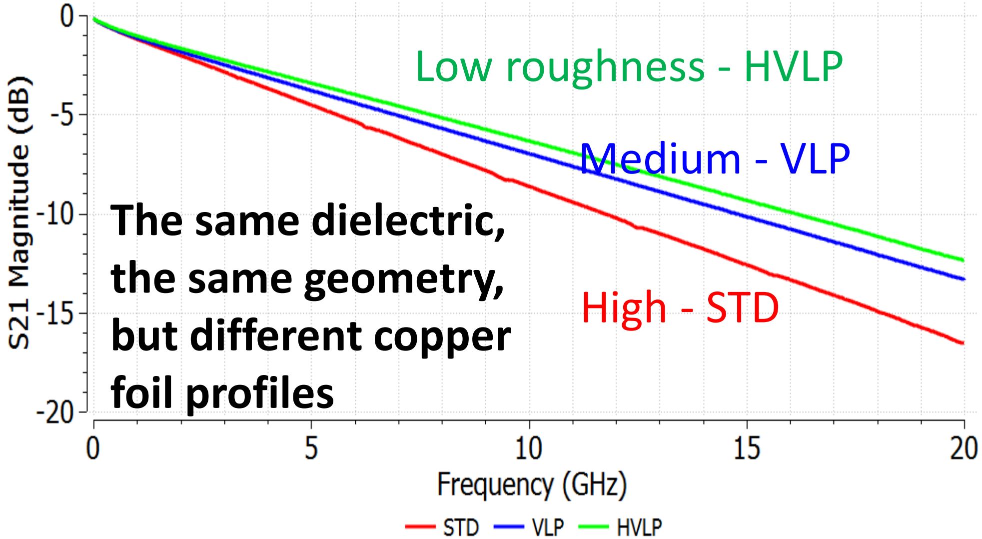




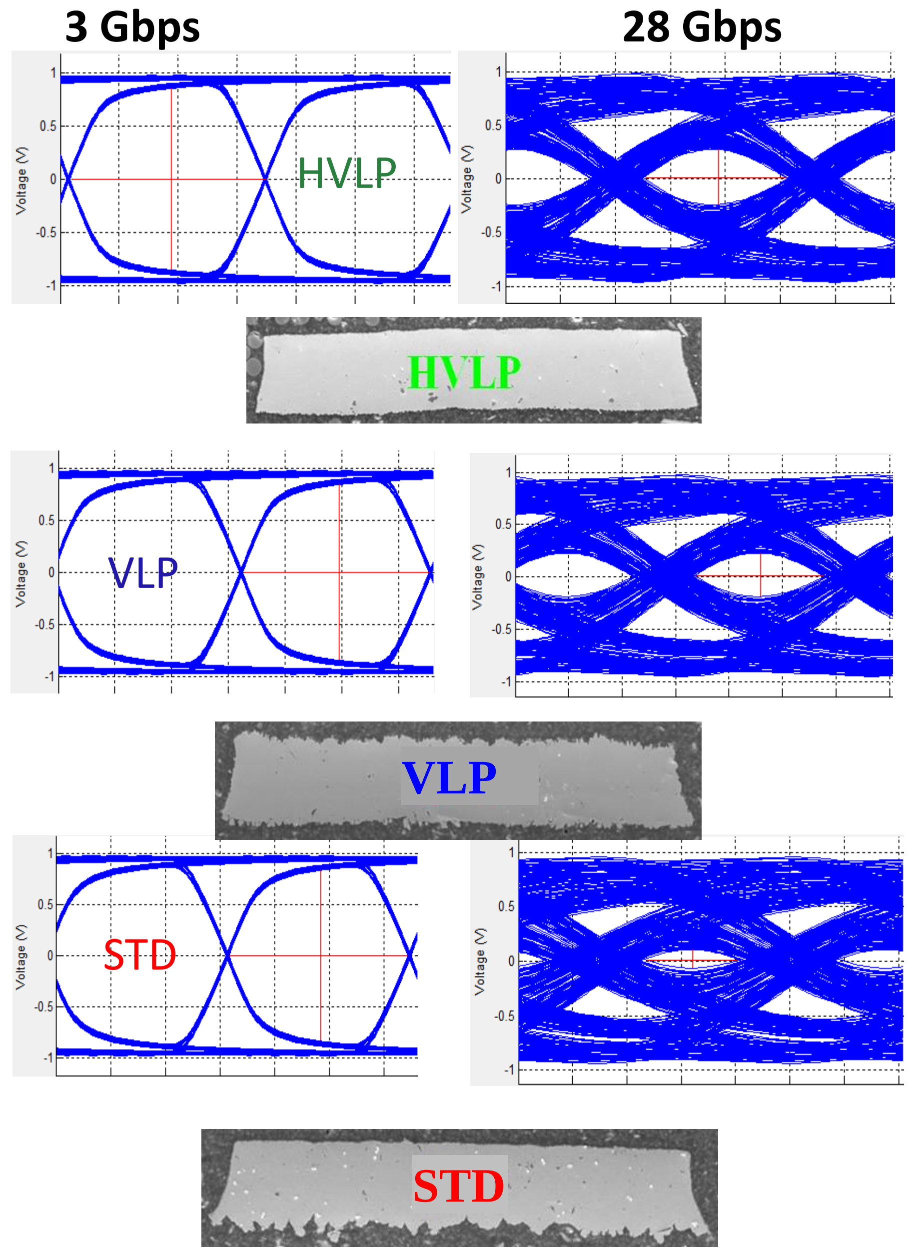


Motivation

- Conductor roughness affects both phase and loss constants in PCB transmission lines and results in eye diagram closure.

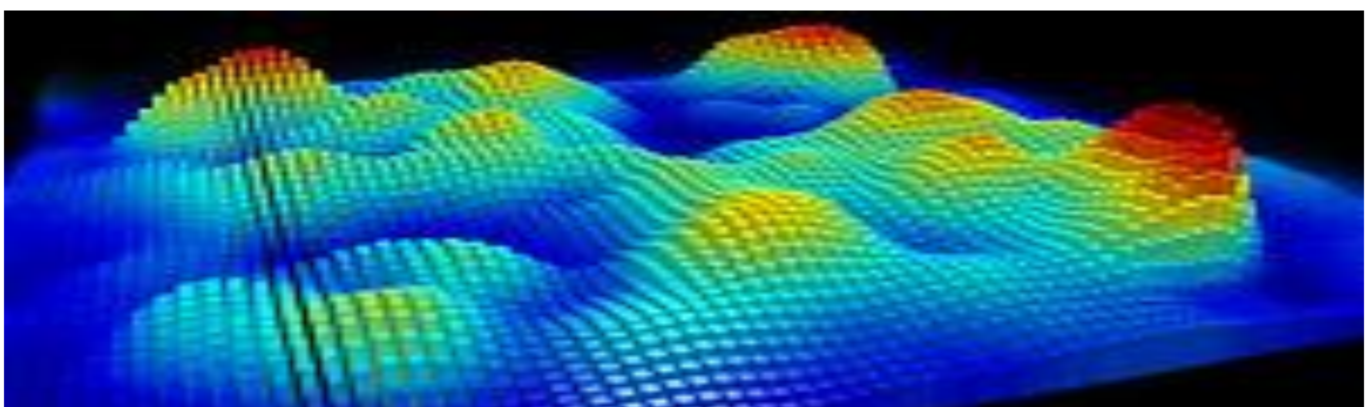


- Conductor surface roughness lumps into laminate dielectric parameters.
- Any existing analytical and numerical models of conductor surface roughness are ***approximations.***
- Study and adequate modeling of wideband behavior of dielectrics and conductors in PCBs is important from SI point of view.



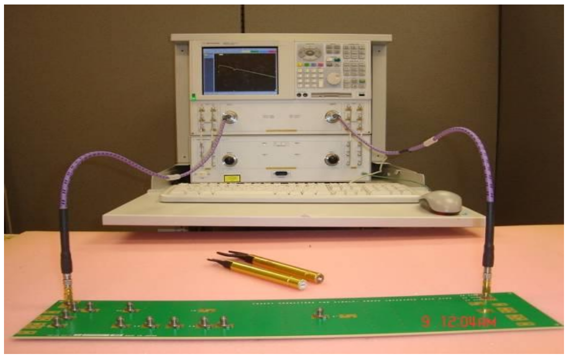
Objectives

- Develop a technique to accurately measure and extract laminate dielectric parameters ($DK=\varepsilon'$ & $DF=\tan\delta$) removing effects of conductors.
- Develop a physics-based model, which allows for simple incorporation of conductor surface roughness in electromagnetic numerical models of transmission lines.
- Test and validate the proposed model using measurements on a multitude of various test boards with different cross-sections and roughness profiles.
- Test and validate the proposed model using electromagnetic numerical simulations with different software tools.
- Develop a database for roughness parameters, corresponding to different types of copper foils used in PCBs.

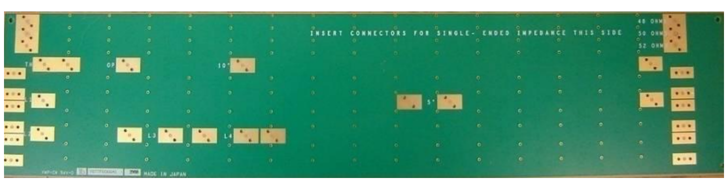


Measurements & Material Parameter Extraction

Measured S-parameters → **Causality, Passivity & Reciprocity check** → **ABCD parameters** → $\gamma = \frac{\operatorname{arccos}h\left(\sqrt{A \cdot D}\right)}{linelength}$ → $\gamma = \alpha_T + j\beta$, $\alpha_T = \alpha_c + \alpha_d$



S-parameters are measured using VNA or TDR with "Through-Reflect-Line" (TRL) calibration in f-domain or t-domain, respectively

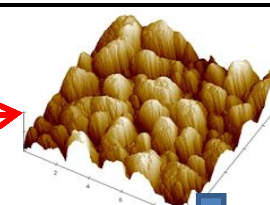


A. Koul, M. Koledintseva, et al, *Proc. IEEE Symp. Electromag. Compat.*, Aug. 17-21, Austin, TX, 2009, 191-196

Model or experimentally retrieve conductor loss for rough stripline conductor

Main problem!

$$\alpha_d = \alpha_T - \alpha_c$$



$$\beta = \frac{\omega}{c} \cdot \sqrt[4]{\varepsilon_r'^2 + \varepsilon_r''^2} . \cos\left(\frac{\delta}{2}\right)$$

$$\alpha_d = \frac{\omega}{c} \cdot \sqrt[4]{\varepsilon_r'^2 + \varepsilon_r''^2} . \sin\left(\frac{\delta}{2}\right)$$

Solve the system of equations to obtain complex permittivity

OPTIONS

- **Analytical Models**
- **Numerical Models**
- **Experimental**

Existing Methods for Conductor Roughness Modeling

I. Correction coefficients for attenuation

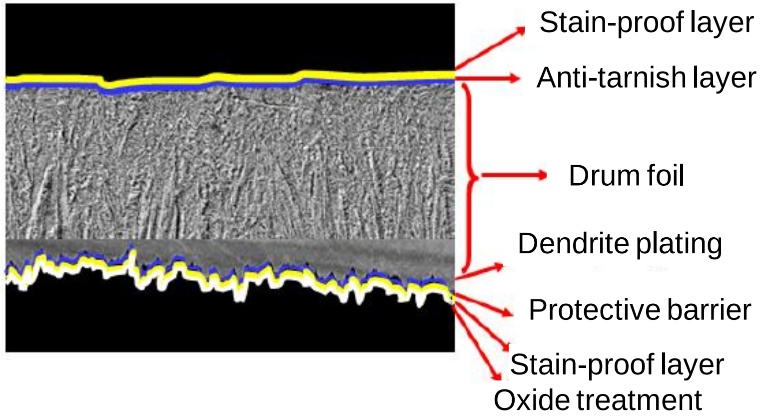
- Periodic roughness models (Morgan, Sanderson, Sundstroem, Lukic)
- Hammerstad model (Hammerstad, Bekkadal, Jensen)
- "Snowball" model (Huray)
- Roughness hemispheres (Hall, Pytel)
- Stochastic models (Sanderson, Tsang, Braunisch)

II. Impedance boundary conditions

- Holloway, Kuester

III. Numerical electromagnetic modeling

- Deutsch
- Shlepnev
- X. Chen



IV. Experimental separation of conductor & dielectric loss

- Koledintseva et al

Our Recently Published Works

- Experiment-based **D**ifferential and **E**xtrapolation **R**oughness **M**easurement techniques (**DERM** and **DERM-2**) have been proposed to refine wideband DK and DF from roughness.

[1] A. Koul, M.Y. Koledintseva, S. Hinaga, and J.L. Drewniak, "Differential extrapolation method for separating dielectric and rough conductor losses in printed circuit boards", *IEEE Trans. Electromag. Compat.*, vol. 54, no. 2, Apr. 2012, pp. 421-433.

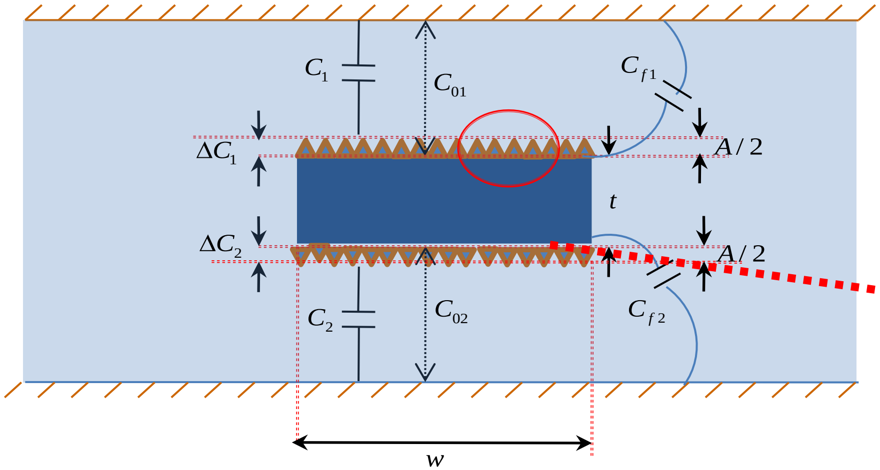
[2] M.Y. Koledintseva, A.V. Rakov, A.I. Koledintsev, J.L. Drewniak, and S. Hinaga, "Improved experiment-based technique to characterize dielectric properties of printed circuit boards", *IEEE Trans. Electromag. Compat.* (to be published soon in 2014)

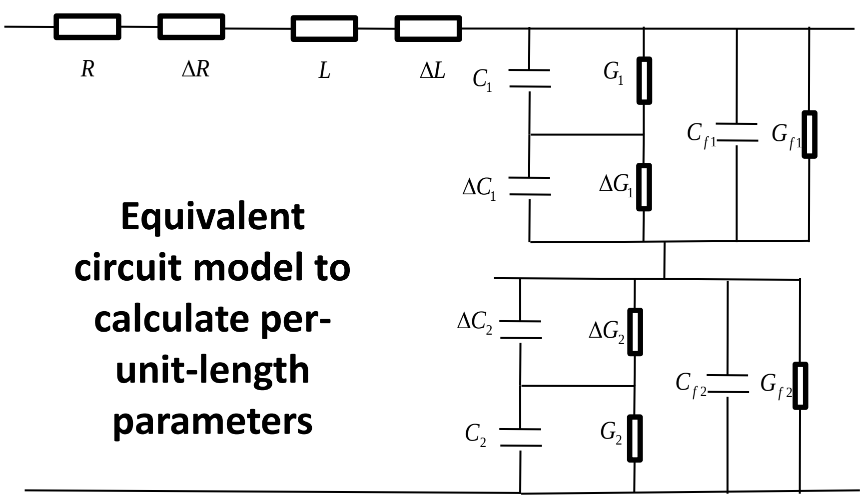
- An **E**ffective **R**oughness **D**ielectric (**ERD**) approach has been proposed to substitute inhomogeneous roughness boundary layer by a layer with homogenized dielectric properties.

[3] M.Y. Koledintseva, A. Razmadze, A. Gafarov, S. De, S. Hinaga, and J.L. Drewniak, "PCB conductor surface roughness as a layer with effective material parameters", *IEEE Symp. Electromag. Compat.*, Pittsburg, PA, 2012, pp. 138- 142.

Idea of "Effective Roughness Dielectric"

Roughness leads to the capacitance increase!

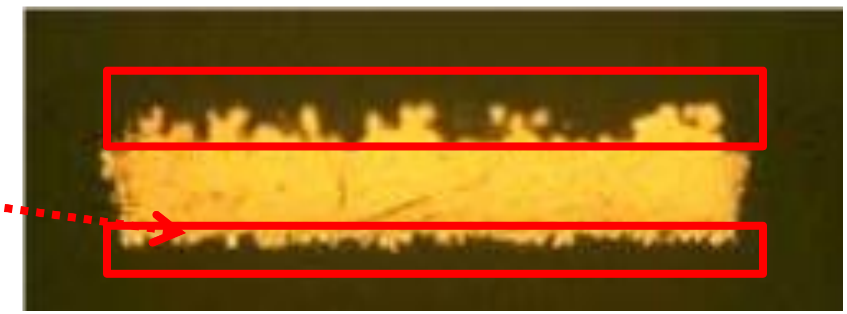


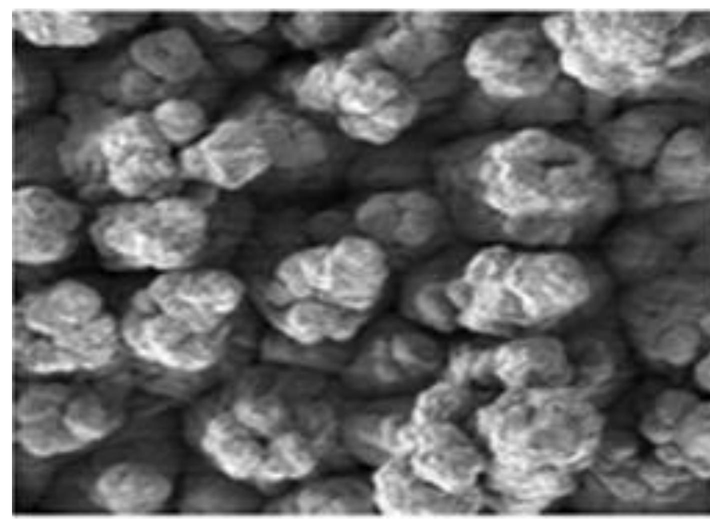


Equivalent circuit model to calculate per-unit-length parameters

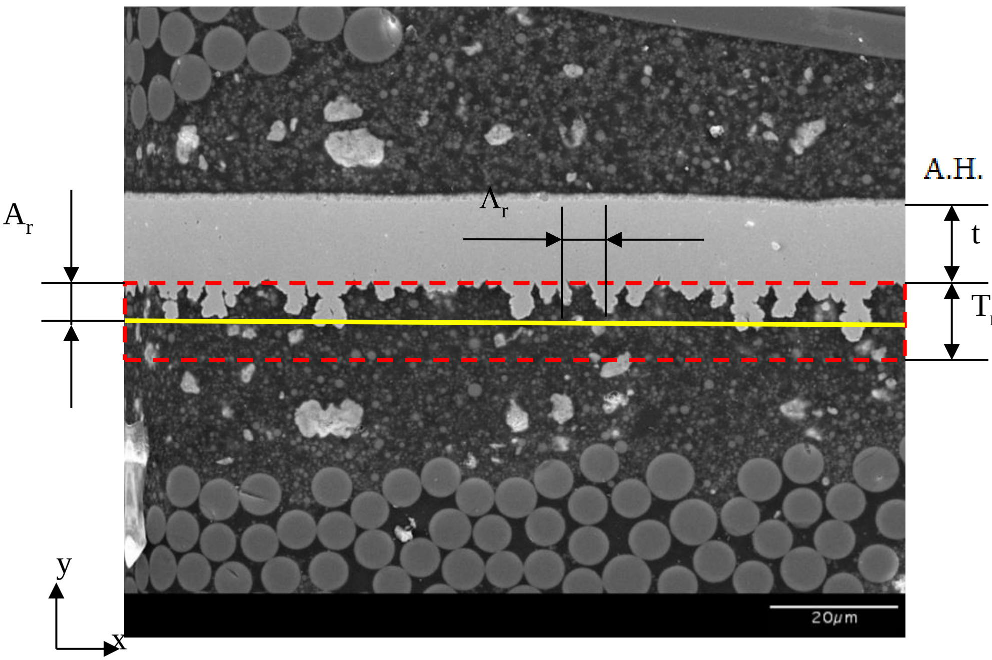
This effect was first noticed in:

A. Deutsch, A. Hueber, et al, "Accuracy of dielectric constant measurement using the full-sheet-resonance technique IPC-T650 2.5.5.6", 311-314, *IEEE Symp. Electrical Performance of Electronic Packaging*, 2002.





Mixing Rule for "Effective Roughness Dielectric"



Maxwell Garnett Mixing Rule for aligned metallic inclusions

A.H. Sihvola, *Electromagnetic Mixing Formulas and Applications*, IEE, 1999.

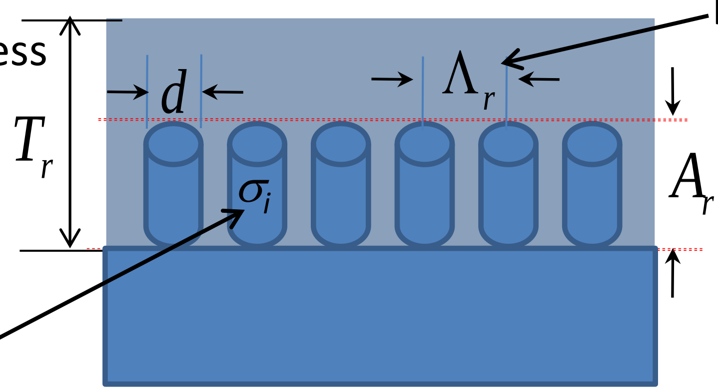
$$\varepsilon_{eff,y} = \varepsilon_{matrix}\left(1 + v_{incl}\frac{\varepsilon_{incl} - \varepsilon_{matrix}}{\varepsilon_{matrix} + (1 - v_{incl})N_y(\varepsilon_{incl} - \varepsilon_{matrix})}\right)$$

$$N_y = \frac{1}{a^2}\ln(a)$$ Depolarization factor of cylindrical inclusions

$a = A_r/d$ Aspect ratio of inclusions

$$\varepsilon_{incl} = \varepsilon_i - \frac{j\sigma_i}{\omega\varepsilon_0} \qquad \varepsilon_{matrix} = \varepsilon'_m - j\varepsilon''_m.$$

Thickness of "roughness dielectric"

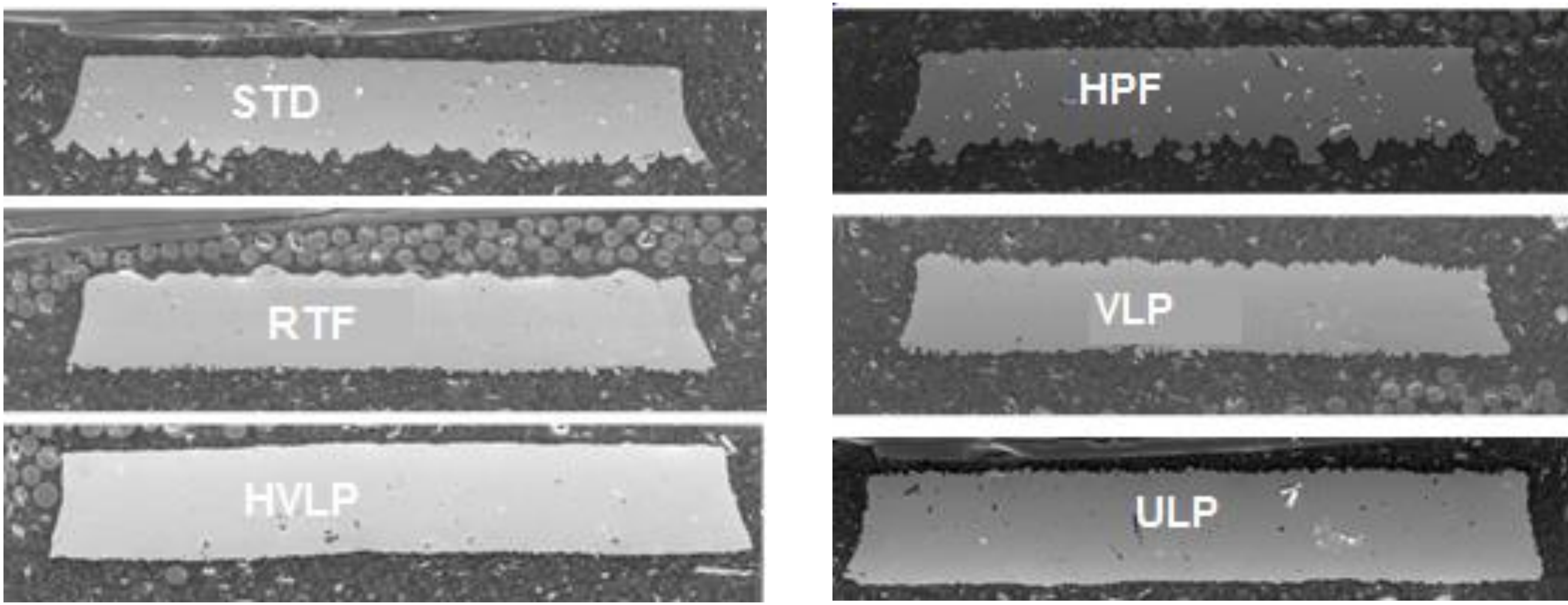


Roughness quasi-period

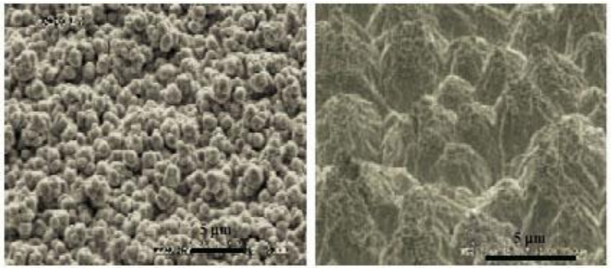
Average peak-to-valley roughness amplitude

Intrinsic conductivity of "roughness inclusions"

Various Types of Foils



- **HPF** (high-performance foil) - 10 µm <Rz <15 µm
- **STD** (standard foil) – 5 µm <Rz<10 µm
- **VLP** (very-low profile foil) – 3 µm <Rz<6 µm
- **RTF** (reverse-treatment foil) – 3 µm <Rz<6 µm
- **HVLP** (hyper-very-low profile foil) – 1 µm <Rz<3 µm
- **ULP** (ultra-low roughness foil) – 0.5 µm < Rz < 1 µm

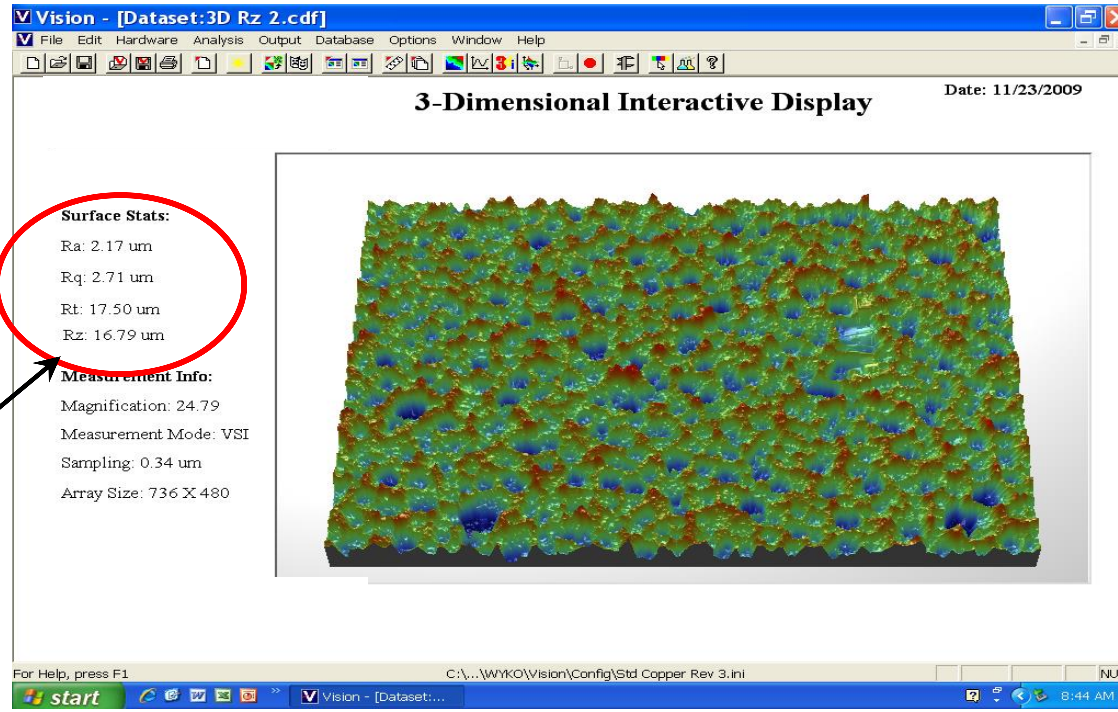


Foils are mostly isotropic in X and Z

Standard Profilometer Roughness Evaluation

Surface Profilometer

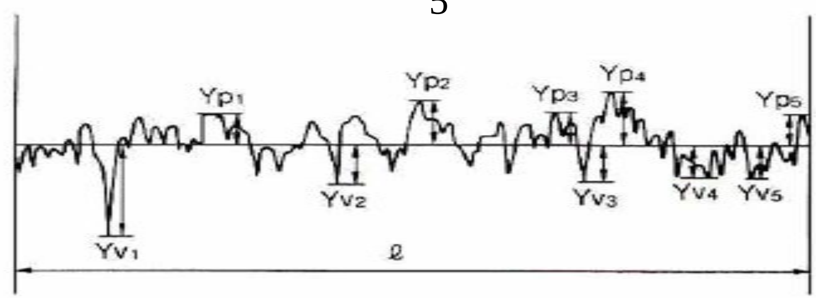
- Mechanical
- Optical



Roughness of conductors on PCB are evaluated based on the **amplitude data only**: Ra, Rq, Rz, and Rt.

Foil / Trace Thickness	t=12μm	t=18μm	t=35μm
Low rough (HVLP)	1.5 μm	1.5 μm	1.5 μm
Medium rough (VLP)	3 μm	3.5 μm	4 μm
Standard foil (STD)	5 μm	6 μm	8 μm

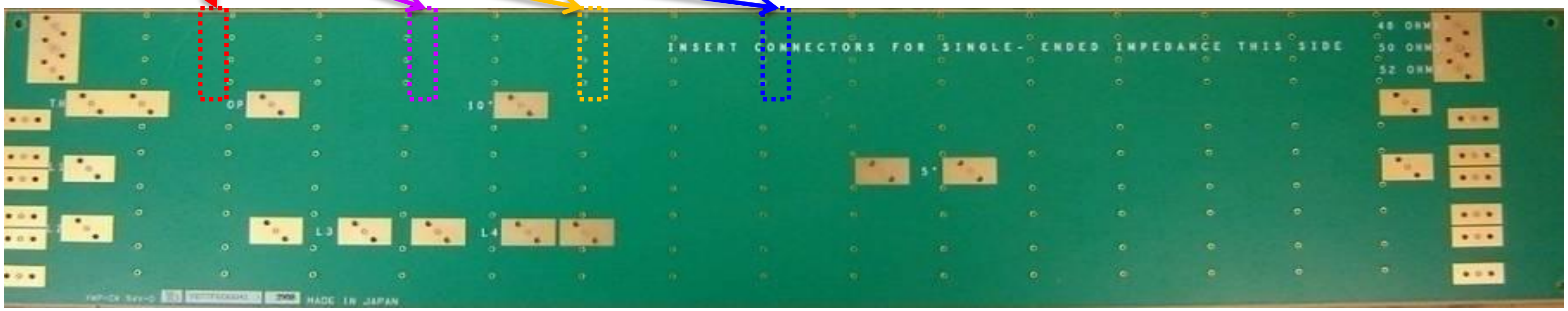
$$R_z = \frac{\left|Y_{p1}+Y_{p2}+Y_{p3}+Y_{p4}+Y_{p5}\right| + \left|Y_{v1}+Y_{v2}+Y_{v3}+Y_{v4}+Y_{v5}\right|}{5}$$

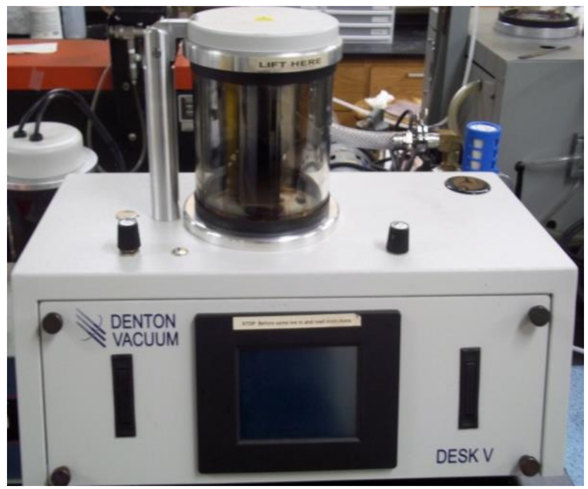


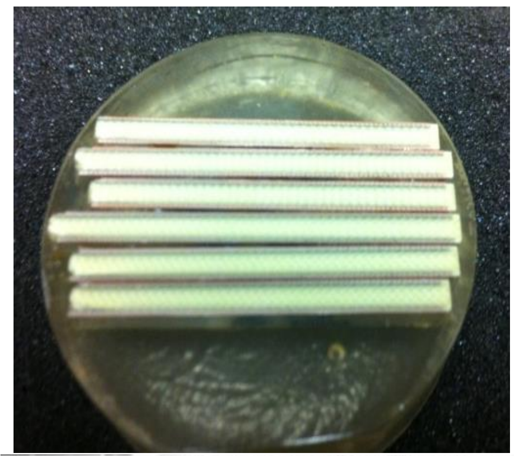
Problem: foil measured is not the same as "in situ".

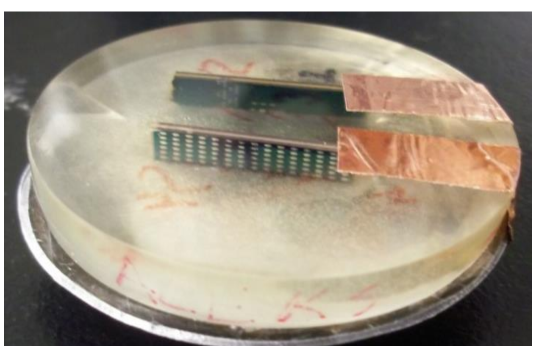
SEM & Oprical Cross-sectional Analysis of PCB Striplines

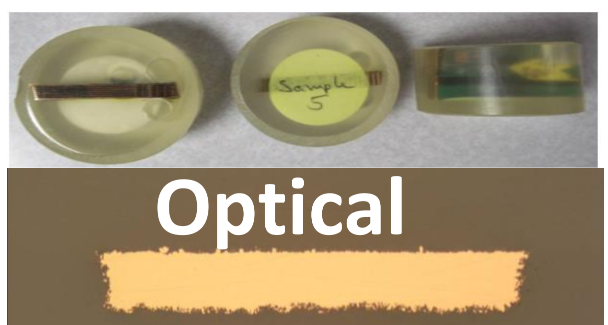
Cutting board for cross-sections



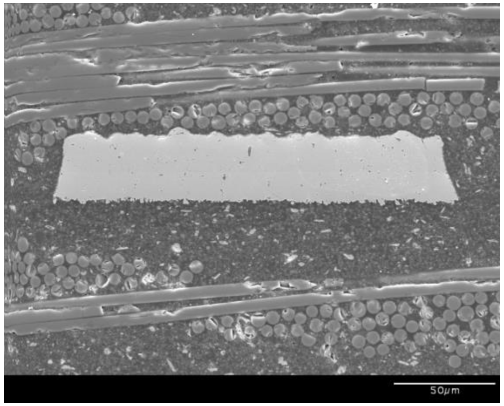


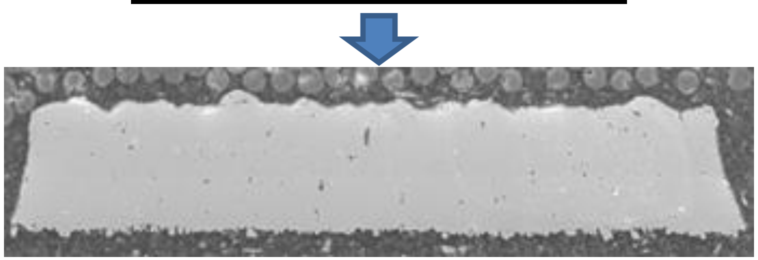


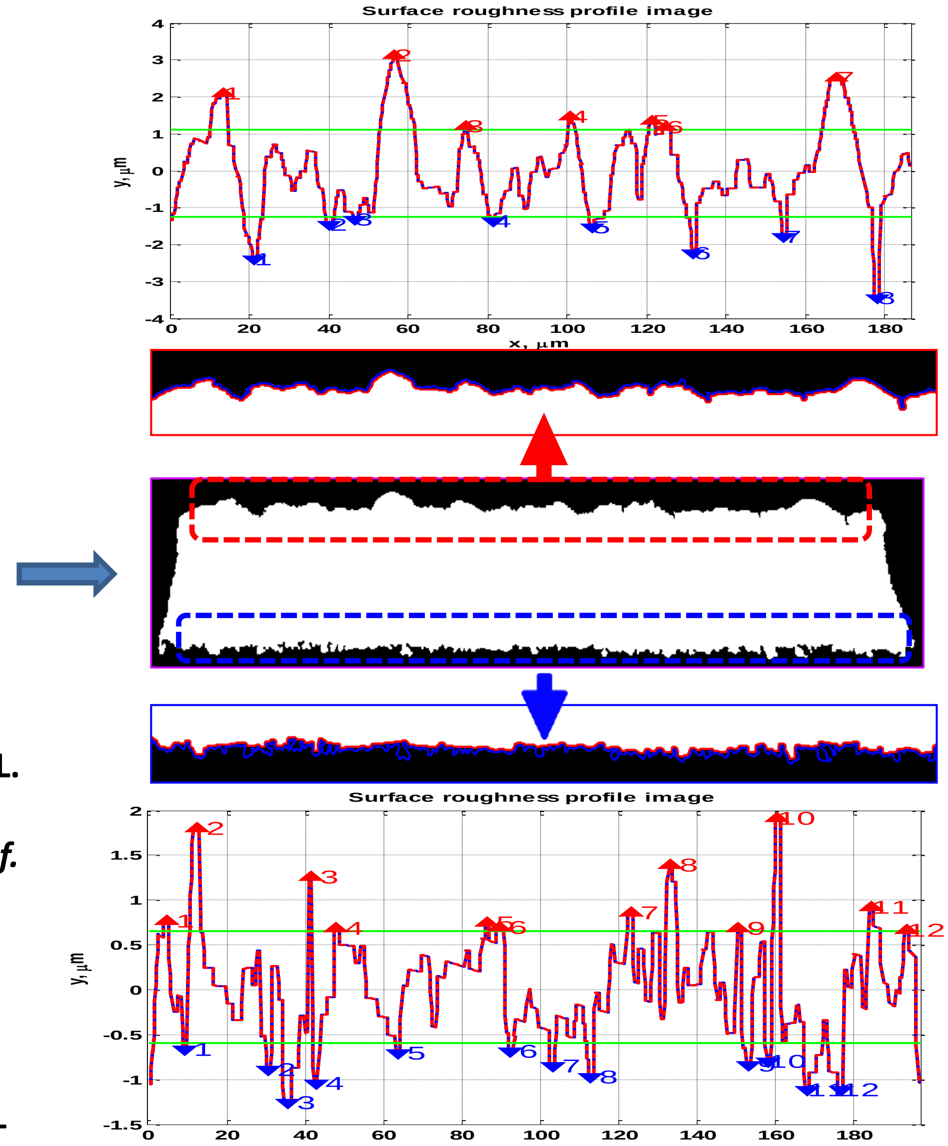




Conductor Roughness Profile Extraction



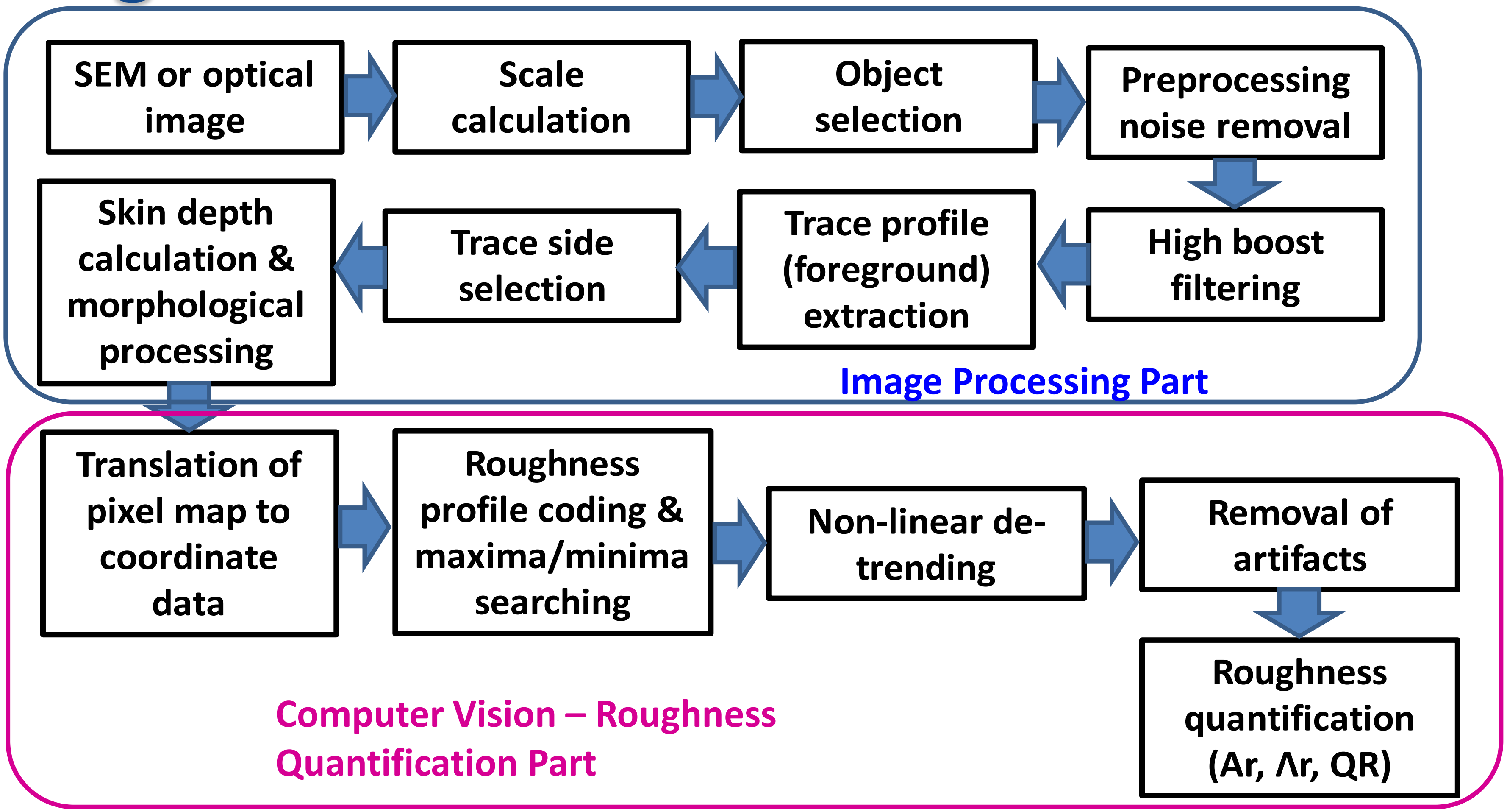


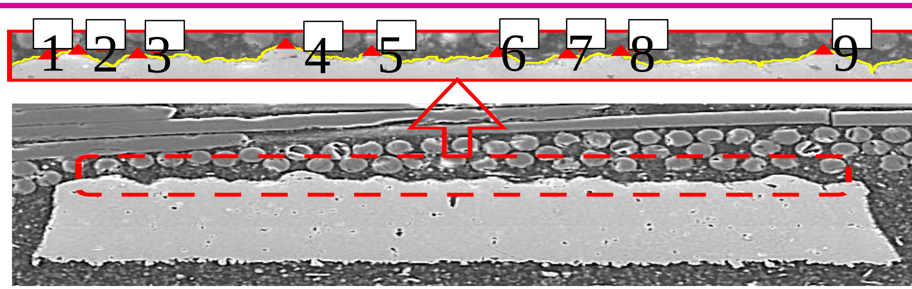


[S. Hinaga, S. De, A.Y. Gafarov, M.Y. Koledintseva, and J.L. Drewniak, "Determination of copper foil surface roughness from microsection photographs", *Techn. Conf. IPC Expo/APEX 2012*, Las Vegas, Apr. 2012].

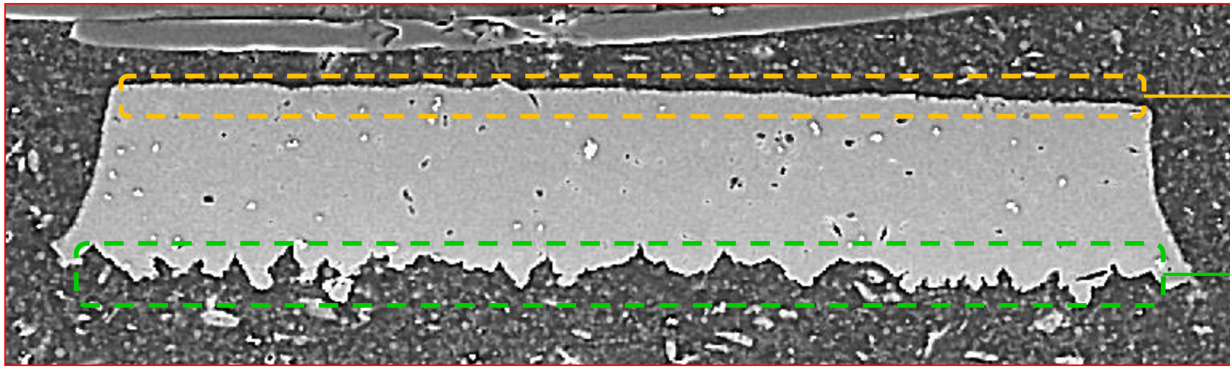
[S. De, A.Y. Gafarov, M.Y. Koledintseva, S. Hinaga, R.J. Stanley, and J.L. Drewniak, "Semi-automatic copper foil surface roughness detection from PCB microsection images", *IEEE Symp. EMC.*, Pittsburg, PA, 2012, pp. 132-137].

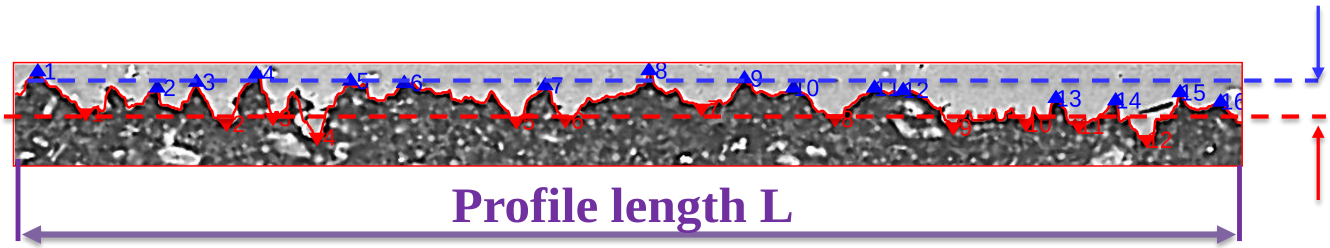
Roughness Characterization Flow Chart





Roughness Factor QR





Average peak-to-valley amplitude: $$A_r = \frac{\sum_{i=1}^{N_{peak}} \left|Y_{i\ peak}\right|}{N_{peak}} + \frac{\sum_{i=1}^{N_{valley}} \left|Y_{i\ valley}\right|}{N_{valley}}$$

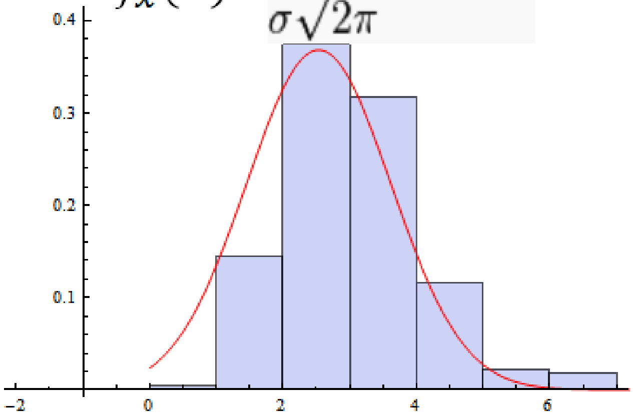
Roughness quasi-period: $$\Lambda = \frac{L \times N_{valley} + L \times N_{peak}}{2 \times N_{valley} \times N_{peak}}$$

Roughness factor: $$QR = \left(\frac{A_r}{\Lambda}\right)_{oxide} + \left(\frac{A_r}{\Lambda}\right)_{foil}$$

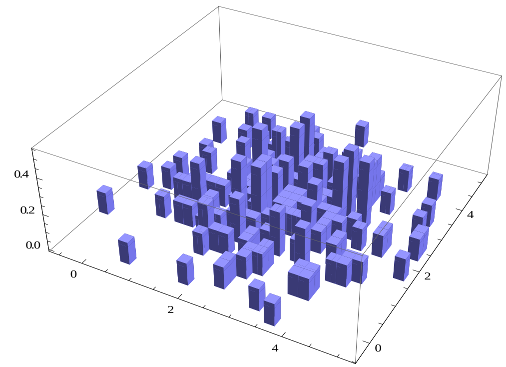
Roughness Surface Generation from Statistical Analysis of Profile

Gauss — **2D PDF**

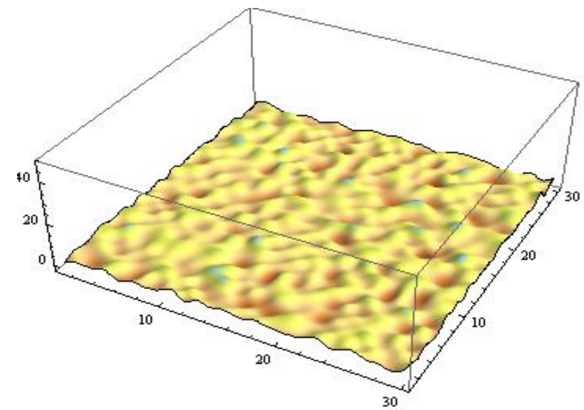
$$f_x(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



3D PDF



Generated Surfaces

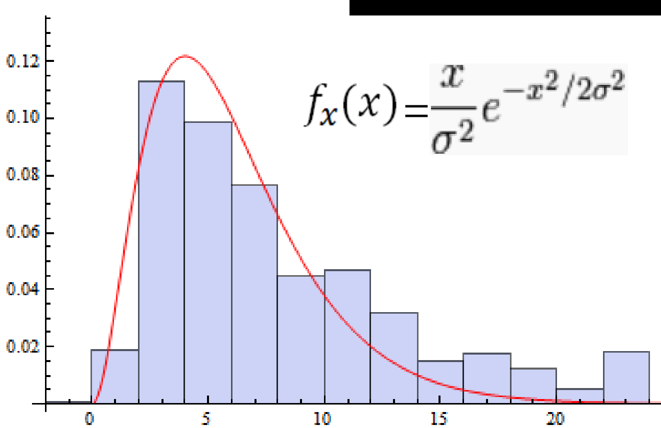


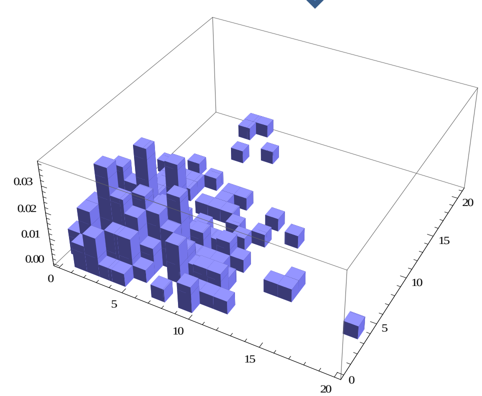
Oxide Side

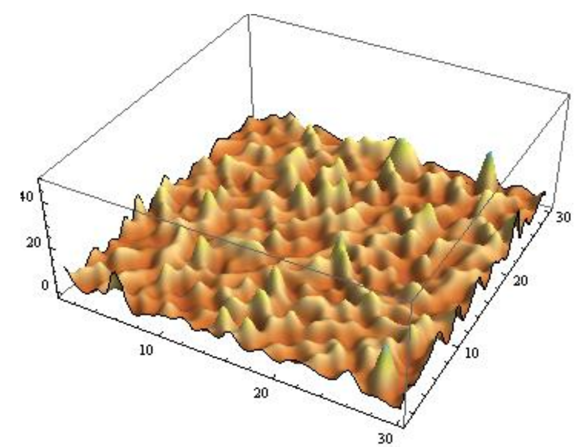
Foil Side

Rayleigh

$$f_x(x) = \frac{x}{\sigma^2} e^{-x^2/2\sigma^2}$$

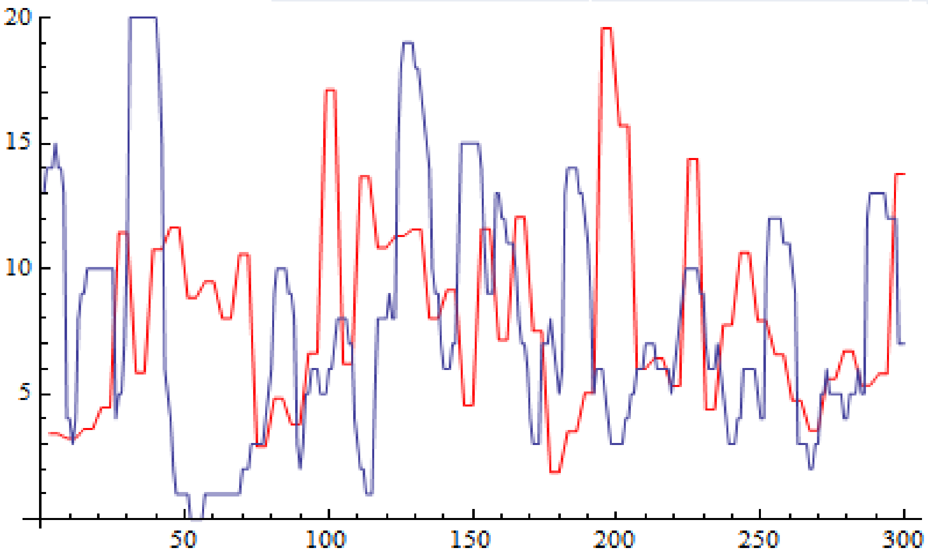


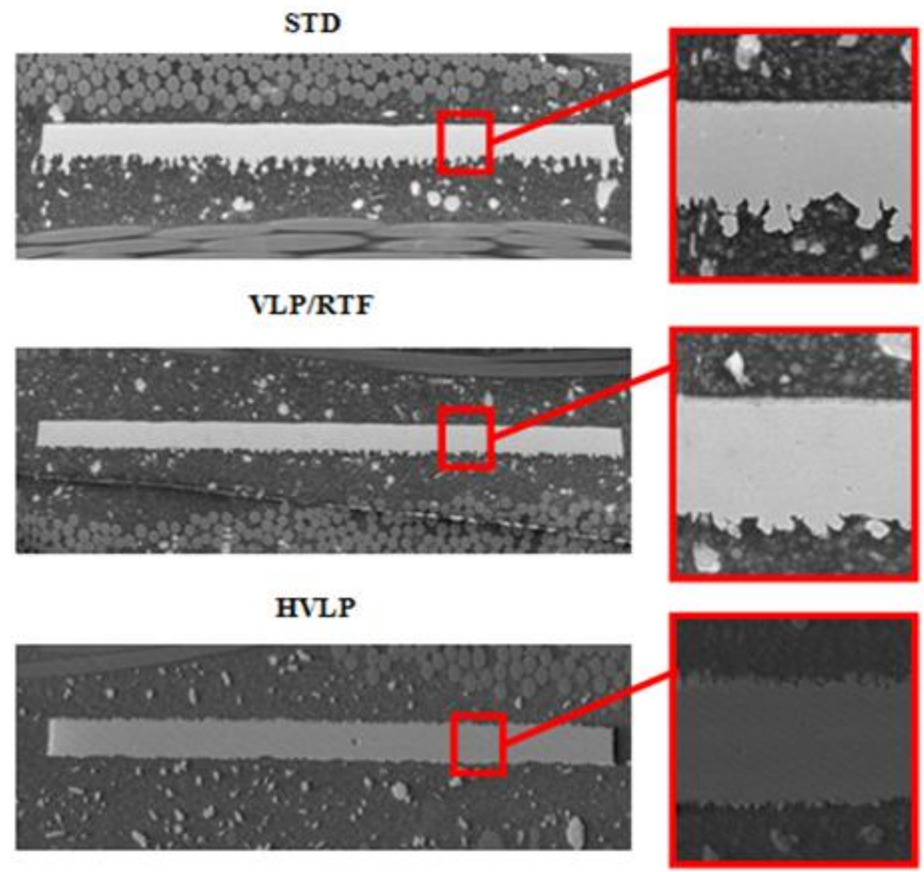




Finding A_r from PDF

Side	STD	VLP	HVLP
Oxide	Gaussian	Gaussian	Gaussian
Foil	Rayleigh	Rayleigh	Gaussian



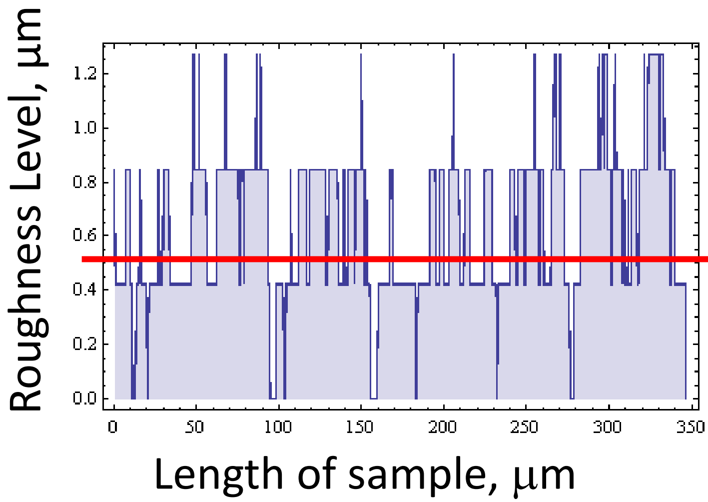


Blue line is measured from actual profile
Red line is generated from PDF

$mean[pixel] \Rightarrow A_r = 2 \cdot mean[pixel] \cdot pix$

$$mean\ is\ E[x] = \int_0^\infty x f_x(x)dx \Rightarrow A_r = 2 \cdot E[x] \cdot pixel's\ value$$

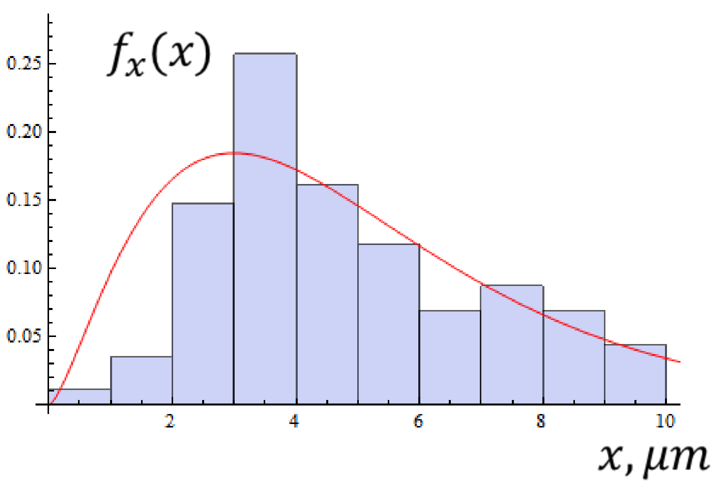
Average Peak-to-Valley Roughness Amplitude and PDF



Mean

$$A_r = 2 \cdot E[x] \cdot pixel's\ value$$

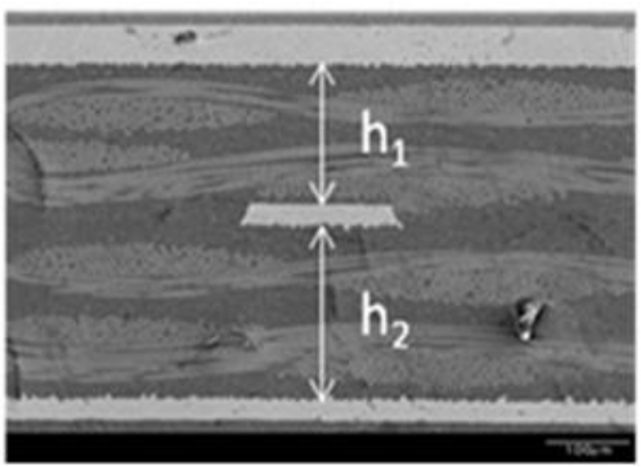
		STD	VLP	HVLP
Set 1	Oxide	0.862 µm	0.914µm	0.863 µm
	Foil	6.250 µm	2.557 µm	1.234 µm
Set 2	Oxide	1.100 µm	1.195µm	1.250µm
	Foil	6.066 µm	3.430µm	1.119µm
Set 3	Oxide	1.318 µm	1.308µm	1.778µm
	Foil	6.169 µm	2.592µm	1.217µm

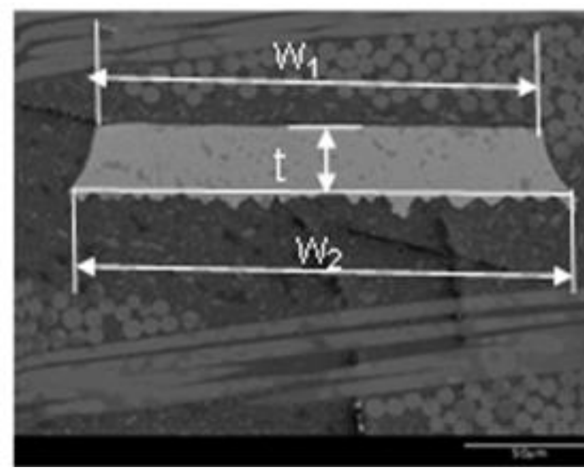


Geometry and Roughness Parameters of Some Test Samples with Different Foils

	w_1, µm	w_2,µm	H, µm	P, µm	h_1, µm	h_2, µm	A_{r1}, µm	A_{r2}, µm	Λ_1, µm	Λ_2, µm	QR_1	QR_2	QR
STD	337.9	343.2	16.44	712.8	308	286	0.85	6.2	25	14.2	0.034	0.44	0.474
VLP	364.3	368.5	16.8	769	308	286.4	0.87	2.38	24.7	13	0.035	0.18	0.215
HVLP	329.3	331.3	15.3	691.7	303	292	1.25	1.13	14.3	19.2	0.087	0.06	0.147

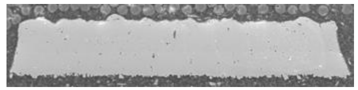
The presented samples have almost the same cross-sectional geometry, but different copper foil roughness profiles.





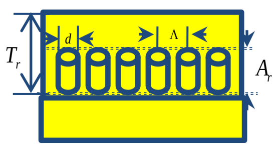
"Effective Roughness Dielectric" Extraction

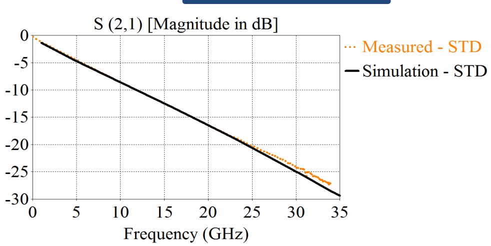
Inspection of SEM/optical image



Estimation of "roughness dielectric" parameters A_r, T_r, d, a, v_{incl}, and σ_i

Calculation of "roughness dielectric" DK and DF using MG mixing rule



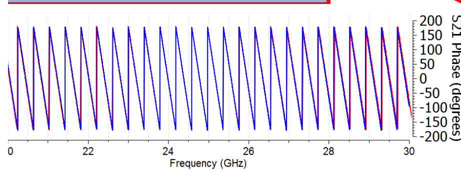


Correction

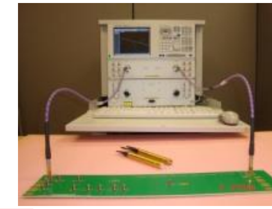
$\varepsilon_{rough} = \varepsilon'_{rough} - j\,\varepsilon''_{rough}$

Correction

Unacceptable (> 0.1 dB; ±10°)

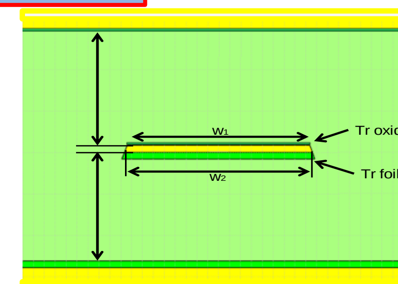


Measurements of S-parameters



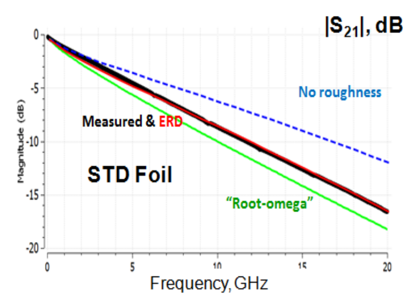
Extraction of true DK and DF of PCB dielectric (*DERM, DERMW*)

2D-FEM Model



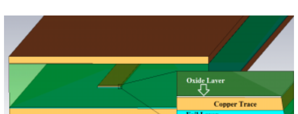
Comparison of measured and modeled S_{21} (both IL & phase)

Acceptable (< 0.1 dB)

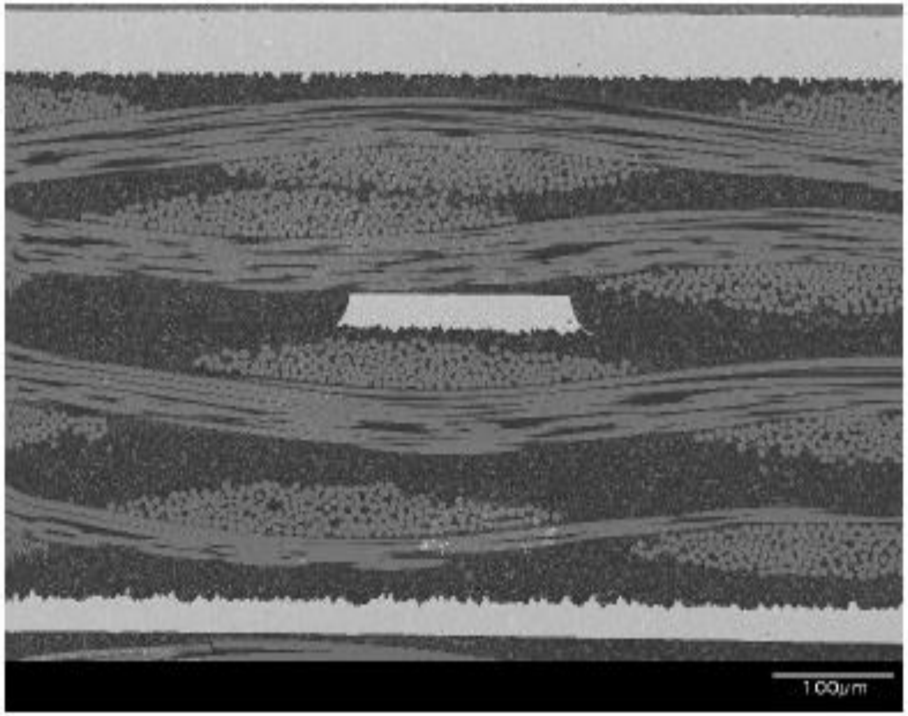


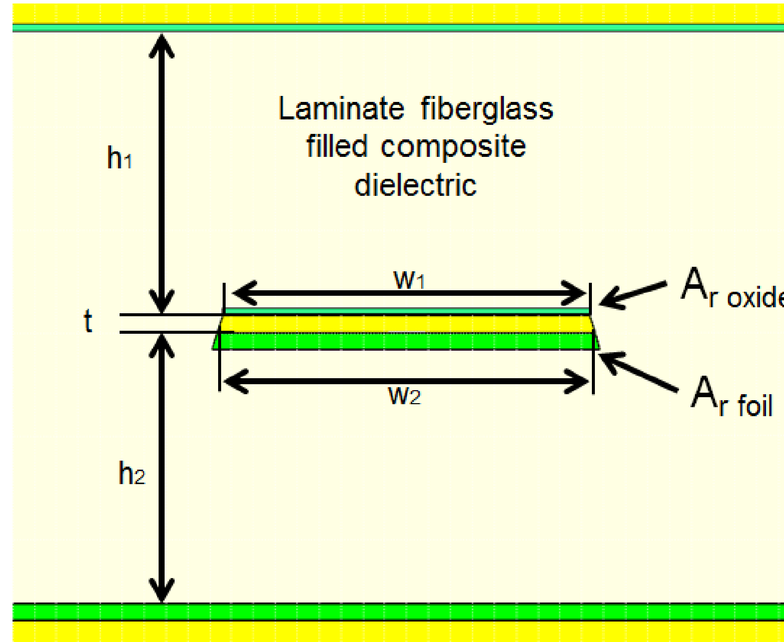
Extracted ERD $\varepsilon_{rough} = \varepsilon'_{rough} - j\,\varepsilon''_{rough}$

Validation by full-wave simulation



Numerical Model Setup Using ERD Layers





Copper foil conductors

Effective 'roughness dielectric'

Laminate dielectric

Spectral Approach to Propagation Constant

$$\alpha_T = K_1\sqrt{\omega} + K_2\omega + K_3\omega^2 + K_{r1}\sqrt{\omega} + K_{r2}\omega + K_{r3}\omega^2$$

Smooth conductor loss | **Dielectric loss** | **Loss due to conductor roughness**

Curve-fit data behaves as $\sqrt{\omega}$, ω & ω^2

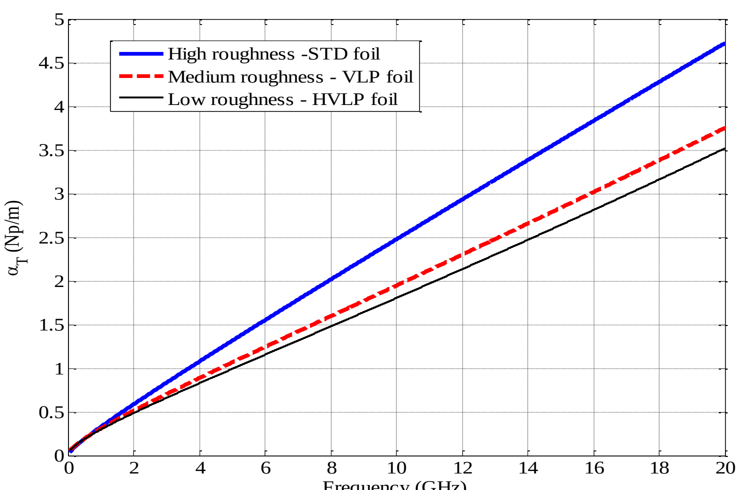
$$\alpha_T = \alpha_c + \alpha_d$$

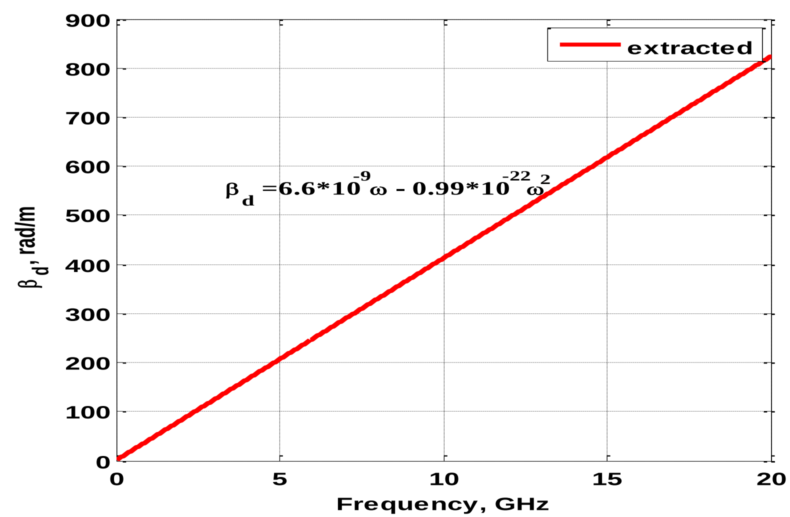
$$\beta_T = B_1\sqrt{\omega} + B_2\omega + B_3\omega^2 + B_{r1}\sqrt{\omega} + B_{r2}\omega + B_{r3}\omega^2$$

Due to skin depth in conductor | **Due to propagation in the dielectric** | **Due to conductor roughness**

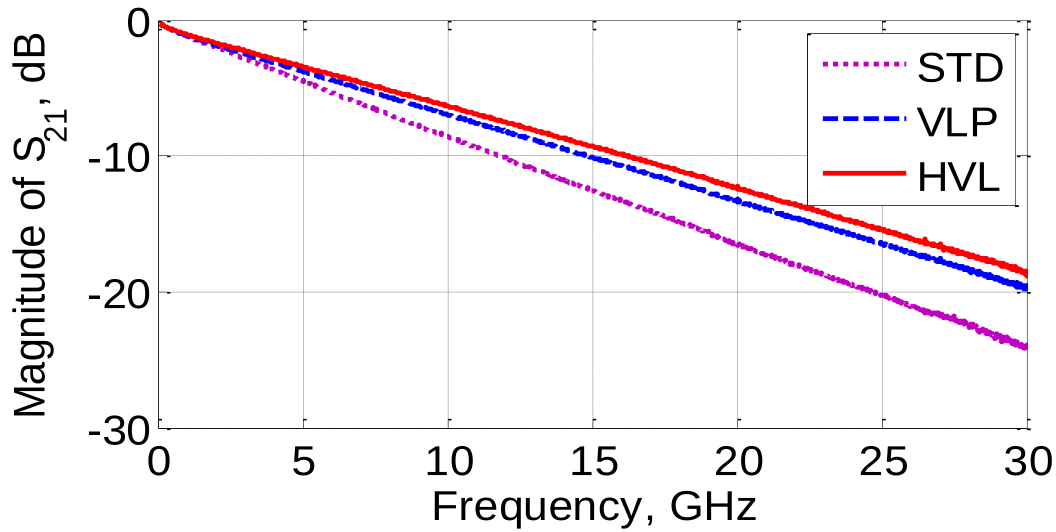
Curve-fit data behaves as $\sqrt{\omega}$, ω & ω^2

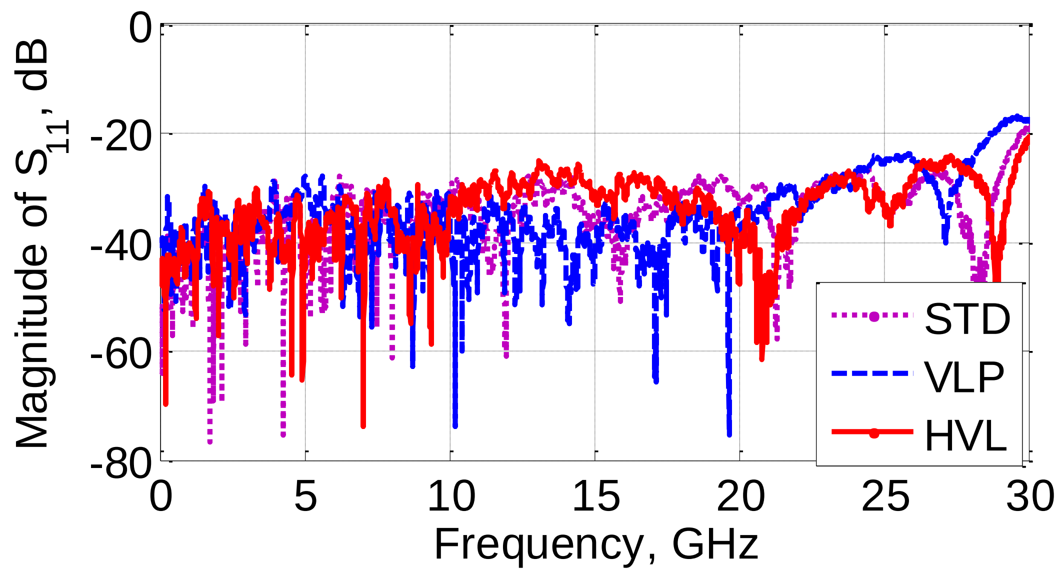
$$\beta_T = \beta_c + \beta_d$$





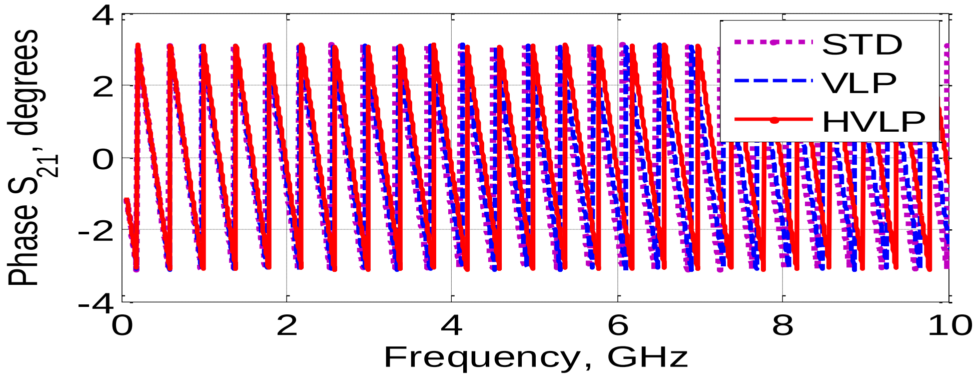
Measured Magnitudes of S_{11} and S_{21}

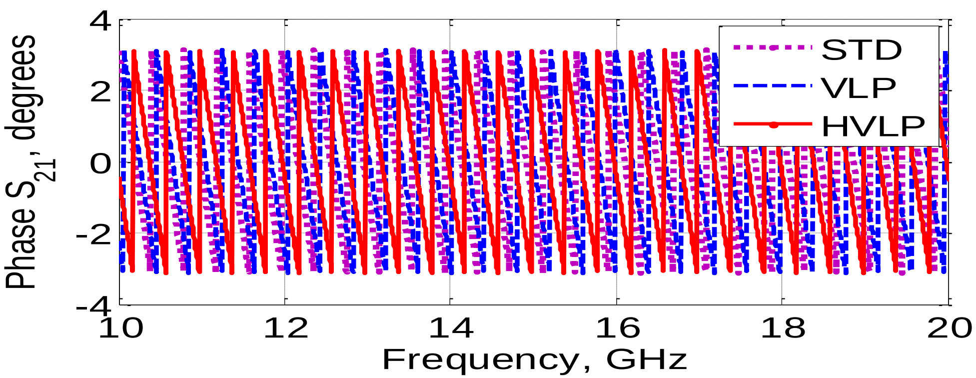


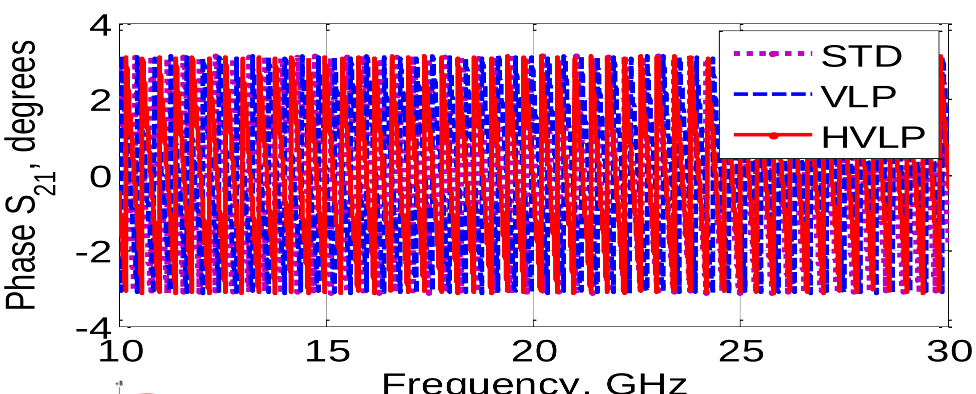


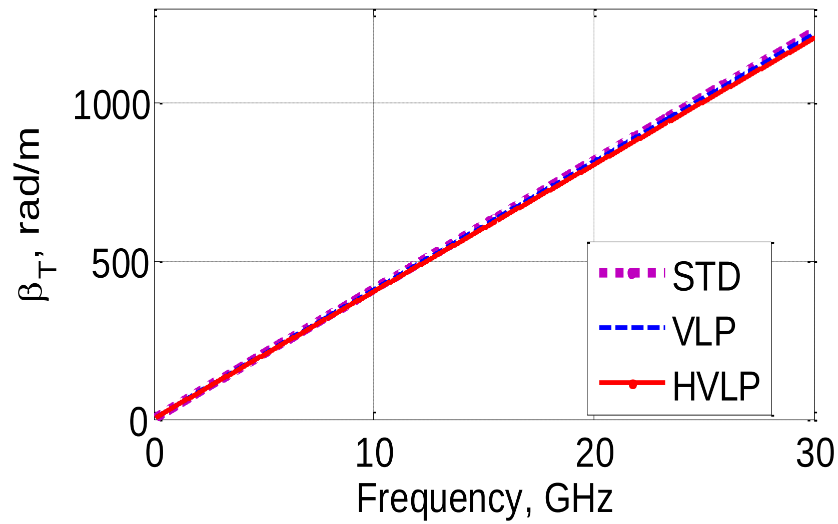
- Length of all the test striplines =15,410 mils.
- Striplines are 13 mils wide.
- Laminate dielectric and cross-sectional geometry are the same for all the boards.

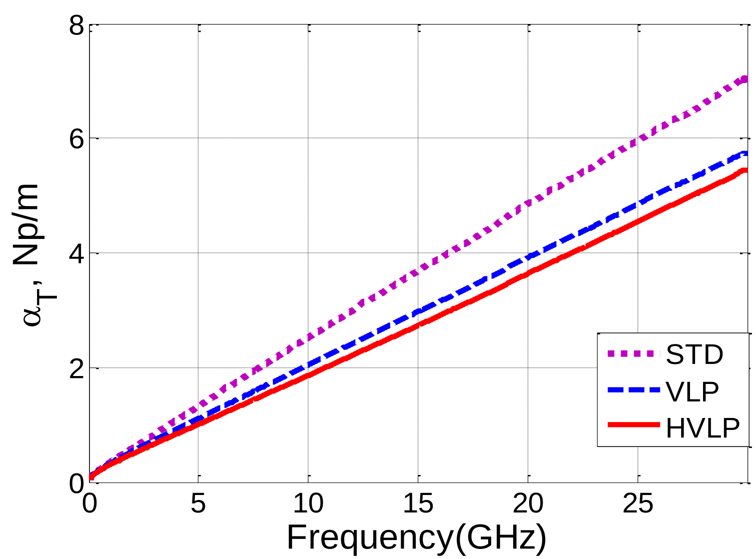
Measured Phase of S_{21} and Propagation Constant



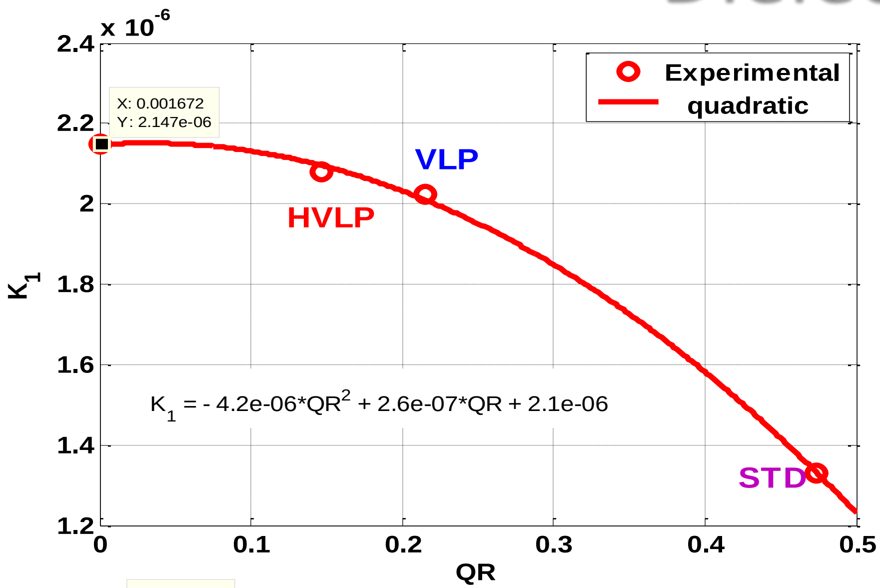


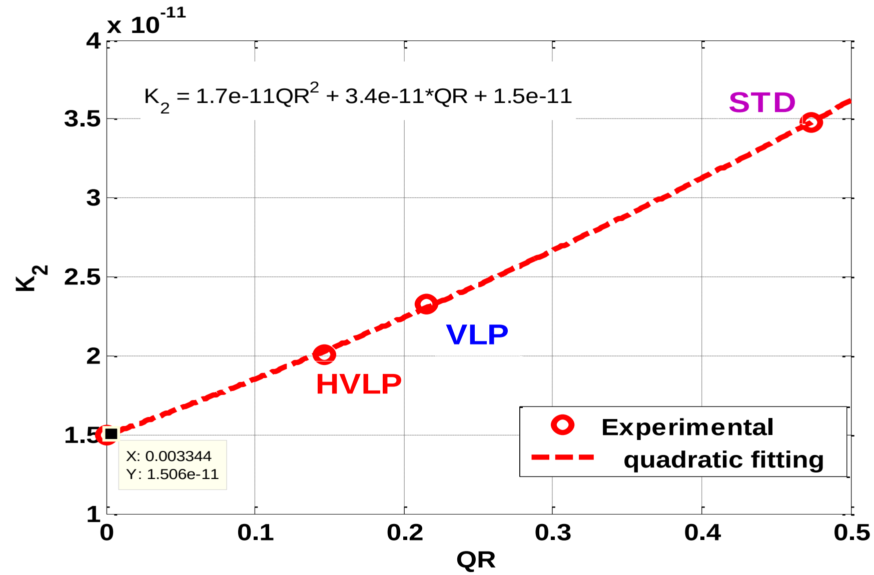


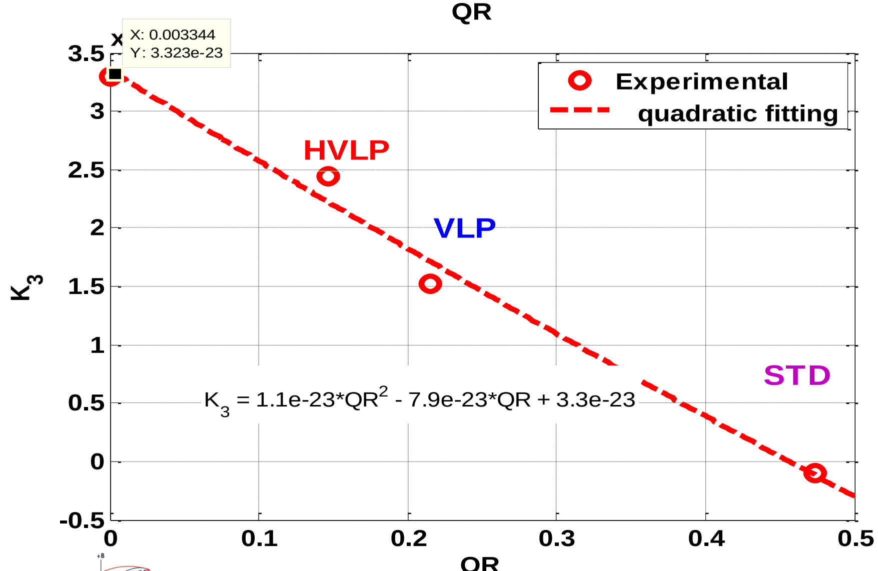




Extrapolation to Zero Roughness in α to Refine Dielectric Loss



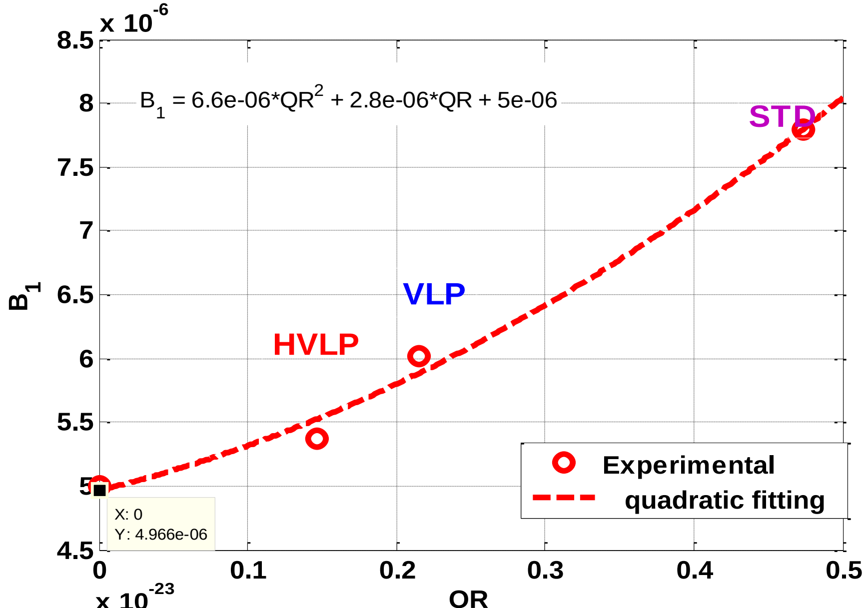


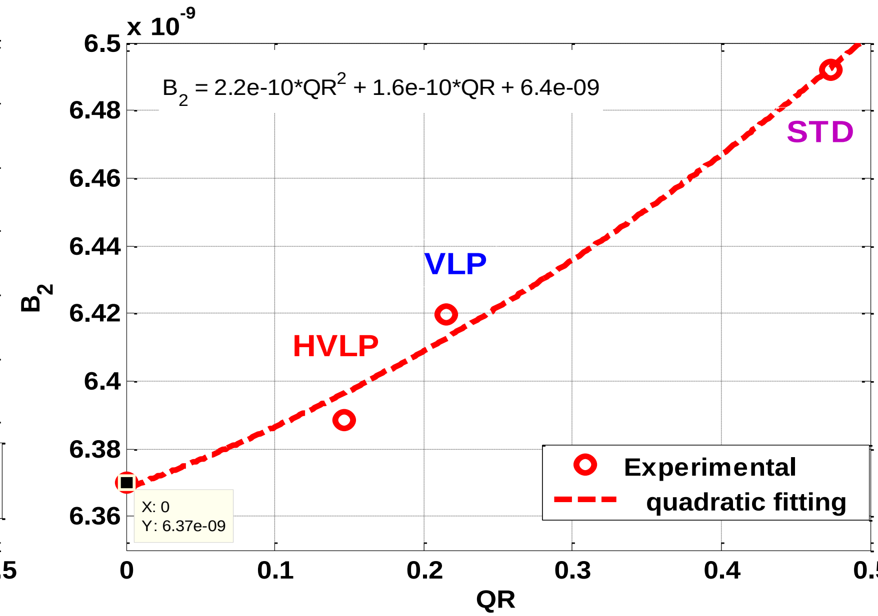


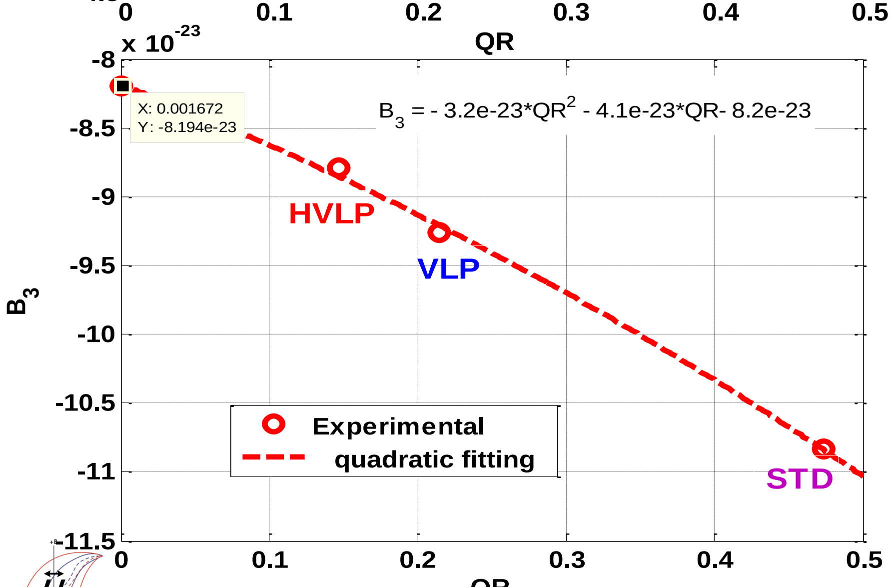
$$\alpha_{c0} = 2.15\times10^{-6}\sqrt{\omega}$$

$$\alpha_d = 1.51\times10^{-11}\omega + 3.3\times10^{-23}\omega^2$$

Extrapolation to Zero Roughness in β to Refine Dielectric-Related Phase Constant

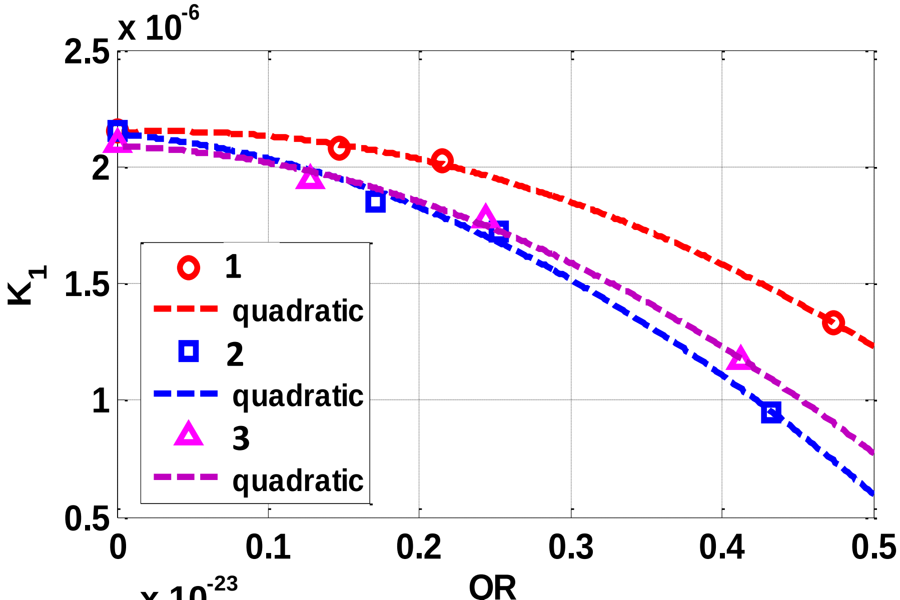


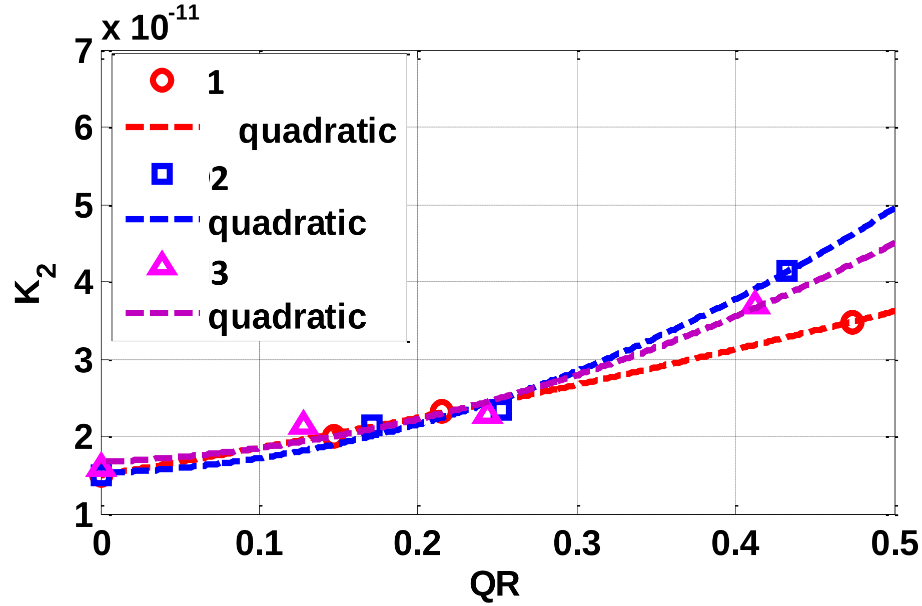


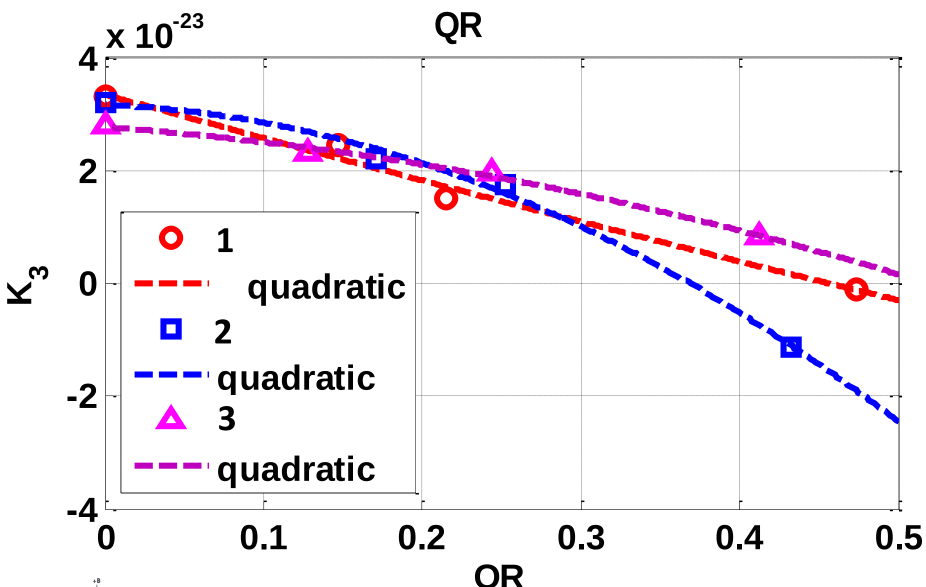


$$\beta_c = 5.0 \times 10^{-6} \sqrt{\omega}$$
$$\beta_d = 6.37 \times 10^{-9} \omega - 0.82 \times 10^{-23} \omega^2$$

Additional Procedure to Refine Dielectric Loss (with Two other Sets of Test Vehicles with Different Types of Foil)





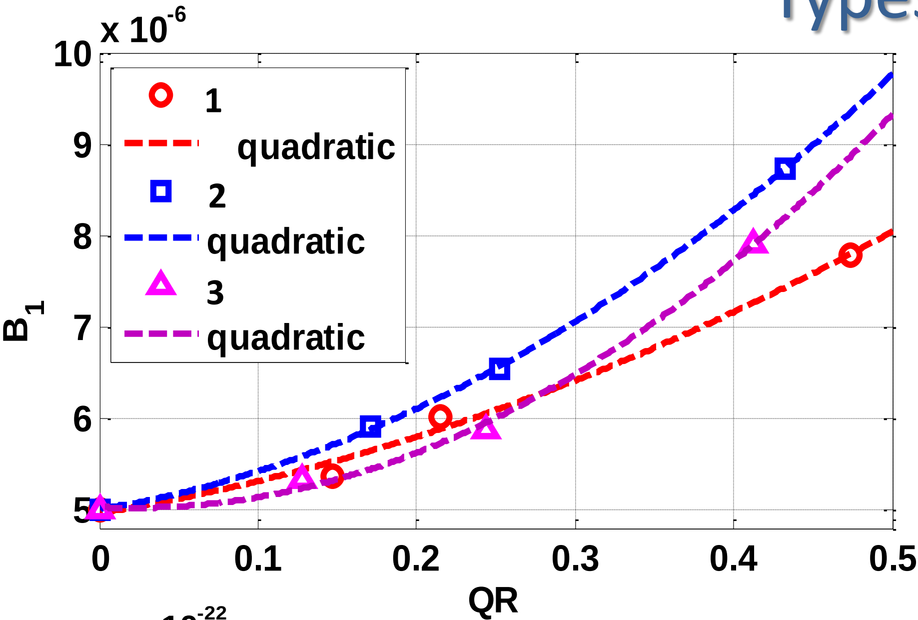


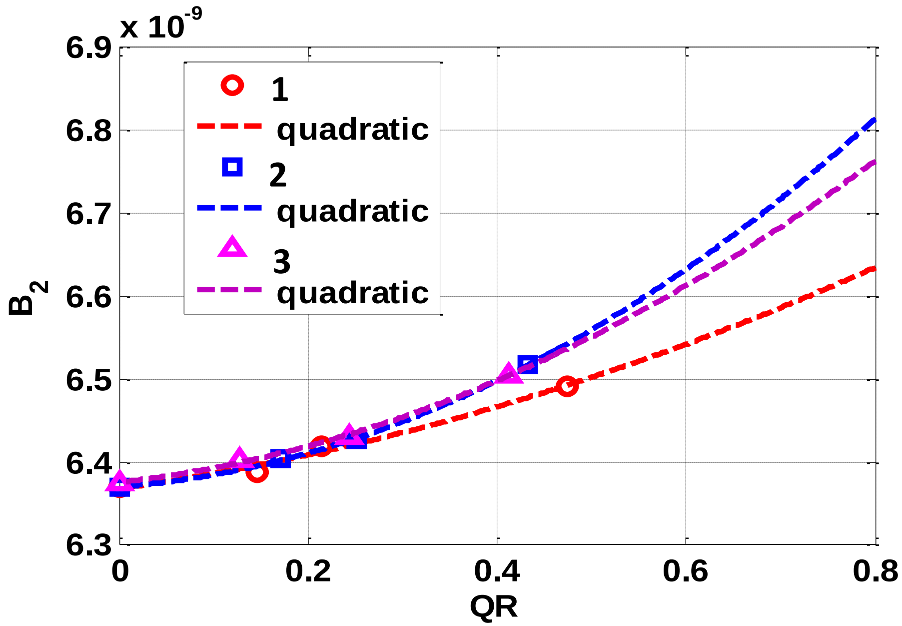
This increases accuracy of extraction.

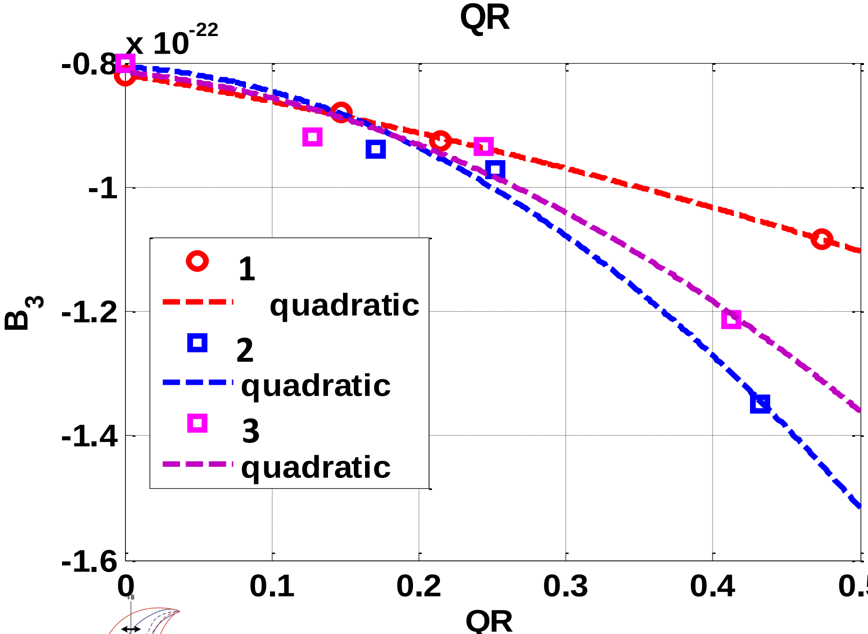
$$\alpha_{c0} = 2.15\times10^{-6}\sqrt{\omega}$$

$$\alpha_d = 1.5\times10^{-11}\omega + 3.0\times10^{-23}\omega^2$$

Additional Procedure to Refine Phase Constant (with Two other Types of Foil)







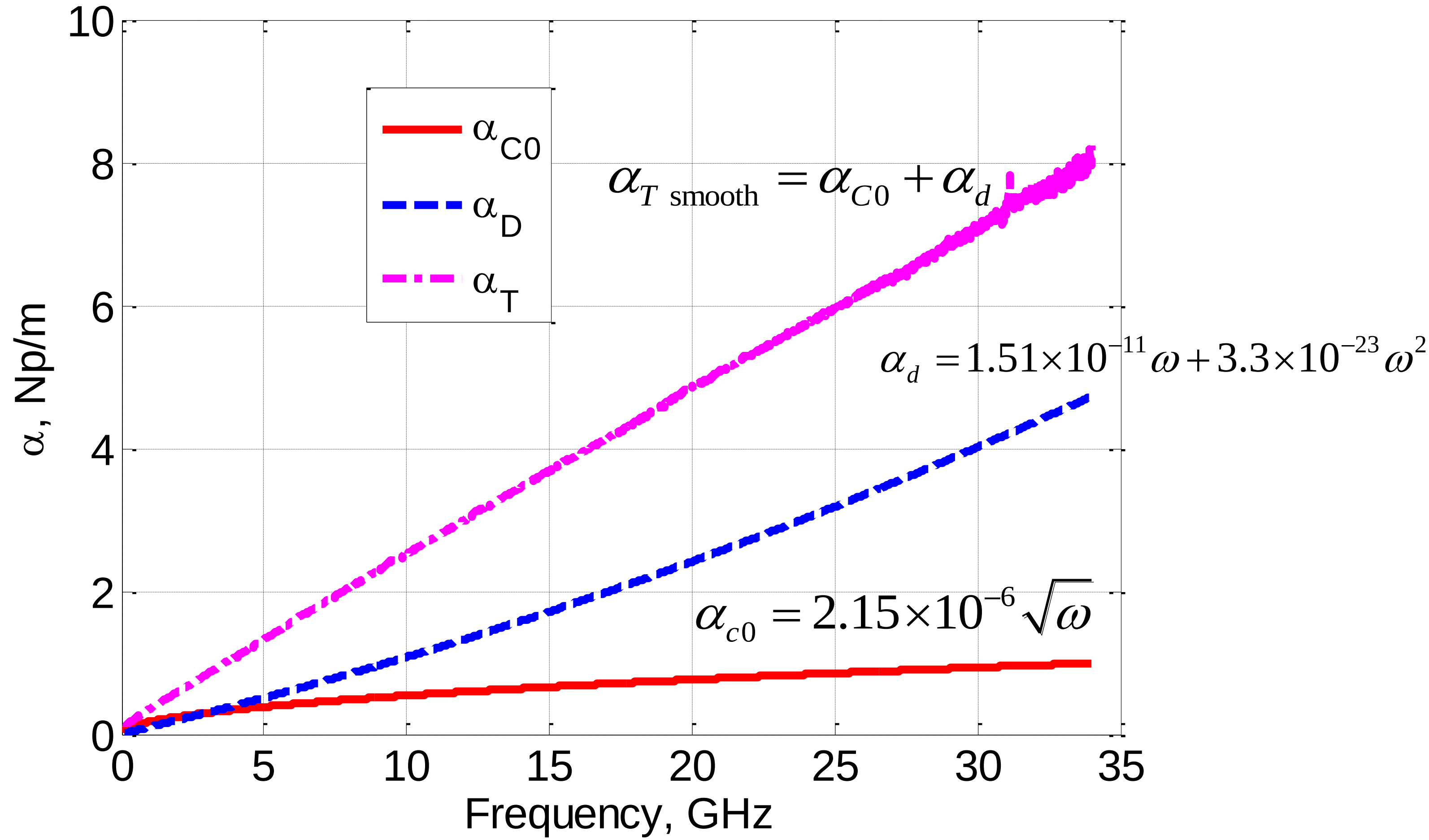
This increases accuracy of extraction.

$$\beta_c = 5.0 \times 10^{-6} \sqrt{\omega}$$

$$\beta_d = 6.38 \times 10^{-9} \omega - 0.8 \times 10^{-23} \omega^2$$

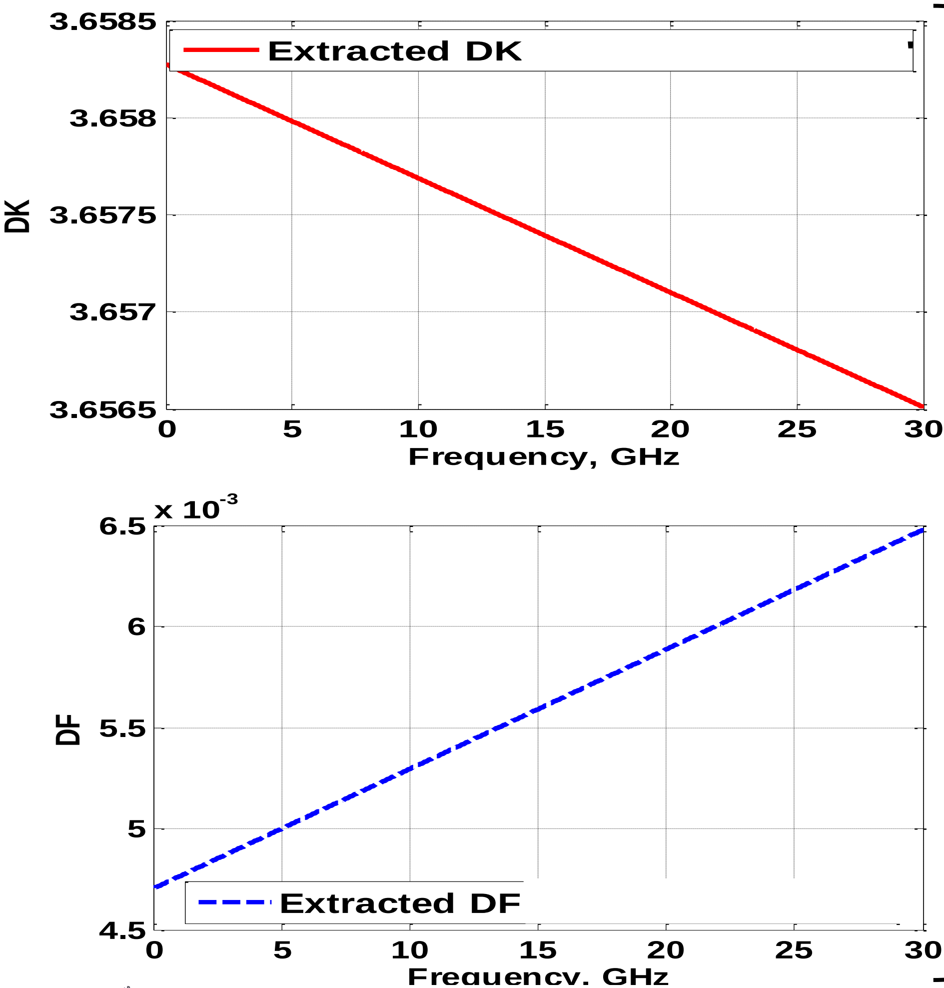
Extracted Loss in a Smooth Conductor

(Roughness Parts are Removed)

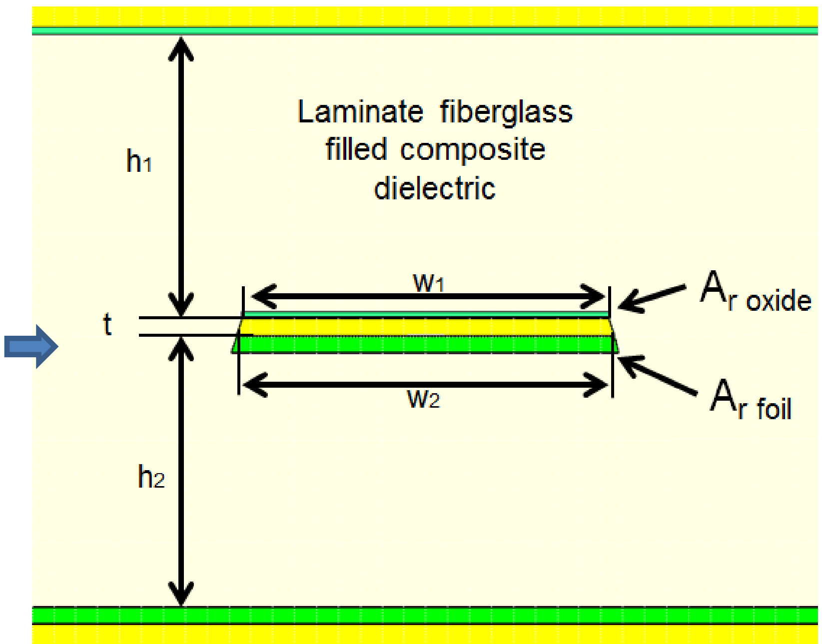


Extracted Dielectric Properties of PCB Laminate Substrate

The refined dielectric data (DK and DF) for all the test vehicles is used in numerical electromagnetic modeling (2D-FEM)

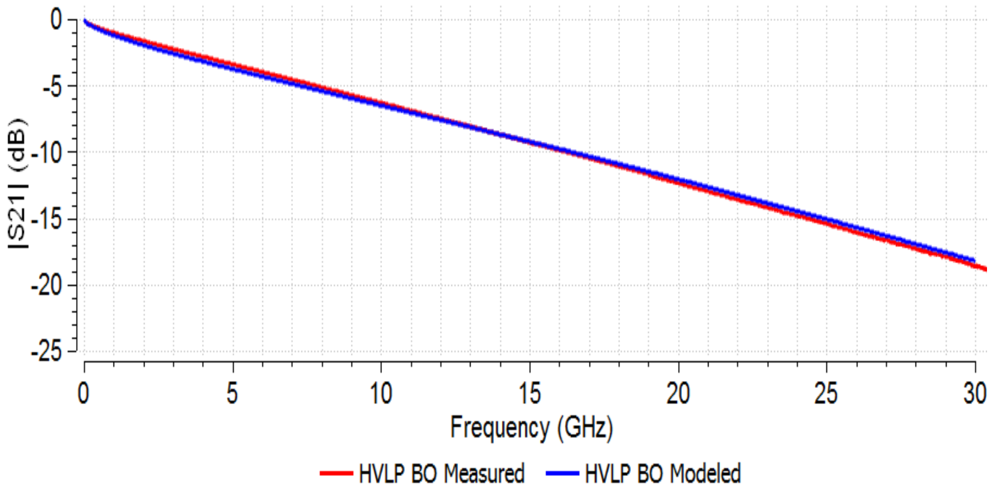


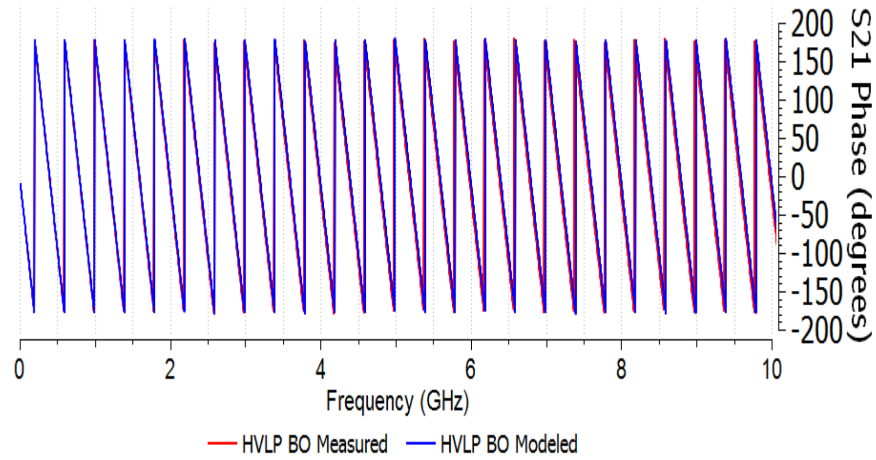
Numerical model 1: Ansoft Q2D (2DFEM)

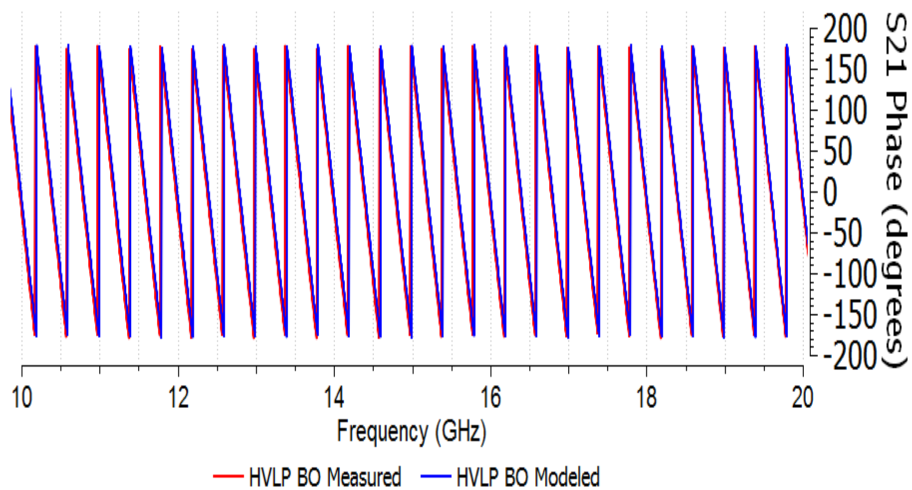


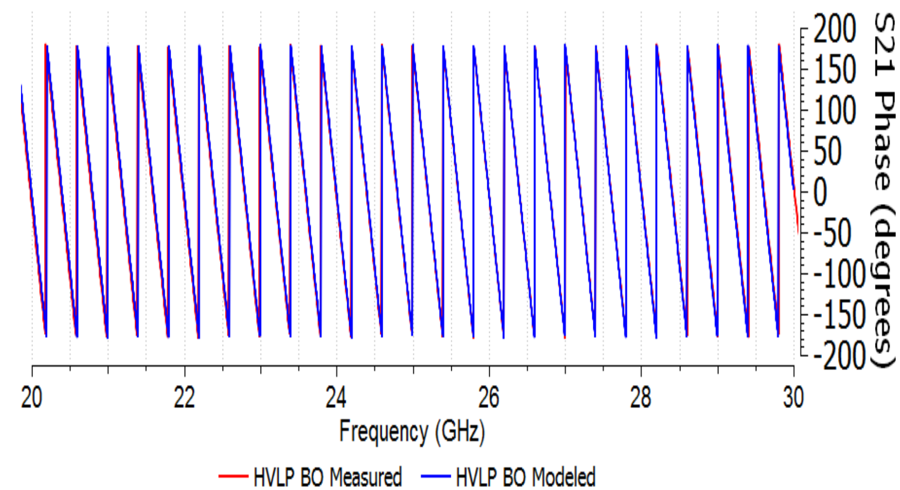
This model is used to extract parameters of Effective Roughness Dielectric (ERD): bright-green layers

Modeled & Measured S_{21} for Stripline with HVLP Foil (Q2D)

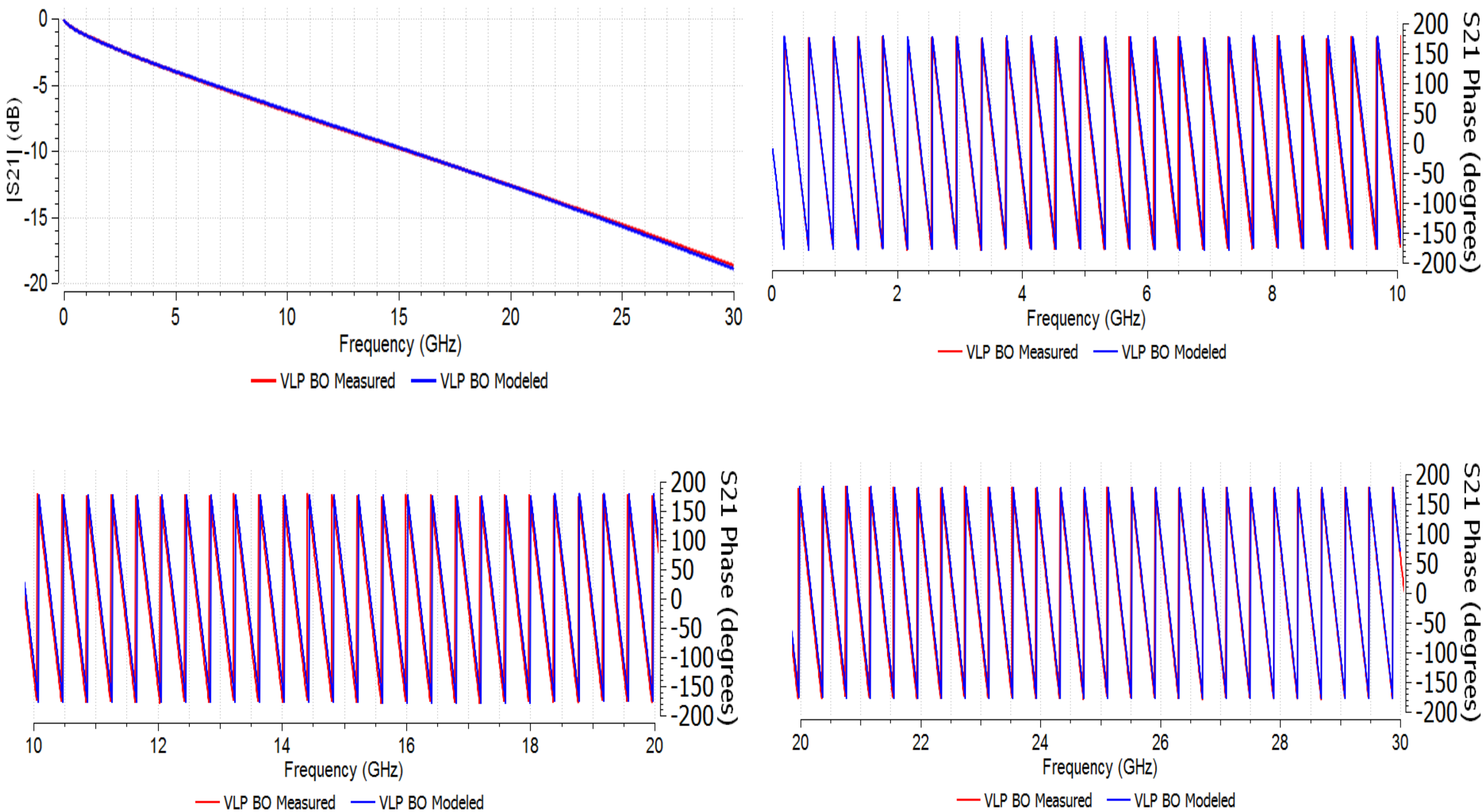




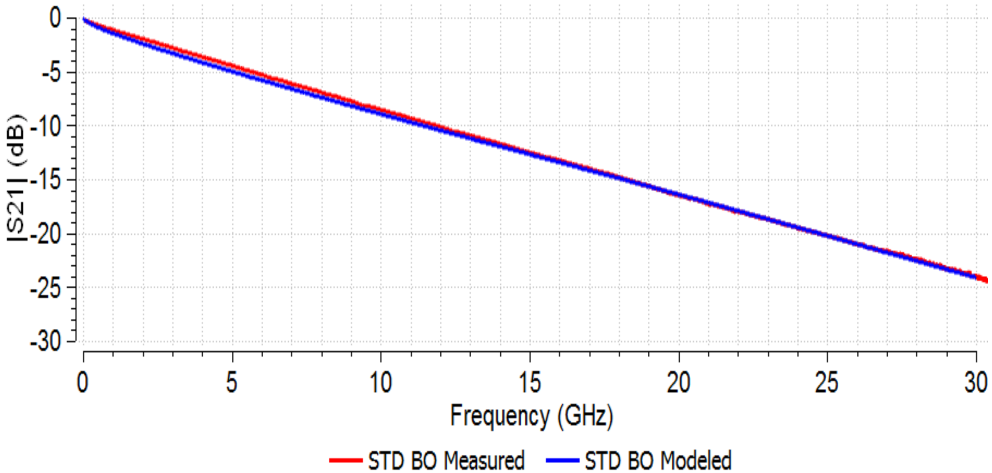


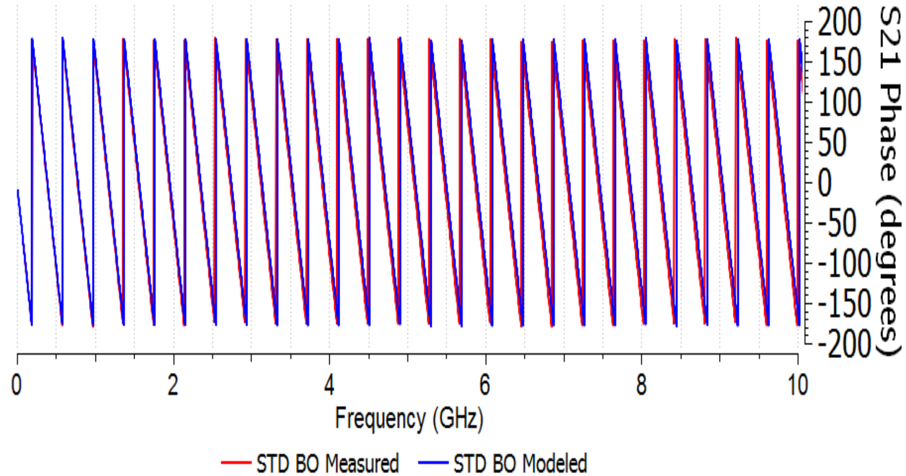


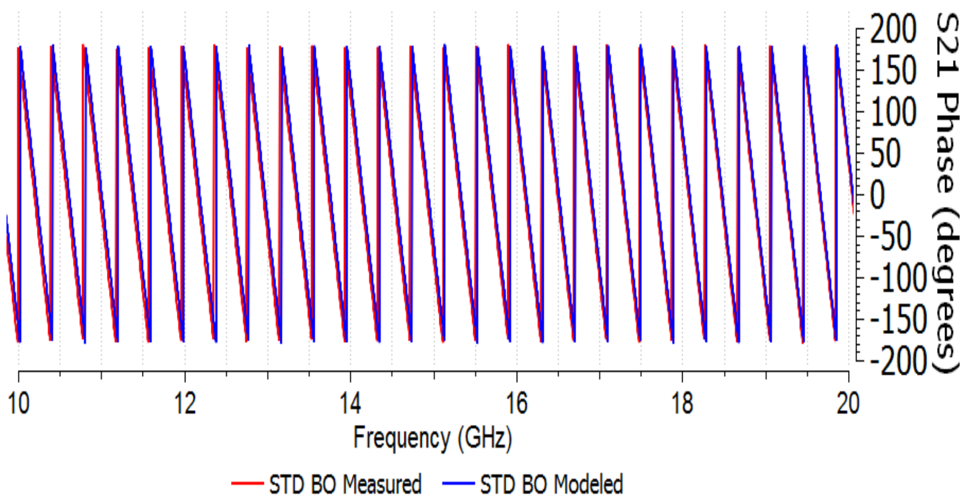
Modeled & Measured S_{21} for Stripline with VLP Foil (Q2D)

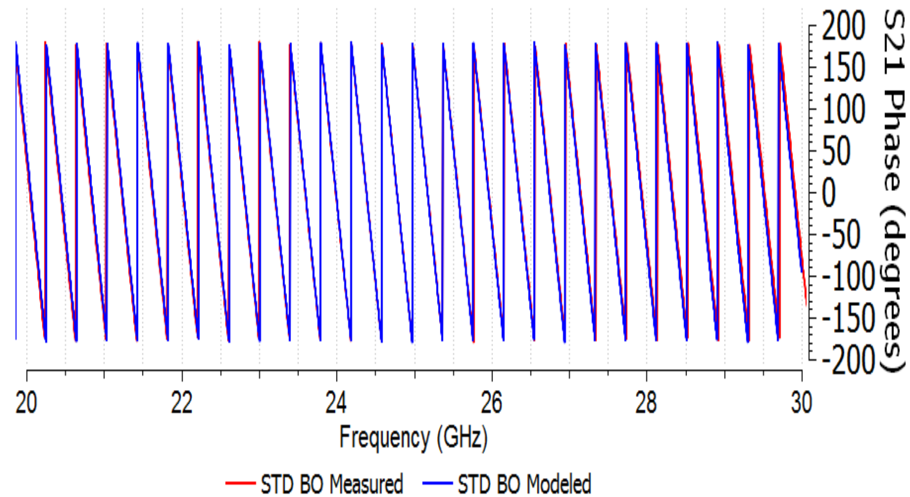


Modeled & Measured S_{21} for Stripline with STD Foil (Q2D)









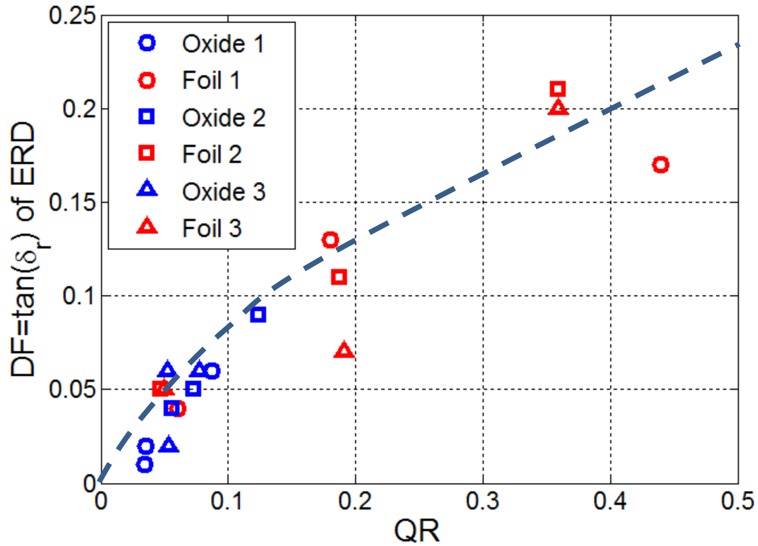
Extracted Properties of Effective Roughness Dielectric

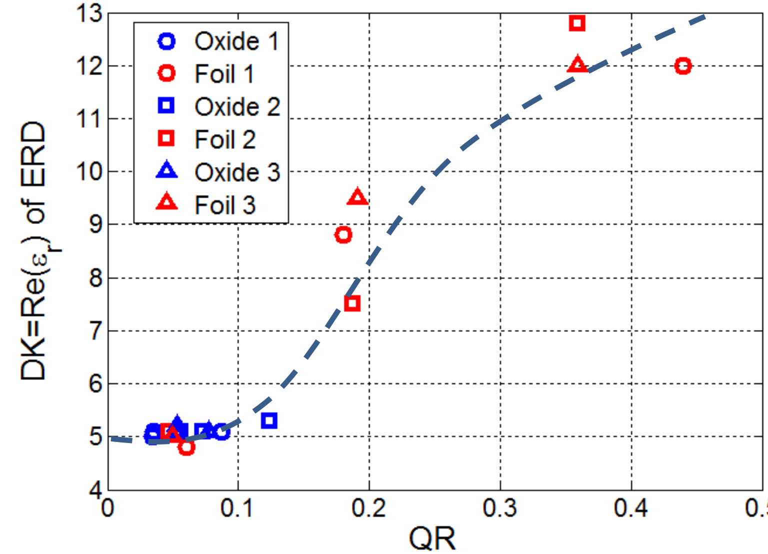
The refined dielectric data (DK and DF) for all the test vehicles is used in numerical electromagnetic modeling (2D-FEM)

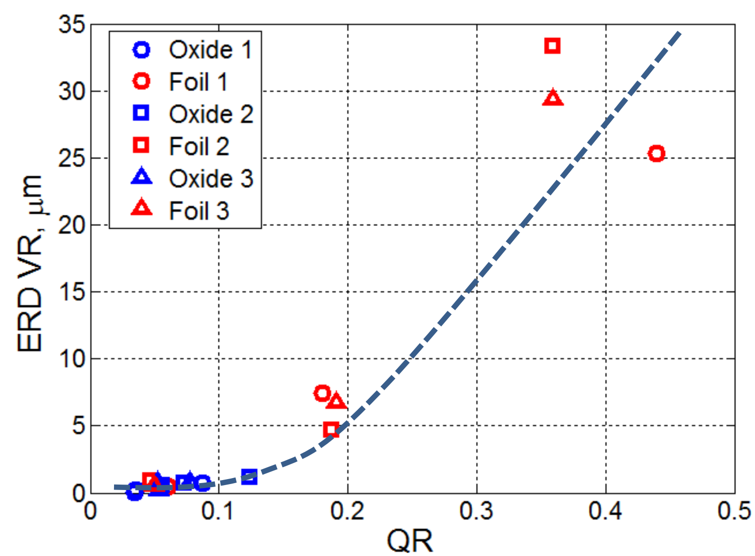
Set 1

Foil Type	T_{r1} (ox), μm	T_{r2} (foil), μm	$\tan\delta_r$ (ox)	$\tan\delta_r$ (foil)	ε_r (ox)	ε_r (foil)	QR (ox)	QR (foil)	VR (ox), μm	VR (foil), μm
STD	1.7	12.4	0.01	0.17	5.0	12.0	0.034	0.44	0.085	25.30
VLP	1.74	4.76	0.02	0.13	5.1	9.0	0.035	0.18	0.178	7.42
HVLP	2.50	2.26	0.06	0.04	5.1	4.8	0.087	0.06	0.765	0.433

Effective Roughness Dielectric Parameters as a Function of Roughness Factor

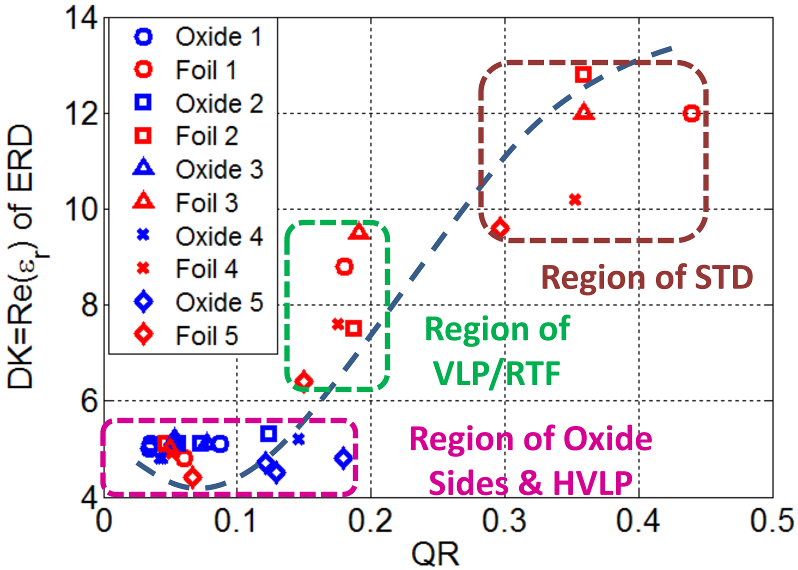


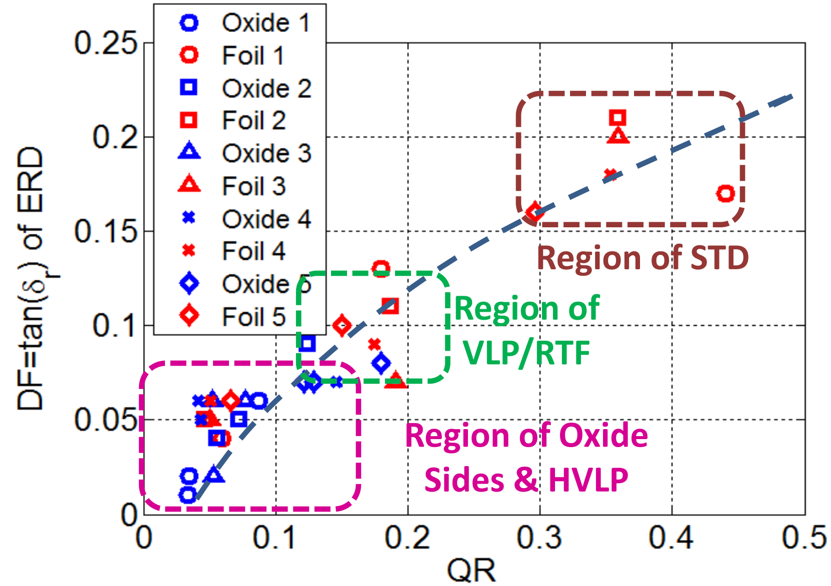


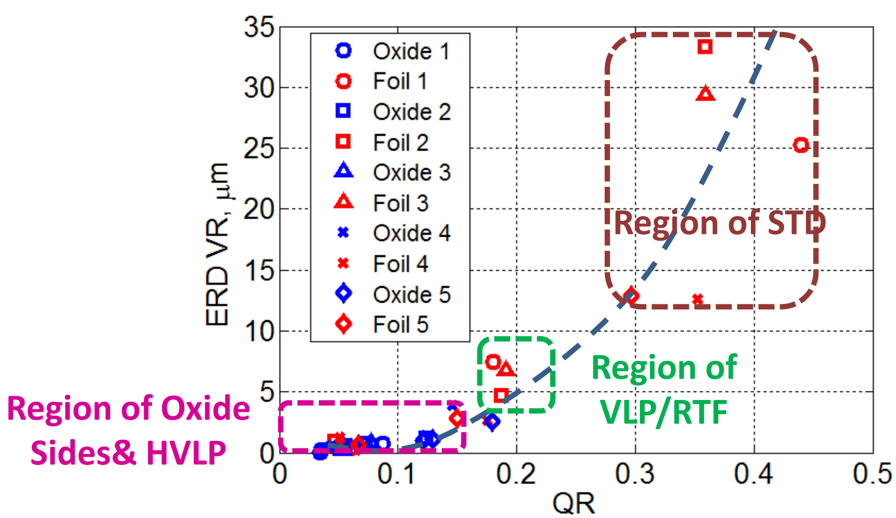


$$VR = \varepsilon_r'' \times T_r = \varepsilon_r' \times \tan\delta_r \times T_r$$

Effective Roughness Dielectric Parameters as a Function of Roughness Factor







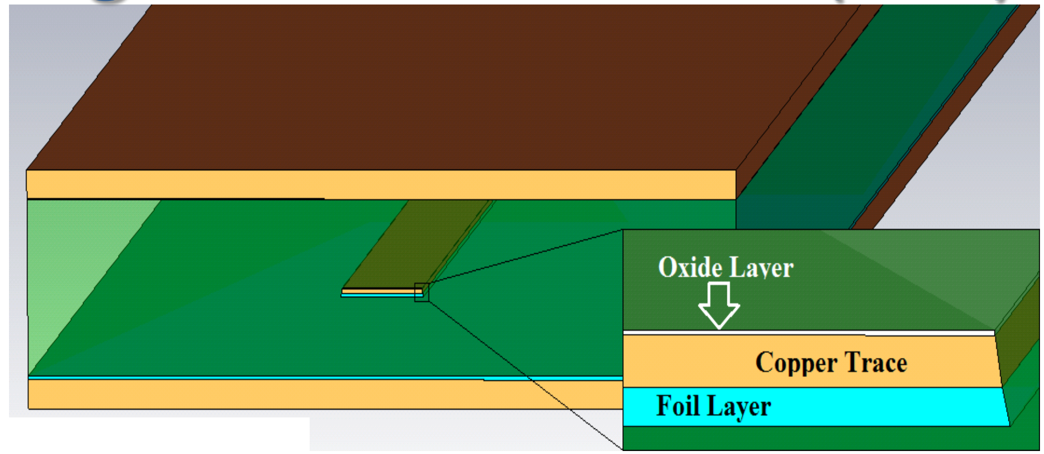
Sets 1,2,3 – **13mil** trace width

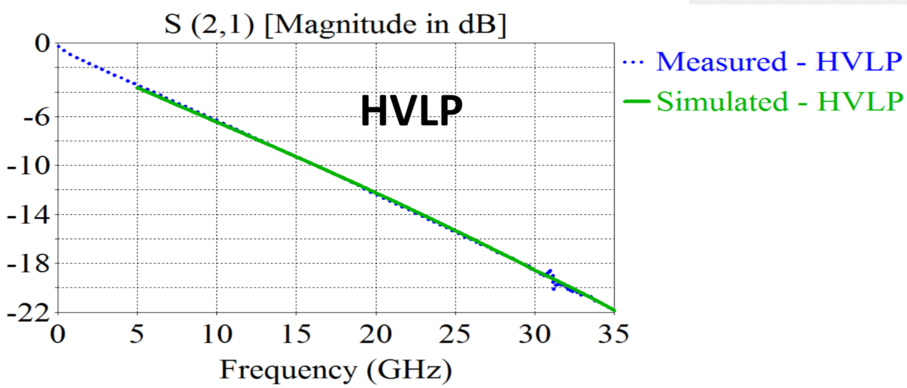
Sets 4, 5 – **7 mil** trace width

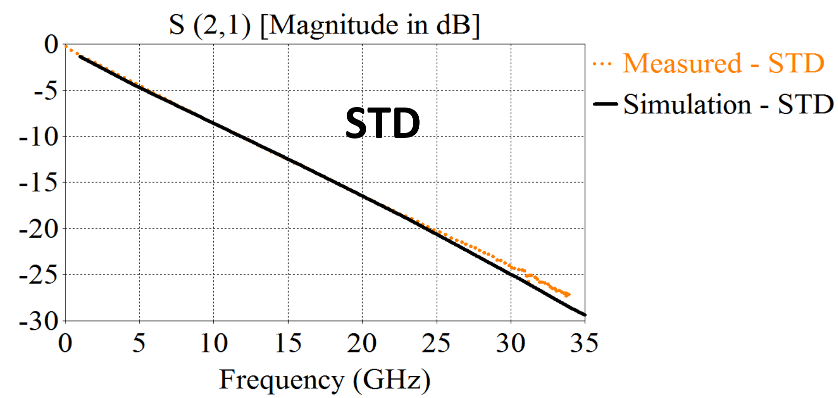
$$VR = \varepsilon_r'' \times T_r = \varepsilon_r' \times \tan\delta_r \times T_r$$

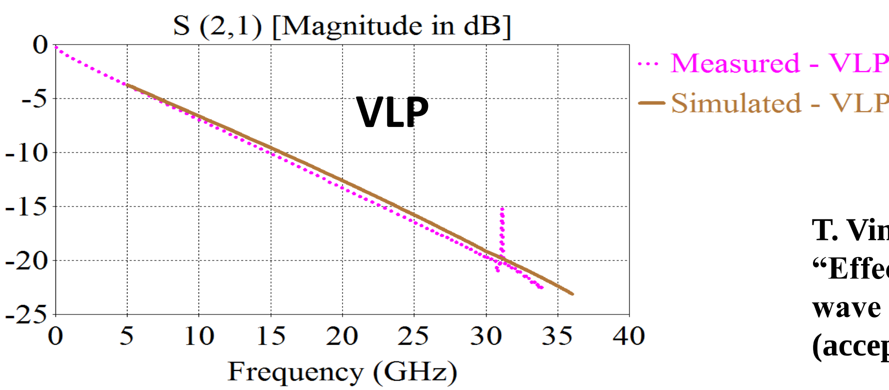
Validation Using Full-wave Model (CST)

Numerical model 2: CST Studio Suite 3D (Full-wave FD MoM) – this model is used for validation of the extracted ERD data



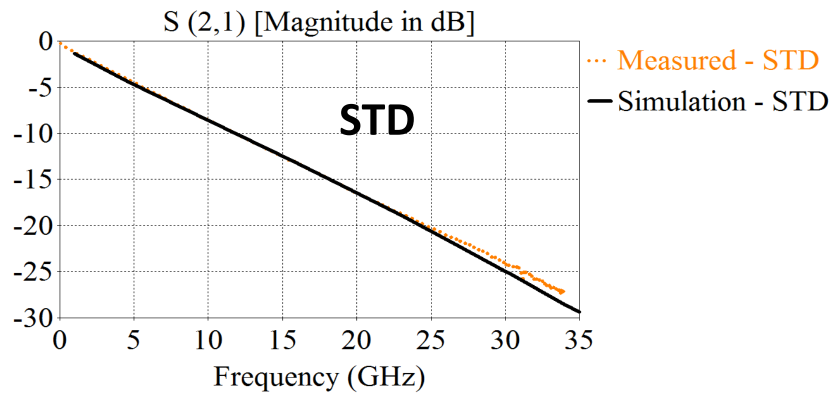


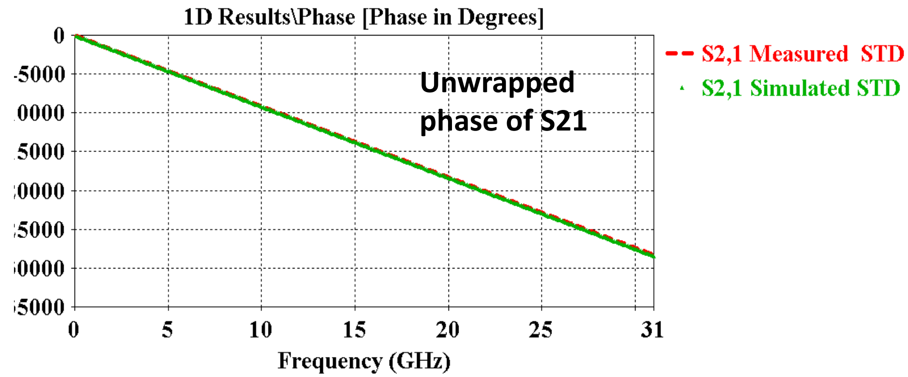


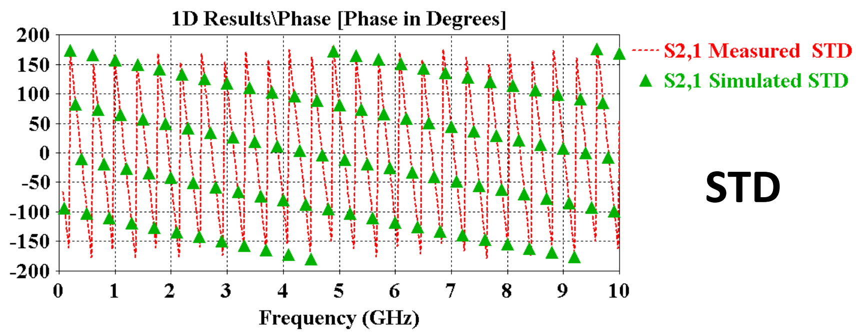


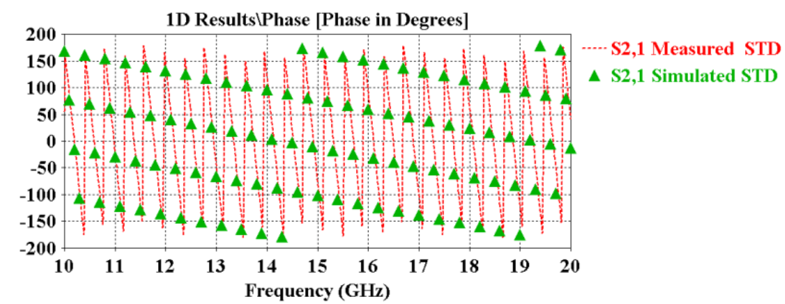
T. Vincent, M. Koledintseva, A. Ciccimancini, and S. Hinaga, "Effective roughness dielectric in a PCB: measurement and full-wave simulation verification", IEEE Symp. EMC, Aug. 2014 (accepted)

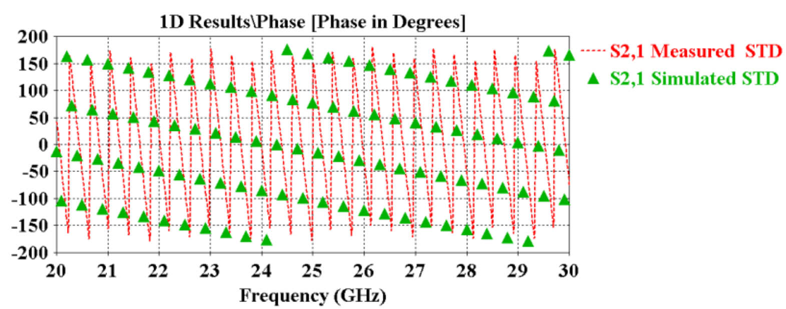
S_{21} CST Modeled vs. Measured)









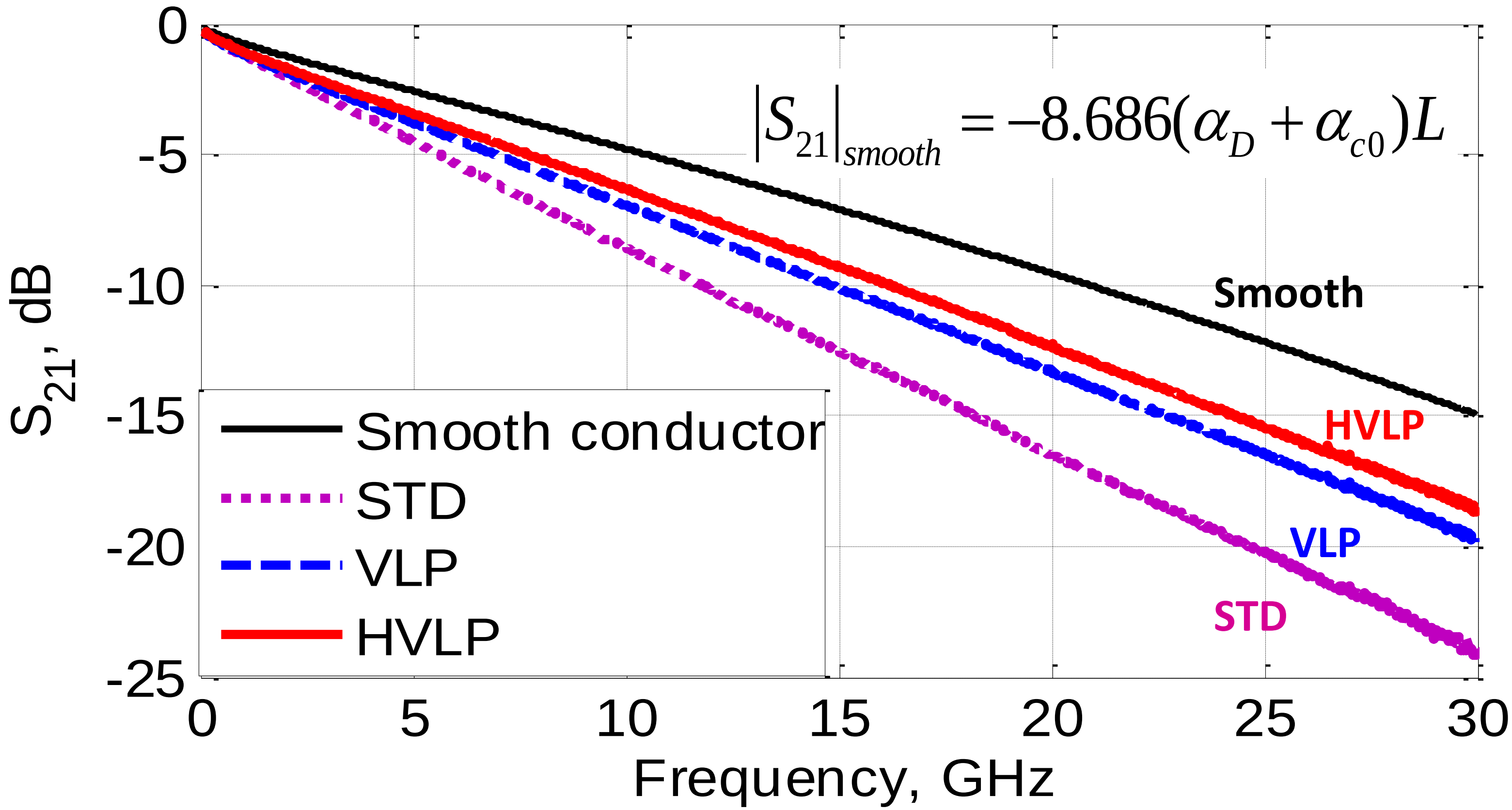


T. Vincent, M. Koledintseva, A. Ciccimancini, and S. Hinaga, "Effective roughness dielectric in a PCB: measurement and full-wave simulation verification", IEEE Symp. EMC, Aug. 2014 (accepted)

Modeled & Measured Magnitude of S_{21} for Striplines with Different Foils

Slope of S21 as a function of frequency increases with the increase of surface roughness

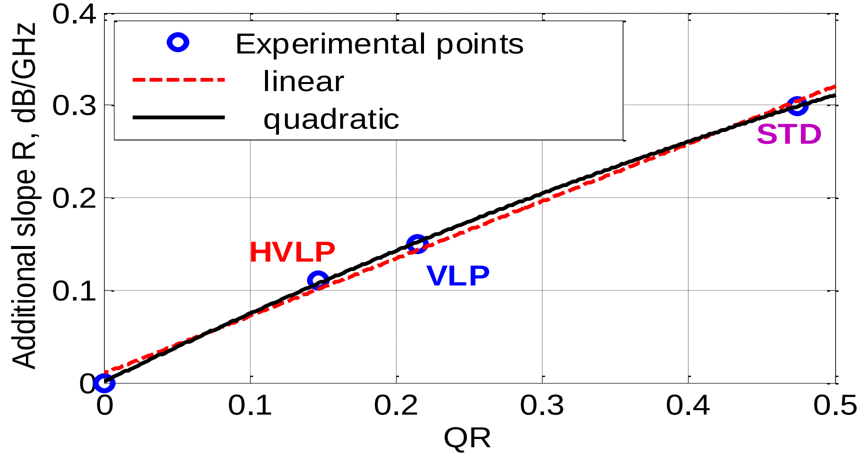
$$\alpha_c = \alpha_{c0}(1+r) \qquad r = \frac{\Delta\alpha_r}{\alpha_{c0}} \qquad \Delta\alpha_r = \alpha_c - \alpha_{c0}$$

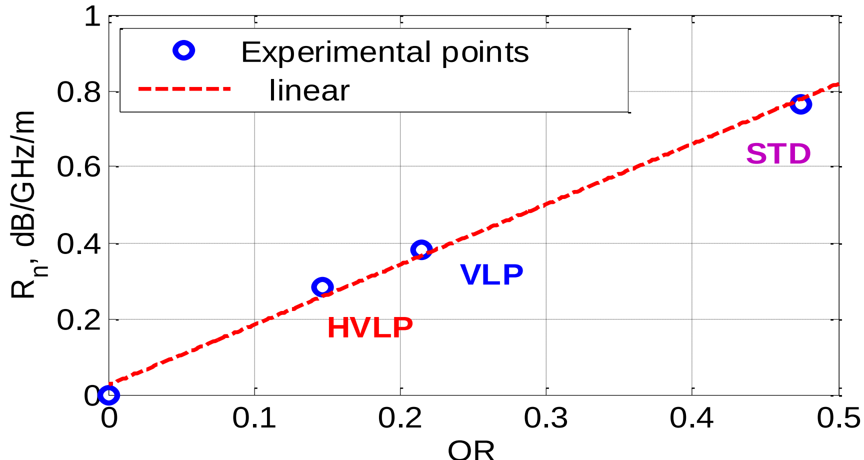


Additional Slope in S_{21} as a Function of Roughness Factor

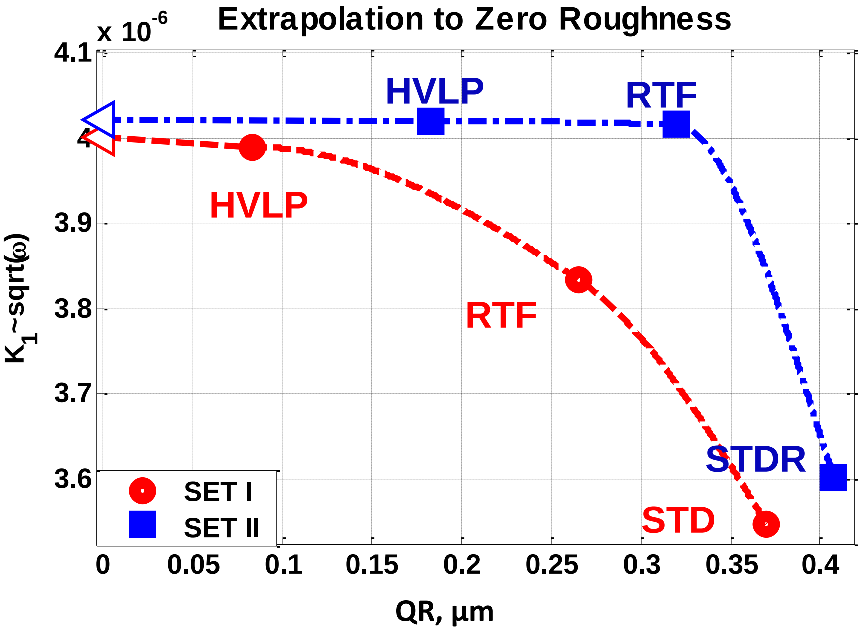
$$R=(\Delta S_{smooth}-\Delta S_{rough})/\Delta f \quad [\text{dB/GHz}]$$

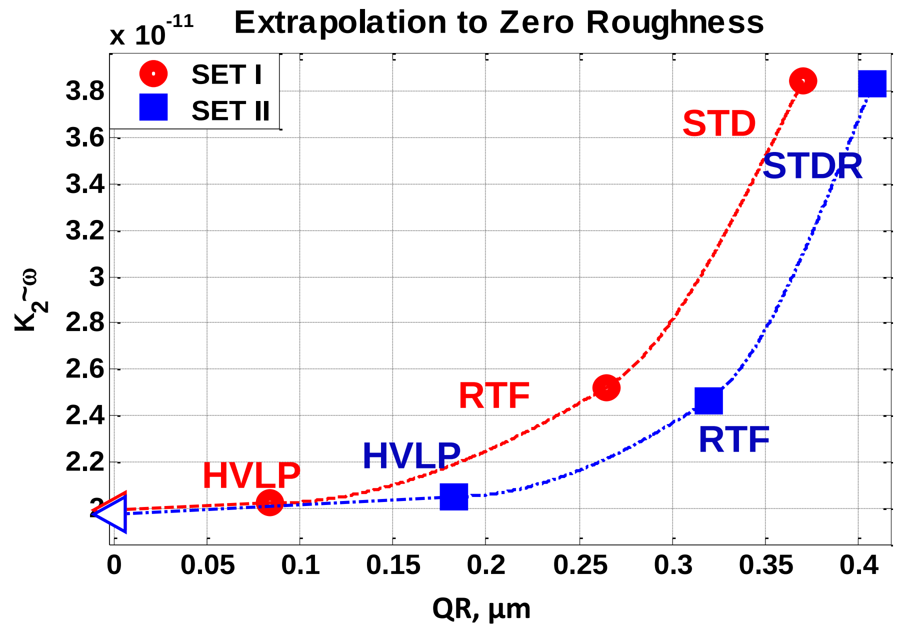
$$R_n=(\Delta S_{smooth}-\Delta S_{rough})/\Delta f/L \quad [\text{dB/GHz/m}]$$

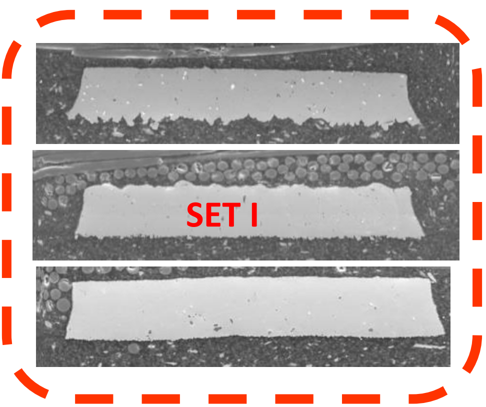


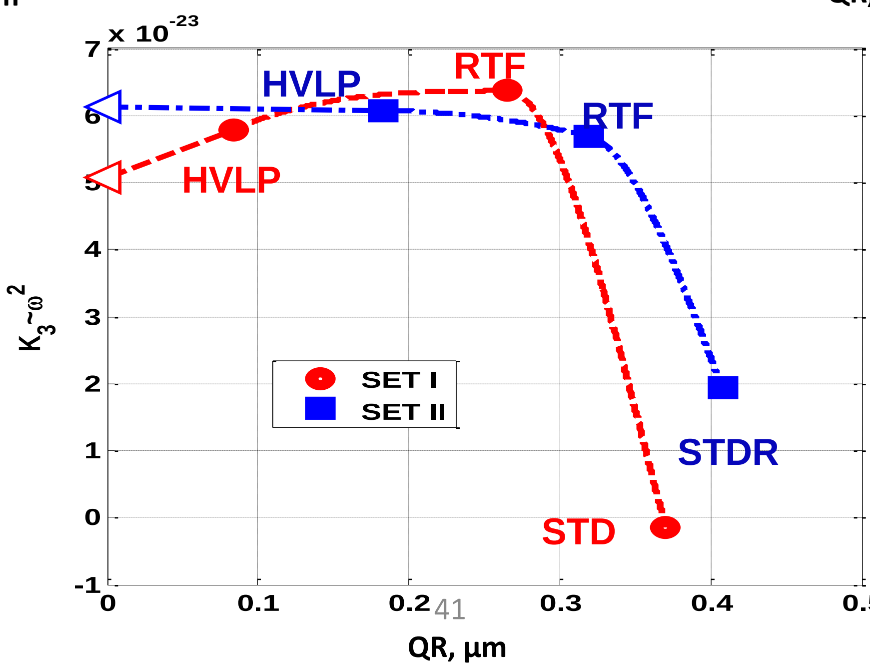


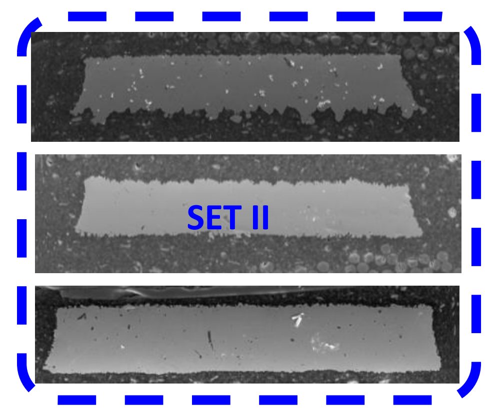
Extrapolation to Zero Roughness in α (7-mil Lines)



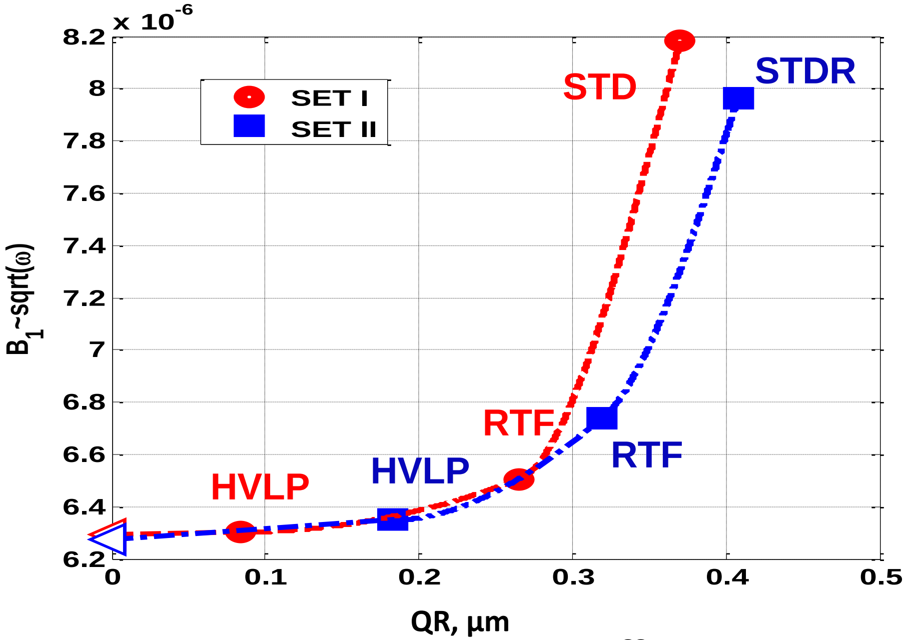


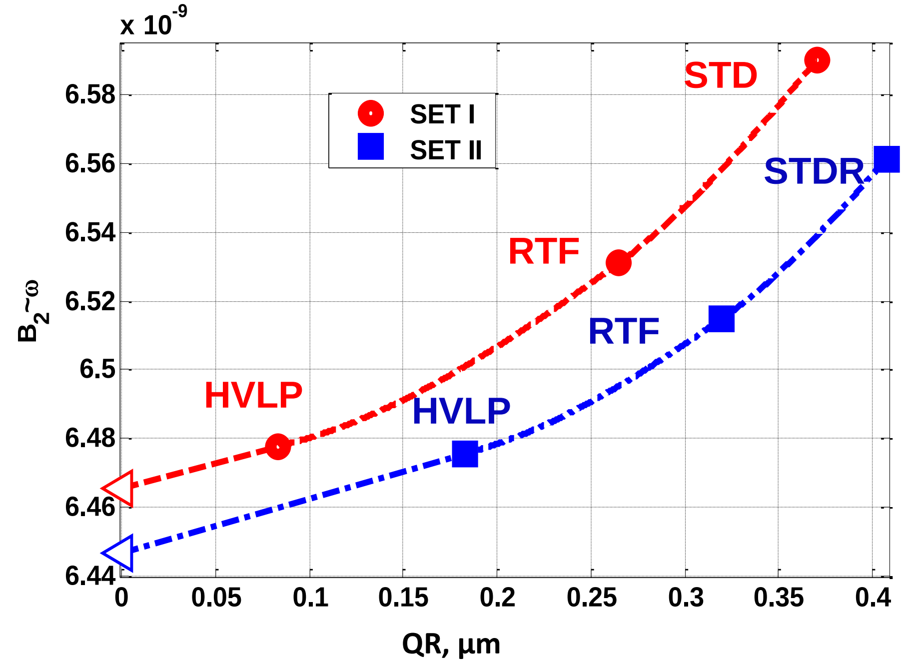


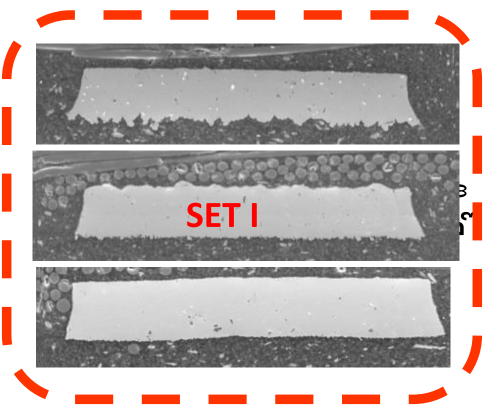


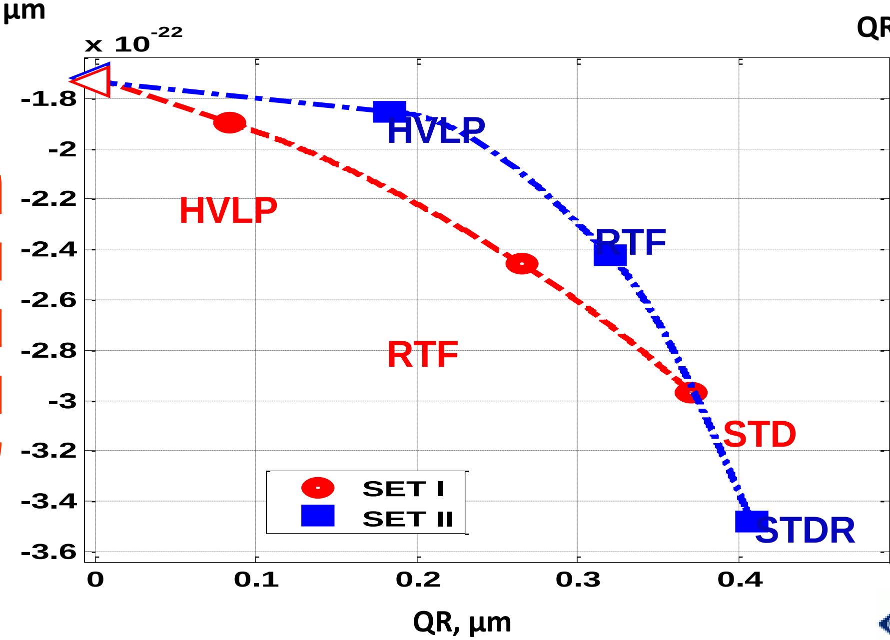


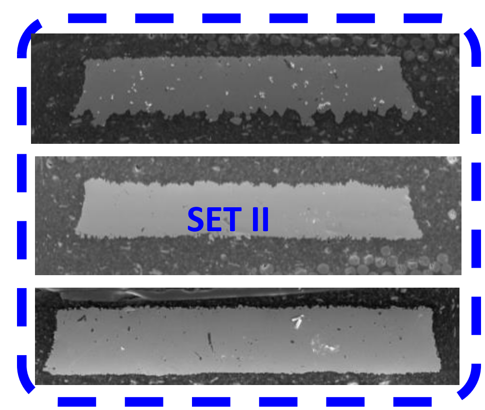
Extrapolation to Zero Roughness in β





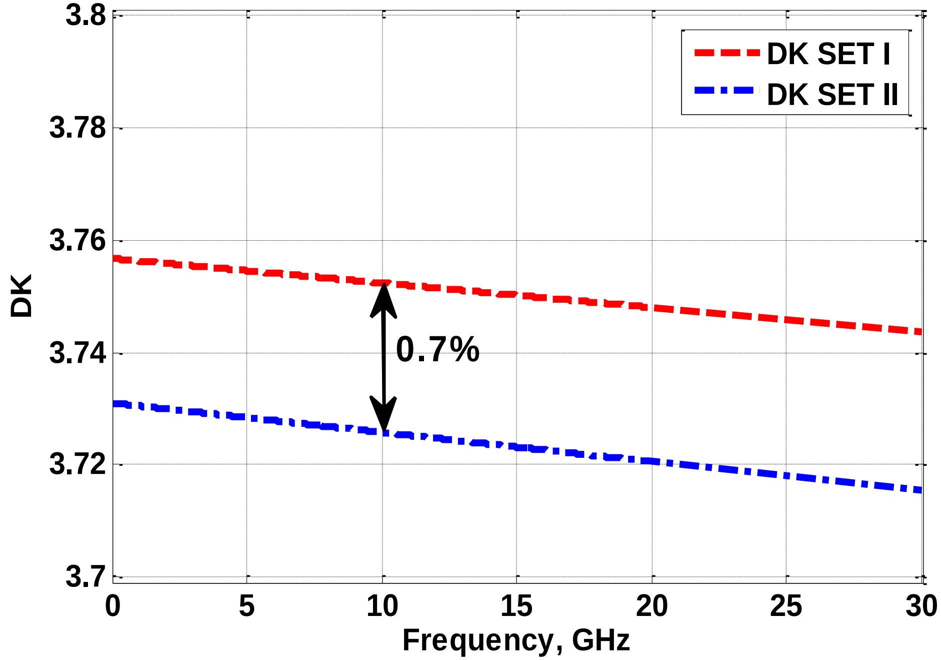


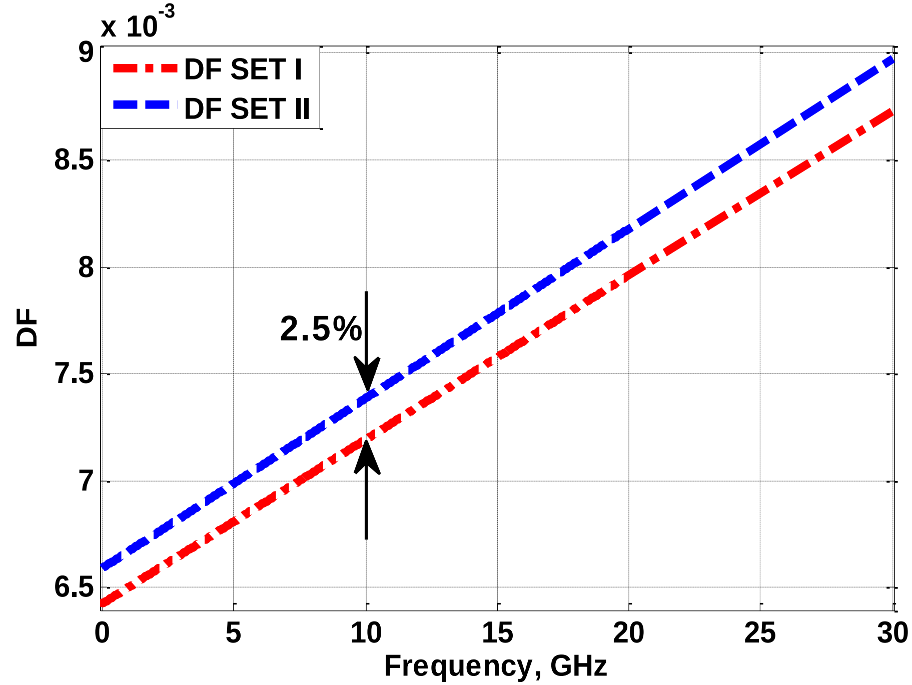




Santa Clara Valley CHAPTER

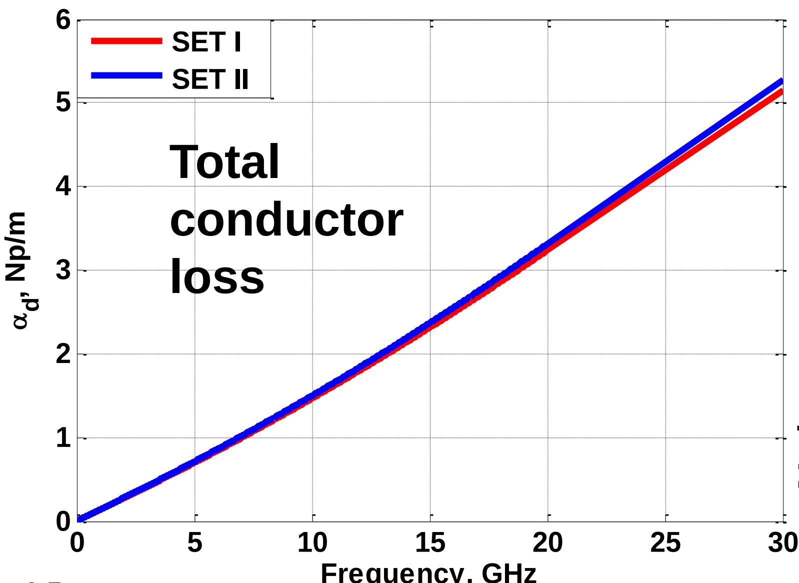
Refined DK and DF

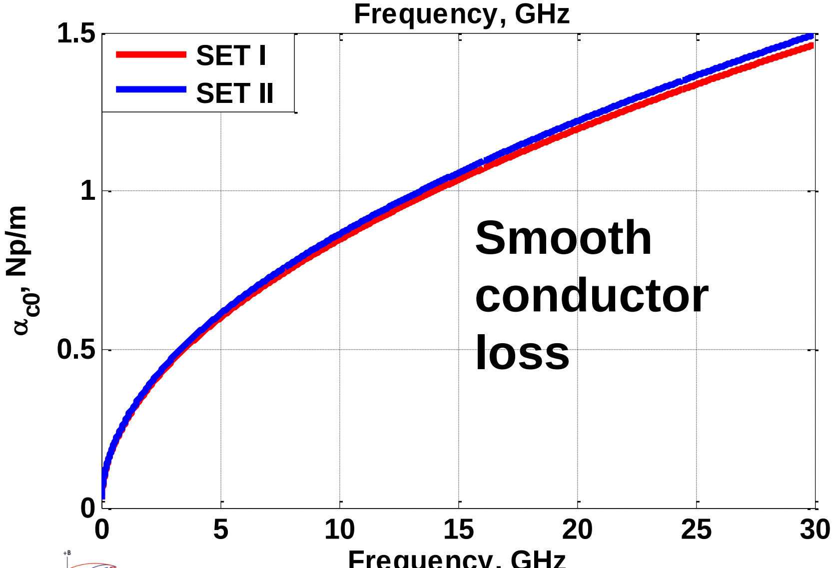




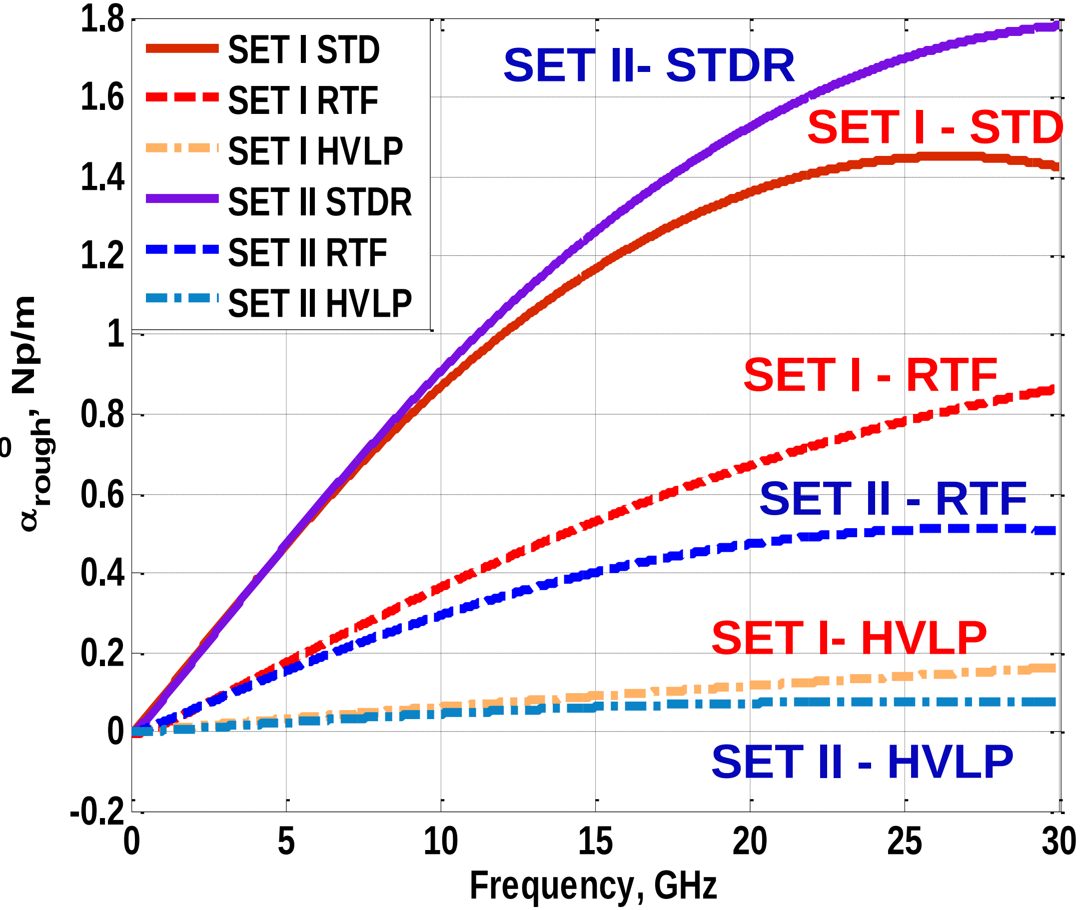
Excellent agreement between the results of extraction of dielectric parameters of two independent sets of boards (3+3 boards total) with the same dielectric and the same geometry, but different types of foil roughness has been obtained! Frequency range is from **10 MHz to 30 GHz.**

Dielectric Loss and Smooth & Rough Conductor Losses



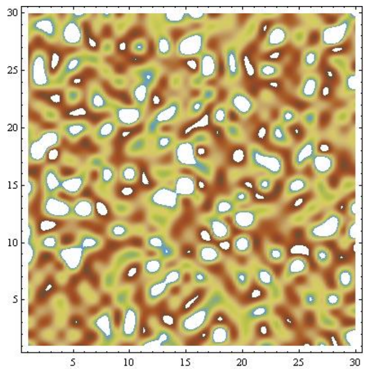


Rough conductor loss

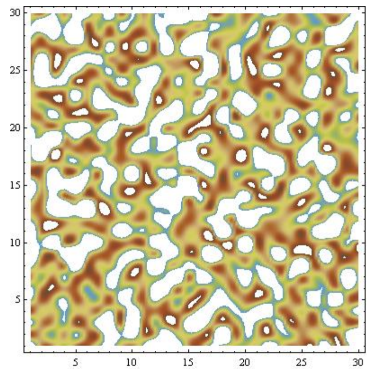


Effective Roughness Dielectric Approximation

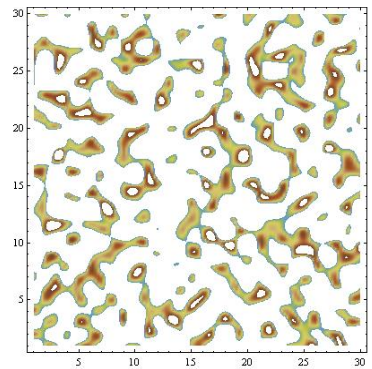
Concentration of "roughness inclusions" decreases with distance from zero-roughness plane



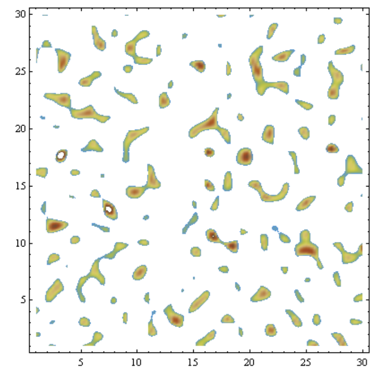
Close to smooth conductor, y_0=0



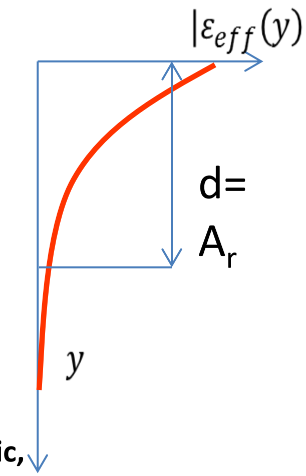
Deeper inside ambient dielectric, $y_1>y_0$



Deeper inside ambient dielectric, $y_2>y_1$



Closer to ambient dielectric, $y_3>y_2$



Maxwell Garnett mixing rule requires knowledge of volume concentration of "roughness inclusions". This volume concentration $\nu(y)$ varies as a function of the height *y*. ***Hence the dielectric properties homogenized by Maxwell-Garnett in each incremental layer are also functions of y.***

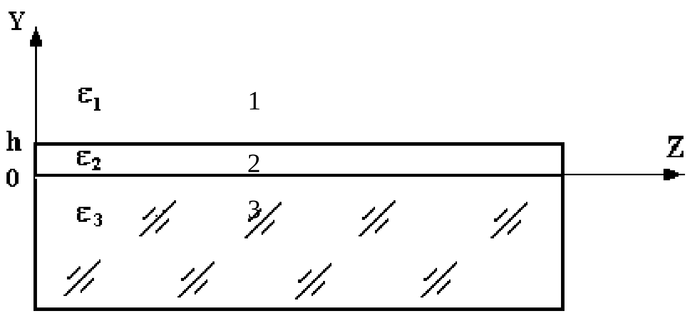
$$\varepsilon_{MG}(y) = \varepsilon_{matrix}\left(1+\nu(y)\frac{\varepsilon_{incl}-\varepsilon_{matrix}}{\varepsilon_{matrix}+(1-\nu(y))N_y(\varepsilon_{incl}-\varepsilon_{matrix})}\right)$$

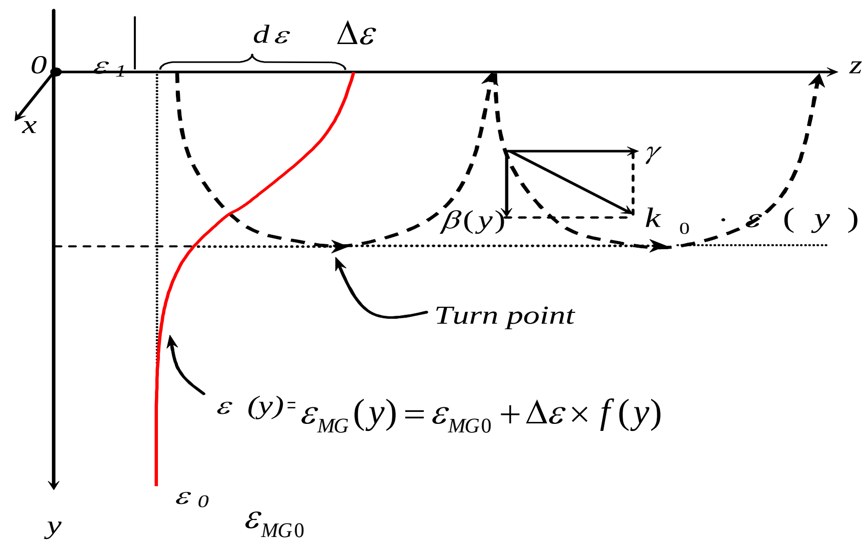
N_y is the depolarization factor in y-direction.

$$\varepsilon_{incl} = 1 - j\frac{\sigma}{\omega\varepsilon_0} \quad \text{and} \quad \varepsilon_{matrix} = 3.7 - j0.07$$

Boundary Layer – Gradient Waveguide Model

Using Maxwell Garnett mixing rule the roughness could be described as gradient layer with exponential distribution $\varepsilon_{MG}(y) = \varepsilon'_{MG}(y) - j\varepsilon''_{MG}(y)$.
Loss is due to non-propagating surface waves in the structure with variable permittivity.





The characteristic equation for wave propagation in a gradient waveguide:

$$k_0 \cdot \int_0^{y_t} \sqrt{\varepsilon_{MG}(y) - \varepsilon_{eff}}^{\,2} dy = \arctan\left(\frac{(\varepsilon_{MG0} + \Delta\varepsilon) \cdot \sqrt{\varepsilon_{eff} - \varepsilon_1}}{\varepsilon_1 \cdot \sqrt{(\varepsilon_{MG0} + \Delta\varepsilon) - \varepsilon_{eff}}} \right) + \pi \cdot (l-1) + \frac{\pi}{4}$$

Resultant effective roughness dielectric

$$\varepsilon_{eff} = \varepsilon'_{eff} - j\varepsilon''_{eff}$$

Where $\varepsilon_1 = \varepsilon_{incl} = 1 - j\frac{\sigma}{\omega\varepsilon_0}$ and $\Delta\varepsilon$ is the difference of $\varepsilon_{MG} - \varepsilon_{incl}$

Results for the Gradient Model: Set 1, Foil Side

Extracted from Gradient Model (on Foil Sides)						Extracted from Q2D		
		Solution #	Turning point= Ar	$\tan\delta_{rough}$	$\varepsilon'_{rough\,eff}$	Ar	$\tan\delta_{rough}$	$\varepsilon'_{rough\,eff}$
Set 1	STD	15	6.489	0.203	12.7	6.496	0.17	12.0
		13	5.05	0.124	5.02			
	VLP	6	2.739	0.130	8.08	2.752	0.13	9.0
		5	1.932	0.100	13.58			
	HVLP	2	1.083	0.048	5.01	1.086	0.04	4.8
		1	0.158	0.203	44.76			

There is a reasonable agreement; however, the results were obtained only for a limited number of samples.

Conclusions

- A new improved technique DERM2 to extract dielectric properties of a laminate dielectric for a set of five test vehicles is demonstrated.
- A semi-automatic roughness profile extraction and quantification procedure has been applied to SEM or optical microscopy pictures of microsections of PCB stripline.
- A metric called "roughness factor" QR to quantify roughness profiles has been introduced.
- The correlation between the additional slope in insertion loss due to roughness and the roughness factor QR has been established. The effective roughness dielectric layer concept was applied to numerically model (in 2D FEM) all the five test vehicles.
- In the numerical models, the dielectric parameters of ambient dielectric were taken as those obtained using the DERM2 procedure; the boundary roughness layers were substituted by Effective Roughness Dielectric.
- This model and analysis lead to the development of the "design curves" (additional slopes of insertion loss, or additional conductor loss as a function of roughness parameter), which could be used by SI engineers in their designs.

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Thanks

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