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Signal Link-Path Characterization Up To 20 GHz Based On A Stripline Structure

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***Abstract*—Dielectric properties and losses are two critical issues in signal link-path characterization. To obtain the substrate dielectric properties for a planar transmission line, an analytical solution is derived and validated based on a stripline structure and measured scattering parameters with TRL de-embedding. The characterized dielectric property is used to evaluate dielectric loss and conductor loss. The total loss is thereby found from their summation. The calculated total loss is compared to the measured total loss, and the conductor loss and dielectric loss are then quantifiable. Since the conventional description using the loss tangent and dielectric constant to represent material properties is usually insufficient as the frequency reaches 20 GHz, a Debye model is proposed. The second order Debye parameters are subsequently extracted using a genetic algorithm. A full wave simulation is implemented to verify the determination of two-term Debye model parameters.**

Keywords-signal link-path characterization; dielectric property; Debye dispersion law; loss quantification; stripline; TEM wave; TRL de-embedding; genetic algorithms

I. INTRODUCTION

Switching speeds for signals propagating in modern digital systems are getting progressively faster. When the on-board data rates exceed hundreds of Mb/s, or especially in the Gb/s range, traces on the printed circuit boards (PCBs) no longer behave as simple conductors, but instead exhibit high-frequency effects, and behave as transmission lines that are used to transmit or receive electrical signals to or from neighboring components [1]. In addition, timing issues associated with the transmission lines are becoming a significant percentage of the total timing margin. Therefore, an accurate simulation of high frequency effects, such as dielectric dispersion and skin effect loss, on transmission lines is necessary for high-speed digital design. Otherwise, improper modeling of these transmission lines will result in poor SI (Signal Integrity) analyses. Hence, characterizing material dielectric properties to support accurate full wave modeling, and quantifying losses to provide an appropriate loss budget in a signal link-path analyses become vital in modern digital systems. The dielectric properties of the substrates used in PCBs are usually unknown exactly. Furthermore, the conventional description using loss tangent and a frequency independent dielectric constant to represent material properties is not sufficient as the frequency approaches 20 GHz. It is therefore beneficial to develop an accurate method to characterize the dispersive substrate materials and quantify losses including dielectric loss and conductor loss so that the full wave modeling can be performed precisely, and the signal link-path loss budgets can be adjusted properly.

The knowledge of complex dielectric properties of materials is fundamental in the study of electromagnetic energy absorption, high-speed IC (Integrated Circuit) package, and multi-gigabit signaling link-path characterization [2]-[5]. Numerous techniques are reported to characterize material dielectric properties over different bands of frequencies [2-9]. Each technique has its advantages for a specific material or a certain frequency band. For example, the resonant-cavity technique is widely used for obtaining dielectric properties at high frequencies with high accuracy, but it is limited to narrow-band frequencies. The coaxial-line technique achieves wideband material property characterization with no leakage and radiation losses, but it is only applicable to powder or liquids. Furthermore, the port de-embedding, which is critical as the frequency goes up to 20 GHz, is difficult. Direct measurement of the dielectric constant and loss tangent can be made on an impedance analyzer but this is only available at low frequencies with a narrow frequency span. However, these techniques characterize substrate material properties for PCBs either at a number of discrete frequencies distributed over a narrow range or the method is not applicable for substrate materials. These limitations make accurate full-wave modeling either difficult or degradation accuracy. In addition, the signal link-path loss budget depends on the complex dielectric properties of the substrate materials. Therefore, the objective herein is to develop an accurate method to characterize the substrate materials for a stripline geometry; to simultaneously quantify the conductor loss and dielectric loss; and to provide a dispersion law for the substrate material instead of measured "raw" data for full-wave modeling.

The method presented herein for signal link-path characterization is based on scattering parameter (S-parameter) measurements with TRL de-embedding techniques, analytical

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models (stripline formulations), the Debye dispersion law (Debye formulations), and genetic algorithms. Section II discusses the theoretical background, formulations and application of a GA (genetic algorithm). Measurement with de-embedding, material characterization, loss quantification, and the determination of two-term Debye parameters, and full-wave modeling are presented in Section III. Conclusions are summarized in Section IV.

II. THEORETICAL BACKGROUND AND FORMULATIONS

A. Reconstruction of permittivity from measured S-paramters

For a stripline having a cross section as shown in Figure 1, the TEM wave is the fundamental propagation mode. The first higher order mode for a wide stripline for *b/w*>0.35, is determined by [10]

$$f_{c1} = \frac{15}{\sqrt{\varepsilon_r^{'}}\left(w + b\frac{\pi}{4}\right)}, \tag{1}$$

where b and w are in centimeters; f_{c1} is in GHz; and $\varepsilon_r^{'}$ is the relative permittivity of the dielectric material of the stripline.

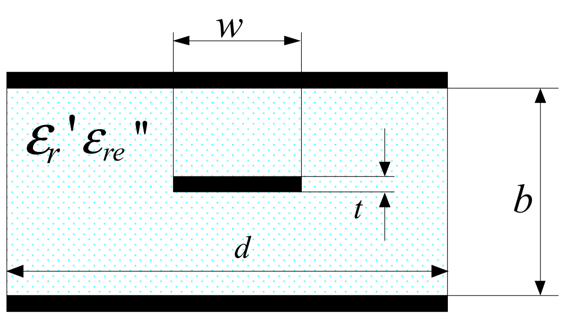


Figure 1. Cross-section of a stripline.

If the S-parameters for a length of stripline are known, the ABCD matrix parameters can be found using the expressions given in [11]

$$\begin{cases} A = \dfrac{(1+S_{11})(1-S_{22}) + S_{12}S_{21}}{2S_{21}} \\ \\ B = Z_0 \dfrac{(1+S_{11})(1+S_{22}) - S_{12}S_{21}}{2S_{21}} \end{cases}, \tag{2}$$

where Z_0 is the reference impedance. Denoting the line length of the transmission line as l, and neglecting port effects, the propagation constant γ and the line impedance Z_c can be found from

$$\begin{cases} \gamma = \dfrac{\cosh^{-1}(A)}{l} \\ \\ Z_c = \dfrac{B}{\sinh(\gamma l)} \end{cases}. \tag{3}$$

Furthermore, the propagation constant γ can be expressed in terms of the attenuation constant α and the phase constant β through

$$\gamma = \alpha + j\beta = \alpha_c + \alpha_d + j\beta = \alpha_c + \gamma_d, \tag{4}$$

where the α_c is the attenuation constant due to the finite conductivity of the conductor constructing the stripline, which indicates the conductor loss; and the α_d is the attenuation constant from the contribution of dielectric loss. The conductor loss can be estimated for the stripline based on TEM wave propagation as [11]

$$\alpha_c = \begin{cases} \dfrac{2.7\times10^{-3} R_s \varepsilon_r^{'} Z_c}{30\pi(b-t)}\xi & \text{for } \sqrt{\varepsilon_r^{'}}Z_c \le 120 \\ \\ \dfrac{0.16R_s}{Z_c b}\zeta & \text{for } \sqrt{\varepsilon_r^{'}}Z_c > 120 \end{cases}, \tag{5}$$

with

$$\begin{cases} \xi = 1 + \dfrac{2W}{b-t} + \dfrac{b+t}{\pi(b-t)}\ln\left(\dfrac{2b-t}{t}\right) \\ \\ \zeta = 1 + \dfrac{b}{0.5W + 0.7t}\left(0.5 + \dfrac{0.414t}{W} + \dfrac{1}{2\pi}\ln(\dfrac{4\pi W}{t})\right) \end{cases}, \tag{6}$$

where Z_c is the characteristic impedance of the line; ξ and ζ are constants associated with the structure of the stripline; and R_s is the surface resistance

$$R_s = \sqrt{\frac{\omega\mu}{2\sigma}}, \tag{7}$$

with σ denoting the conductivity of the stripline conductors. It is seen from (5) that the conductor loss is dependent on frequency (associated with R_s) and $\varepsilon_r{}'$, as well as some geometric factors.

The propagation constant γ_d, associated with the bulk material properties in the propagation medium, is defined as

$$\gamma_d = \alpha_d + j\beta = j\sqrt{\omega\mu\left(\omega\varepsilon^{'} - j\omega\varepsilon_{re}^{''}\right)}, \tag{8}$$

where the $\omega\varepsilon_{re}^{''}$ is the effective dielectric loss, including the effective shunt conduction loss (σ_e), and the dielectric damping loss ($\omega\varepsilon''$). Equation (8) can be expressed in the form of real and imaginary parts as

$$\begin{aligned}\gamma_d = &-\omega\sqrt{\varepsilon_0\mu}\sqrt[4]{\left(\varepsilon_r^{'}\right)^2+\left(\varepsilon_{re}^{''}\right)^2}\sin\left(\tan^{-1}\left(\frac{-\varepsilon_{re}^{''}}{\varepsilon_r^{'}}\right)/2\right)\\ &+j\omega\sqrt{\varepsilon_0\mu}\sqrt[4]{\left(\varepsilon_r^{'}\right)^2+\left(\varepsilon_{re}^{''}\right)^2}\cos\left(\tan^{-1}\left(\frac{-\varepsilon_{re}^{''}}{\varepsilon_r^{'}}\right)/2\right)\end{aligned}. \tag{9}$$

Substituting (9) and (8) into (4) and solving the equation for both $\varepsilon_r^{'}$ and $\varepsilon_{re}^{''}$ yields

$$\begin{cases}\varepsilon_r^{'} = \dfrac{-\omega^2\mu + 2\alpha k_g + \sqrt{\left(\omega^2\mu - 2\alpha k_g\right)^2 + 4k_g^2\left(\beta^2-\alpha^2\right)}}{2k_g}\\[2ex] \varepsilon_{re}^{''} = \dfrac{2(\alpha-\alpha_c)\beta}{\omega^2\mu\varepsilon_0}\end{cases}, \tag{10}$$

where ω is the angular frequency; the subscript r indicates relative permittivity; and, for a stripline as shown in Figure 1, the factor k_g is determined from

$$k_g = \frac{2.7\times10^{-3} R_s Z_c \xi}{30\pi(b-t)\varepsilon_0}. \tag{11}$$

Assuming only TEM wave propagation, the dielectric loss can be calculated [11] as

$$\alpha_d = \frac{k\tan(\delta)}{2} = \frac{\omega\varepsilon_{re}^{''}}{2c_0\sqrt{\varepsilon_r^{'}}}, \tag{12}$$

where the c_0 is the light speed in free space.

B. Debye Dispersion Law and the Application of Genetic Algorithms

The Debye dispersion law, as the simplest law of frequency dispersion, is often used [12-14] to describe the permittivity of a dispersive material as,

$$\varepsilon(\omega) = \varepsilon_0\varepsilon_\infty + \varepsilon_0\sum_{i=1}^{N}\frac{A_i}{1+j\omega\tau_i} - \frac{j\sigma_e}{\omega}, \tag{13}$$

where the second term on the right-hand-side is responsible for the Debye behavior based on a summation of N terms, and the third term introduces the effective conductivity loss of the material [11]. In (13), A_i is the ith Debye dielectric susceptibility amplitude, which is the difference between the static dielectric constant ε_{si} and the high-frequency ("optical") relative permittivity ε_∞; τ_i is the relaxation constant for the ith Debye component; and, σ_e is the effective conductivity. Since the frequency of interest is up to 20 GHz, a simple one-term Debye model is not sufficient to represent the material properties. Two Debye terms are therefore used, which means that six Debye parameters need to be found to describe the substrate material including ε_{s1}, ε_{s2}, ε_∞, τ_1, τ_2, and σ_e. By manipulating (13) into its real and imaginary parts for the two-term Debye model, the $\varepsilon(\omega)$ becomes

$$\begin{aligned}\varepsilon(\omega) &= \varepsilon_0\left(\varepsilon_\infty + \frac{\varepsilon_{s1}-\varepsilon_\infty}{1+(\omega\tau_1)^2} + \frac{\varepsilon_{s2}-\varepsilon_\infty}{1+(\omega\tau_2)^2}\right)\\ &-j\varepsilon_0\left[\frac{(\varepsilon_{s1}-\varepsilon_\infty)\omega\tau_1}{1+(\omega\tau_1)^2} + \frac{(\varepsilon_{s2}-\varepsilon_\infty)\omega\tau_2}{1+(\omega\tau_2)^2} + \frac{\sigma_e}{\varepsilon_0\omega}\right].\\ &= \varepsilon_r^{'d}\varepsilon_0 - j\varepsilon_{re}^{''d}\varepsilon_0\end{aligned} \tag{14}$$

where $\varepsilon_r^{'d}$ is the real part of the relative permittivity of the two-term Debye representation, and $\varepsilon_{re}^{''d}$ is the imaginary part.

To find the solution for the six unknowns, six independent equations are necessary. However, the number of the known equations is much greater than 6 since the number of the measured S-parameters is at least 201 measured frequency points, which means the restored dielectric property of the substrate material is represented by at least 201 frequency points. This indicates that to find the solution for the six unknowns forms an optimization problem. A genetic algorithm, has the properties of being powerful, robust, and efficient in global searching and optimization [15], and is used herein. To implement a GA for finding a set of optimum Debye parameters to represent the material property, the problem needs to be mathematically formulated. An analytical equation is necessary to describe the Debye model, and it is given in (13). An objective function serves as the optimization goal and defined as

$$\Delta=\frac{1}{N}\sqrt{\sum_{i=1}^{N}\left\{\left[\frac{\left\|\varepsilon_r^{'}(f_i)\right|-\left|\varepsilon_r^{'d}(f_i)\right\|}{\max\left|\varepsilon_r^{'}\right|}\right]^2+\left[\frac{\left\|\varepsilon_{re}^{''}(f_i)\right|-\left|\varepsilon_{re}^{''d}(f_i)\right\|}{\max\left|\varepsilon_{re}^{''}\right|}\right]^2\right\}}, \quad (15)$$

where $\left|\varepsilon_r^{'}(f_i)\right|$ and $\left|\varepsilon_{re}^{''}(f_i)\right|$ are the real and imaginary parts of the dielectric permittivity of the substrate material as determined from measured S-parameters at frequencies f_i; The $\max\left|\varepsilon_r^{'}\right|$ and $\max\left|\varepsilon_{re}^{''}\right|$ are the maximum absolute value from the restored material property data set; and $\left|\varepsilon_r^{'d}(f_i)\right|$ and $\left|\varepsilon_{re}^{''d}(f_i)\right|$ are evaluated real and imaginary parts of the dielectric property of the substrate material at frequency f_i using (13). The purpose of $\max\left|\varepsilon_r^{'}\right|$ and $\max\left|\varepsilon_{re}^{''}\right|$ in (15) is to normalize the difference between the measurement and the modeling to consider that the real and imaginary parts of the material property are equally weighted. The optimum parameters of the dispersive substrate are determined when all the parameters to be extracted in the GA search pool converge, and the value of Δ is minimized.

III. Measurement, Characterization And Full-Wave Simulation

A stripline and a specific TRL calibration pattern were designed in an 8-layer test board with the dimensions of the board as 264 mm wide, 248 mm high, and 2.69 mm thick. The frequency range of interest was from 200 MHz to 20 GHz. The TRL calibration pattern was used to de-embed the port effects (vertical SMA connectors) of the stripline, and to move the VNA measurement reference plane behind the SMA port 12.7 mm at each end of the stripline. The port effects, such as higher order modes, losses, and electrical length due to the SMA connectors, were eliminated from the measurements. To achieve good TRL calibrations, the entire frequency span of interest was separated into three frequency ranges, i.e., 200 MHz to 930 MHz, 930 MHz to 4.3 GHz, and 4.3 GHz to 20 GHz, in the TRL calibration pattern so that the requirement of the insertion phase and the usable band width for the TRL pattern at each frequency span could be readily met. The total length of the stripline (after moving the TRL calibration measurement reference) is 202.6 mm, and its dimensions, referring to Figure 1, are t=0.03 mm, b=0.75 mm, w=0.32 mm and d=7.3 mm. Using (1), the frequency of the first higher-order mode of the stripline is calculated as 82 GHz, which indicates the stripline supports TEM wave propagation over the entire frequency range of interest. The measurement was performed with an HP 8720ES VNA (Vector Network Analyzer with ATN-4112 S-parameter Test Set) from 200 MHz to 20 GHz using TRL calibration de-embedding techniques.

A. Dielectric Property Characterization

The measured S-parameters with port effects eliminated by TRL calibration were used to characterize the substrate of the stripline. The characteristic impedance of the stripline was 50 Ω, which was determined from measurement. The permeability of the substrate was assumed to be the same as free space. Using the formulas given in Part A of Section II, the real and imaginary parts of the relative permittivity were calculated. They are shown in Figures 2 and 3. The imaginary part of the effective permittivity of the material includes the σ_e term. As indicated in [11], the σ_e term is hard to distinguish from the dielectric damping loss term ($\omega\varepsilon''$), and therefore there is no further attempt to separate these quantities.

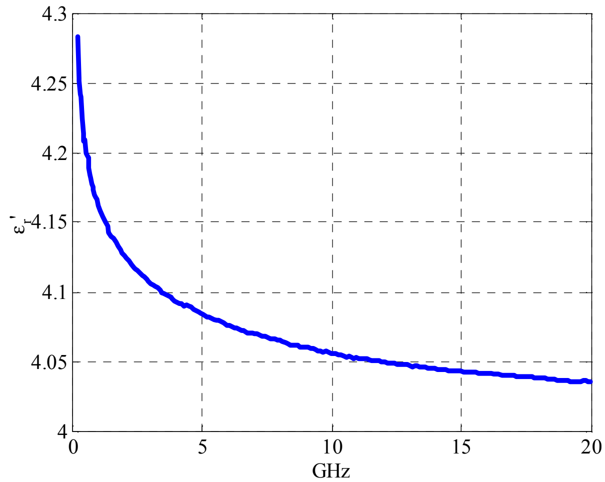


Figure 2. Characterized the real part of the permittivity of the stripline.

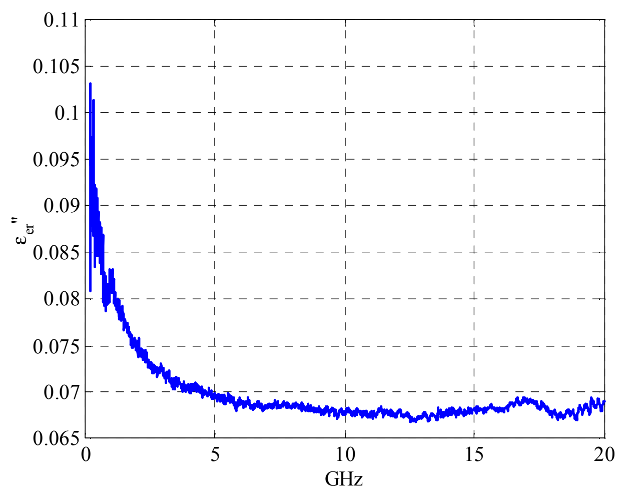


Figure 3. Characterized the imaginary part of the permittivity of the stripline including σ_e.

B. Loss Quantification

The characterized substrate dielectric properties were used in the calculation of dielectric loss and conductor loss with the formulas given in Part A of Section II. The summation of the dielectric loss and conductor loss is the calculated total loss. The total loss was compared to the measured total loss. The dielectric loss, conductor loss, and measured total loss are shown in Figure 4. The relative contributions of the dielectric and conduction losses are displayed in Figure 5.

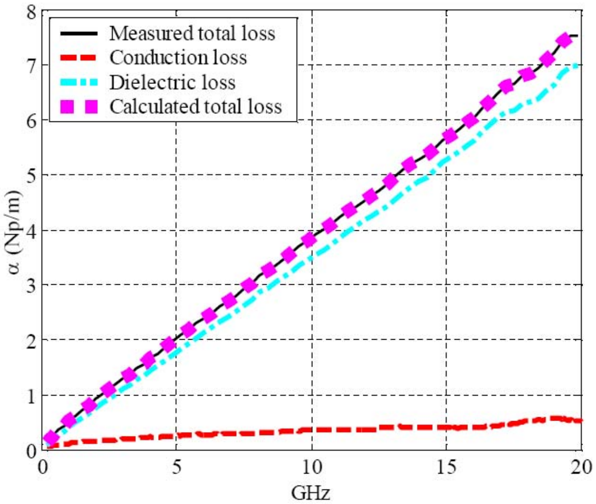


Figure 4. Calculated dielectric loss, conductor loss, and total loss as well as the measured total loss.

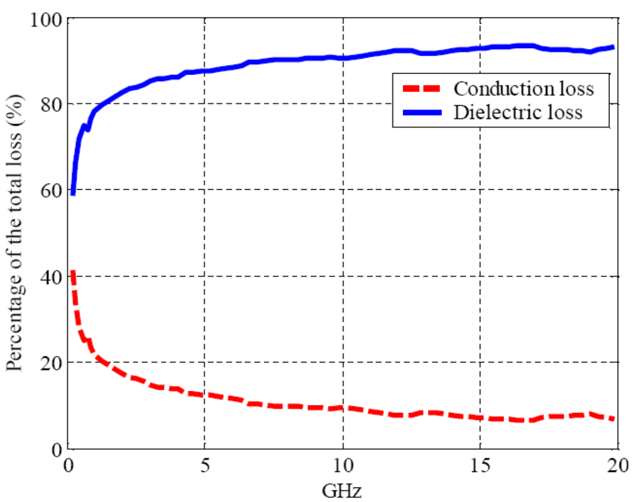


Figure 5. Quantified dielectric loss and conductor loss.

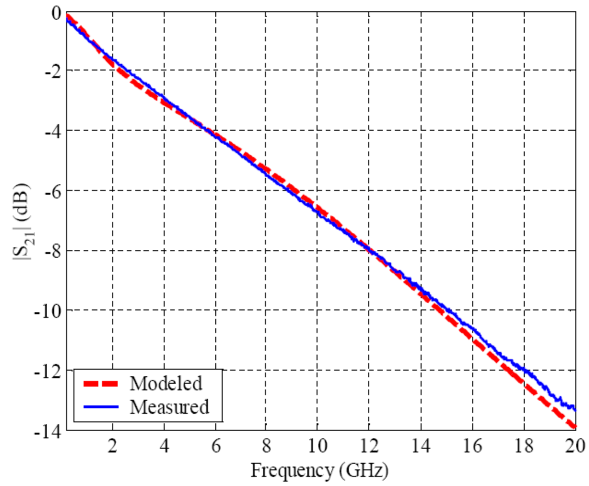
C. Two-term Order Debye Paramter Extraction and Full-wave Simulation

Using the characterized material property parameters ($\varepsilon_r^{'}$, $\varepsilon_{re}^{''}$) as the objective data and implementing the GA as discussed in Part *B* Section II, the two-term Debye parameters were extracted and are given in Table I.

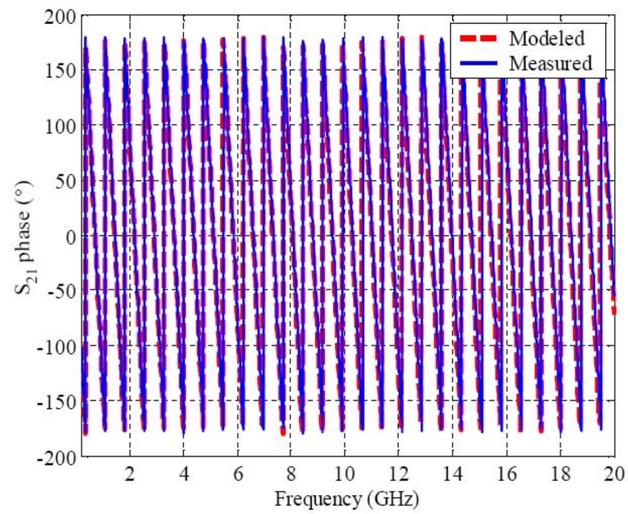
TABLE I. EXTRACTED SECOND ORDER DEBYE PARAMTERS

ε_{s1}	ε_{s2}	τ_1 (pS)	τ_2 (pS)	ε_∞	$\sigma_e (mS/m)$
4.081	4.068	82.12	5.712	3.95	1.136

The extracted Debye parameters were implemented in an FIT (finite integration technique) full-wave simulation, and two wave ports were used in the model. The comparison between simulation and measurement is shown in Figure 6 (a) and (b) for S_{21}, both in magnitude and phase.



(a)



(b)

Figure 6. Comparison between simulation and measurement: (a) magnitude; (b) phase.

The maximum difference between simulation and measurement is less than 0.7 dB in magnitude over the frequency from 200 MHz to 20 GHz, and the phase difference is hard to distinguish.

IV. CONCLUSIONS

Signal link-path characterization is presented based on a stripline structure with an analytical solution derivation for substrate material property determination, loss quantification, and a two-term Debye representation for the substrate material and full-wave simulation. The calculated total loss including dielectric loss and conductor loss using the restored material property parameters agree well with the measured total loss with the relative error. The full-wave simulated S_{21} both in magnitude and phase matches well with the measurements when the a two-term Debye representation was used in the simulation.

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