A Signal Integrity Measuring Methodology in the Extraction of Wide Bandwidth Environmental Coefficients

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Abstract
In technology tendency, signal integrity performance gets more critical upon today's higher signal transmission speed and quantity demand in every field of applications such as computer CPU and GPU chipset levels, system operation frequency and a variety of communication bus and cable like PCI express, SATA II and AGP bus for computer system. Signal communication speed will shift from 5~10 Gbps range up to ~25Gbps depending on applications. Here we propose a simplified, easy and stable PCB wide bandwidth electrical properties extraction methodology over 20 GHz to evaluate and to measure print circuit board's electrical performance and its variation over environmental parameters, process parameters, like temperature, moisture, thermal cycling and stress. The method is based on the theory of microwave measurement calibration and in-plane stripline mathematical model and integrated with instrument control interface technology. It's using a simple two single-end or two differential pair in different length circuit traces without regular full SOLT, TRL calibration circuits or others disc structures. Measuring these two lines scattering parameters under desired conditions like temperature at this case study, the purely traces insertion loss, characteristic impedance and Dk/Df of constructed material over frequency are extracted.

Introduction
The issues of signal distortion and electromagnetic interference (EMI) deteriorate as the rise time of signals in printed circuit board (PCB) decreases. The continuously increasing high-speed, high-frequency and wideband applications, therefore, push PCB industry to enhance the performances of manufacturing technologies and material systems. Various monitoring or qualifying procedures and associated test vehicles were proposed by several famous international system companies to evaluate the qualities of the PCBs manufactured by their supply chains; for example, short pulse propagation (SPP) method of IBM, single-ended TDR/TDT to differential insertion loss (SET2DIL) method of Intel, and stripline S-parameter sweep MST S3 method of Cisco. Among these evaluation methods single-ended or differential lines were frequently used as test vehicles, since the frequency-dependent characteristic impedances, propagation constants and permittivity of PCB interconnects or transmission lines play key roles to the signal integrity (SI) issues. The propagation characteristics of interconnects or transmission lines in PCB are now required by designers to estimate the qualities of communication signals, e.g., eye-diagram evaluation. In addition to precise impedance control, PCB manufacturers now should establish the capability to characterize wideband propagation properties of interconnects and provide useful data for their customers. The permittivity of PCB material.

Uniform transmission lines, e.g., microstrip and stripline are frequently used as test vehicles for material permittivity characterization. Frequency-dependent propagation constant, are measured first based on specific recovering model, and material permittivity are then extracted from those recovered propagations. This paper demonstrates that only a pair of two test lines is needed to efficiently extract wideband propagation constant if sufficient loss or length difference was introduced. Based on the two-line method, we can extend the application to extract material coefficient of environment parameters, like temperature with good accuracy and repeatability.

Extraction Model for Dk and Df

Propagation constant characterizes the electrical behavior of a transmission line, the attenuation constant α represents per-unit-length insertion loss and phase constant β represents per-unit-length insertion phase. Propagation constant can also be viewed as the transfer function of a uniform transmission line that describe its characteristics of insertion loss and phase. Propagation constant of a uniform transmission line, therefore, embeds the information of Dk and Df. Dk and Df can be extracted indirectly from the propagation constant if it was measurable. It is well known that frequency-dependent propagation constant of line standards can be extracted from TRL calibration procedure. It had been shown that the issue of limited frequency span resulted from numerical ill conditions of TRL calibration procedure was significantly reduced by introducing sufficient line loss. Increasing the length difference of the test vehicle would introduce more line loss and stabilize the recovering procedure; therefore the extraction bandwidth was immensely increased. The value of Dk can then be extracted from the recovered phase constant β based on electromagnetic model of the associated test line. To extract Df the conductor loss must be properly estimated and take away from the recovered attenuation constant α, and then the value of Df is extracted from the electromagnetic model of the associated test line.

Propagation Constant Extraction

The TRL calibration procedure measures S-parameters of two line standards with different lengths, and the common propagation constant of the line standards can be extracted from these measured data through appropriate model. The line standards are replaced by test lines in this investigation. Fig. 1 illustrates that the test line is embedded between transitions A and B, and they account for systematic error between test ports and reference planes. The reference planes can be chosen at positions where only travelling waves of the lines exist and all the test lines have their reference planes been set at the same distances away from line ends. The reference planes of the shortest line are generally set at the middle of the line, and it is adopted in this investigation. Therefore cascade matrices T_A, T_B, and T_L represent the electrical properties of transition A, transition B, and matched line respectively. The measured S-parameters include the effects of both transitions A and B. If T_{M1} and T_{M2} respectively matrices of lines 1 and 2, they can be expressed by matrices T_A, T_B and T_L as

$$T_{M1} = T_A T_{L1} T_B = T_A \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} T_B \tag{1}$$

$$T_{M2} = T_A T_{L2} T_B = T_A \begin{bmatrix} e^{-\gamma(L_2 - L_1)} & 0 \\ 0 & e^{\gamma(L_2 - L_1)} \end{bmatrix} T_B \tag{2}$$

Then an Eigen-equation can be formed as follow,

$$T_{M2}T_{M1}^{-1} = T_A \begin{bmatrix} e^{-\gamma(L_2-L_1)} & 0 \\ 0 & e^{\gamma(L_2-L_1)} \end{bmatrix} T_A^{-1} \tag{3}$$

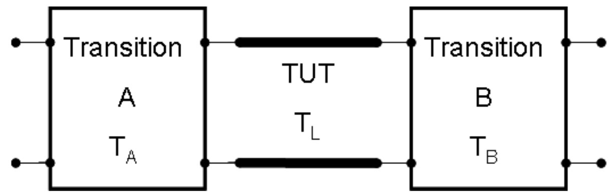


Figure 1. Connection diagram and associated cascade matrices for test line measurement. TUT represents transmission line under test.

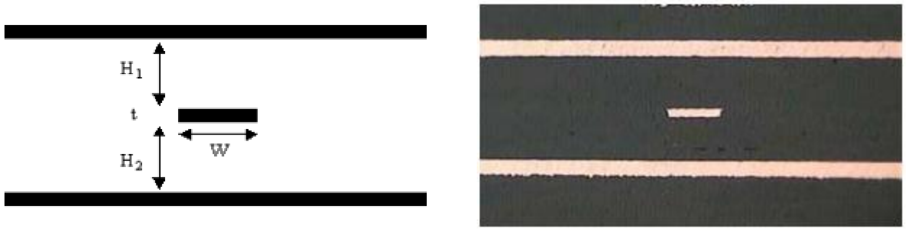
L_1 and L_2 denote the lengths of lines 1 and 2, respectively. Theoretically, (1) and (2) need to be linearly independent to provide sufficient non-repeated information to extract systematic errors that contained in T_A and T_B. If insertion loss is small and length difference near multiple half-wavelengths, the system of equations formed by (1) and (2) becomes ill-conditioned, and the measurable frequency span is limited. In general it requires several lines to stabilize numerical condition and expand frequency span. If the insertion loss, however, is increased, the numerically ill conditions will be improved. Equation (3) also indicates that matrix $T_{M1}T_{M2}^{-1}$ is similar to a diagonal matrix that contains the two eigenvalues of $T_{M1}T_{M2}^{-1}$, therefore propagation constant γ can be extracted from these eigenvalues by taking logarithmic operation.

Conductor Loss Estimation

To properly recover Df from propagation constant measurement, conductor loss must be subtracted from the measured attenuation constant α. The conductor loss can be estimated based on empirical models of characteristic impedance, conductor loss mechanisms and structure parameters of test line. The cross-sectional dimensions required for conductor loss estimation are indicated on Fig. 2(a). Fig. 2(b) shows a real trapezoid signal conductor and it will be approximated as a rectangular one with width equals to the average of the top and bottom widths of the trapezoid conductor. The conductor roughness that enhances substrate adhesion will significantly increase conductor loss and should be corrected. The work of Hammerstad is used to correct the increased conductor loss caused by trace roughness.

$$\alpha_c = \alpha_{co}\left[1 + \frac{2}{\pi}\mathrm{actan}\left(1.4\left(\frac{\Delta}{\delta}\right)^2\right)\right] \tag{4}$$

Where α_{co} is the conductor loss of smooth conductor, Δ is the root-mean-square (RMS) surface roughness, and δ is the skin depth.



(a) (b)

Figure 2. Pictorial structure diagram and associated parameters of a PCB stripline. (b) A real cross-section of a stripline embedded in PCB board.

Extractions of Dk and Df

Since stripline is used as test vehicle and the PCB material is assumed to be homogeneous, the complex relative dielectric constant ε_r or Dk and Df can be extracted by

$$\varepsilon_r = \mathrm{Dk}(1 - j\mathrm{Df}) = -\left(c\gamma^{*}/\omega\right)^2 \tag{5}$$

γ^* denotes the conductor-loss compensated propagation constant, c represents the free-space velocity of light, and ω is the radian frequency.

Measurement and Comparison

The test vehicles follows MST S3 pattern design and used to be characterized by the extraction procedure proposed in this paper. There are several lines with identical cross-section but different lengths are fabricated on the same PCB board. In MST S3 method, the longest 16” line is adopted as test line to evaluate the characteristic of the PCB and Dk and Df properties. The remaining shorter lines are used to make wideband TRL calibration, and the test line is measured under this calibrated scenario. Two stripline that have identical cross-section but sufficient length difference can be adopted as test lines of the proposed characterization procedure and efficiently recover the propagation constant with wide bandwidth. Total eight different line of TRL calibration traces from 0.59” up to 16” are adopted in this two-line Methodology investigation.

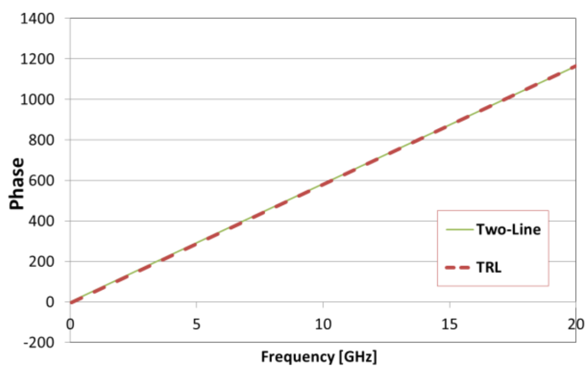


Figure 3(a). Comparison of recovered phase of two-line and TRL method.

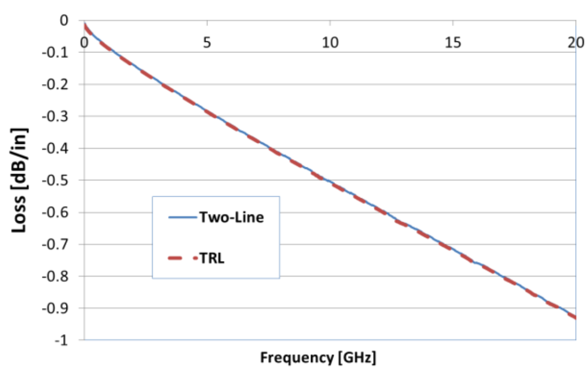


Figure 3(b). Comparison of recovered insertion loss of two-line and TRL method.

The measured S-parameters of the two test lines are under room temperature and then processed with the mathematical model mentioned above to recover the common propagation constant of the test lines. The recovered phase and attenuation constants are exhibited in Figure 3(a) and Figure 3(b) in red dash lines. The propagation property of the 16” line which is measured by TRL method under identical room temperature is compared in solid line. The measured TRL S11 and S22 parameters are smaller than -20dB over the frequency range, therefore S21 is representative of the intrinsic propagation characteristics of the 16” line. Those data measured by the two-line method are consistent with those obtained from TRL method.

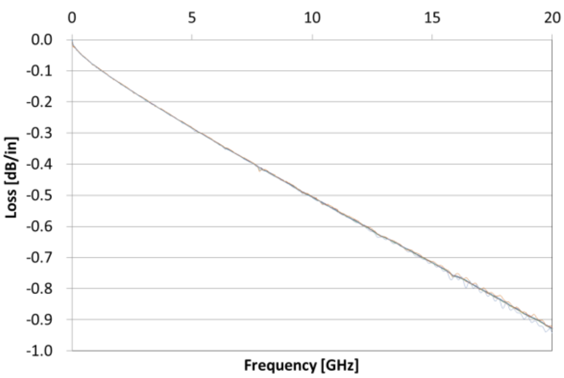


Figure 4(a). Extracted S21 thru two-line method over length difference with fixed L2.

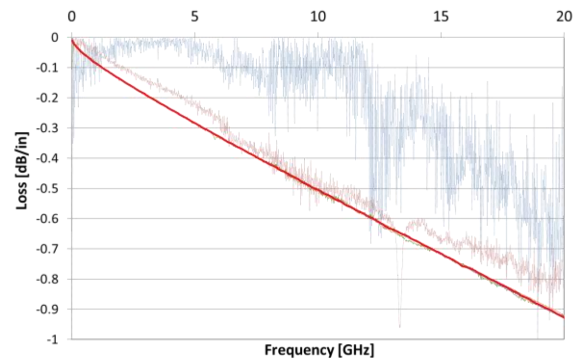


Figure 4(b). Extracted S21 thru two-line method over length difference with fixed L1.

The basic methodology model for two-line method is that sufficient loss or length difference must be introduced. The test utilizes TRL design of different trace length from 0.59”, 0.64”, 0.82”, 2.18”, 5.0”, 8.9”, 10” and 16” to understand the limitation of two-line method with Df 0.005 very low loss material. The recovered insertion loss with length difference from 10” to 15.41” pairs get matched results and all lumped in a S21 line up to 20 GHz when fixed 16” L2 in Figure 4(a). Because the area is limited for PCB design, short L1 and short delta-L with broad bandwidth is preferred for propagation constant extraction. Extracted insertion loss with fixed L1 0.59” and different L2 span (delta-L 0.05” ~ 15.41”) is exhibited in Figure 4(b). This case study show that the S21 will start get more stable up to 20 GHz when the sufficient loss, length difference greater than 1.59” (0.59” vs 2.18”) was introduced.

Coefficient of propagation constant over Temperature

Temperature coefficient is one of critical environment factor for electrical device, especially for high power consumption device and/or high temperature operation environment. The test follows previous Df 0.005 material, stripline design and two-line propagation constant extraction methods with temperature environment control from -40ºC up to 130ºC span.

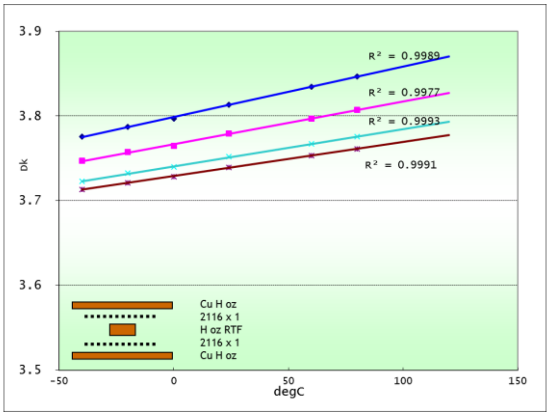


Figure 5(a). Extracted Dk over temperature and frequency at 4, 8, 15 and 20 GHz lines from up to down.

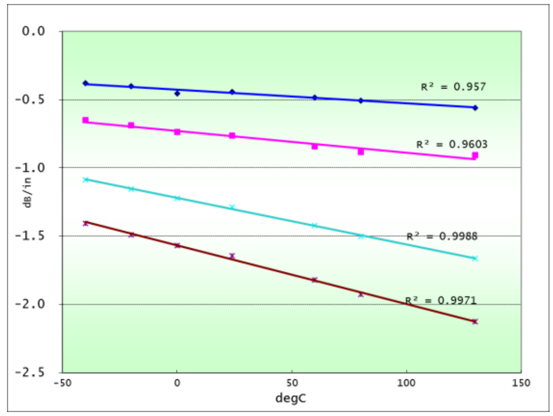


Figure 5(b). Extracted insertion loss over temperature and frequency at 4, 8, 15 and 20 GHz lines from up to down.

The extracted S21 insertion loss and Dk value was checked at -40ºC, -20ºC, 0ºC, 25ºC, 60ºC, 80ºC and 130ºC. The extracted Dk and S21 is stable with excellent linear regression results over temperature and frequency up to 20 GHz as exhibited in Figure 5(a) and Figure 5(b).

Conclusion

Based on TRL calibration algorithm, the two-line method with sufficient length difference can effectively recover the propagation constant and Dk/Df of PCB board. Larger length difference introduce more loss to stabilize the ill conditions of numerical process, and wider band characteristic properties can be extracted. This procedure is also suitable for characterizing environment parameters, like temperature dependent coefficient of Dk/Df and insertion loss of PCB board. Since only two simple and short stripline are used, this procedure could also save the PCB surface area occupied by the test vehicle and potentially a good method for mass signal integrity monitor.

A Signal Integrity Measuring Methodology

- Wide Bandwidth Environmental Coefficient

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KuenFwu Fuh / National United University

Outline

- Introduction / Two-Line Method
- Extraction model for Dk and Df
- Temp. coefficient and measuring methodology
- Extraction from un-calibrated VNA
- Conclusion

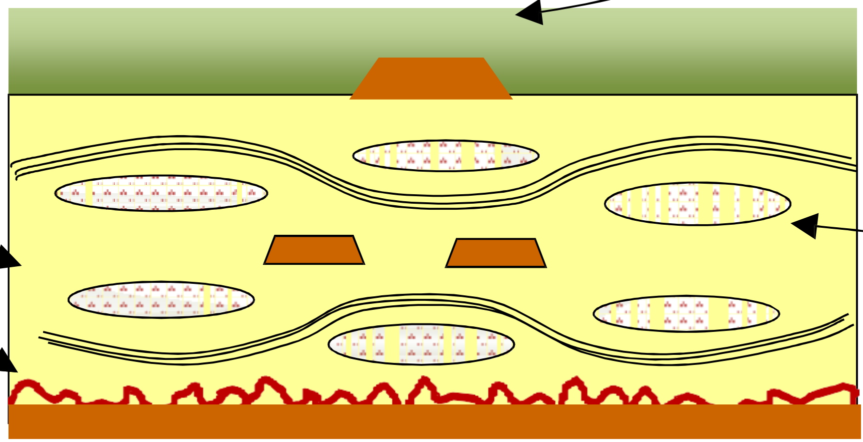
Do you really know the performance ?

Resin

Low Dk, High Df

Solder Mask

Dk/Df, thickness



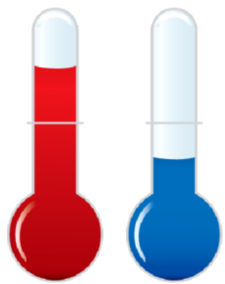
Roughness

Rz, oxide

Glass Fabric

High Dk, Low Df

Humidity



Temperature

Two-Line Method : For GHz range

- Simple method to extract insertion loss with acceptable accuracy.
- Use VNA to extract two SE / Diff lines pair in different length.
- No need build-in calibration structures.
- Effectively for mass measurement and environment impact study.

  (temp. / moisture / thermal shock..)
- Dk/Df extraction algorithms updated to account for Cu roughness.

Calibration Method

	SOLT	Unknown Thru	TRL	AFR
Calibration standards	Short Open Load Thru	Short Open Load	Thru Reflection Line(s)	2x Thru
Pros	Classic method	Thru pattern is not needed	Suitable for DUTs in PCBs or packages where commercial SOL standards are not available	- Only 2x Thru pattern is needed - Smallest number of standards is needed
Cons	- Low accuracy at high frequency (accurate high-frequency characteristics of the standards need to be provided) - Expensive calibration kit - DUT needs to have the same cable/probe ports as the commercial kit		- # of line patterns increase as frequency goes higher - Time-consuming - Discontinuities(fixtures) in all standards are assumed to be identical	- Symmetry in the 2x Thru is assumed - Minimum spacing between discontinuities in the 2x Thru is needed - Discontinuities in the 2x Thru and DUT are assumed to be identical - Not suitable for on-chip or in-package de-embedding

Source：Missouri S&T EMC Laboratory

Calibration Method

Calibration Type	Standards	Parameters	Error Terms	General Accuracy	Application
Reflection Normalization	Open or Short	S_{11} (or S_{22}, ...)	Reflection tracking	Low to medium	Reflection measurements on any port.
Transmission Normalization	Through	S_{12}, S_{21} (or S_{13},...)	Transmission tracking	Medium	Transmission measurements in any direction and between any combination of ports.
TOSM (2-port, 3-port or 4-port) or UOSM	Open, Short, Match[1] (at each port), Through[2] (between all combinations of 2 ports)	All	Reflection tracking, Source match, Directivity, Load match, Transmission tracking,	High	Reflection and transmission measurements on DUTs with 2, 3, or 4 ports; classical 12-term error correction model.
TRL (2-port, 3-port or 4-port)	Reflect (at both ports), Through, Line1, Line2/3 (optional), combination with TRM (optional)	All	Reflection tracking, Source match, Directivity, Load match, Transmission tracking	High, high directivity	Reflection and transmission measurements on DUTs with 2, 3, or 4 ports, especially for planar circuits. Limited bandwidth.
TNA (2-port, 3-port or 4-port)	Through, Attenuation, Symmetric network	All	Reflection tracking, Source match, Directivity, Load match, Transmission tracking	High, lowest requirements on standards	Reflection and transmission measurements on DUTs with 2, 3, or 4 ports, especially for planar circuits.

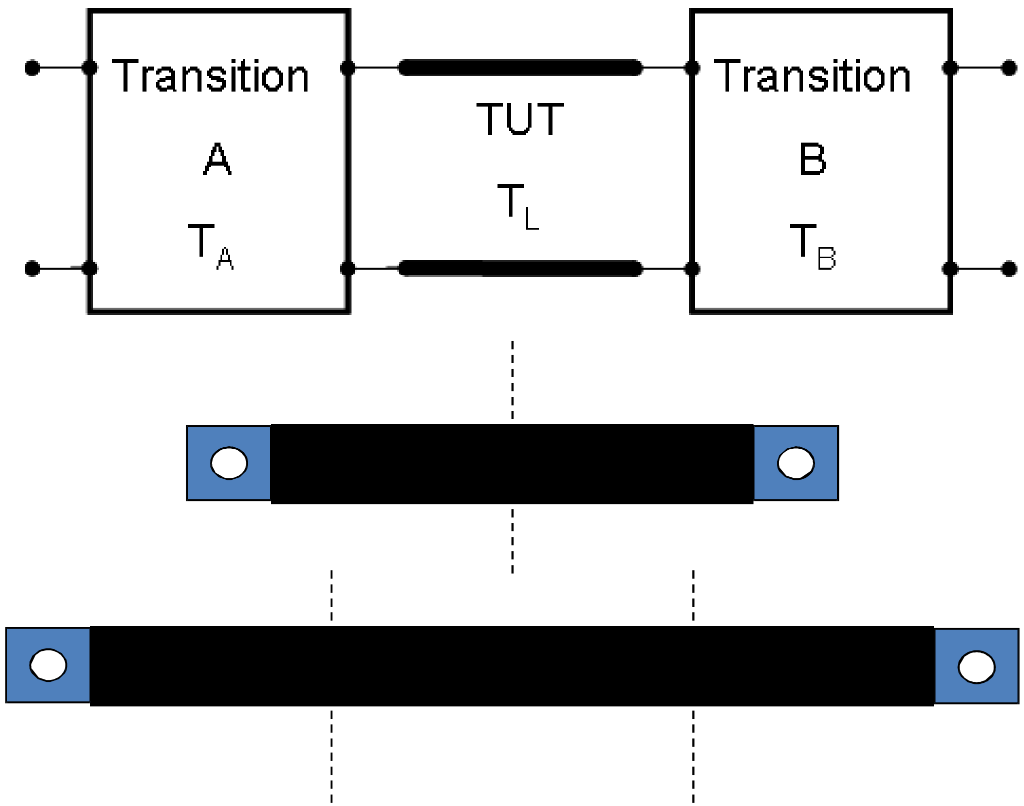
Source : ROHDE&SCHWARZ

Industrial Methodology

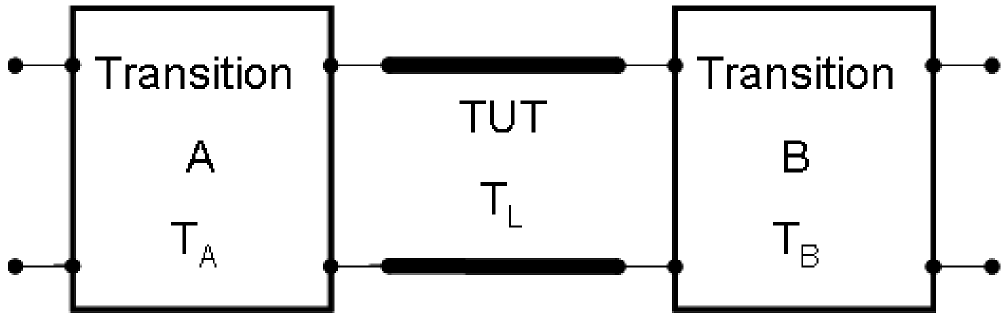
Developed by		Facility	Output	Bandwidth	Suitability	Technically	Remark
SPP	Ref: IBM	TDR 2P	Single-End S-parameters Dk,Df, R,L,G,C	~20GHz	Engineering certification	High	extract $\alpha_c+\alpha_d$ Count Rz in Df
MST	Ref: CISCO	VNA 2P	Single-End S-parameters Dk,Df	~20GHz	Engineering certification	Middle	extract $\alpha_c+\alpha_d$
SET2DIL	Ref: INTEL	TDR 2P	SDD21	~12GHz	Quality Control	Low	overall loss include via
Two-Line		VNA 2P/4P	SE, Diff S-parameters Dk,Df	~20GHz	Engineering certification Quality Control	Low	extract $\alpha_c+\alpha_d$

Two-Line Method

Reference Planes



Two-Line Method



$$T_{M1} = T_A T_{L1} T_B = T_A \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} T_B$$

$$T_{M2} = T_A T_{L2} T_B = T_A \begin{bmatrix} e^{-\gamma(L_2 - L_1)} & 0 \\ 0 & e^{\gamma(L_2 - L_1)} \end{bmatrix} T_B$$

Eigen-Equation for γ

$$T_{M2}T_{M1}^{-1} = T_A \begin{bmatrix} e^{-\gamma(L_2-L_1)} & 0 \\ 0 & e^{\gamma(L_2-L_1)} \end{bmatrix} T_A^{-1}$$

$$\gamma(L_2\text{-}L_1) = \alpha\Delta L + j\beta\Delta L \ \sim \ 0 + jn\pi \ ?$$

Eigen-Equation for γ

$$T_{M2}T_{M1}^{-1} = T_A \begin{bmatrix} e^{-\gamma(L_2-L_1)} & 0 \\ 0 & e^{\gamma(L_2-L_1)} \end{bmatrix} T_A^{-1}$$

$$\gamma(L_2-L_1) = \alpha\Delta L + j\beta\Delta L \;\sim\; 0 + jn\pi \text{ ?}$$

Conductor-Loss Estimation

$$\alpha_c = \alpha_{co}\left[1 + \frac{2}{\pi}\operatorname{atan}\left(1.4\left(\frac{\Delta}{\delta}\right)^2\right)\right]$$

Δ is the root-mean-square (RMS) surface roughness, and δ is the skin depth.

Conductor-Loss Estimation

α_{co} is the conductor loss of smooth conductor, it was calculated by empirical models of characteristic impedance, conductor loss mechanisms and structure parameters of test line

$$\alpha_c = \alpha_{co}\left[1 + \frac{2}{\pi}\operatorname{actan}\left(1.4\left(\frac{\Delta}{\delta}\right)^2\right)\right]$$

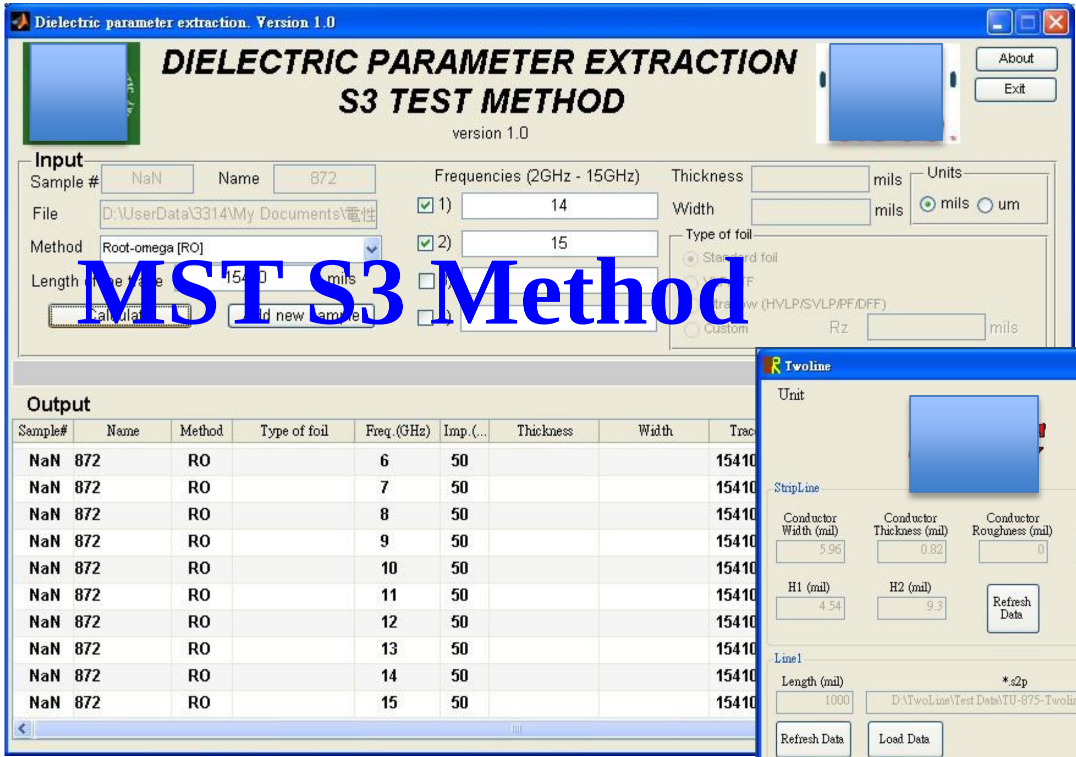
Δ is the root-mean-square (RMS) surface roughness, and δ is the skin depth.

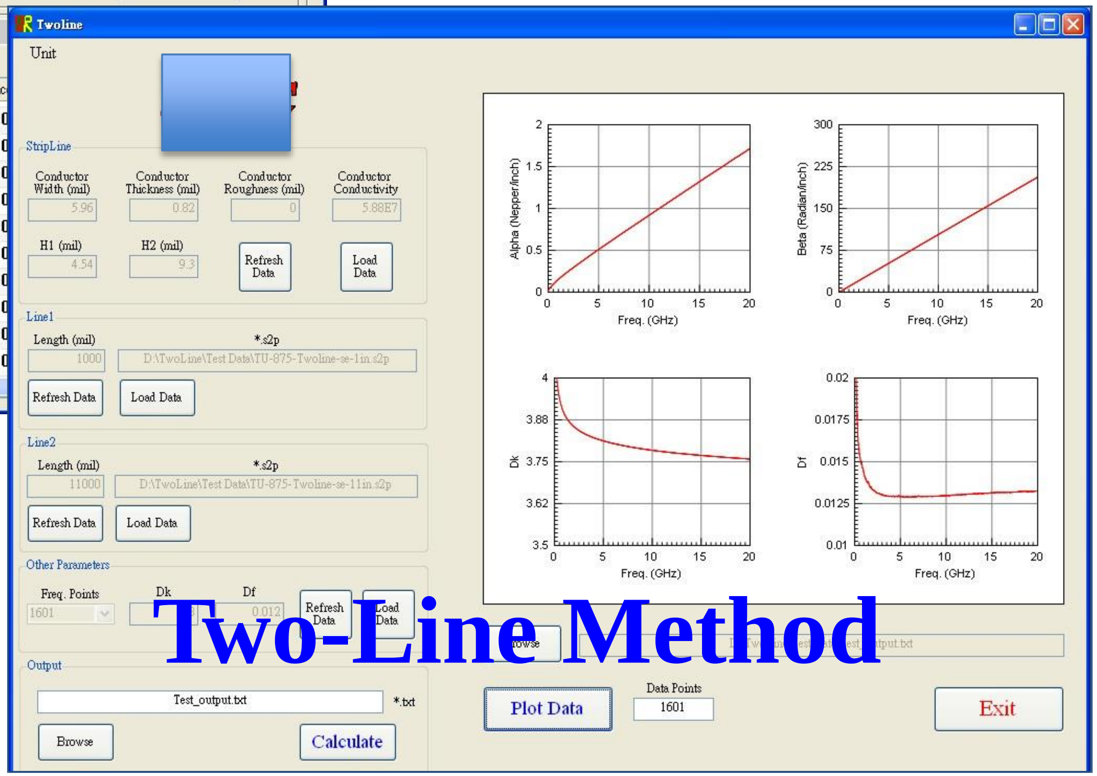
* Work of Hammerstad

Extractions of Dk and Df

$$\varepsilon_r = \mathrm{Dk}(1 - j\mathrm{Df}) = -\left(c\gamma^* / \omega\right)^2$$

γ^* denotes the conductor-loss compensated propagation constant, c represents the free-space velocity of light, and ω is the radian frequency.


Dielectric parameter extraction. Version 1.0
DIELECTRIC PARAMETER EXTRACTION
S3 TEST METHOD
version 1.0
About
Exit
Input
Sample #
Name
File
Method
Root-omega [RO]
Frequencies (2GHz - 15GHz)
Thickness
Width
mils
Units
mils
um
Type of foil
Output
Sample#
Name
Method
Type of foil
Freq.(GHz)
Thickness
Width
MST S3 Method


Twoline
Unit
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Conductor Width (mil)
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Conductor Roughness (mil)
Conductor Conductivity
H1 (mil)
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Refresh Data
Load Data
Line1
Length (mil)
*.s2p
Line2
Other Parameters
Freq. Points
Dk
Df
Output
Test_output.txt
*.txt
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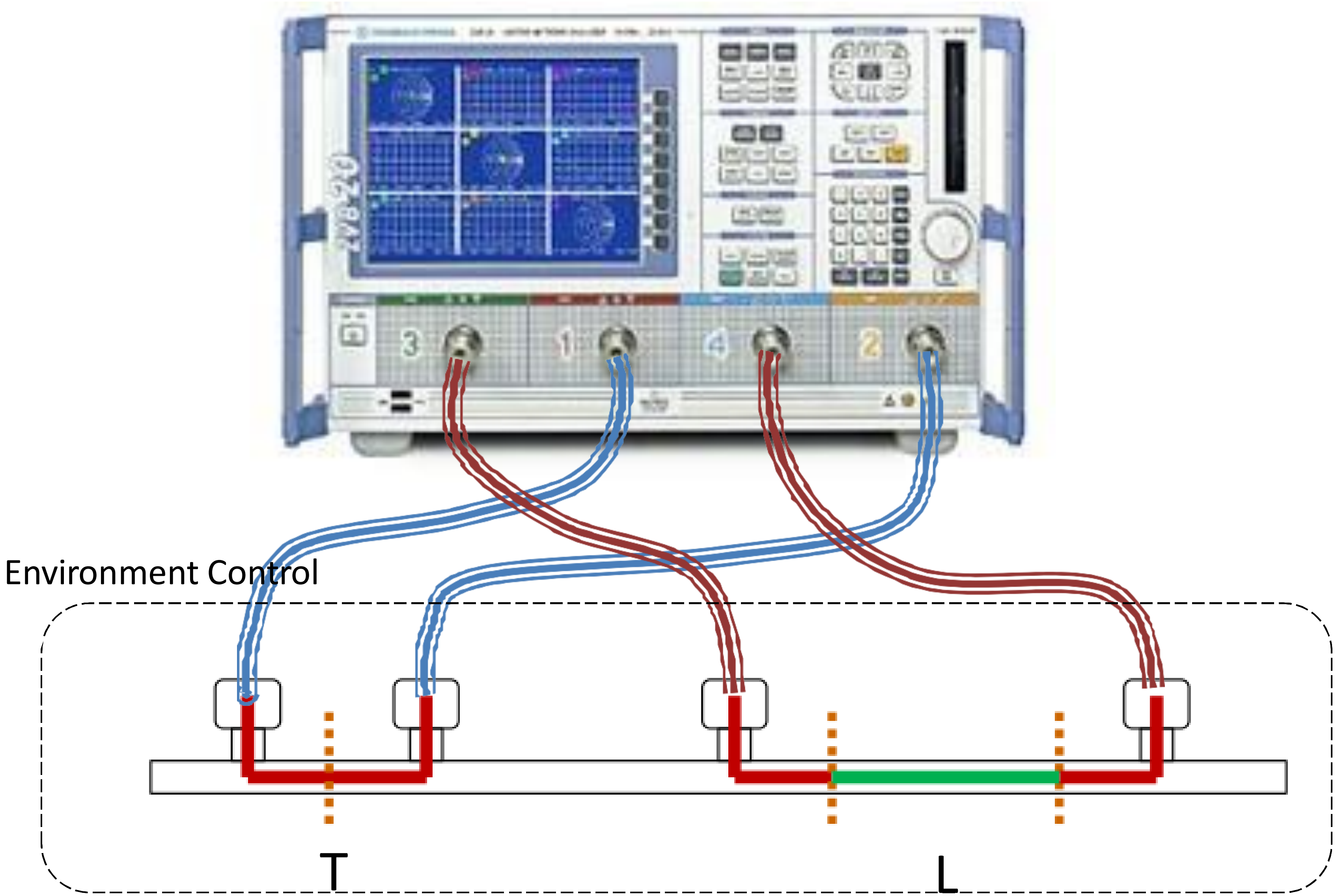
Df
Freq. (GHz)
Two-Line Method

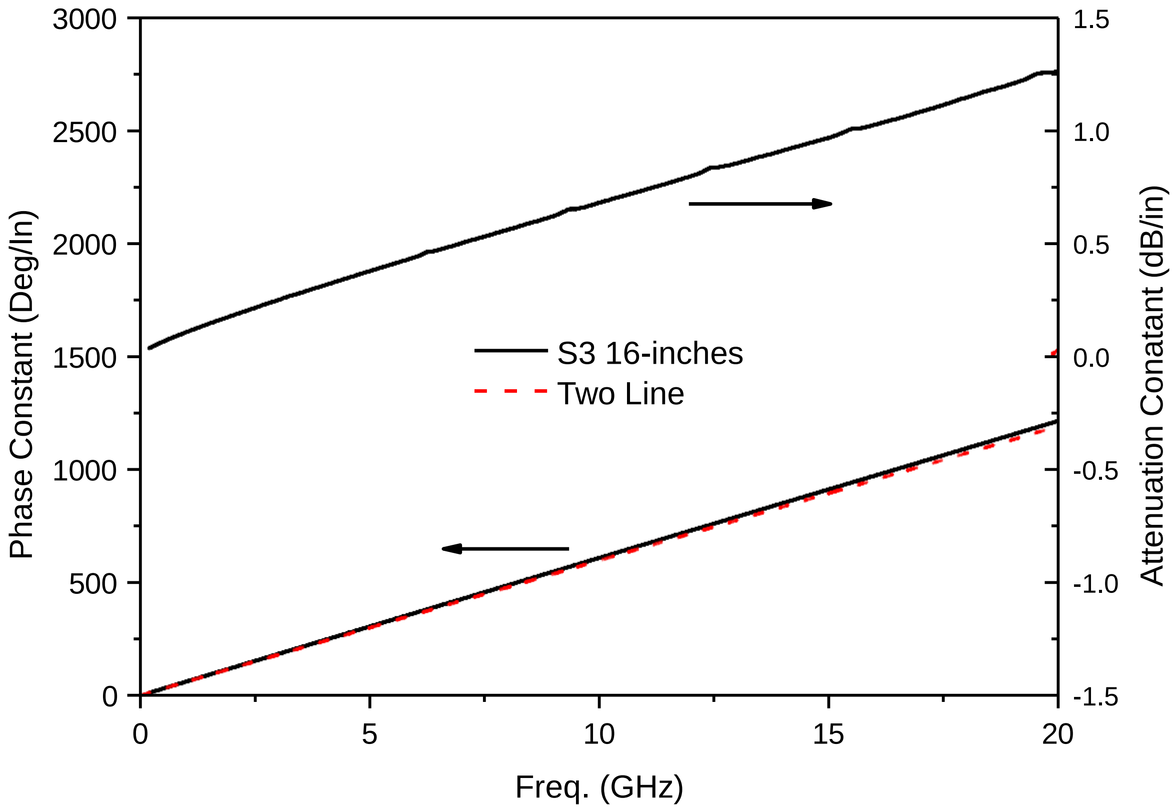

3
1
4
2
Environment Control
T
L

Signal distortion over temperature

-40C ~ 130C

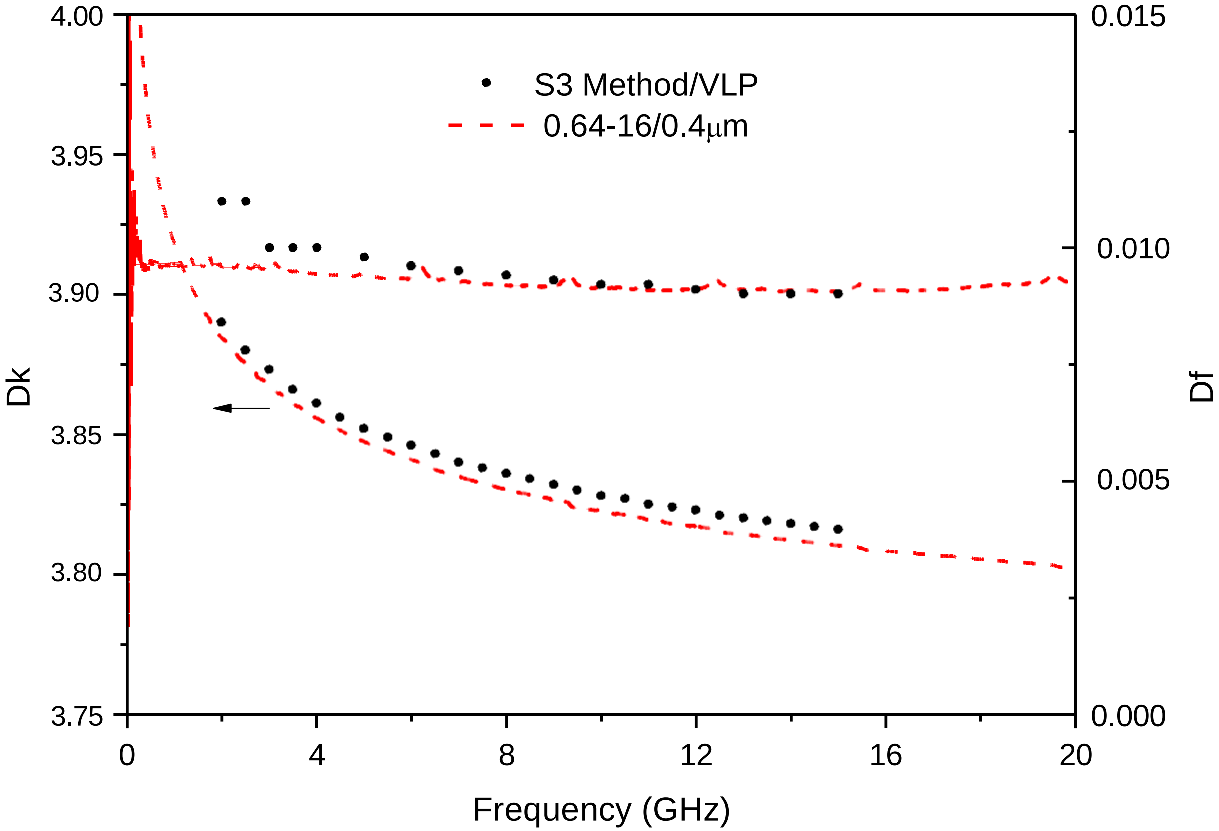
Measurement Results

Comparison of recovered propagation constants and those obtained from MST S3 method



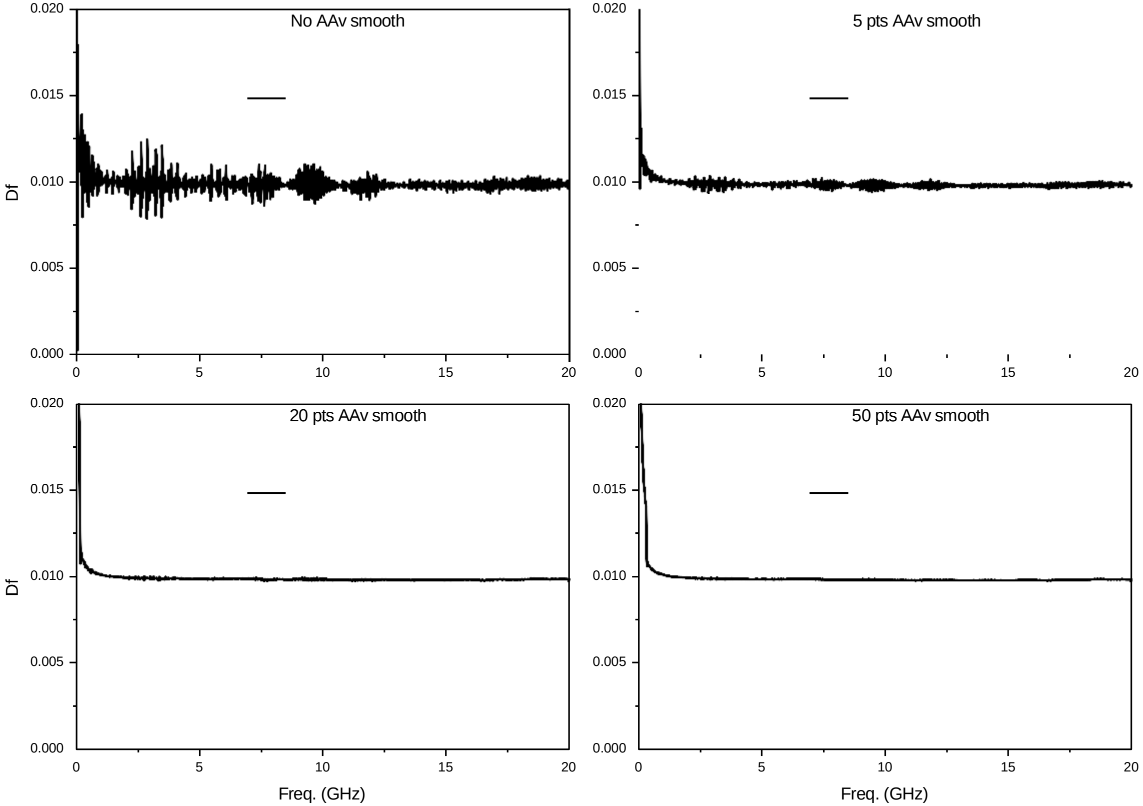
Measurement Results

Comparison of recovered dispersive Dk's and Df's with those obtained from MST S3 method.

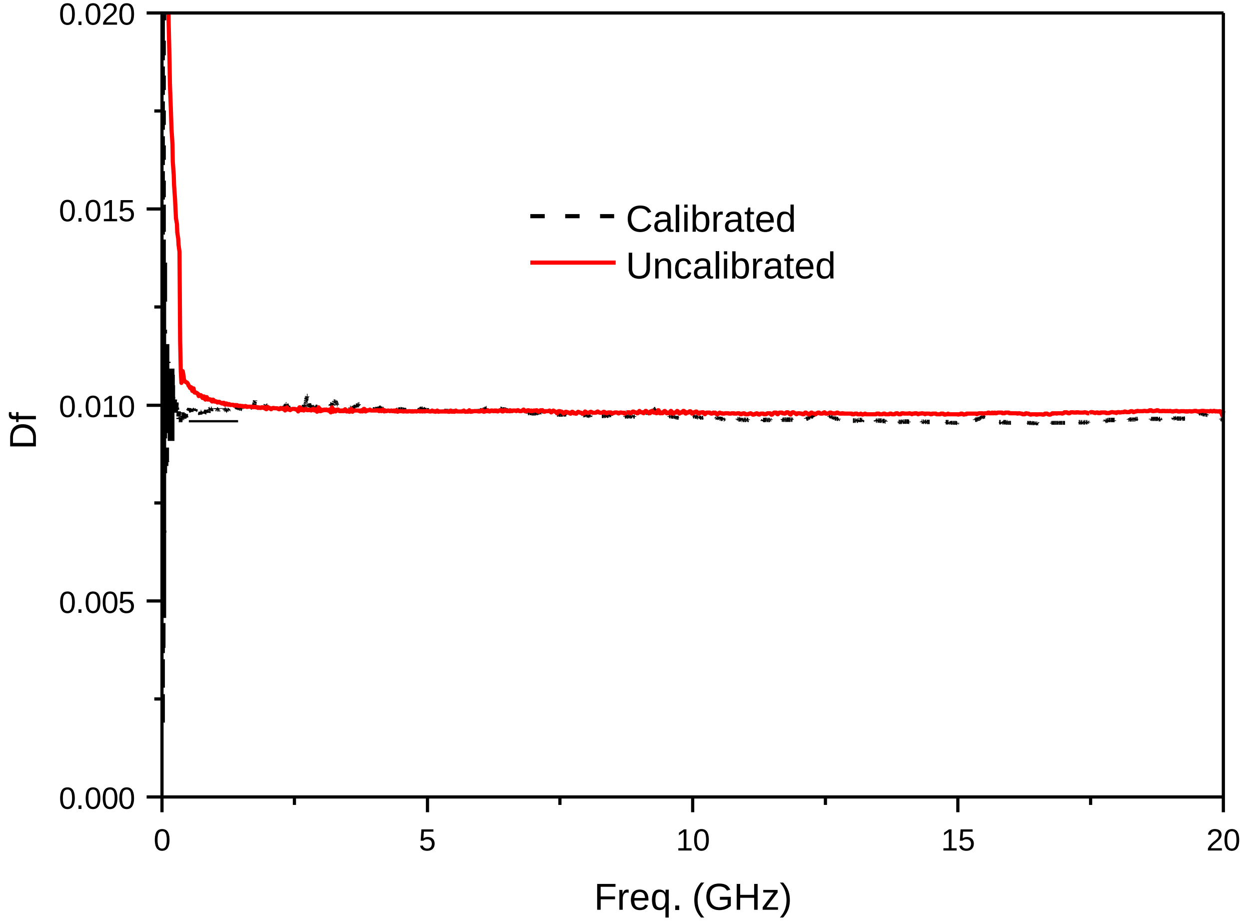


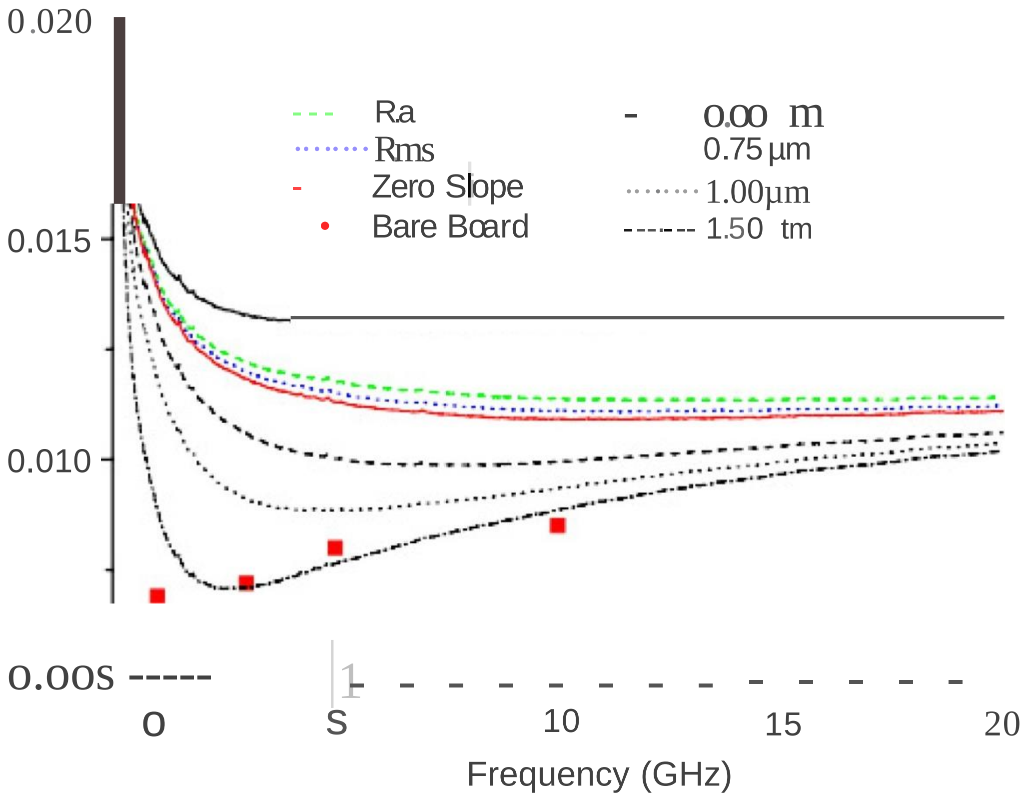
Un-calibrated S-Parameters

Apply adjacent average (AAv) to smooth the recovered dispersive Df's extracted from un-calibrated S-parameters.



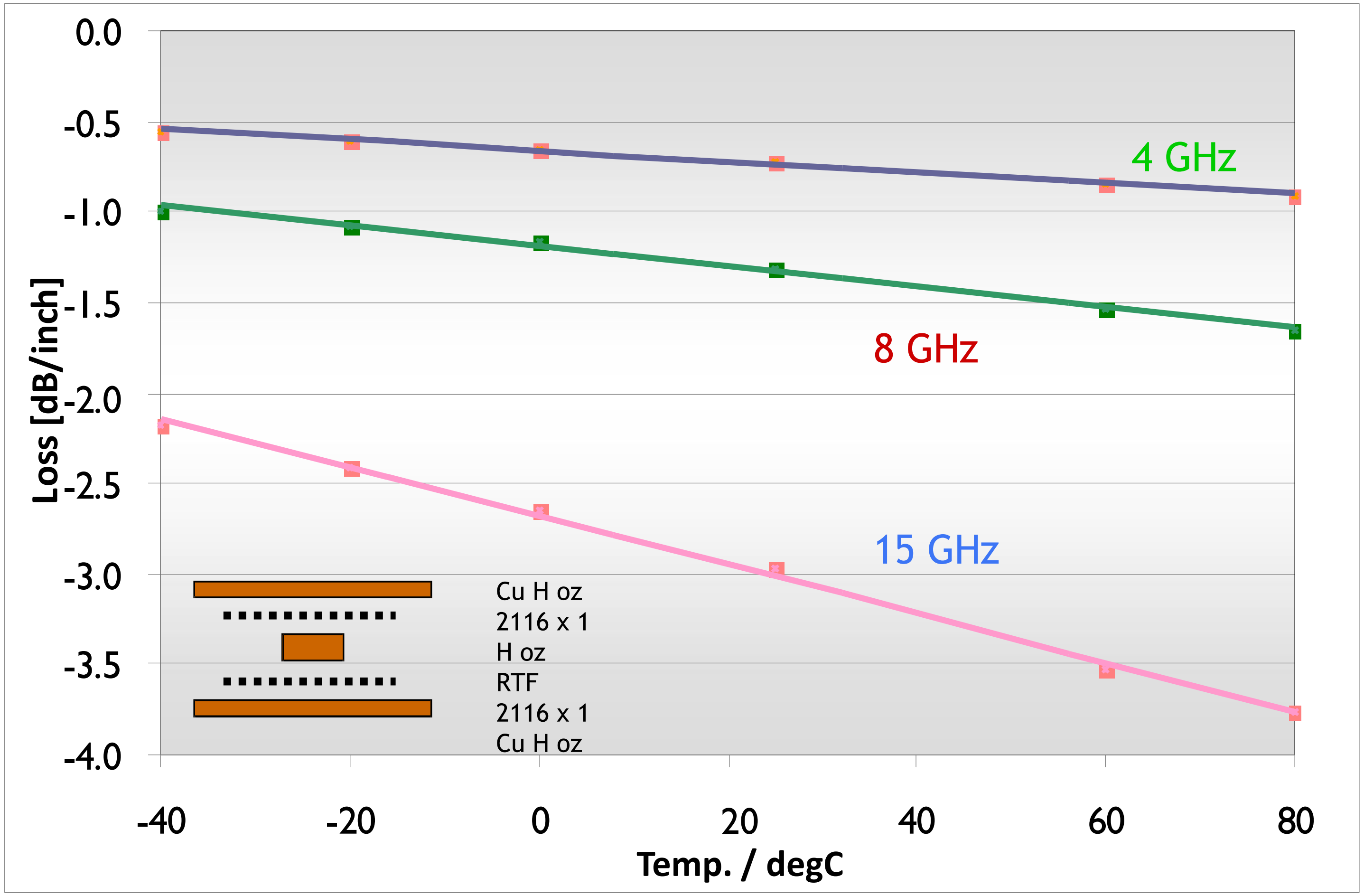
Calibrated vs. Un-calibrated



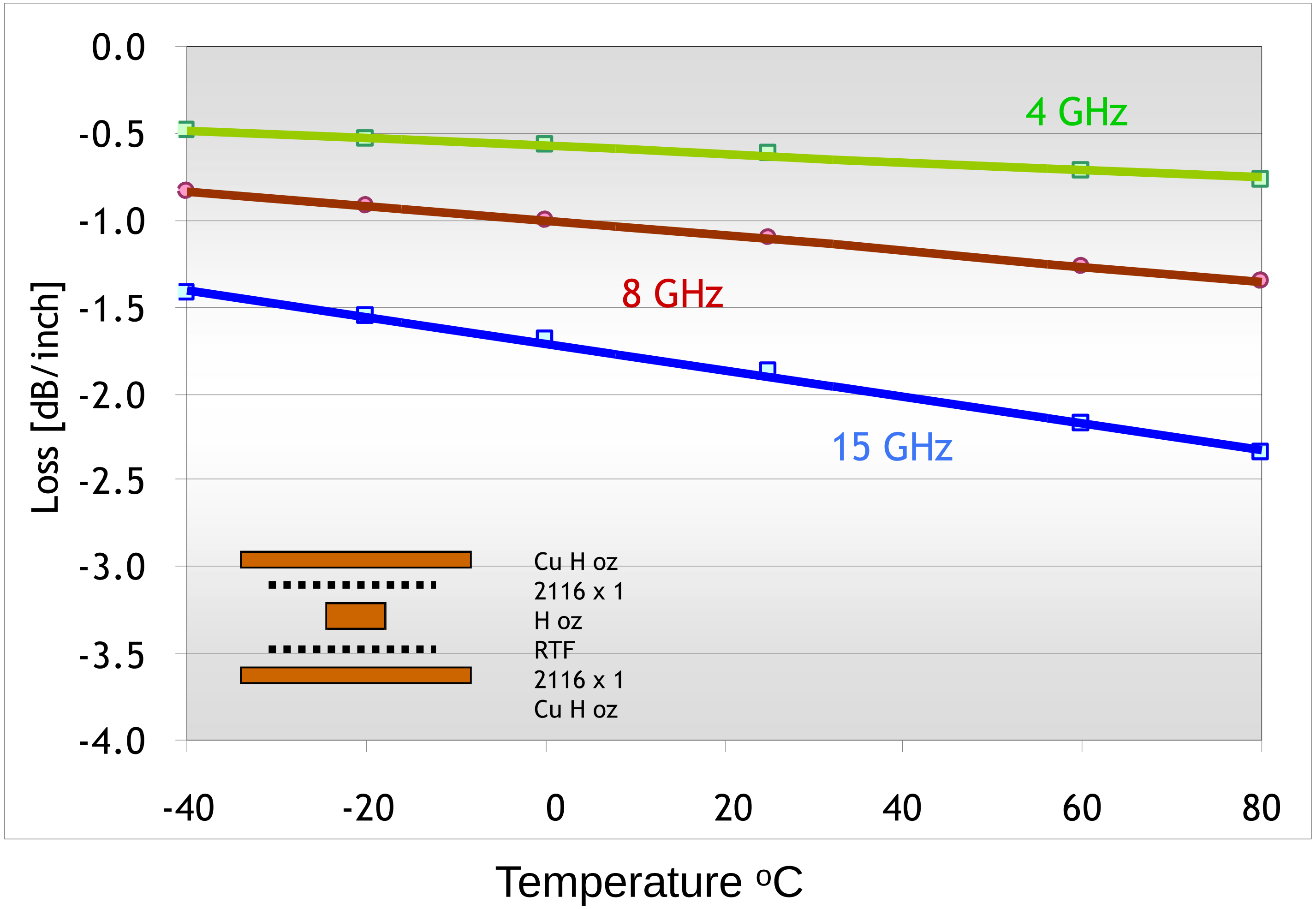


· ·timation of dispersive tan 6 based on different rougl nes or conductor-lo ·. a ·sumption ·.

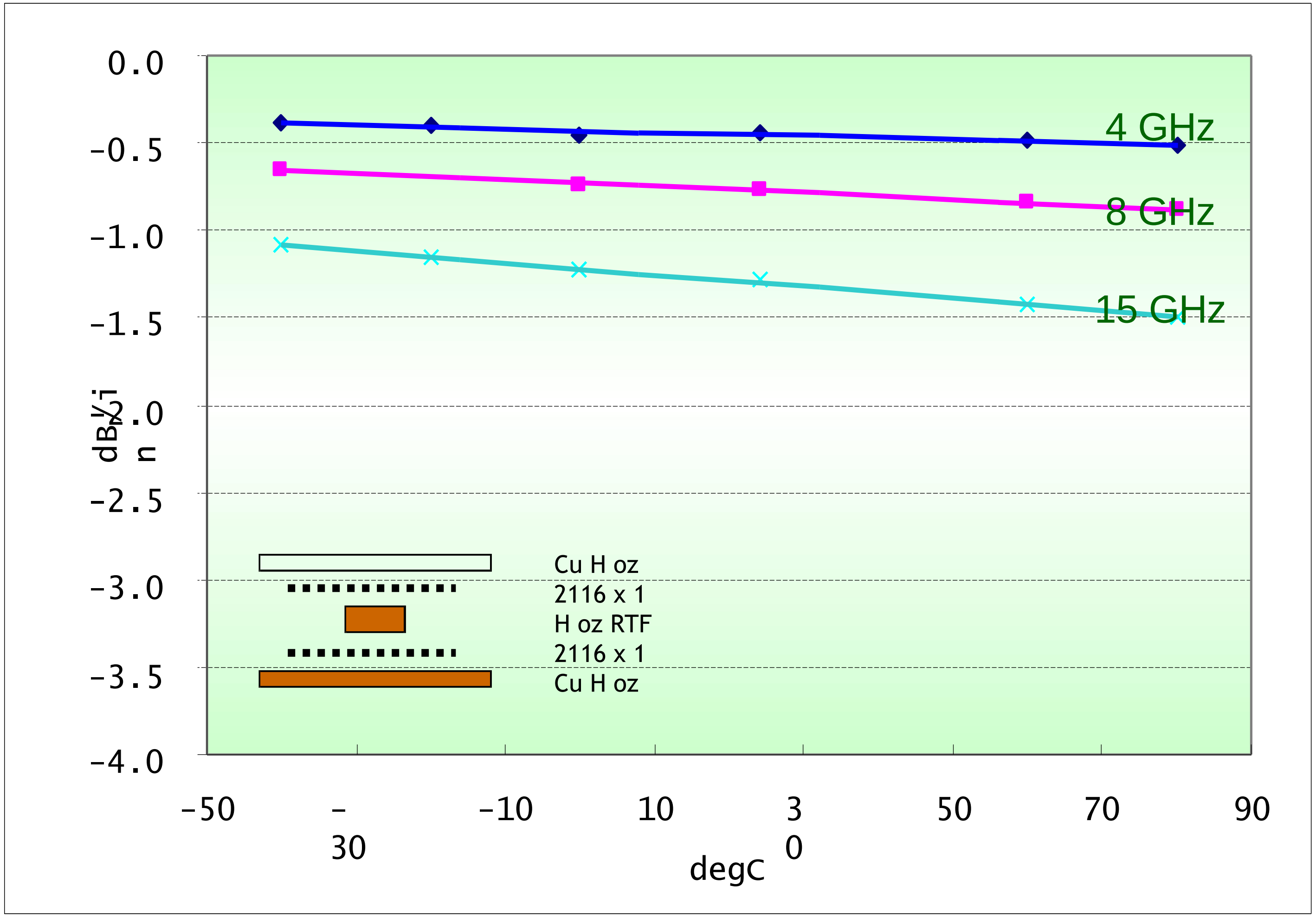
Standard FR-4



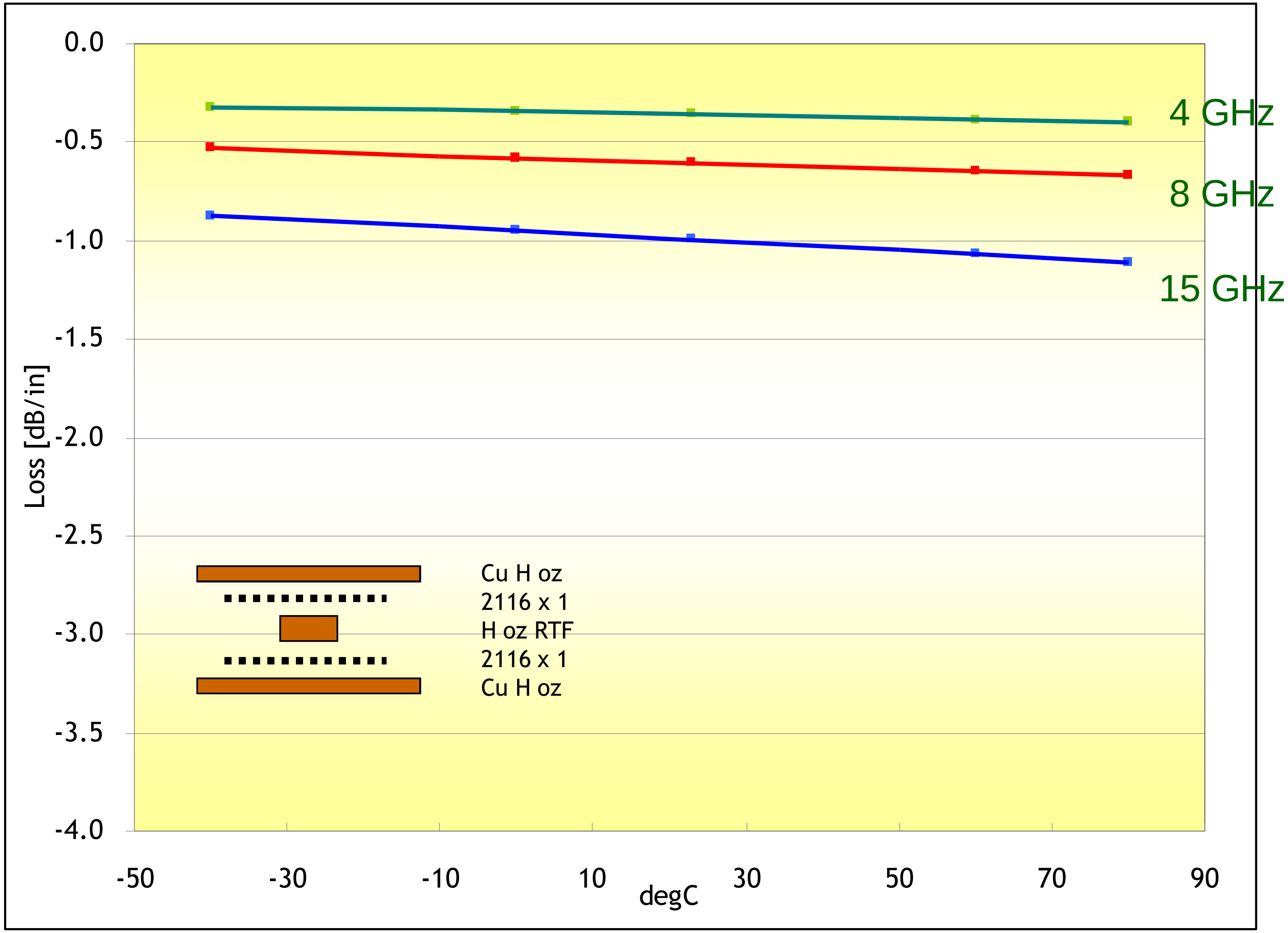
Mid-Loss


0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
Loss [dB/inch]
4 GHz
8 GHz
15 GHz
Cu H oz
2116 x 1
H oz
RTF
2116 x 1
Cu H oz
-40
-20
0
20
40
60
80
Temperature oC

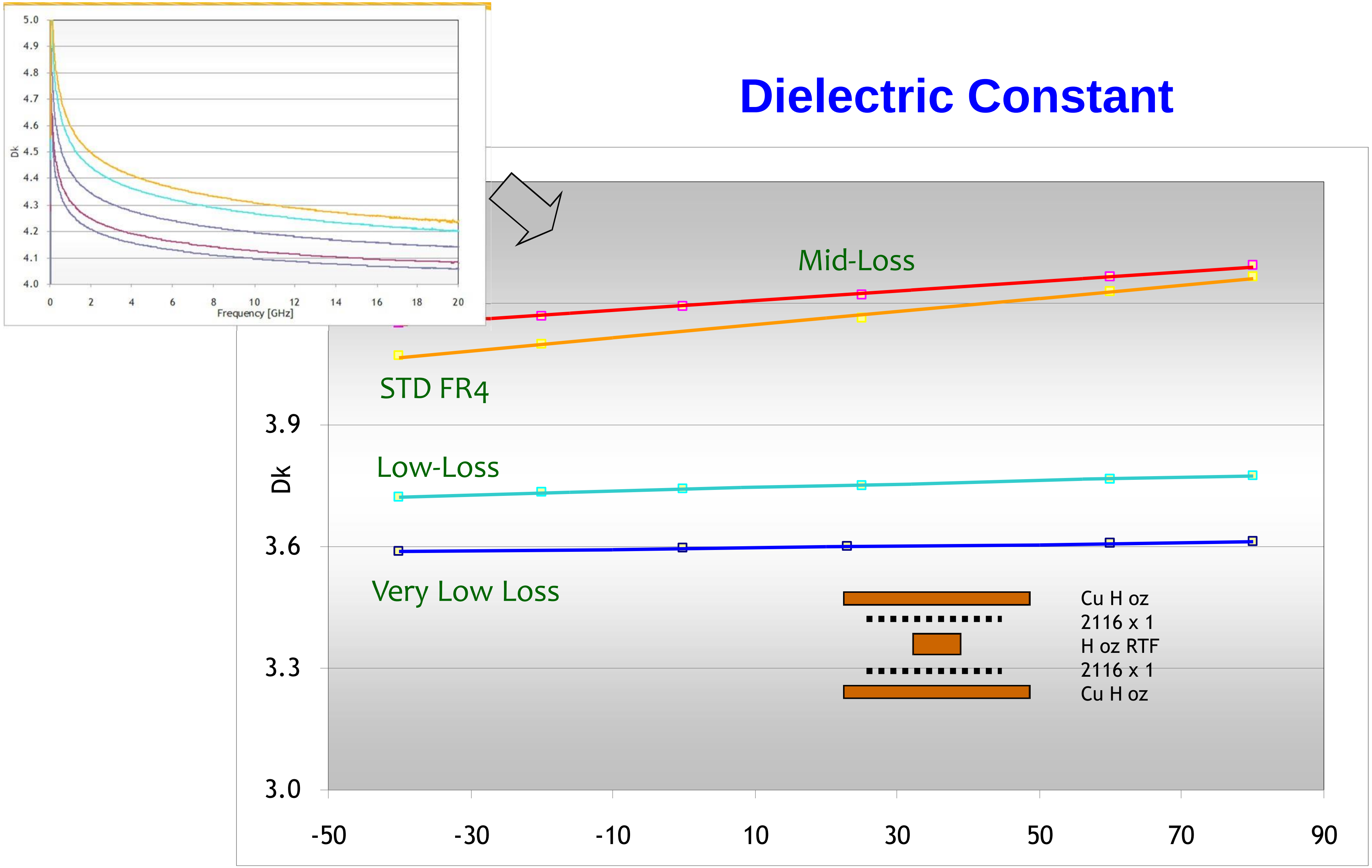
Low Loss


0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
dB/in
4 GHz
8 GHz
15 GHz
Cu H oz
2116 x 1
H oz RTF
2116 x 1
Cu H oz
-50
-30
-10
10
30
50
70
90
degC

Very Low Loss



Dielectric Constant



Dk @ 15 GHz

Two-Line Method : For GHz range

- Simple method to extract insertion loss with acceptable accuracy.
- Use VNA to extract two SE / Diff lines pair in different length.
- No need build-in calibration structures into the board.
- Effectively for mass measurement and environment impact study.
- Dk/Df extraction algorithms updated to account for Cu roughness.

Discussion