DesignCon® 2014

Elimination of Conductor Foil Roughness Effects in Characterization of Dielectric Properties of Printed Circuit Boards
14 TH1

Marina Koledintseva, Aleksei Rakov, Alexei Koledintsev, James Drewniak (Missouri S&T) and
Scott Hinaga (Cisco Systems)

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UBM Tech

Abstract

- The proposed experiment-based technique **DERM2** is the further development of the differential extrapolation roughness measurement (**DERM**) method to refine dielectric properties of PCB laminate dielectrics from conductor roughness.
- The **DERM2** is applied to both loss constant and phase constant (DERM deals with the loss constant only) to improve accuracy of **DK & DF extraction**, as well as losses due to smooth conductor and rough conductor-dielectric interface.
- A new metric called “roughness factor” **QR** to quantify roughness profiles has been introduced.
- The DERM2 procedure is applied to a **set of test vehicles** with the same dielectric and geometry, but different copper foil roughness profiles. Five test vehicles are employed in this extraction.
- The correlation between additional slope in insertion loss due to roughness and the QR factor has been established. This allows for building the “**design curves**”, which could be used by SI engineers in their designs.

Outline

I. Introduction:

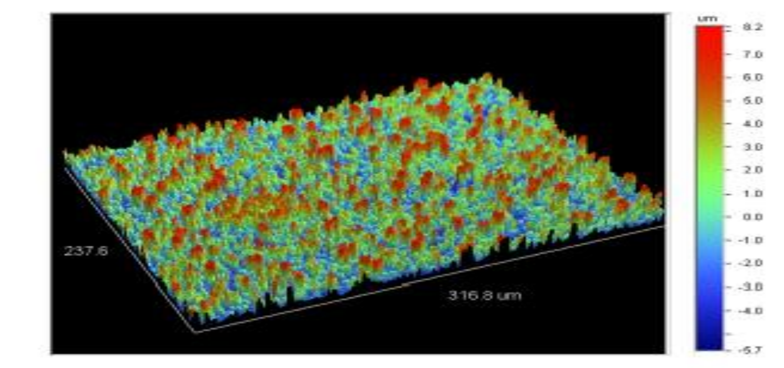
II. Description of Test Vehicles

III. Image Processing and Quantification of Roughness Profiles

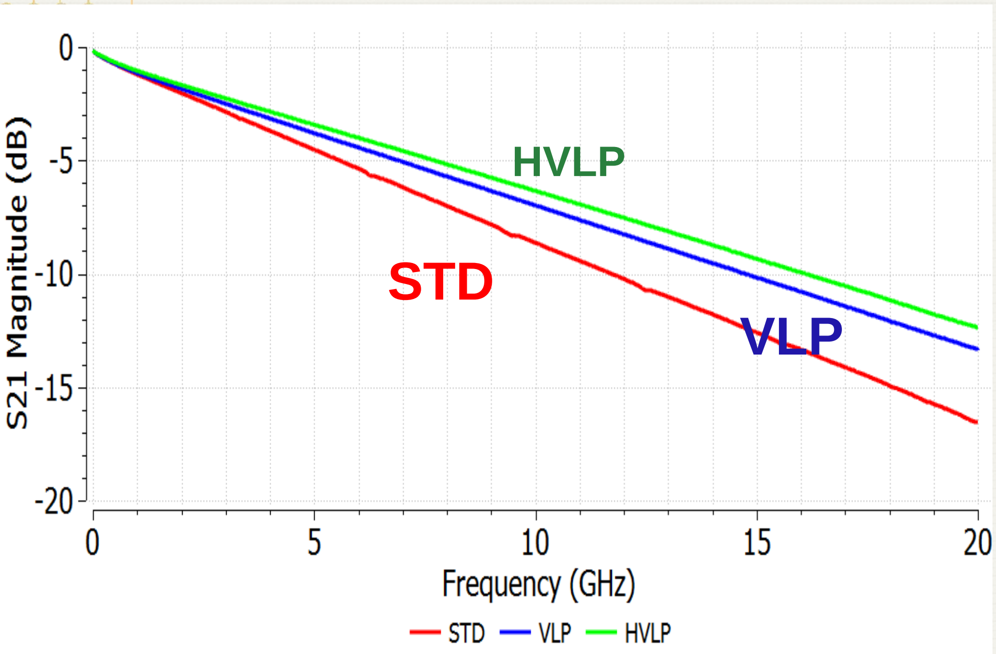
IV. Extrapolation to Zero Roughness & Material Parameters Extraction

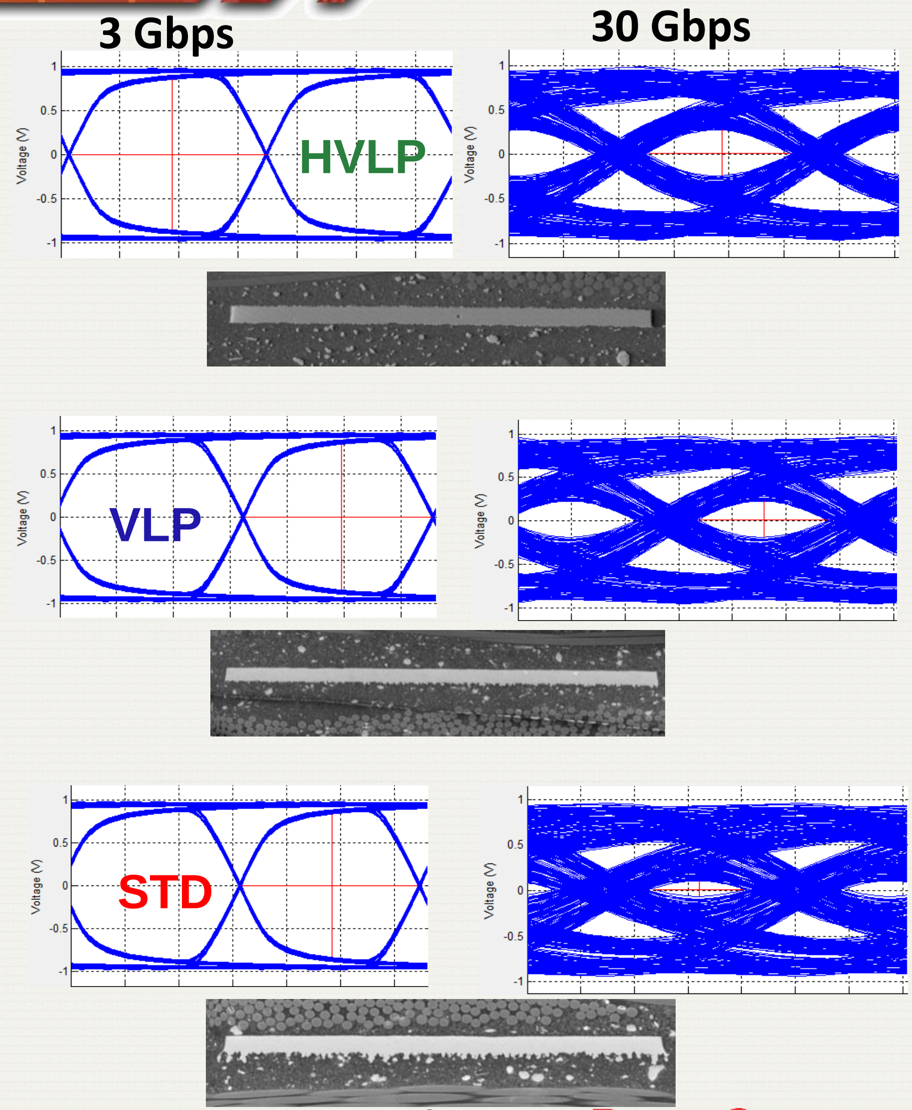
V. Measurements and Numerical Electromagnetic Modeling of Test Vehicles

VI. Conclusions



Introduction





Motivation: study and adequate modeling of wideband behavior of laminate dielectric and conductors on PCBs, taking into account roughness at the boundary, is important for signal integrity.

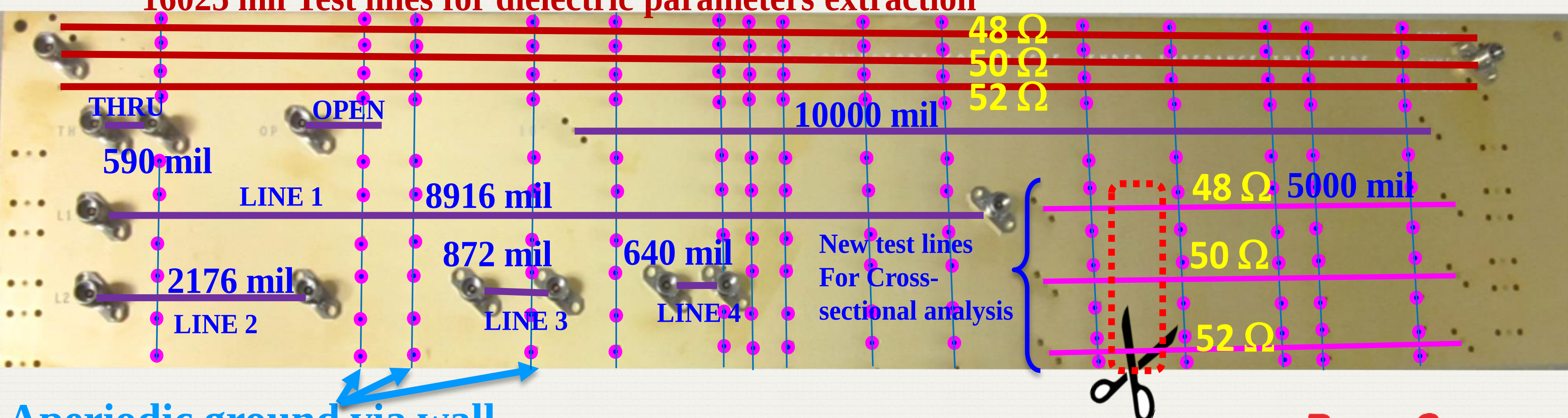
Test Boards with TRL Calibration

30-GHz Test Vehicle

Periodic ground via wall

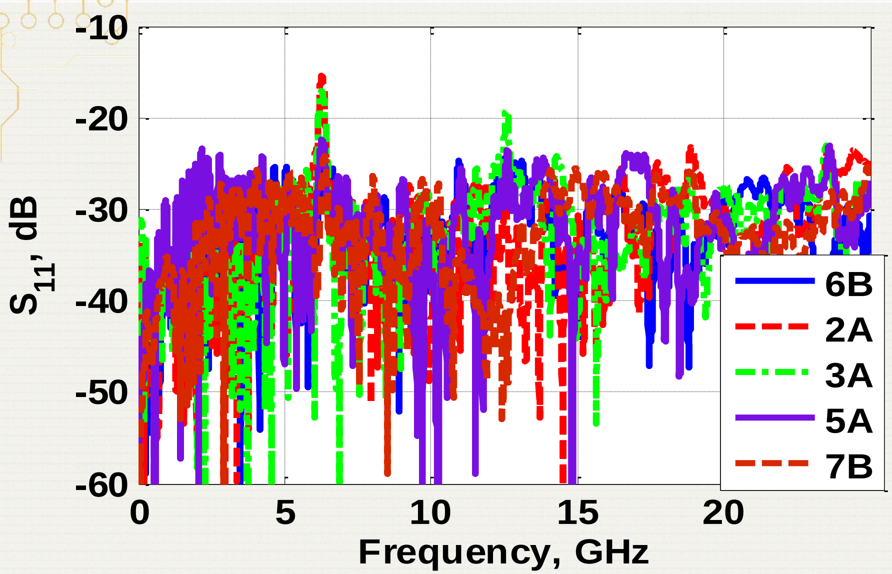
50-GHz Test Vehicle

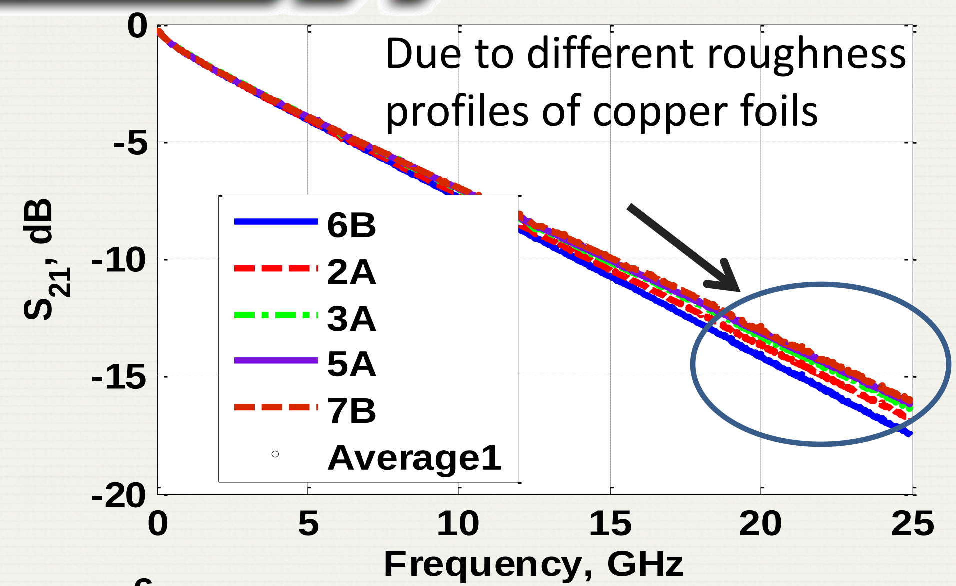
16025 mil Test lines for dielectric parameters extraction

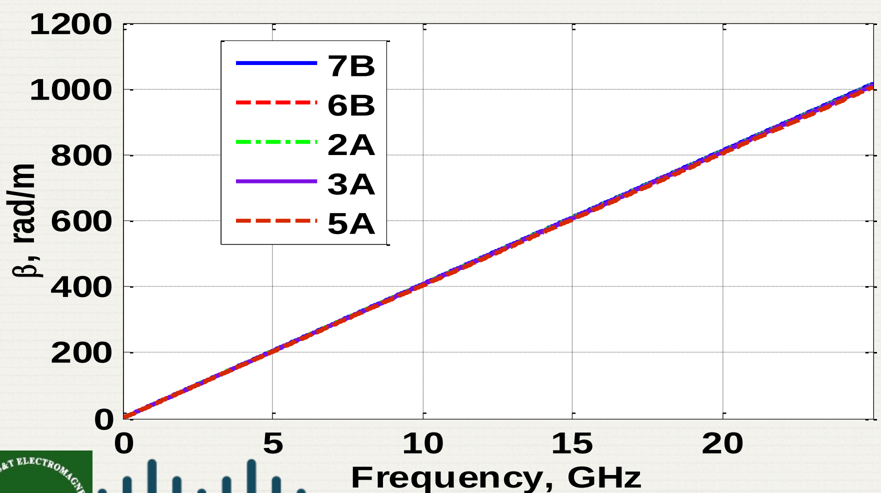


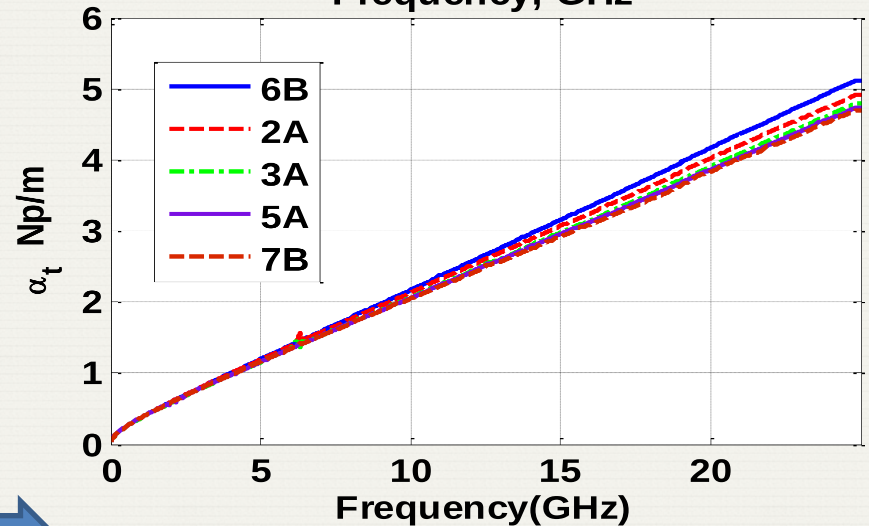
Aperiodic ground via wall

Measured Parameters of Test Vehicles









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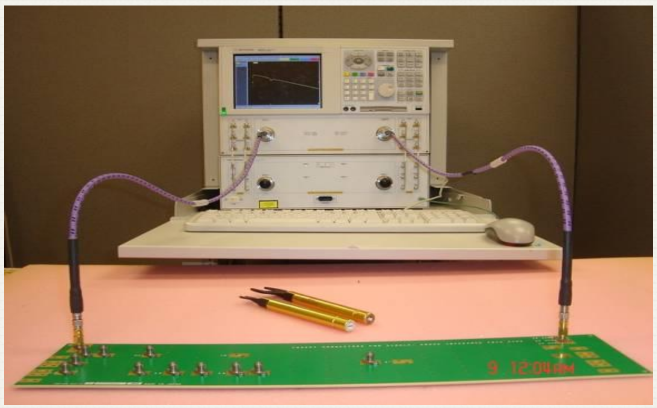
S3 Technique to Extract DK & DF of PCB Dielectrics

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

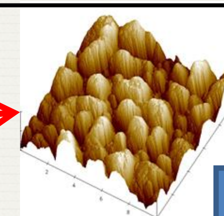


S-parameters are measured using VNA or TDR with "Through-Reflect-Line" (TRL) calibration in f-domain or t-domain, respectively

Model or experimentally retrieve conductor loss for rough stripline conductor

Main problem!

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



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

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

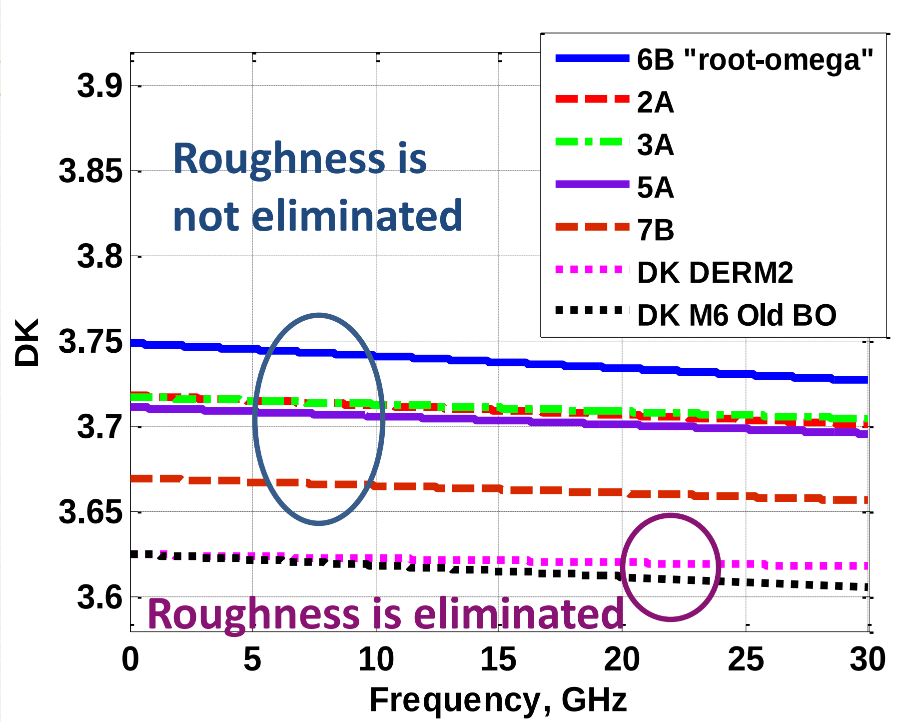
Solve the system of equations to obtain complex permittivity

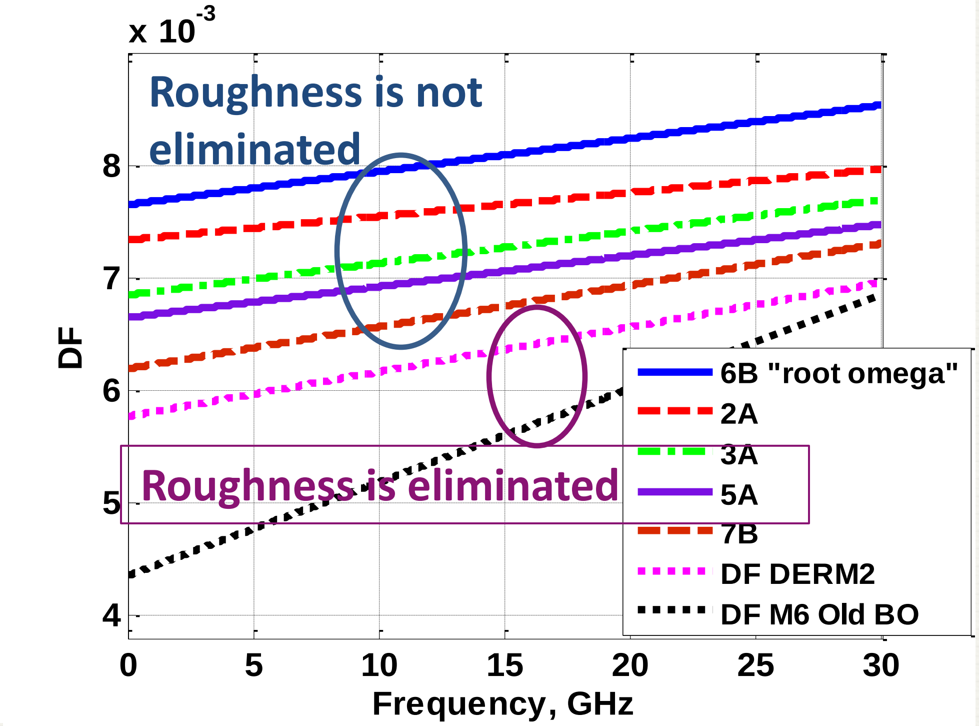
OPTIONS

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

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

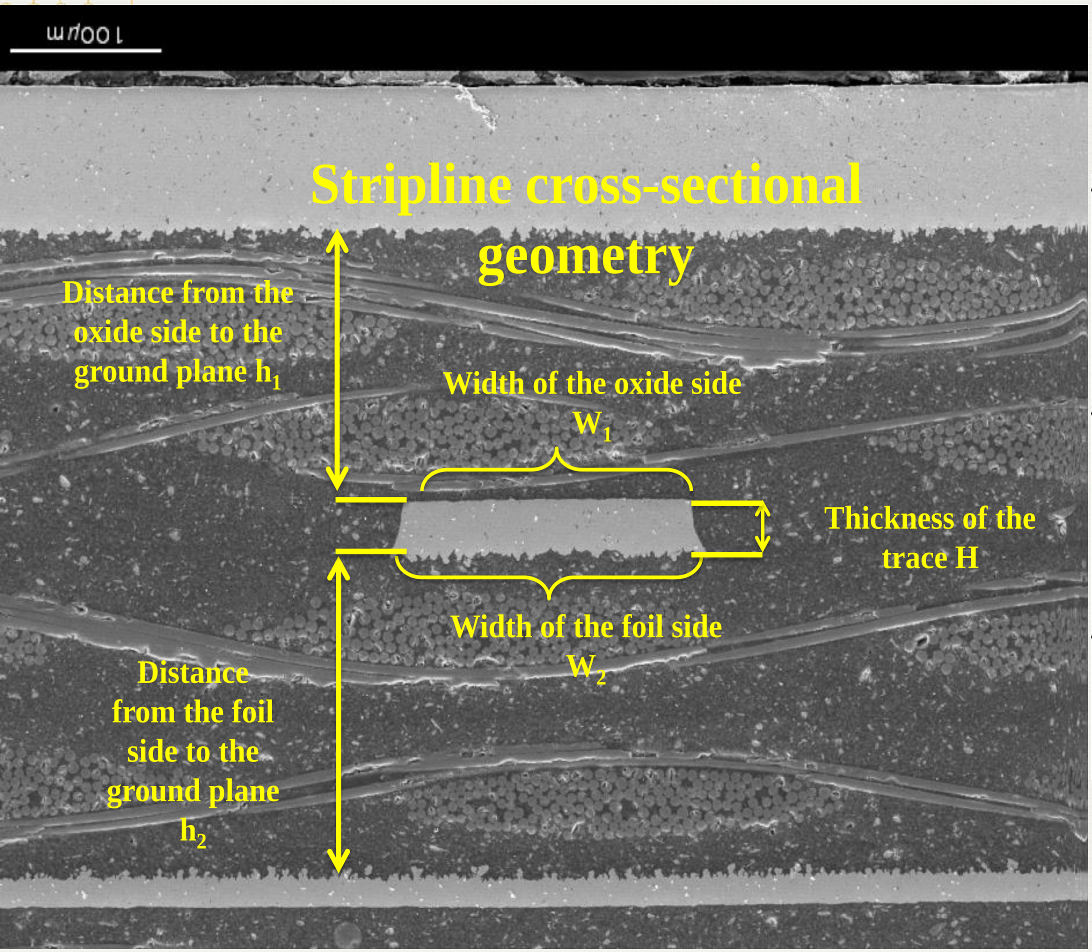
DK & DF Extraction if Roughness Effect is not Eliminated

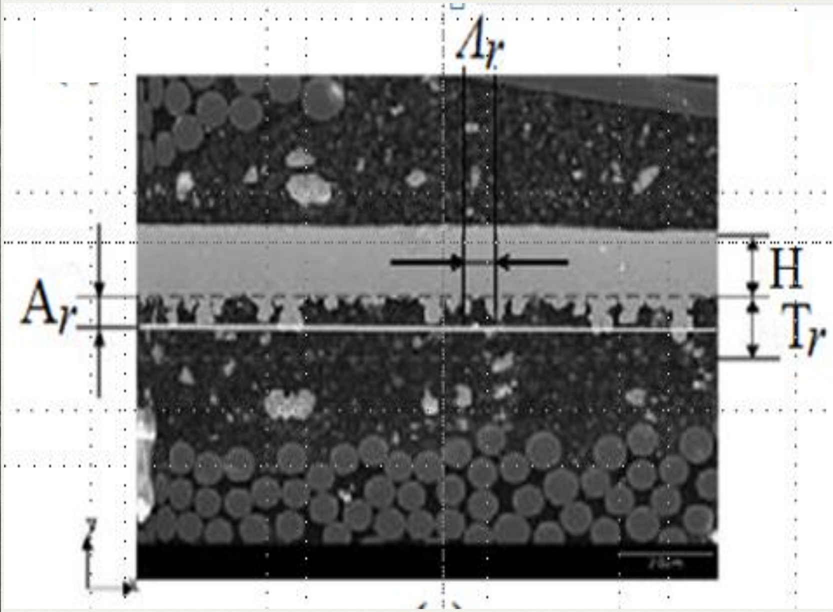




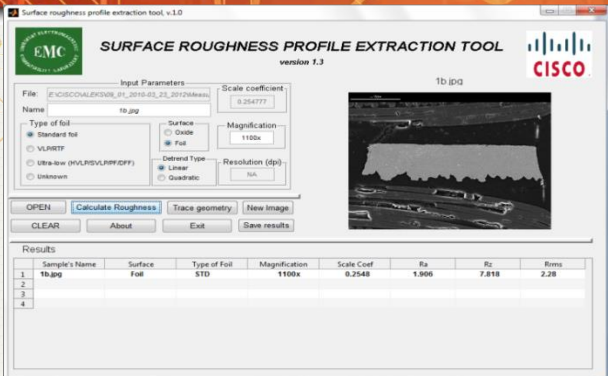
If conductor roughness effects are not eliminated, there is ambiguity in DK and DF extracted data for identical dielectric substrates.
The objective is to get rid of this ambiguity.

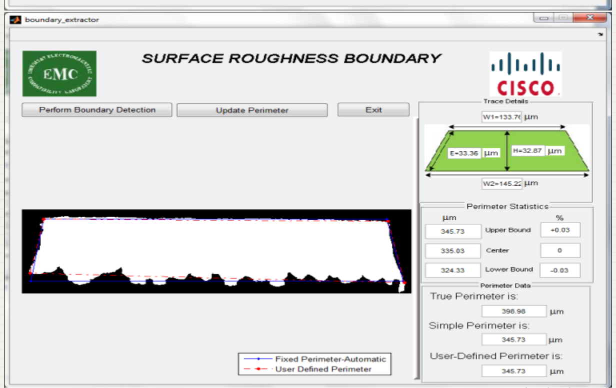
Cross-sectional Geometry

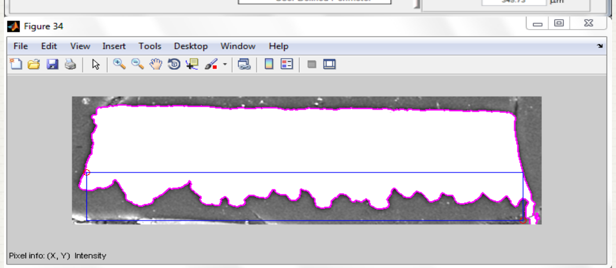


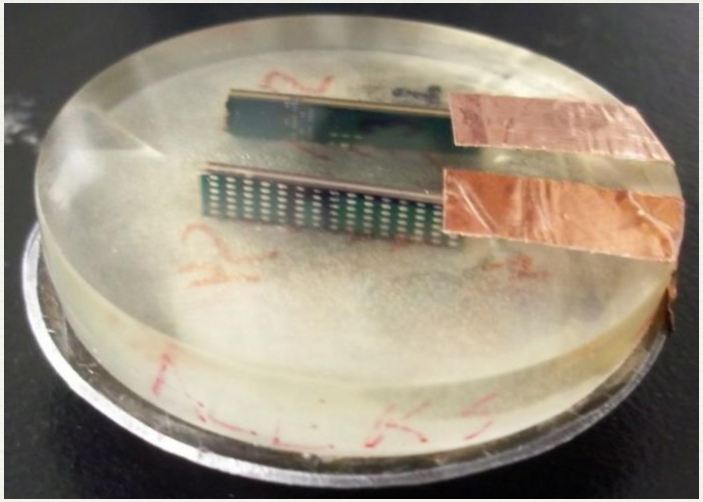


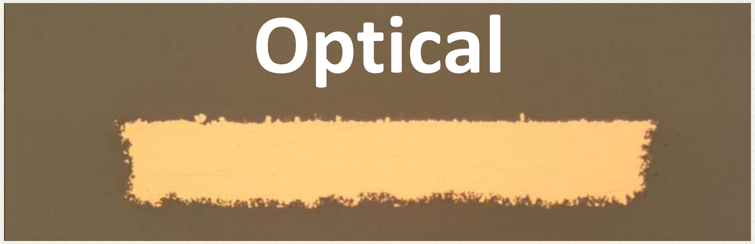
Microscopy – Optical & SEM

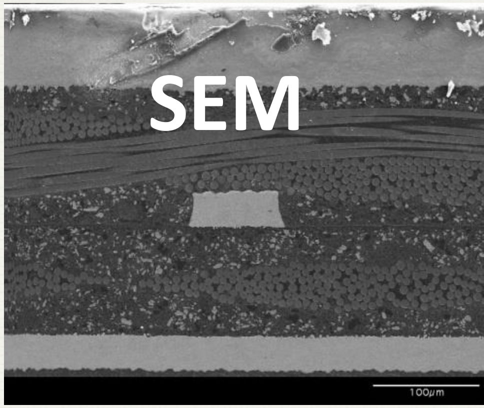




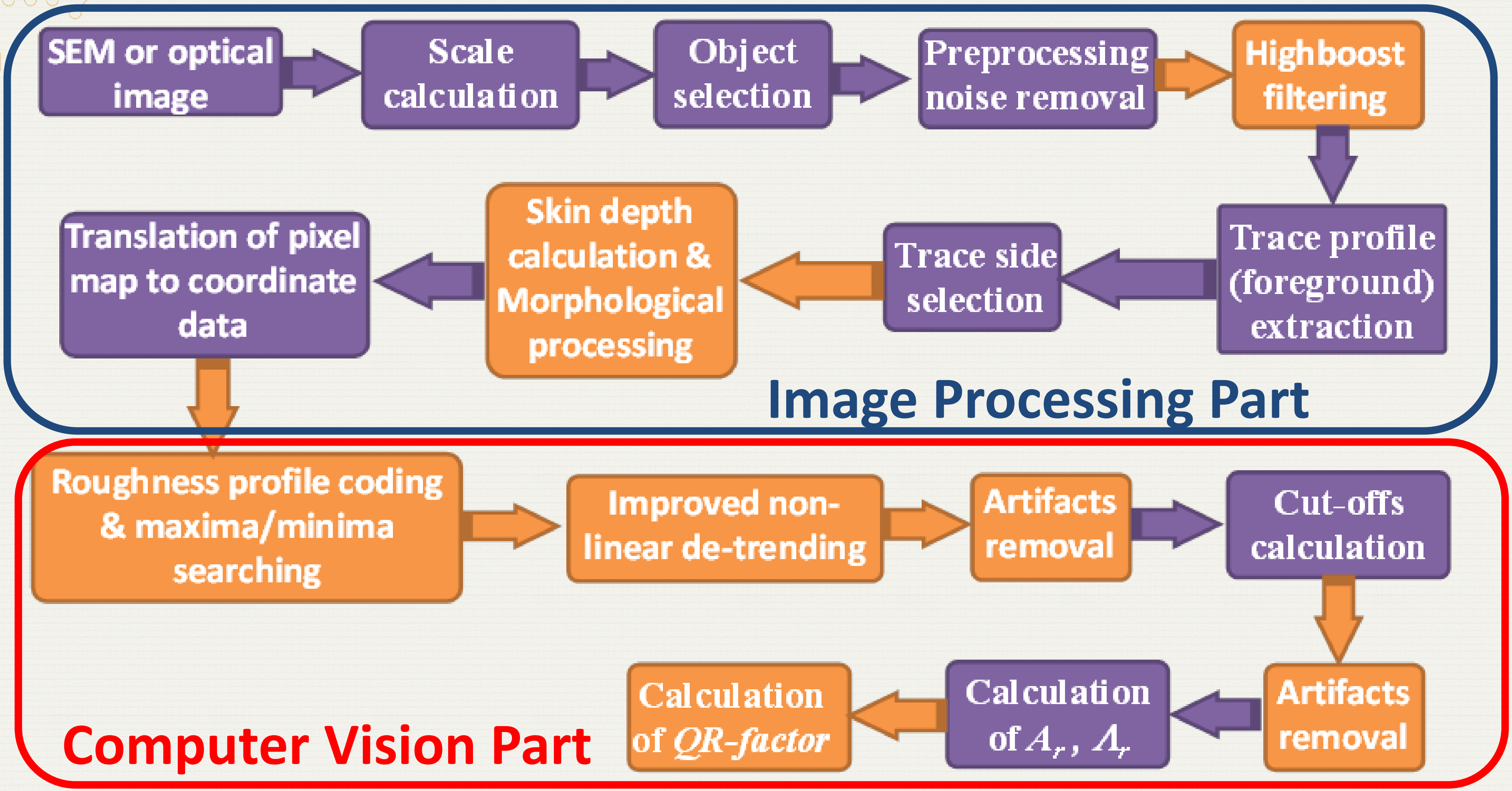






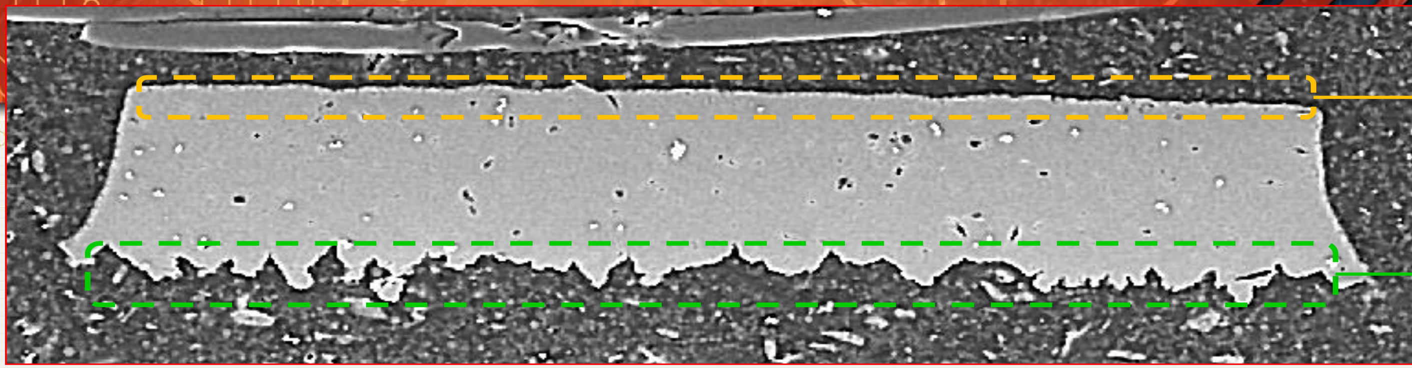


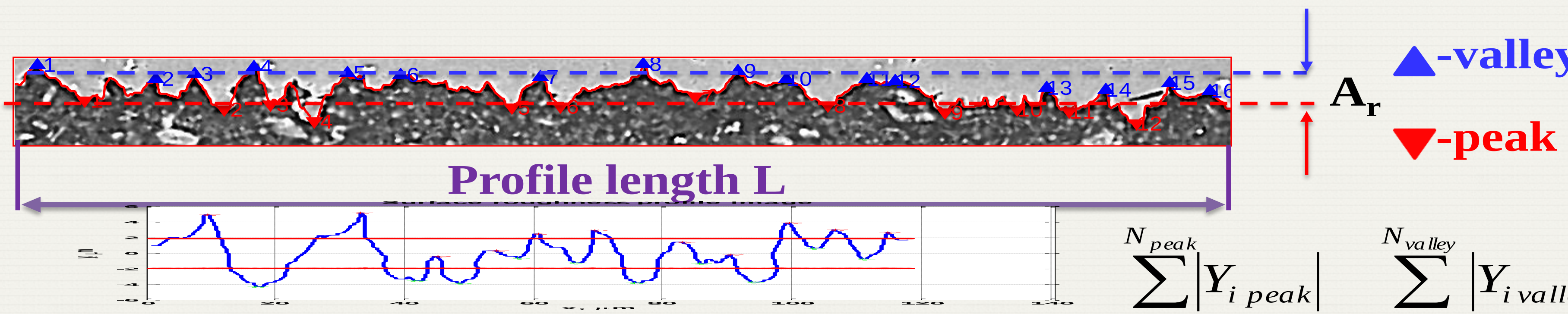
Algorithm to Extract & Quantify Roughness Profile



US Pat 8,559,678

Roughness Quantification

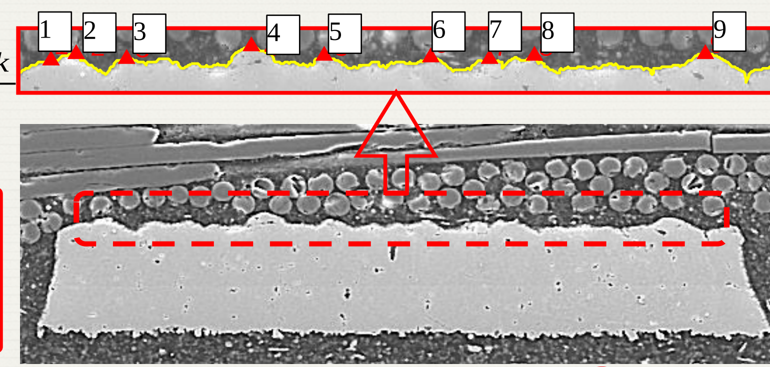




Average peak-to-valley amplitude:

$$A_r = \frac{\sum_{i=1}^{N_{peak}} \left|Y_{i\ peak}\right|}{N_{peak}} + \frac{\sum_{i=1}^{N_{valley}} \left|Y_{i\ valley}\right|}{N_{valley}}$$

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



Roughness Factor:

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

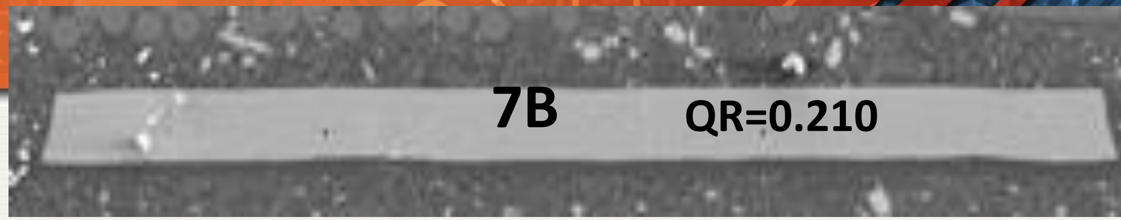
Geometrical and Roughness Data for Five Test Vehicles

	w_1, µm	w_2, µm	t, µm	P, µm	h_1, µm	h_2, µm	A_{r1}, µm	A_{r2}, µm	Λ_{r1}, µm	Λ_{r2}, µm	QR_1	QR_2	QR_{total}
7B	267.6	274.3	16.4	575.2	228.4	249.1	0.58	1.11	6.15	9.43	0.092	0.118	0.210
5A	263.0	269.3	14.7	562.5	234.1	243.8	0.80	1.12	5.07	4.82	0.158	0.232	0.390
3A	265.9	274.2	17.4	576.0	232.0	241.2	0.76	1.21	4.70	4.48	0.161	0.271	0.432
2A	267.5	273.3	14.3	569.7	231.2	243.2	1.25	1.02	5.58	4.63	0.224	0.220	0.444
6B	265.6	275.9	16.2	575.5	227.6	241.8	0.835	2.60	6.90	5.559	0.121	0.468	0.590

Five test vehicles have been used in extraction procedure for this work. All of them are made of **Megtron 6** with foils of different roughness profiles.

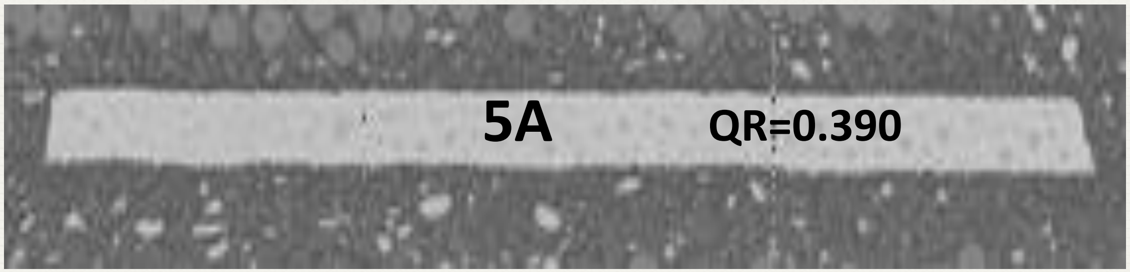
Cross-sections of Signal Traces

oxide Ar=0.58 µm
foil Ar=1.11 µm



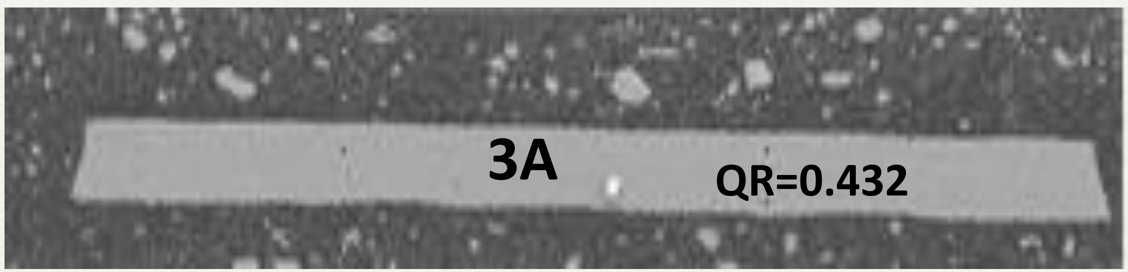
oxide Rz=0.6 µm
foil Rz=1.18 µm

oxide Ar=0.8 µm
foil Ar=1.12 µm



oxide Rz=1.18 µm
foil Rz=1.2 µm

oxide Ar=0.76 µm
foil Ar=1.21 µm

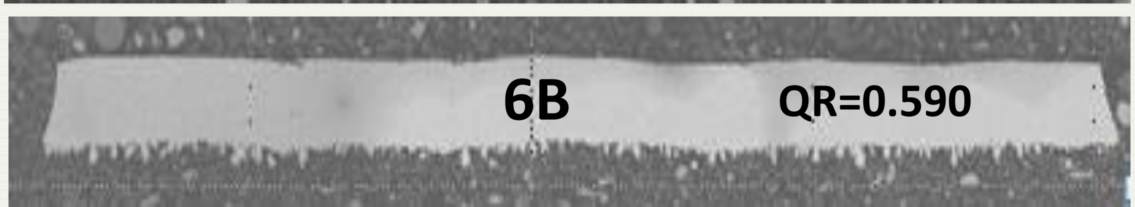


oxide Rz=1.12 µm
foil Rz=1.12 µm

oxide Ar=1.25 µm
foil Ar=1.02 µm

oxide Rz=1.28 µm
foil Rz=1.3 µm

oxide Ar=0.84 µm
foil Ar=2.6 µm



oxide Rz=1.3 µm
foil Rz=2.8 µm

Separation of Dielectric, Conductor, and Boundary Roughness Effects

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

Curve-fitting to $\sqrt{\omega}$, ω & ω^2

Loss in smooth conductor | Dielectric loss | + | Loss due to roughness

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

DERM2: $\beta_T = B_1\sqrt{\omega} + B_2\omega + B_3\omega^2 + B_{r1}\sqrt{\omega} + B_{r2}\omega + B_{r3}\omega^2$

Curve-fitting to $\sqrt{\omega}$, ω & ω^2

Due to skin-effects in conductor | Due to dielectric | Due to roughness

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

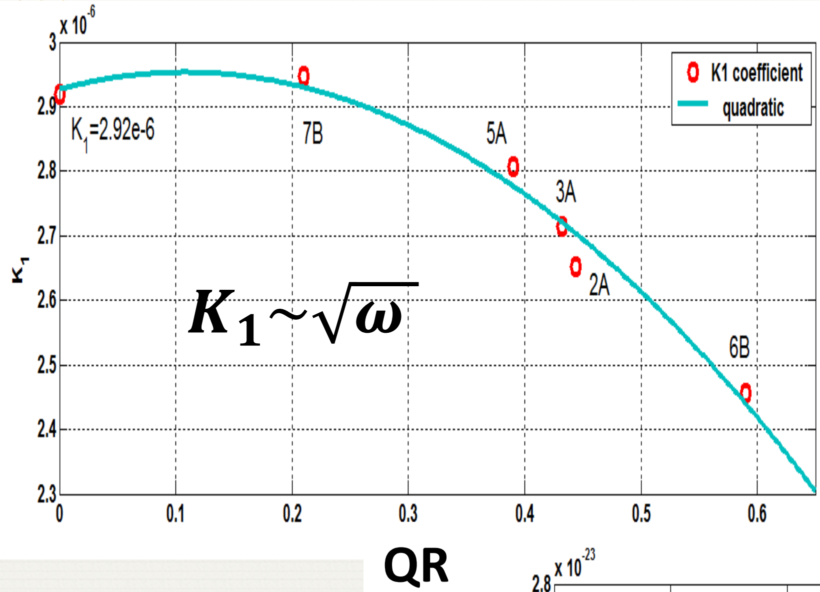
Reference: M.Y. Koledintseva, A.V. Rakov, et al, "Improved experiment-based technique to characterize dielectric properties of printed circuit boards", *IEEE Trans. Electromag. Compat.* (accepted Dec. 2013)

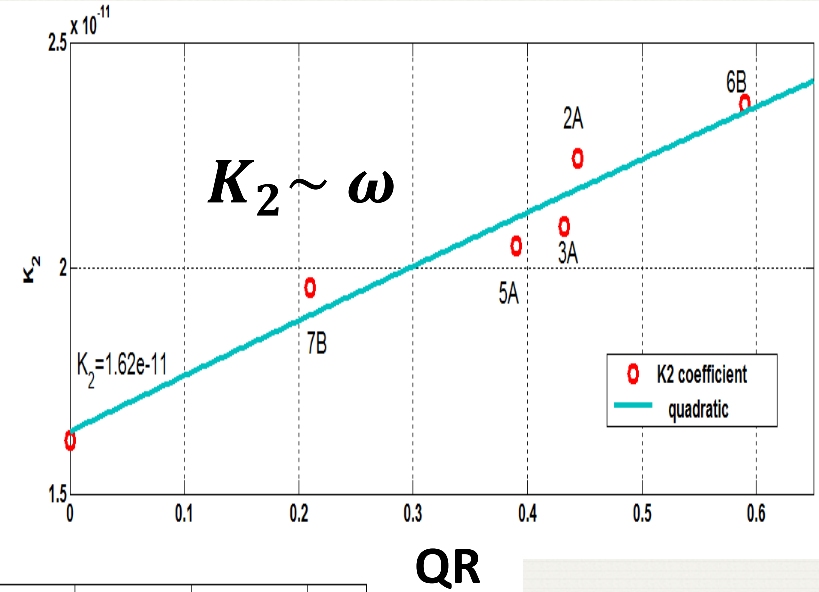
Reference: A. Koul, M.Y. Koledintseva, et al, "Differential extrapolation method for separating dielectric and rough conductor losses in printed circuit boards", *IEEE Trans. Electromag. Compat.*, vol. 54, no. 2, Apr. 2012, pp. 421-433.

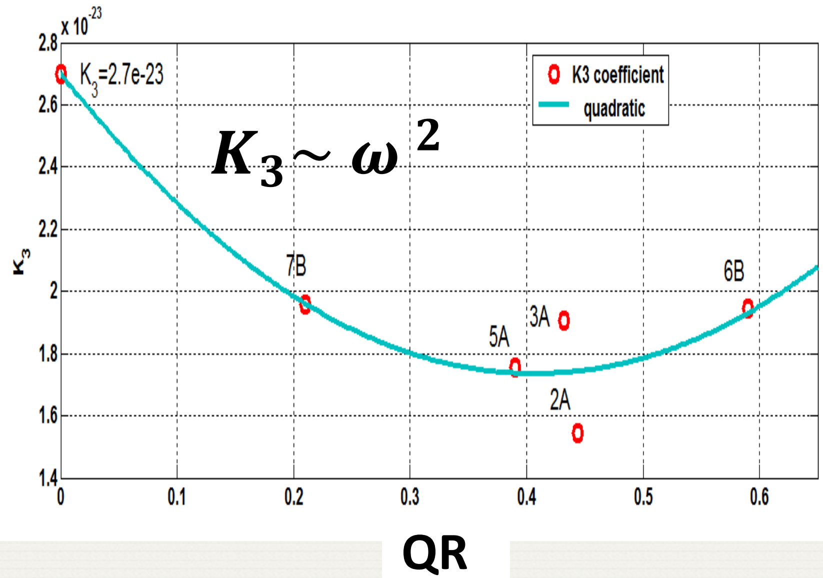
Curve-fitting Coefficients for α and β

	K_1 $\times 10^6$ $(\sqrt{\omega})$	K_2 $\times 10^{11}$ (ω)	K_3 $\times 10^{23}$ (ω^2)	B_1 $\times 10^6$ $(\sqrt{\omega})$	B_2 $\times 10^9$ (ω)	B_3 $\times 10^{23}$ (ω^2)	R_1 $\times 10^6$ $(\sqrt{\omega})$	R_2 $\times 10^9$ (ω)	R_3 $\times 10^{23}$ (ω^2)	QR
7B	2.916	1.958	1.959	6.609	6.390	-6.032	-0.004	0.338	-0.741	0.210
5A	2.808	2.050	1.755	6.645	6.425	-6.830	-0.112	0.431	-0.945	0.390
3A	2.716	2.091	1.906	6.647	6.433	-6.695	-0.205	0.471	-0.795	0.432
2B	2.653	2.244	1.545	6.658	6.432	-8.0212	-0.267	0.624	-1.155	0.444
6B	2.457	2.362	1.944	6.692	6.458	-9.873	-0.463	0.742	-0.756	0.590

Extrapolation to Zero Roughness: α_T



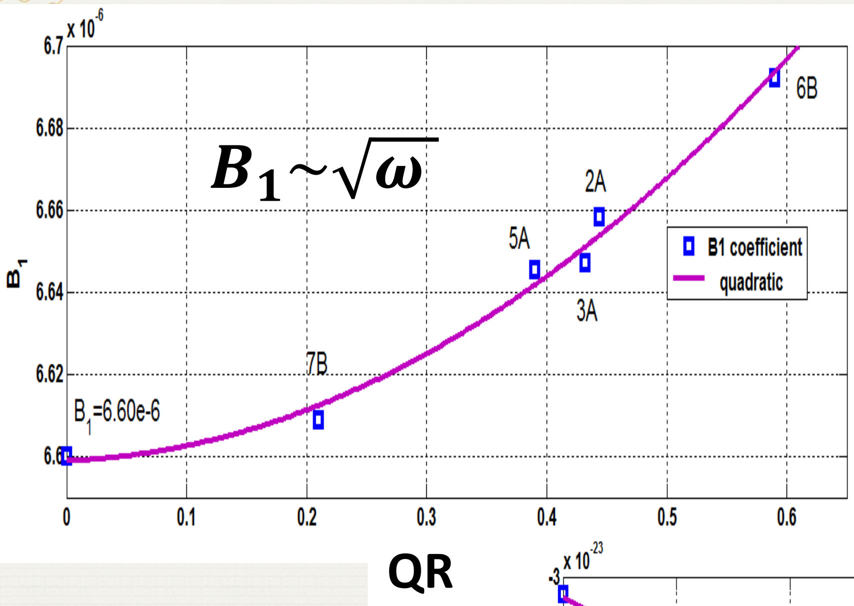


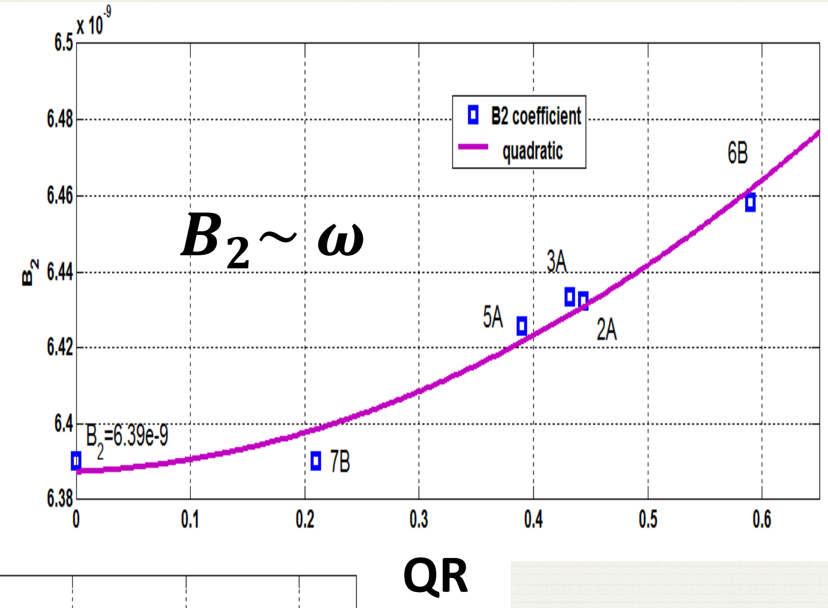


$$\alpha_{c0} = 2.92\times10^{-6}\sqrt{\omega}$$

$$\alpha_d = 1.61\times10^{-11}\omega + 2.7\times10^{-23}\omega^2$$

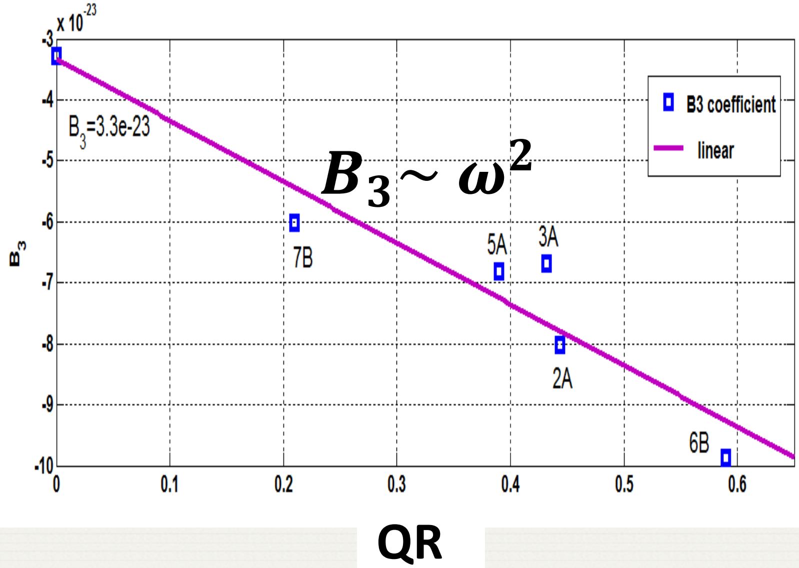
Extrapolation to Zero Roughness: β_T



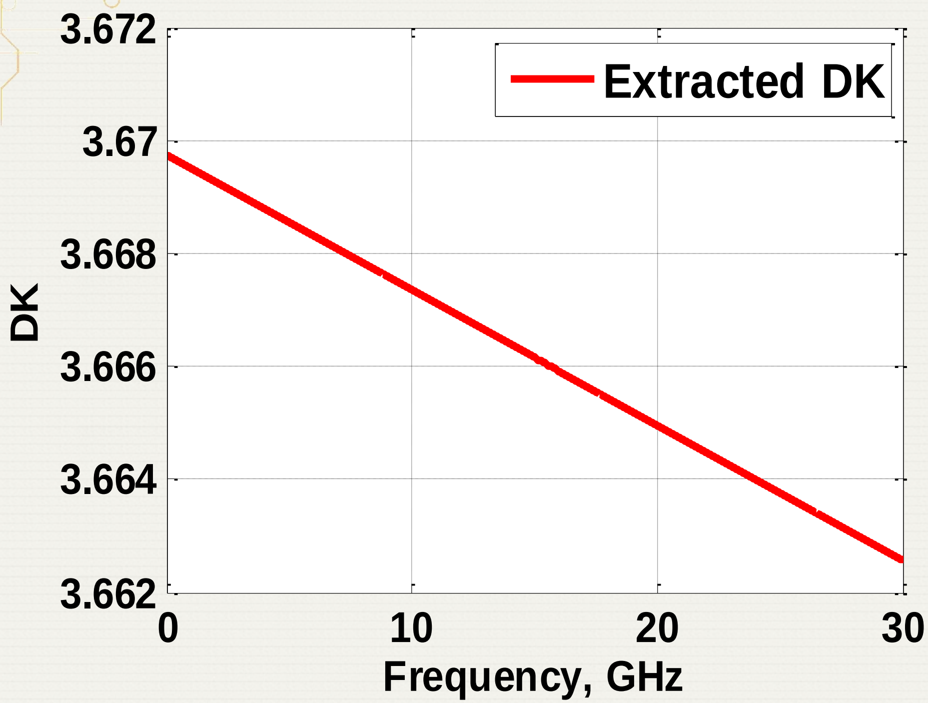


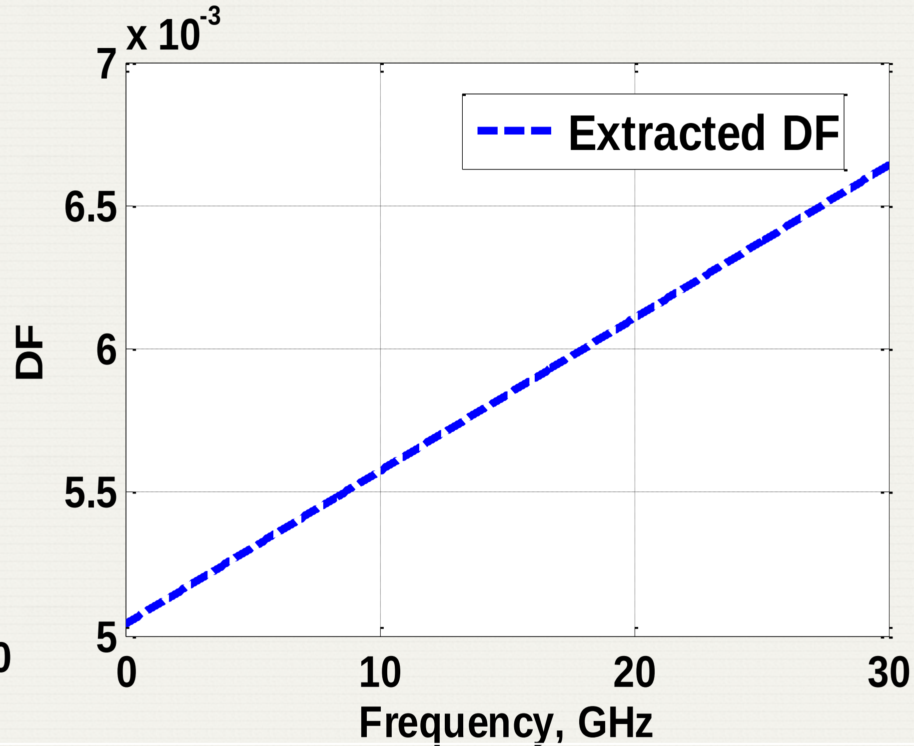
$$\beta_{c0} = 6.60 \times 10^{-6} \sqrt{\omega}$$

$$\beta_d = 6.39 \times 10^{-9} \omega - 3.3 \times 10^{-23} \omega^2$$



Extracted DK & DF

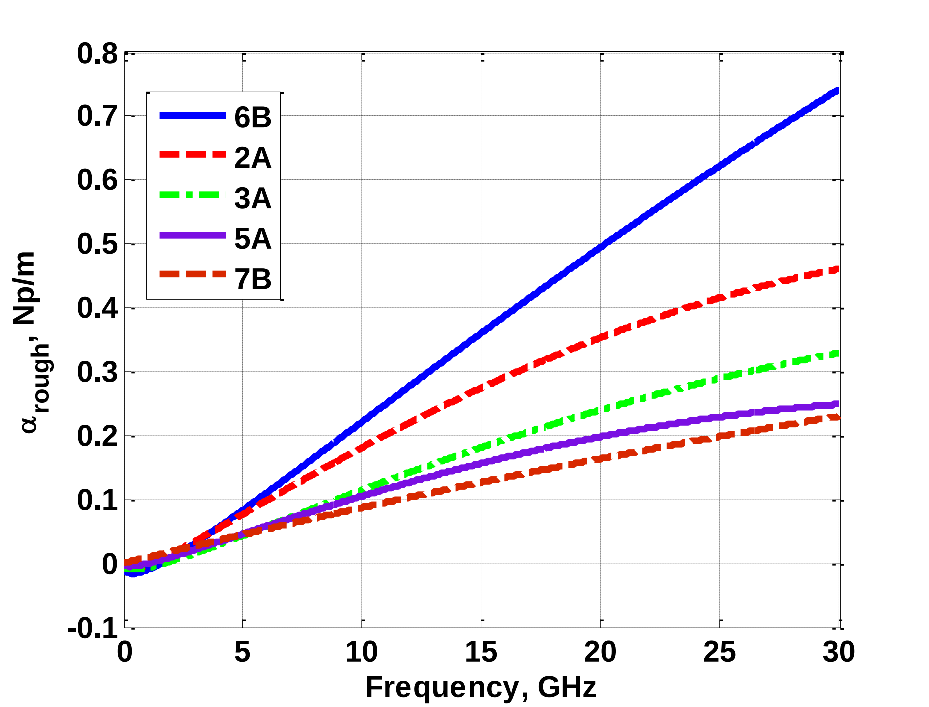


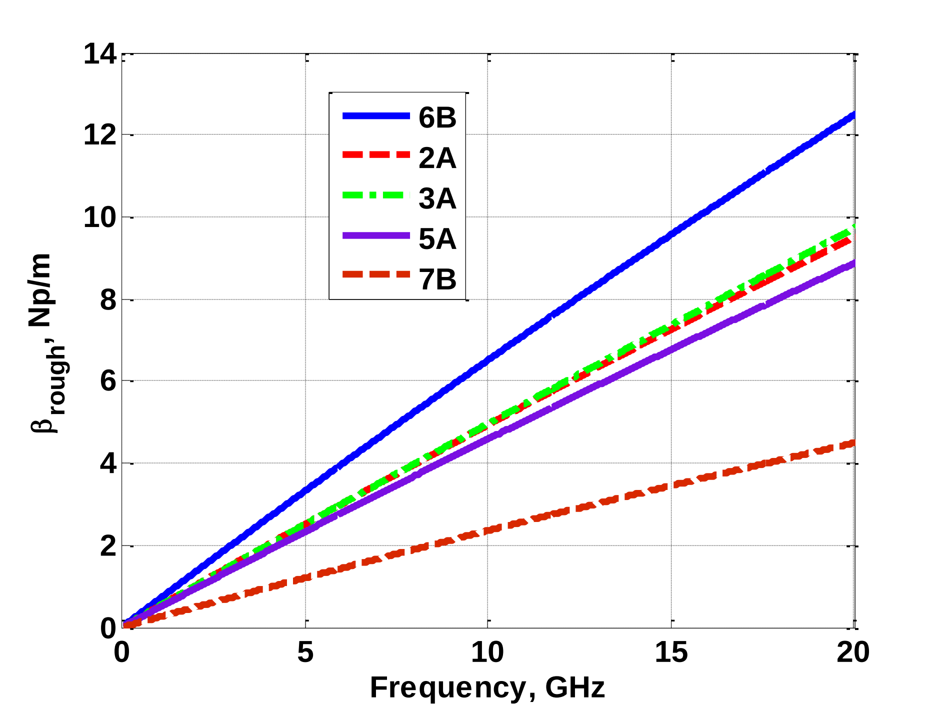


Identical refined dielectric properties of the laminate dielectric substrate for all five test vehicles

(no ambiguity due to roughness!)

Roughness Parts in α_T and β_T





Even though all five test vehicles have different types of foils, these foils are different, have different roughness profiles, and result in different contributions to loss and phase constant.

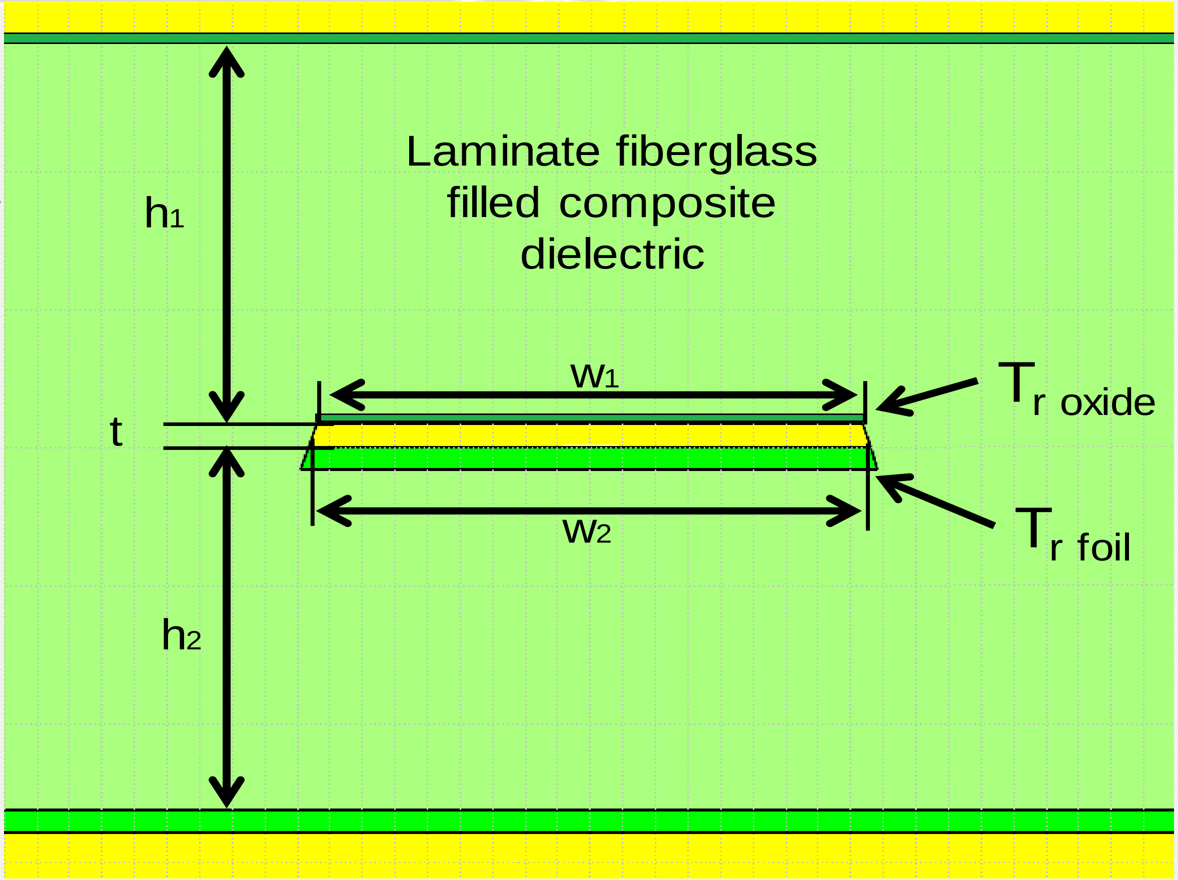
Numerical (Ansoft Q2D- 2D-FEM) Model Setup

Oxide side ‘roughness dielectric’

Copper foil conductors

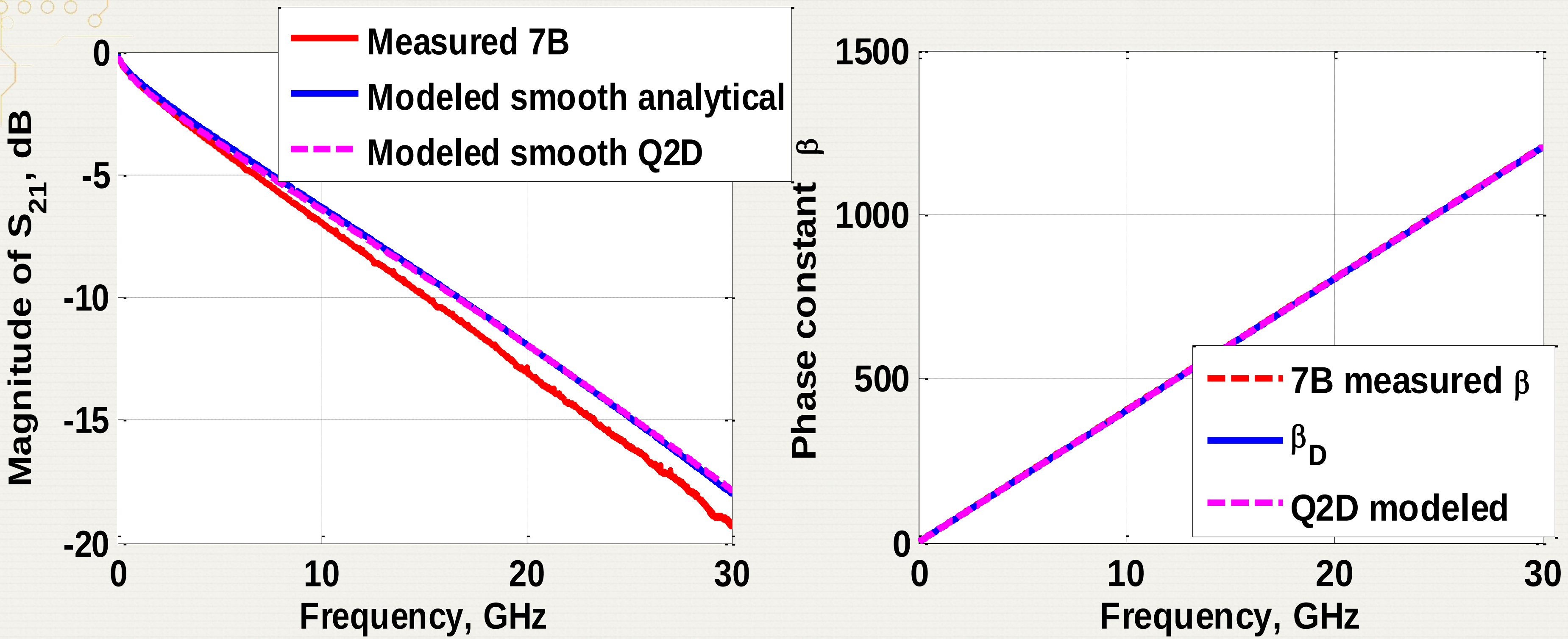
Foil side ‘roughness dielectric’

Laminate dielectric



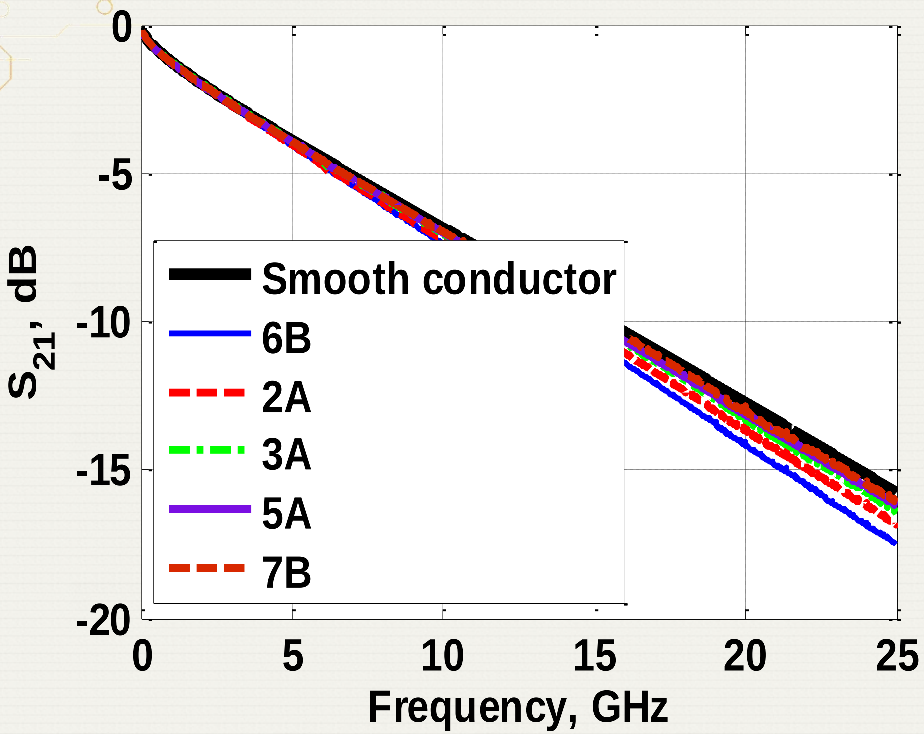
- Laminate dielectric parameters are extracted from DERM2 (for both α and β).
- Heights of ERD $T_{r\ oxide}$ and $T_{r\ foil}$ are taken as $2A_{r\ oxide}$ and $2A_{r\ foil}$, respectively.

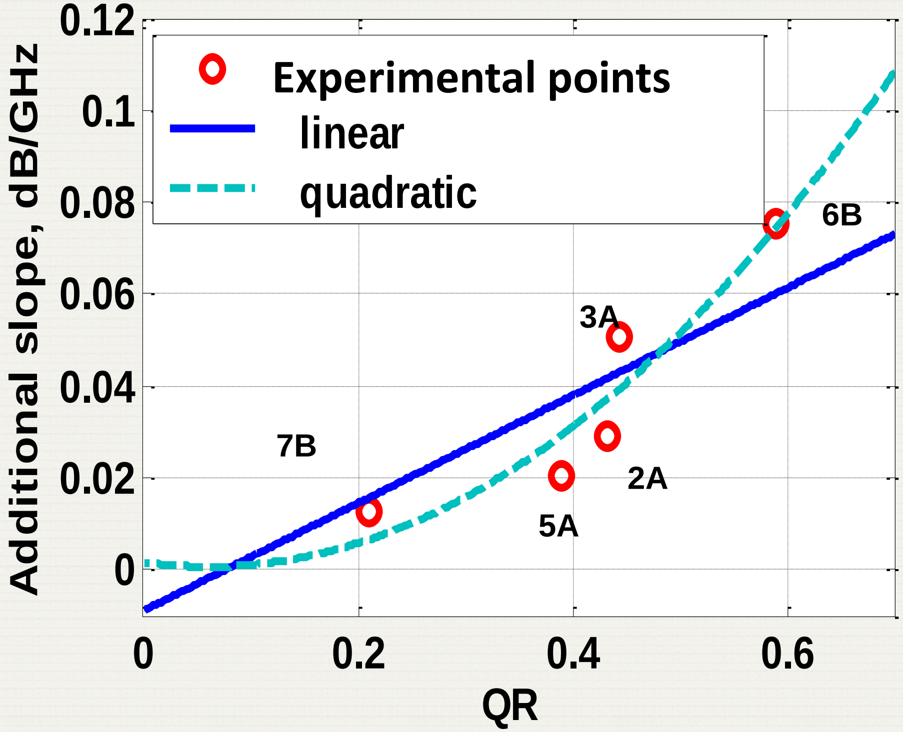
Validation of Extracted DK & DF of Laminate Dielectric



Validation of the extracted DK and DF for the laminate dielectric using the 7B test vehicle with the smoothest foil. Smooth case modeled analytically and in Q2D for $|S_{21}|$ overlap.

Additional Slope in $|S_{21}|$ due to Roughness



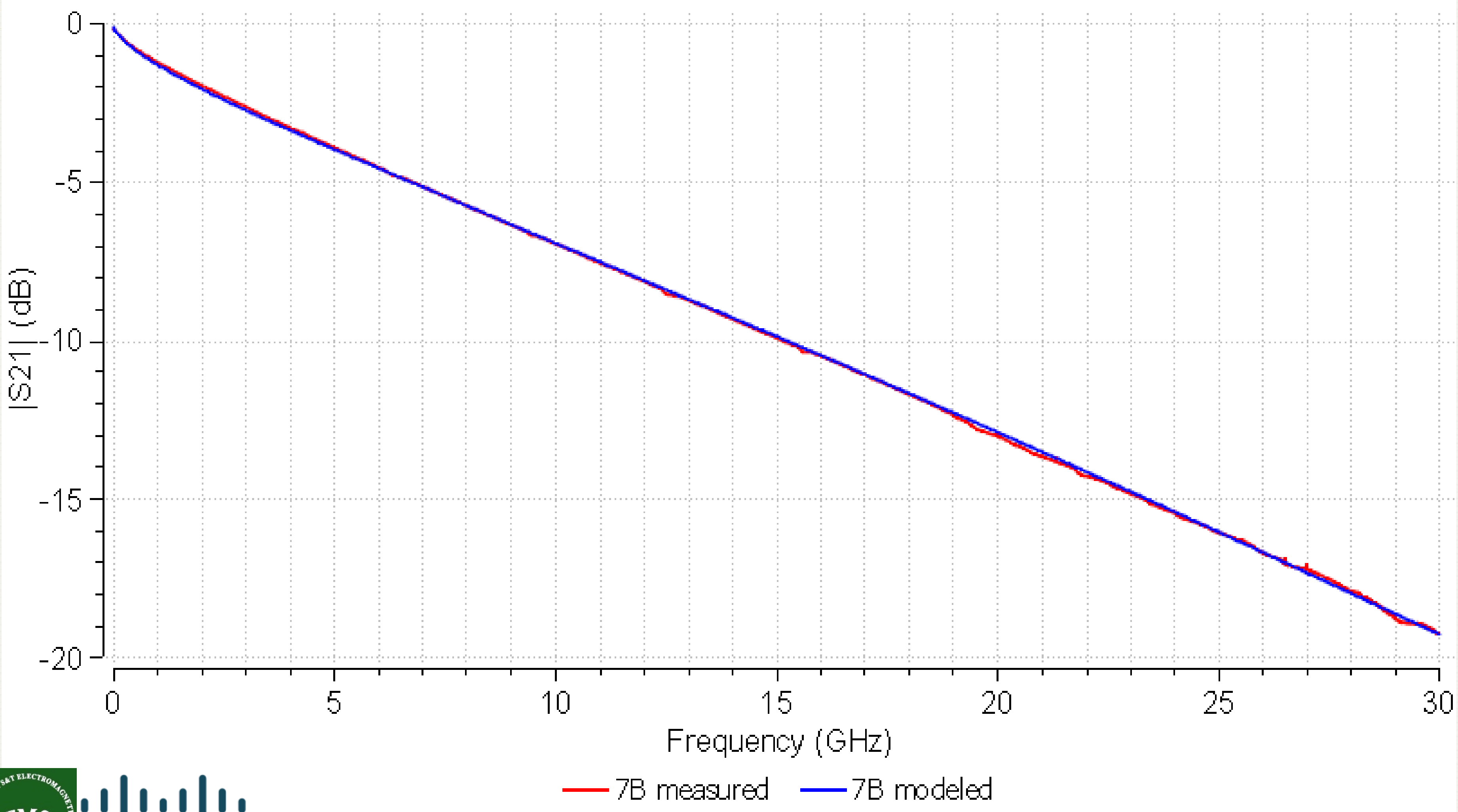


Conductor surface roughness results in an additional slope of the insertion loss as a function of frequency. The additional slope depends on the roughness factor QR.

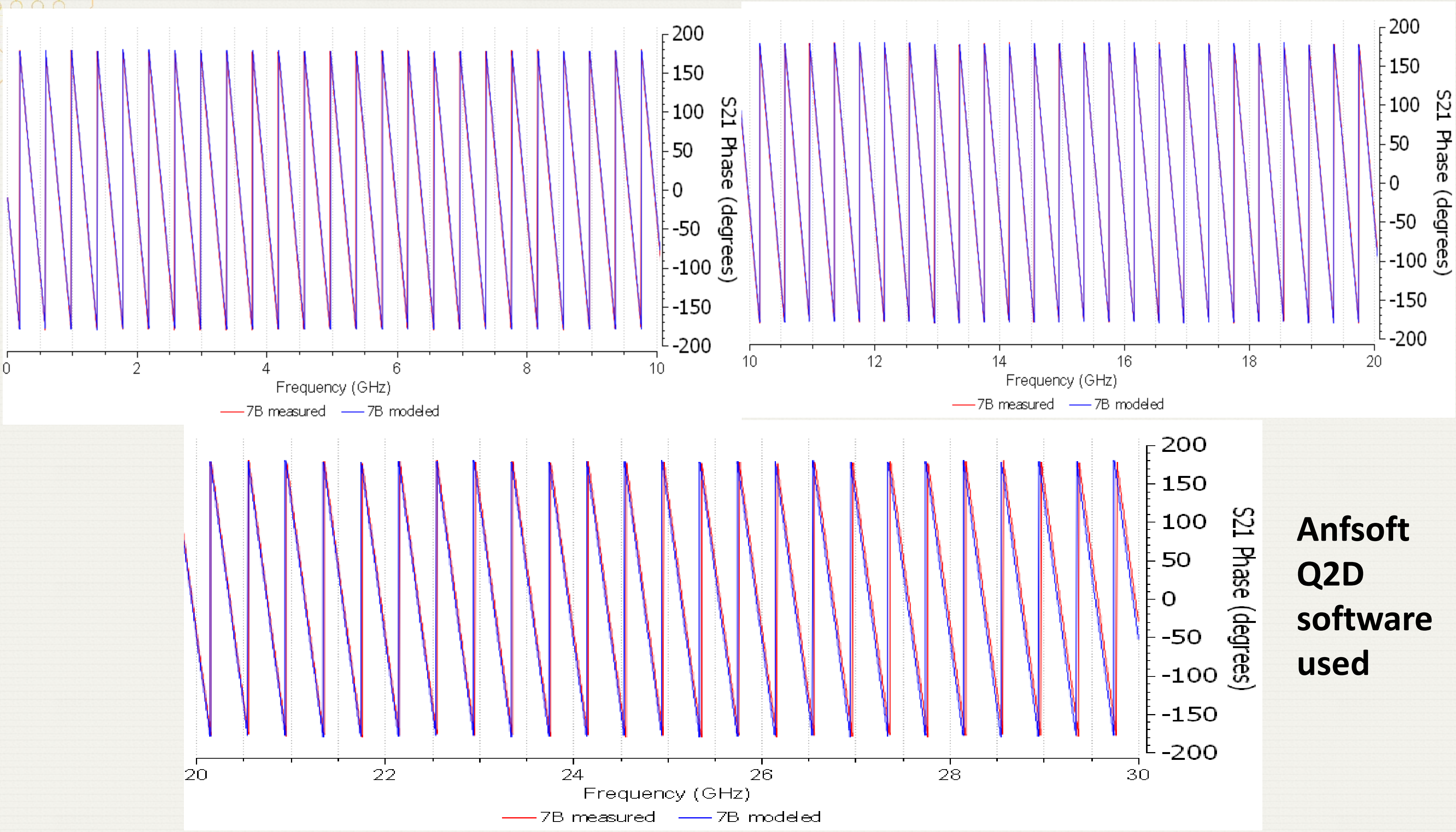
Extracted Effective Roughness Dielectric

	T_{r1}, µm (ox.)	T_{r2}, µm (foil)	$\tan\delta_{r1}$ (ox.)	$\tan\delta_{r2}$ (foil)	$\tan\delta_{r}$ (sum)	ε_{r1} (ox.)	ε_{r1} (foil)	QR_1 (ox.)	QR_2 (foil)	QR
7B	1.15	2.22	0.06	0.09	0.15	4.5	5.5	0.092	0.118	0.210
5A	1.60	2.23	0.08	0.09	0.17	5.5	6.0	0.158	0.232	0.390
3A	1.53	2.43	0.08	0.11	0.19	5.5	6.1	0.161	0.271	0.432
2A	2.50	2.04	0.10	0.09	0.19	5.7	5.6	0.224	0.220	0.444
6B	1.67	5.20	0.10	0.11	0.21	5.4	5.5	0.121	0.468	0.590

Extraction of ERD Parameters Using 2D-FEM Modeling: $|S_{21}|$ of 7B Board

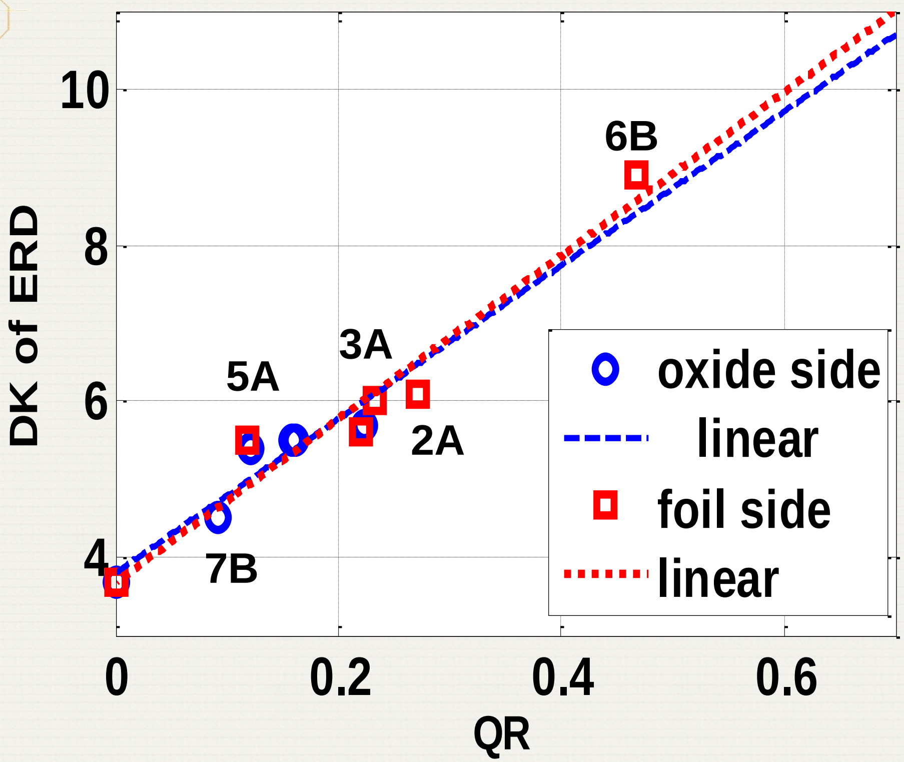


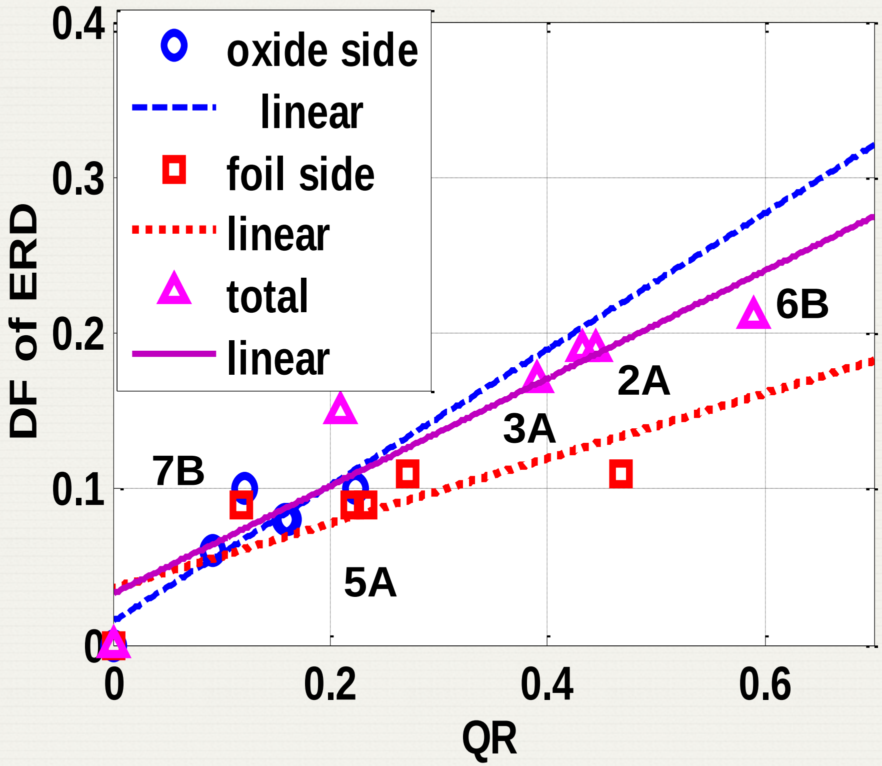
Extraction of ERD Parameters Using 2D-FEM Modeling: Phase of S_{21} of 7B



Anfsoft Q2D software used

ERD Parameters for Five Test Vehicles





Extracted using Q2D (2D-FEM) modeling effective roughness dielectric properties of roughness layers for five test vehicles have linear trends.

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. This leads 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.

Thank you and