Dielectric and Conductor Roughness Models Identification for Successful PCB and Packaging Interconnect Design up to 50 GHz

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Abstract: Meaningful interconnect design and compliance analysis must start with the identification of broadband dielectric and conductor roughness models. Such models are not available from manufacturers and the model identification is the most important element of successful interconnect design for link paths with 10-50 Gbps and higher data rates. Electromagnetic analysis of interconnects without such models may be simply not accurate. Overview of broadband dielectric and conductor roughness models for PCB and packaging interconnect problems is provided in the paper. Theory of model identification with generalized modal S-parameters and separation of dielectric and conductor dispersion and loss effects is described. Practical examples of successful dielectric and conductor roughness model identification up to 50 GHz are also provided.

Introduction

The largest part of interconnects can be formally defined and simulated as transmission line segments. Models for transmission lines are usually constructed with a static or electromagnetic field solvers. Transmission lines with homogeneous dielectrics (strip lines) can be effectively analysed with quasi-static field solvers and lines with inhomogeneous dielectric may require analysis with a full-wave solver to account for the high-frequency dispersion [1], [2]. **Accuracy of transmission line models is mostly defined by availability of broadband dielectric and conductor roughness models.** Wideband Debye (aka Djordjevic-Sarkar or Swensson-Dermer) and multi-pole Debye models [2] are examples of dielectric models suitable for accurate analysis of PCB and packaging interconnects. Expression for complex permittivity of multi-pole Debye model can be written as follows [2]:

$$\varepsilon(f) = \varepsilon(\infty) + \sum_{n=1}^{N} \frac{\Delta\varepsilon_n}{1 + i\dfrac{f}{fr_n}} \qquad (1)$$

Values of dielectric constant at infinity $\varepsilon(\infty)$ as well as pole frequencies fr_n and residues $\Delta\varepsilon_n$ are not known for composite dielectrics and have to be identified. The number of poles *N* for model suitable for analysis of interconnects up to 50 GHz should be 5-10 [2].

Expression for complex permittivity of the wideband Debye model can be written as follows [2]:

$$\varepsilon(f) = \varepsilon(\infty) + \frac{\varepsilon_d}{(m_2 - m_1)\cdot \ln(10)} \cdot \ln\left[\frac{10^{m2} + if}{10^{m1} + if}\right] \qquad (2)$$

As in case of multi-pole Debye model, there is a number of parameters that has to be identified in (2). Values of m1 and m2 define position of the first and last pole in the continuous spectrum defined by the model. Those are typically set to very low and very high values outside of the frequency band of interest. Values of $\varepsilon(\infty)$ and ε_d can be identified with only one measurement of dielectric constant and loss tangent [2]. f in (1) and (2) is frequency.

To simulate effect of conductor roughness, Huray's snowball [3] and modified Hammerstad [4] conductor roughness models can be effectively used. Expression for the conductor surface impedance correction coefficient based on the Huray[s snowball model can be written as follows [4]:

$$K_{rhu} = 1 + \left(\frac{N \cdot 4\pi \cdot r^2}{A_{hex}} \right) \Big/ \left(1 + \frac{\delta}{r} + \frac{\delta^2}{2 \cdot r^2} \right) \qquad (3)$$

This model has 2 parameters: ball radius *r* and ratio of the number of balls to the base tile area *N/Ahex*. Both are not known for commonly used copper foils.

Another practically useful surface impedance correction coefficient is called modified Hammerstad model and can be expressed as follows [4]:

$$K_{rh} = 1 + \left(\frac{2}{\pi} \cdot \arctan\left[1.4 \left(\frac{\Delta}{\delta} \right)^2 \right] \right) \cdot (RF - 1) \qquad (4)$$

It has also two parameters: Δ or surface roughness (SR) parameter (may be associated with rms peak to valley value) and roughness factor *RF* (maximal possible increase of losses due to roughness). Note that classical Hammerstad model has *RF*=2 and just one parameter, but not very useful for characterisation of PCB copper [4]. δ in (3) and (4) is the frequency-dependent skin depth.

Manufacturers of dielectrics usually provide dielectric parameters at 1-3 points in the best cases. It is not possible to construct broadband multi-pole Debye model from just 3 points, to have model bandwidth from 1 MHz to 50 GHz, as typically required for 10-50 Gbps data links. 5 or more points may be required with one of the points close to the highest frequency of interest [2]. In addition, all points have to be consistent and measured with the same method. Manufacturers of advanced PCB dielectric typically provide dielectric constant and loss tangent at 10 GHz or lower frequencies. Though, those points may be acceptable to define the wideband Debye model, because of just one point is needed to identify the model parameters. The constructed model becomes useful over extremely broad frequency range. Things are not so good for the copper roughness models. Manufacturers of copper laminates typically do not have parameters for the electrical roughness models at all. Parameters in datasheets are usable for mechanical purpose, but not for the electrical characterisation. RMS peak-to-valley value Rq can sometime be used for reverse treatment foils as parameter Δ in the modified Hammerstad model. The roughness factor has to be identified. Thus, meaningful interconnect design and compliance analysis must start with the identification or validation of dielectric and conductor roughness models over the frequency band of interest. **Availability of accurate broadband material models is the most important element for design success.** Validation or identification of dielectric and conductor models can be done with generalized modal S-parameters as shown in [5]-[7]. Main steps of the process are described in the next section. Possible methods for separation of dielectric and conductor roughness loss and dispersion effects are also discussed in the paper. Multiple practical examples are provided.

Broadband model identification

Dielectric and conductor roughness models identification can be done by matching measured and computed generalized modal S-parameters (GMS-parameters) for a transmission line segment. S-parameters for two line segments with different length and substantially identical cross-sections and transitions to probes or connectors must be measured first to compute measured GMS-parameters. Before proceeding with the identification of the material models, it is important to verify all dimensions of the test structures on the board. In particular, cross-sections of the transmission lines and length difference between two line pairs have to be accurately measured. Next, quality of measured transmission line S-parameters has to be estimated and TDR used to verify consistency of the test fixtures.

The basic procedure for the dielectric and conductors surface roughness models identification is illustrated in Fig. 1 can be performed as follows:

(1) Measure scattering parameters (S-parameters) for at least two transmission line segments of different length (L1 and L2) and substantially identical cross-section and conductor roughness profile filled with dielectric with known dielectric model.

(2) Compute generalized modal S-parameters of the transmission line segment difference L=|L2-L1| from the measured S-parameters following procedure described in [5].

(3) Compute GMS-parameters of line segment difference L:

(3a) Guess dielectric (1,2) or conductor surface roughness (3,4) model and model parameters.

(3b) Compute generalized modal S-parameter of line segment difference L by solving Maxwell's equations for line cross-section with the broadband material models as described in [4]-[6].

(4) Compare GMS-parameters and adjust model to minimize the difference or output the identified model.

(4a) Compare the measured and computed generalized modal S-parameters - compute metric of difference of two complex GMS-parameters.

(4b) If the difference is larger than a threshold, change model parameters (or model type) and repeat steps (3b)-(4).

(4c) If the difference is less or equal to threshold, the dielectric or conductor roughness model is found.

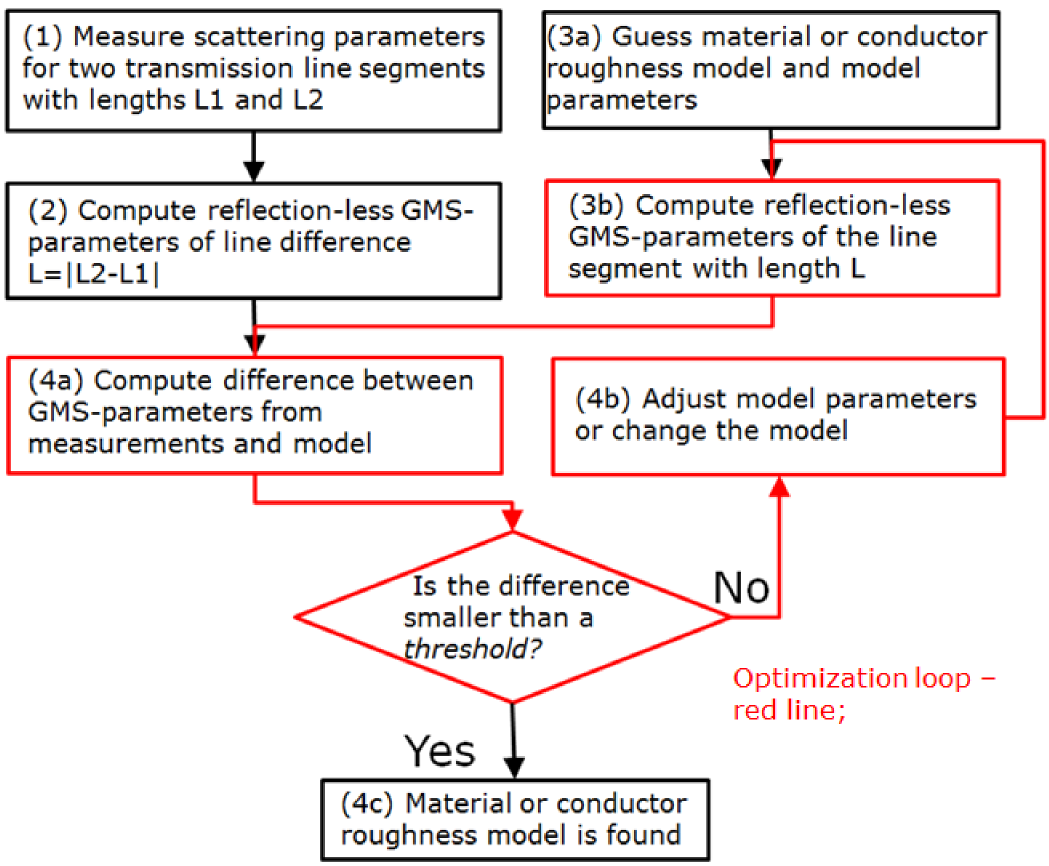

Fig. 1. Dielectric material or conductor surface roughness model identification procedure.

This procedure is implemented and automated in Simbeor software [8], including the model parameters optimization. **The key in this approach is availability of algorithms for analysis of transmission lines that supports the frequency-continuous material models (1-4) in step (3b) of the algorithm shown in Fig. 1.**

It is known that the conductor roughness effect causes signal degradation (losses and dispersion) that are similar to the signal degradation caused by dielectrics [4]. **Thus, it is important to separate the effects of losses and dispersion properly between the conductor roughness and dielectric models, or understand the consequences of not doing such separation.** There are four scenarios to build the conductor surface roughness model without and with separation of the loss and dispersion effects between the dielectric and conductor surface roughness models [7]:

1) **Optimize dielectric model to fit measured and modelled GMS-parameters following the procedure in Fig. 1 and do not use any additional conductor roughness model.** The dielectric model will include effect of conductor surface roughness. Such model may be suitable for the analysis of a particular transmission line and has to be rebuilt if strip width or line type is changed. This combined model may be acceptable in cases of high-loss dielectrics when the effect of conductor roughness is minimal. This case is similar to the dielectric model identification described in [5], [6], but with rough conductors.
2) **Define dielectric model with the data available from the dielectric manufacturer and then identify a roughness model (a roughness correction coefficient) with GMS-parameters following the procedure in Fig. 1.** This approach works well if a manufacturer has reliable procedure to identify the dielectric properties (most of them do). Wideband Debye model can be defined with just one value of dielectric constant and loss tangent specified at one frequency point [5]. This is the simplest way to identify the conductor roughness model.
3) **If dielectric model is not available, identify dielectric and conductor roughness models separately.** In addition to two line segments with rough copper, make two or more transmission line segments with flat rolled copper on the same board. First, use segments with flat copper to identify parameters in dielectric model following the procedure in Fig. 1. Then use the identified dielectric model for rough segments and identify the conductor roughness model following the same procedure Fig. 1, but for the roughness model. This is the simplest way to separate loss and dispersion effects in conductor surface roughness and dielectric models.
4) **If dielectric model is not available, identify dielectric and conductor roughness models simultaneously.** It can be done with multiple line pairs with different widths of strips in each pair (narrow, regular and wide strips made of the same rough copper for instance). Dielectric model and conductor roughness model parameters can be optimized simultaneously following the procedure in Fig. 1, until differences of GMS-parameters for segments with all strip widths reach the stopping criteria. The resulting dielectric and roughness models will be usable for a given range of the strip widths. Though the procedure is the most complicated and may lead to multiple possibilities (ambiguity).

Overall, the material identification procedure described here is the simplest possible. It needs measurements for 2 t-lines with any geometry of cross-section and transitions. No extraction of propagation constants (Gamma) from measured data is required. The extraction of Gamma is difficult and error-prone. Also, no de-embedding of connectors and launches is required. De-embedding of PCB structures is usually difficult or even impossible due to inhomogeneity of dielectrics and manufacturing variations. The approach needs the simplest numerical model - only propagation constant has to be computed for a given cross-section and with the material models to identify. No 3D electromagnetic models of the transitions is required. Procedure with GMS-parameters has minimal number of smooth complex functions to match during the identification process. Specifically, one S-parameter for single and two S-parameters for differential lines have to be matched. All reflection and modal transformation parameters are exactly zeroes. **Identified models are frequency-continuous and models (2)-(4) are not restricted to the frequency band used in the identification process – they are naturally extendable above the upper and below the lower frequencies.**

Practical example

As an example of material parameters identification up to 50 GHz (for 25-50 Gbps data channel) we use measured data provided by Wild River Technology (http://wildrivertech.com/) for CMP-28 channel model platform validation board made with Isola FR-408 materials and regular copper.

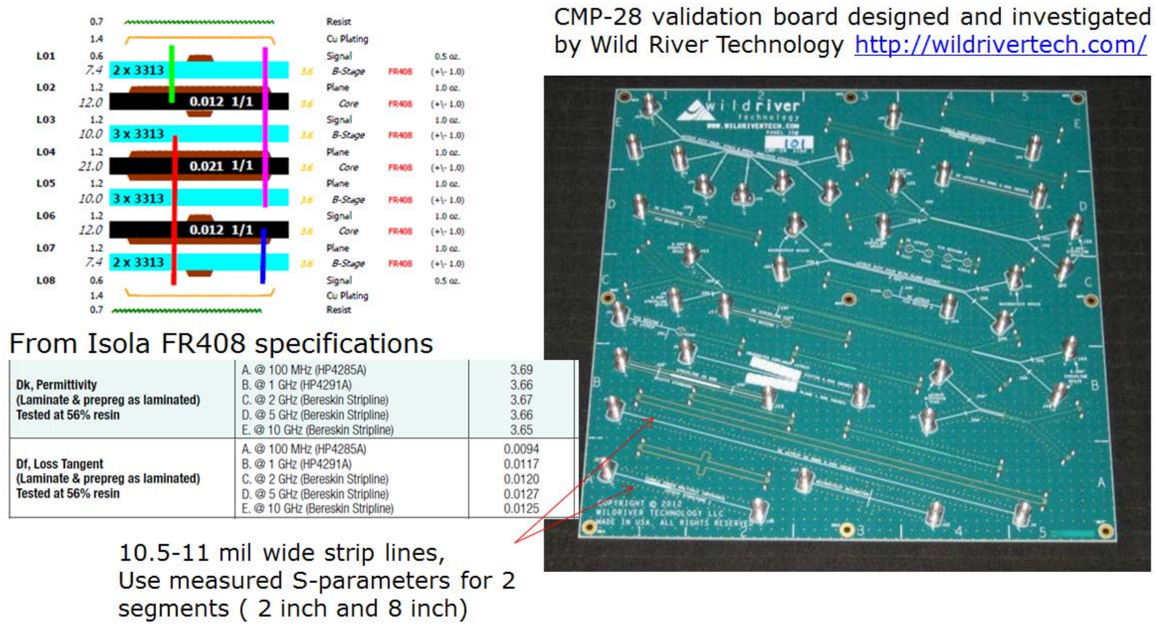

Fig. 2. CMP-28 board stackup and view. Dielectric parameter data from manufactured are also shown.

The board and stackup are shown in Fig. 2. Five points for dielectric constant and loss tangent are available from the datasheet for the FR-408 material. Though, the points are measured with different methods and the maximal frequency is 10 GHz only. Frequency-continuous multi-pole Debye model cannot be accurately defined up to 50 GHz with those data. No data for the conductor roughness was available from the board manufacturer. To identify dielectric and conductor roughness model parameters, we can use 2 and 8 inch single-ended strip line links in layer L03 (see stackup in Fig. 2).

S-parameters measured for two line segments are shown in Fig. 2.

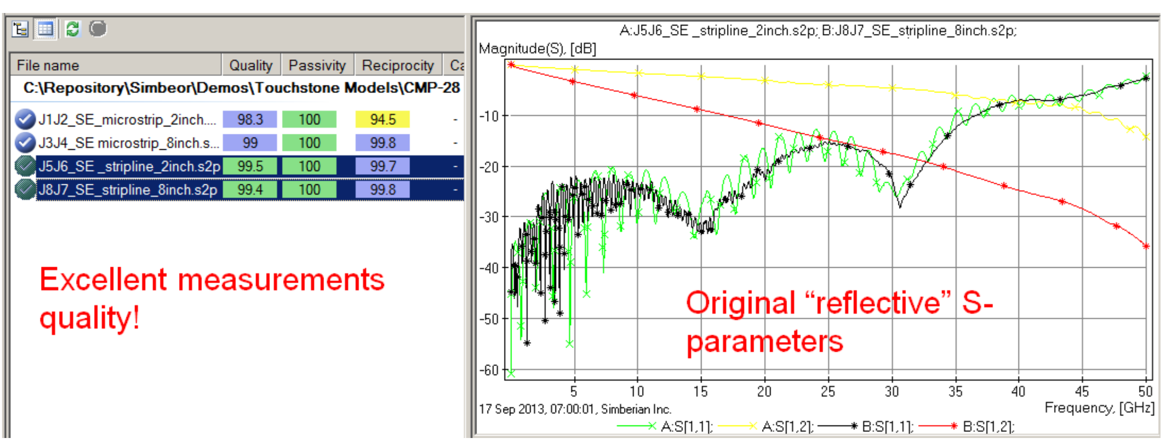

Fig. 3. Measured S-parameters for two strip line links and quality evaluation.

Following the procedure outlined in the previous section, we first estimated measured S-parameters quality in Simbeor Touchstone Analyser tool [8]. As we can see from Fig. 3, the quality of S-parameters for the strip line segments is excellent (final Quality metric is close to 100%). TDRs of both segments have been also evaluated and both links looked consistent (impedance and discontinuities are close). After measured S-parameters for test structures were pre-qualified, we convert the measured reflective S-parameters into generalized or reflection-less S-parameters shown in Fig. 4 (red and blue curves).

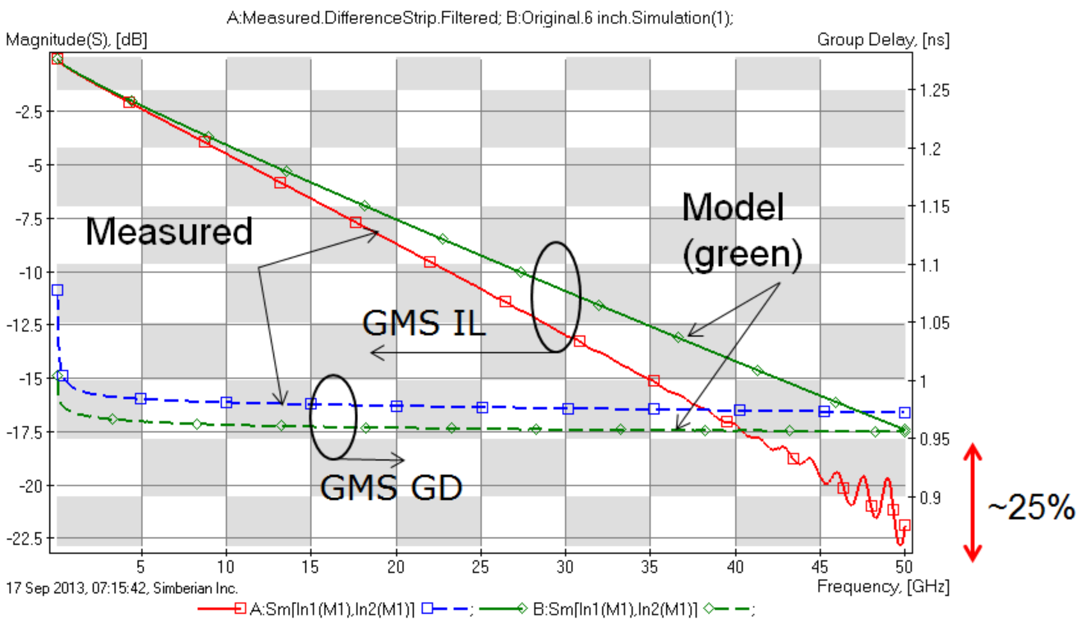

Fig. 4. Measured (red and blue curves) and computed (grin curves) generalized modal insertion loss (left plot) and group delay (right plot) for 6 inch strip line segments (dielectric model from manufacturer and smooth conductor model).

Dielectric specifications (see insert in Fig. 2) show that this dielectric has dielectric constant (Dk) 3.66 and loss tangent (LT) is 0.0117 at 1 GHz (the other points are also consistent with that value and WD model). We can use that point to define the wideband Debye model (2). If we compute GMS-parameters for 6 inch segments with the electromagnetic analysis with wideband Debye model and Dk=3.66 and LT=0.0117 defined at 1 GHz (shown with blue curves in Fig. 4), the difference in the measured and computed group delay is relatively small, but the difference in GMS insertion loss is large (up to 25% as shown in Fig. 4). Dk in the model has to be increased to 3.83, to match the measured group delay – that increase can be explained by the layered structure and anisotropy of the dielectric due to that. How to explain the large difference in the predicted and measured insertion loss? Typically this situation is explained as wrong data from the manufacturer. In this case LT should be increased to 0.0138 to have acceptable match for the insertion loss. With such adjustment, the measured and computed GMS-parameters match well as shown in Fig. 5.

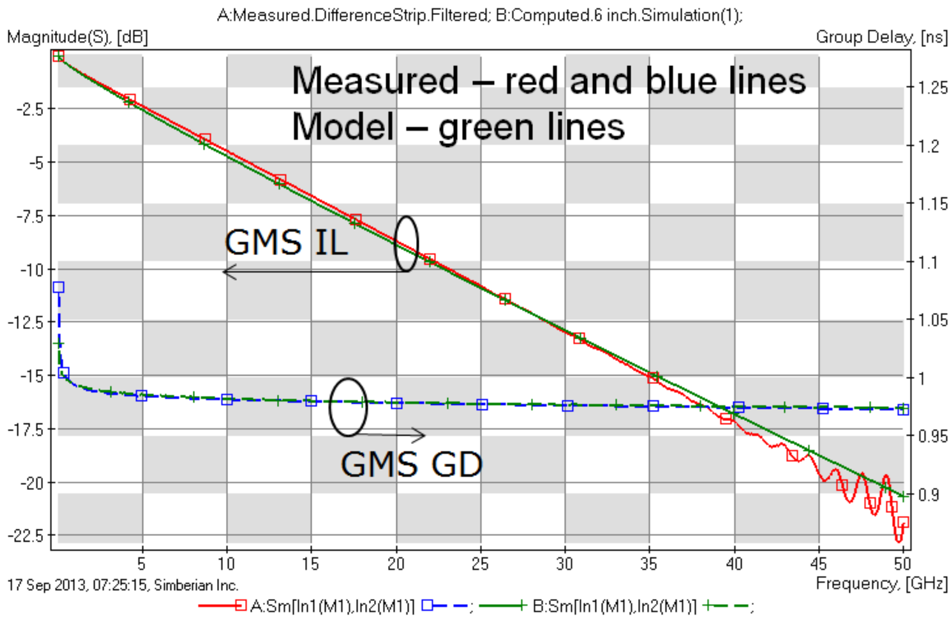

Fig. 5. Measured (red and blue curves) and computed (green curves) GMS insertion loss (left plot) and group delay (right plot) for 6 inch strip line segments (wideband Debye dielectric model with Dk=3.83 (4.6% increase), LT=0.0138 (18% increase), smooth copper surface).

Another option is to assume that the dielectric loss tangent from the manufacturer datasheet is actually accurate enough (it is typically measured with the accurate strip resonator method and strips are made of smooth copper), and attribute all observed excessive losses to the conductor roughness. As shown in Fig. 6, nearly perfect correspondence of measured and computed models can be achieved with the modified Hammerstad model (4) with the roughness parameter 0.32, roughness factor 3.3 and conductor resistivity adjusted to 1.1 (relative to resistivity of annealed copper). To match the GMS group delay, smaller adjustment of the dielectric constant from 3.66 to 3.8 was needed.

As the result of this simple example we ended up with two models – with the conductor roughness effect accounted by increase of dielectric loss tangent from 0.0117 to 0.0138 and another model with loss tangent 0.0117 as in the specs and additional modified Hammerstad model for conductor roughness. Which one is correct? Both models are actually suitable for the analysis of the 10.5 mil strip line on that board. However, if strips with substantially different widths are used, the model without roughness effect will be less accurate, assuming that all additional losses are due to conductor roughness. For instance if we use both models for analysis of 6 inch strip link with strip width 6 mil and 7.5 mil distance, two models will produce up to 10% difference in the insertion loss as illustrated in Fig. 7. Note that FR-408 can be considered as a medium-loss dielectric. Difference in insertion loss between model with increased LT and with proper roughness model can be as large as 30% starting from 3-5 GHz in cases of low loss dielectrics such as Megtron 6 (see details in presentation for [9]). **Model with the rough conductor produces more accurate insertion loss estimation for broader range of strip widths.**

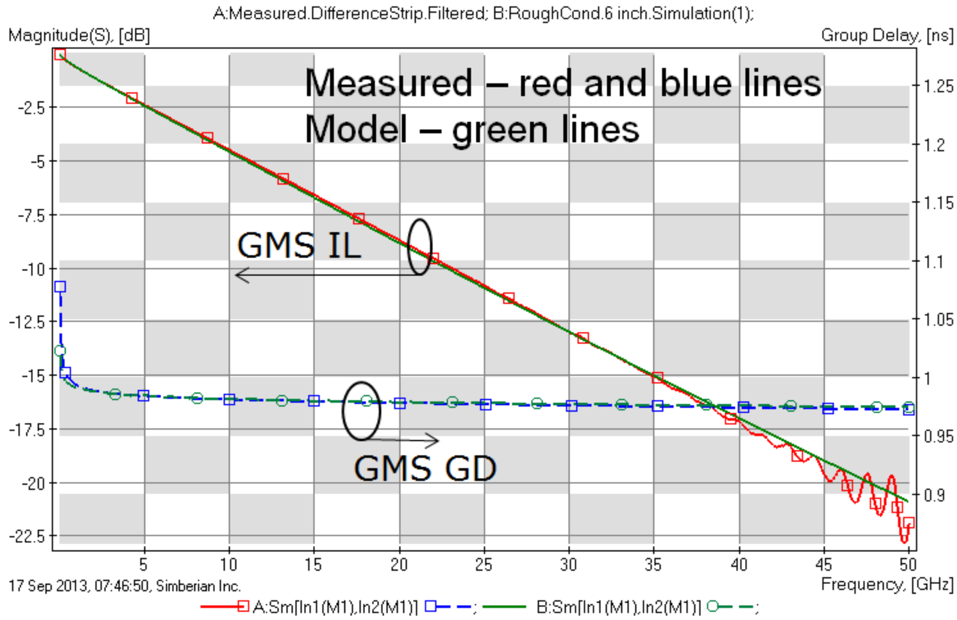

Fig. 6. Measured (red and blue curves) and computed (green curves) GMS insertion loss (left plot) and group delay (right plot) for 6 inch strip line segments (Dk=3.8 (3.8% increase), LT=0.0117 (no change), Wideband Debye model, modified Hammerstadt model with SR=0.32 um, RF=3.3 for copper roughness).

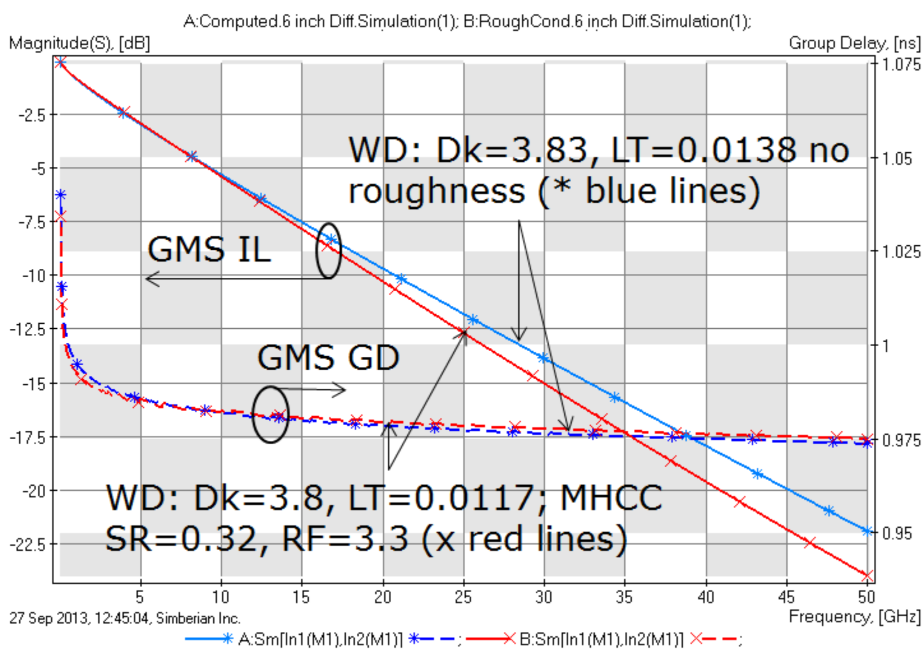

*Fig. 7. GMS insertion loss (left plot) and group delay (right plot) for 6 inch differential strip segments computed with roughness losses included into dielectric model (blue curves with *) and with separated conductor roughness model (red curves with x).*

This example illustrates typical situation and importance of the dielectric and conductor roughness model identification to have analysis to measurement correspondence up to 50 GHz.

Interesting results of dielectric and conductor roughness models identification with GMS-parameters for multiple materials were recently reported in [10] and some data are provided here in Table 1 as another practical example.

Table 1. Broadband material models identified in [10]. Dielectric constant and loss tangent values define Wideband Debye model (2), Dk values in brackets and loss tangent are from datasheets, roughness parameters are for modified Hammerstad model (4).

Model Parameters Board Types	WD Dielectric Constant @ 1 GHz	WD Loss Tangent @ 1 GHz	MH Roughness (SR, rms) (um)	MH Roughness Factor (RF)
Megtron-6 with HVLP copper	3.64 (3.6)	0.002	0.38	3.15
Megtron-6 with RTF copper	3.72 (3.6)	0.002	0.37	4
Nelco N4000-13EPSI with RTF copper	3.425 (3.4)	0.008	0.49	2.3

Note that all dielectric and conductor roughness models identified here are actually not restricted to the upper frequency 50 GHz used in the identification process. The models are frequency-continuous and can be useful well above that frequency. This is one of the advantages of the broad-band models identification over approaches with resonators where dielectric properties are identified only at some frequency points.

Conclusion

Overview of frequency-continuous dielectric and conductor roughness models is provided in the paper. Such models have to be used in the PCB and packaging interconnect analysis to have analysis to measurement correlation up to 50 GHz and beyond. Practical procedure for the identification of the model parameters have been described in details. It is shown that proper separation of loss and dispersion effects between dielectric and conductor models is very important. Without proper roughness model, dielectric models become dependent on the width of strips used in the test structures. If strip width is changed, difference in insertion loss predicted by models with roughness effect accounted in the dielectric models may be up to 20-30% off from the proper model with conductor roughness. Note that PCB materials are composed of glass fiber and resin and have layered structure and thus, anisotropy. Separate dielectric models for composite and resin layers may be required as shown in [10] or vertical and horizontal components of dielectric constant have to be separately identified. Also, differences in dielectric properties of glass and resin can cause further signal degradation in form of skew and jitter induced by the fiber-weave effect. Composite material models to account for all these effects are available in Simbeor software [8].

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