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Full-wave time domain modeling of interconnects

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Abstract

Frequency-domain 3D Electromagnetic modeling approaches always have the potential for causality and passivity violation issues, especially when applied to greater than 20Gbsec data rates applications: initial applications for 3D Electromagnetic modeling methods were only used in low bandwidth frequency-domain microwave designs. A new and inherently passive and causal time-domain oriented approach for 3D Electromagnetic modeling is introduced in detail. The authors show specific advantages of this approach for baseband-NRZ very high-speed backplanes, interconnects, and general board design for digital systems. Selecting the correct loss model will be included and the model results will be compared to actual measurements to 20 GHz using a test board specifically designed for this presentation.

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Martin Schauer received the Dipl.-Ing. degree in Electrical Engineering from the Technische Universität Darmstadt in 1999. In the same year, he joined the Computational Electromagnetics Laboratory (TEMF) for Theory of Electromagnetic Fields, where he earned his Ph.D. in 2005. Since 1999 he is with Computer Simulation Technology (CST), where he developed 3D electromagnetic simulation software until 2005. Currently he is working as a principal application engineer and technical key account manager for CST of America in the San Francisco Bay area. His main interests are numerical methods and their application towards low and high frequency electromagnetic problems.

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Introduction

Current state-of-the-art virtual prototyping techniques use 3D model extraction based on frequency domain techniques. In order to achieve a meaningful output of system level jitter and signal integrity, special attention needs to be paid to the causality and passivity enforcement techniques and any introduced errors. This paper proposes a material modeling extension for a well established 3D time-domain technique: The Finite Integration Technique (FIT) [1]. This time marching algorithm is forced to use causal models, as any causality violation would require information about the future in the simulation,. The same holds true for passivity: Any passivity violation would result in instable time integration, therefore passivity needs to be proven for the algorithm itself.

For the FIT a proof exists [2] and due to the matrix formalism requirements for algorithm extensions are developed. Therefore charge and energy conservation is maintained even for extensions like the perfect boundary approximation (PBA) [3] and a multilevel subgridding scheme. In order to make use of this algorithm for high-speed digital applications, the available material models and the workflow to generate them from measurements needs to be validated.

This paper is organized in the following way: Chapter 2 discusses the available material models and a recent development of higher-order material models. Chapter 3 applies these material models to the solution of an inverse problem of material characterization using measurements and simulation. Finally the results of this paper are summarized.

Modeling Dielectric Dispersion in Time Domain

Review of known material models

For high speed serial links the dielectric modeling has become one of the most critical parts if any meaningful prediction should be performed. In this chapter we first introduce known dispersion models, which allow us to treat the microscopic behavior using a macroscopic model. Then we discuss their use in a 3D Time Domain simulation.

The typical PCB laminates can be seen as dispersive dielectric materials. We first introduce a complex permittivity in the frequency domain $\varepsilon(\omega) = \varepsilon' - j\omega\varepsilon''$ and the loss tangent,

$$\tan\delta(\omega) = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} . \qquad (1)$$

Please note that most material characterizations are given in the frequency domain. We discuss later how they are implemented in a time domain simulation. The electrical dispersion characteristic is due to electric polarization of the molecules. One of the frequently used macroscopic models for such a dielectric is the Debye[1] dispersion model [4], with the following frequency dependency for the first order model,

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[1] Other classical causal dispersion models are the Drude and Lorentz model, which are less suitable for PCB laminates in the discussed frequency range.

$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{1 + j\,\omega\tau}, \qquad\qquad (2)$$

with the relaxation time τ, which also translates into a pole frequency and the pole strength Δε. An important property of this model is its causality, which can be proven by testing the Kramers - Kronig relationship between the real and imaginary part, please refer to [5]. One can extend this model toward higher order, by summing up multiple first order models, while the causality is still maintained.
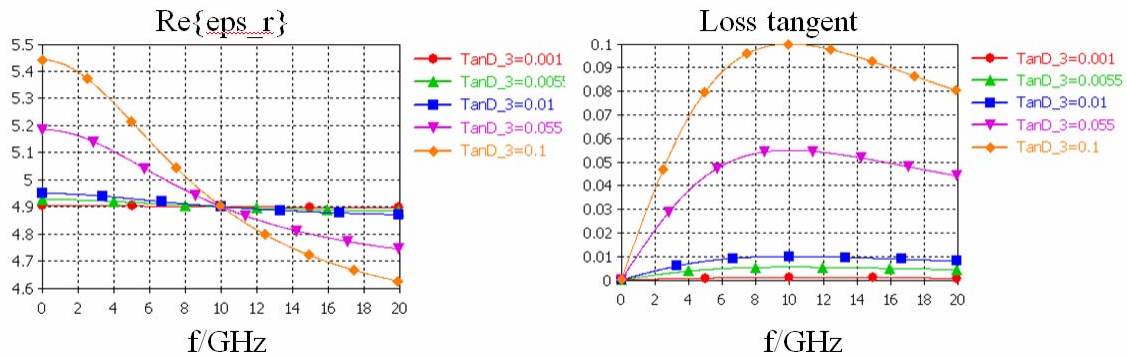

Figure 1: Real part and loss tangent for different loss tangent values over 0-20 GHz

In order to grasp how the material behaves vs. frequency quickly we now look at the real part and the loss tangent separately, Figure 1, as well as the Cole-Cole plot [6] of the first order Debye model, Figure 2.
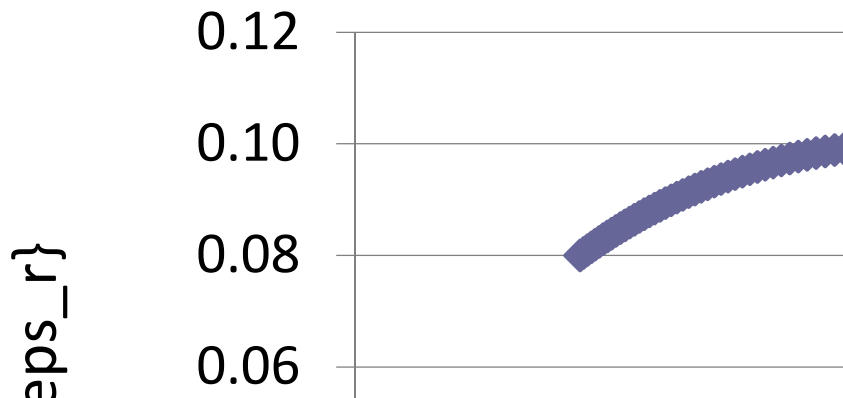

Figure 2: Cole-Cole plot for a first order Debye model

In Figure 2 the imaginary part is plotted over the real part for all the frequencies of interest. In order to match the material properties of low cost FR4 PCB laminates better higher order material model have been developed. One of them is the summation of an infinite number of first order poles within a given frequency range [7][8], which we will refer to as "band limited, infinite order Debye", see formula 3 and figure 3.

$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{m2-m1} \frac{\ln\left(\frac{\omega_2+j\omega}{\omega_1+j\omega}\right)}{\ln 10} \qquad (3)$$
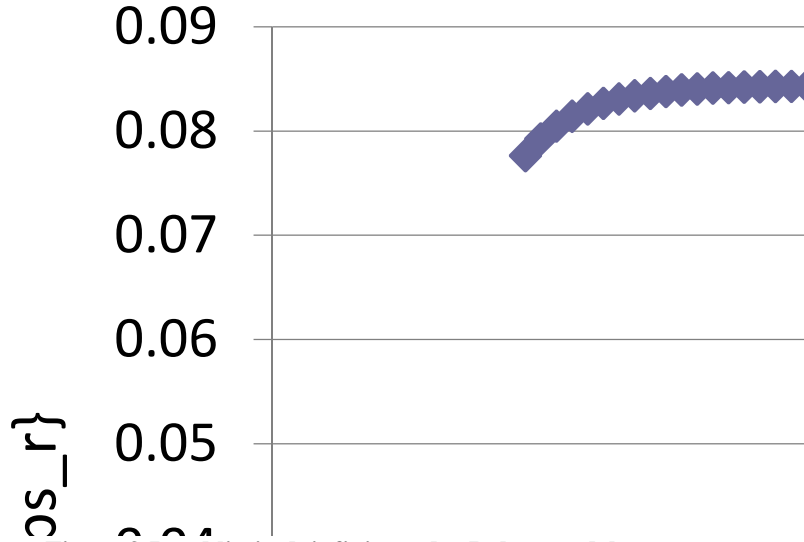

Figure 3:Band limited, infinite order Debye model

Implementation of dispersion models into a 3D Time Domain FIT full wave algorithm

Since all of these models are defined in the frequency domain their implementation in a frequency domain solver is straightforward. For each solved frequency the material properties need to be adjusted. There is really no constraint on how these are modified, even unphysical behavior is possible, such as a constant loss tangent from f_{min}=0Hz to $f_{max}\rightarrow\infty$. In addition it is necessary to use an interpolation technique between the calculated frequency samples, which maintains the causality, even if the behavior of the underlying model is already causal.

In the time domain simulation, the model needs to be causal and passive as discussed earlier. Each pole in a dispersion model can be seen as a memory, which stores information from previous times in the simulation. Therefore the higher the dispersion order, the more memory will be necessary for these materials. This also motivates, why we want to use the lowest order possible for the simulation, which fulfills the accuracy requirement. A very elegant way was implemented in [9], where a given material behavior is fitted using multiple poles and a given accuracy. It makes use of general dispersion models:

1st order general $\qquad\qquad \varepsilon(\omega) = \varepsilon_\infty + \dfrac{\beta_0}{a_0 + j\omega} \qquad (4)$

2nd order general $\qquad\qquad \varepsilon(\omega) = \varepsilon_\infty + \dfrac{\beta_0 + j\omega\beta_1}{a_0 + j\omega a_1 - \omega^2} \qquad (5)$

General Nth order
$$\varepsilon(\omega) = \varepsilon_\infty + \sum_{n=1}^{N} \frac{\beta_{0,n}}{a_{0,n} + j\omega} + \sum_{n=1}^{M} \frac{\gamma_{0,n} + j\omega\gamma_{1,n}}{\delta_{0,n} + j\omega\delta_{1,n} - \omega^2} \qquad (6)$$

Comparing the coefficients we find, that the general first order can be a seen as a first order Debye model,[10], with special settings: $\alpha_0 = \dfrac{1}{\tau}$ and $\beta_0 = \dfrac{\Delta\varepsilon}{\tau}$. Please note that (6) also contains complex poles, which makes the fitting algorithm universal for all kind of materials. For FR-4 PCB type laminates this second order term is normally not necessary.

Characterizing PCB Laminates from Measurements

With these flexible material models on hand we now discuss how these can be used for simulation of PCBs. One of the most challenging tasks is the characterization of the material for the given layout and stack-up. Due to the manufacturing process the real material properties might be slightly different from the ones published by the vendor. Therefore a reliable characterization is necessary.
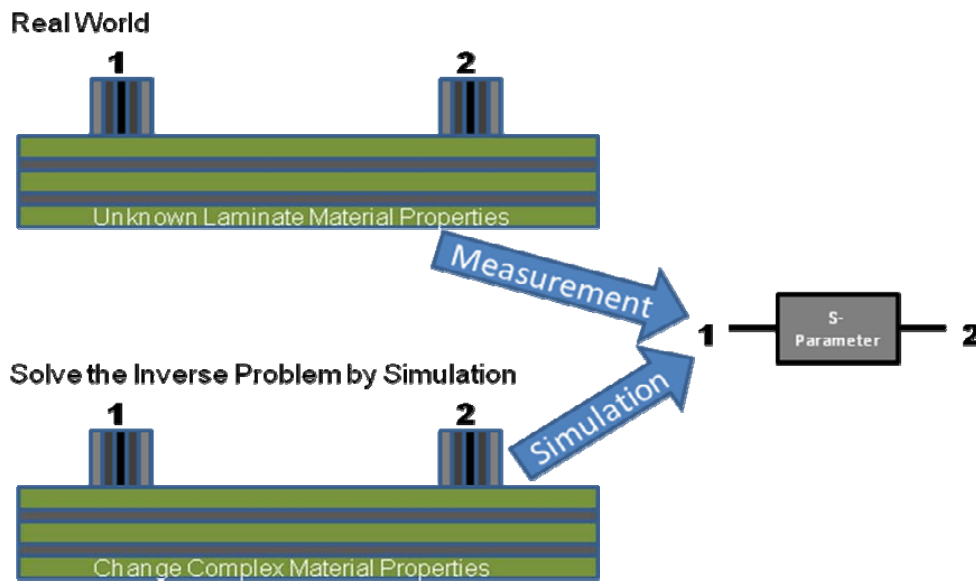
Figure 4: Inverse Problem of finding the right material properties from simulation that match measurement

Figure 4 demonstrates the required task to perform a measurement and simulation assisted material characterization. Based on a given set of measured S-Parameters we want to create a simulation model which produces S-Parameters with a given deviation (accuracy) from the original S-Parameter. This task is mathematically an inverse problem, where internal material parameter should be determined from a measurement at input and output only. Inverse problems are often ill posed and we first need to discuss the requirements for a successful extraction. As input we would like to use the complex insertion loss of a two port system only. In this case the requirement for the model is that it only consists of one material, see figure 5. With the insertion loss we can't distinguish if the material passes two different materials or only one material with the average

properties. Therefore the solution to this inverse problem is not unique. There exists multiple configurations of material properties, which all produce the same S-Parameters at the ports.
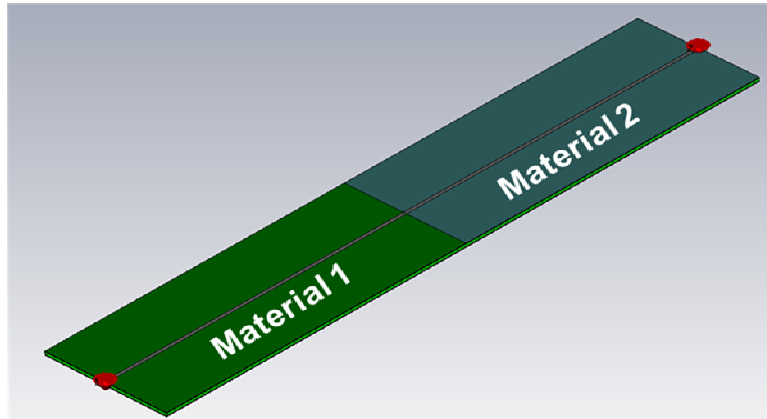
Figure 5: Microstrip line over two different substrate materials. Example for an inverse problem, which is not unique.

For accurate validation numerous evaluation structures were be measured using TRL/LRM calibration methods on a "Physical Layer Reference Design" board [11]. This board has microstrip traces and a very thin top layer of solder mask. For the studies, we will use a given model for the solder mask and then adjust the material properties of the FR-4 in order to match the measurement as suggested in [11]. This can be done either manually, involving valuable engineering time or as proposed in this paper automatically by means of a least square optimization. Using a general optimizer also allows us to use arbitrary material models and materials. It is the most general concept for this task.
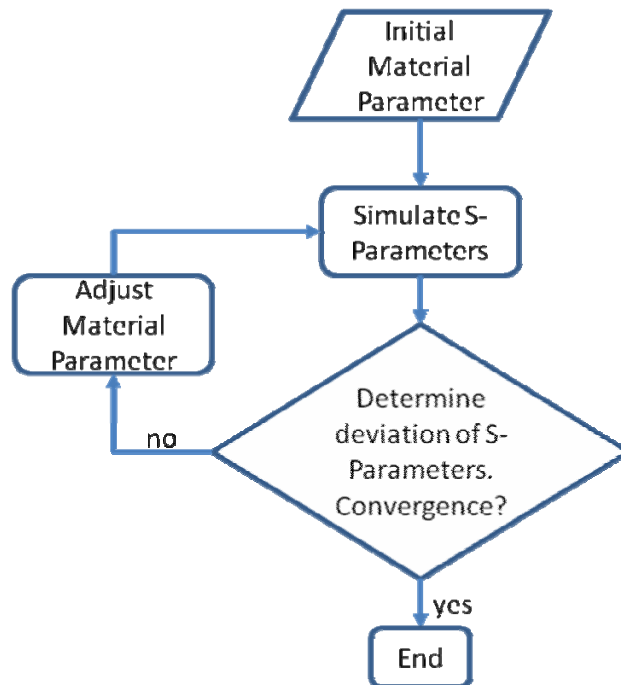
Figure 6: Process of optimizing the material parameters for a given measured S-Parameter dataset

Figure 6 illustrates the procedure. In order to apply it we need to define how the error and therefore convergence respectively is defined. The comparison of both magnitude and phase of the S-Parameters between measurement and simulation of a particular model can be used to develop model accuracy metrics. We propose the following error metric for the deviation of the insertion loss,

$$err = \sum_{f_i=f_{min}}^{f_{max}} \sqrt{\left(Re\left\{S_{12}^{meas}(f_i)\right\} - Re\left\{S_{12}^{sim}(f_i)\right\}\right)^2 + \left(Im\left\{S_{12}^{meas}(f_i)\right\} - Im\left\{S_{12}^{sim}(f_i)\right\}\right)^2} \quad (7)$$

or in words: the sum of the magnitude of the deviation in a given frequency range. Please note that this is different from "the deviation of the magnitude" and takes both the match of magnitude and phase into account.

Another remaining questions is, after we know the error, how do we adjust the material parameter. Fortunately, in mathematics many optimization techniques are studied. [9] includes Newton, Powell, Nelder-Mead, Genetic and Particle Swarm optimization techniques. If the initial material properties are close to the final values a local optimizer such as a Newton algorithm can be used for a parameter fitting of the dispersion model's degrees of freedom: Number of poles, pole frequency, and pole strength are all considerations. In the other case a global optimizer e.g. particle swarm or genetic algorithm ensures that the best global minimum is found, even if the original model was off from the optimal parameter set.

Finally we can also choose the number of poles, which corresponds to the order of the used dispersion model, see eq. 6. Generally, the accuracy will increase with increasing number of poles used in the material description. The studies performed for this paper showed that it is advisable to start with a lower order dispersion model, e.g. second order and increase the number if higher accuracy if required. The more parameters we can fix or eliminate in advance, hence predefining the model, the less parameters need to be fitted. One common choice is to use 1-2 fixed frequencies per decade for the poles of the dispersion model. If for example S-Parameters from 0-20 GHz are required, a second order model with poles at 1 GHz and 10 GHz, can give very accurate results. In this case three remaining parameters need to be optimized: $\varepsilon_\infty, \Delta\varepsilon_1, \Delta\varepsilon_2$
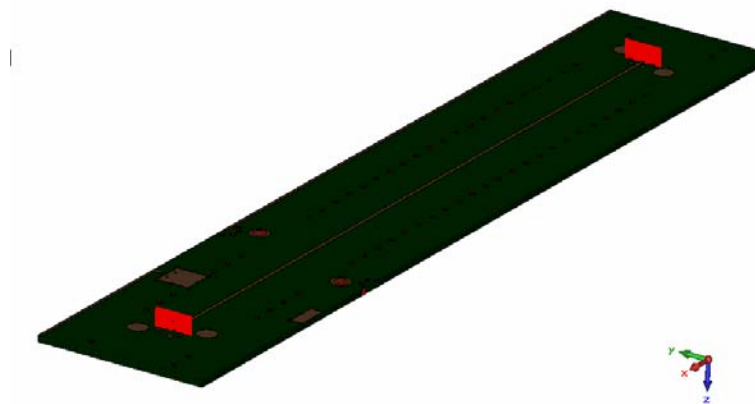
Figure 7: Example model of the PLRD board: 3.5 inch straight stripline
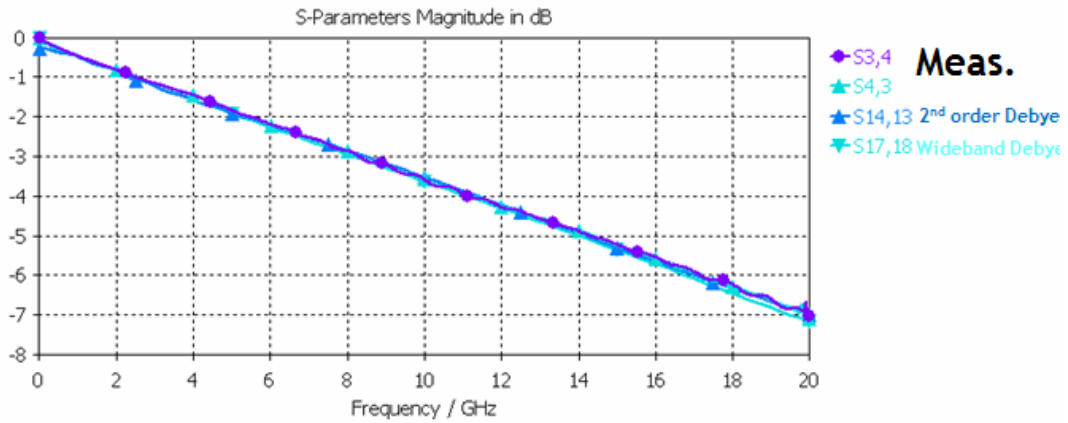
Figure 8: Comparison Measured insertion loss, 2nd order dispersion Model and a band limited infinite order Debye (wideband)
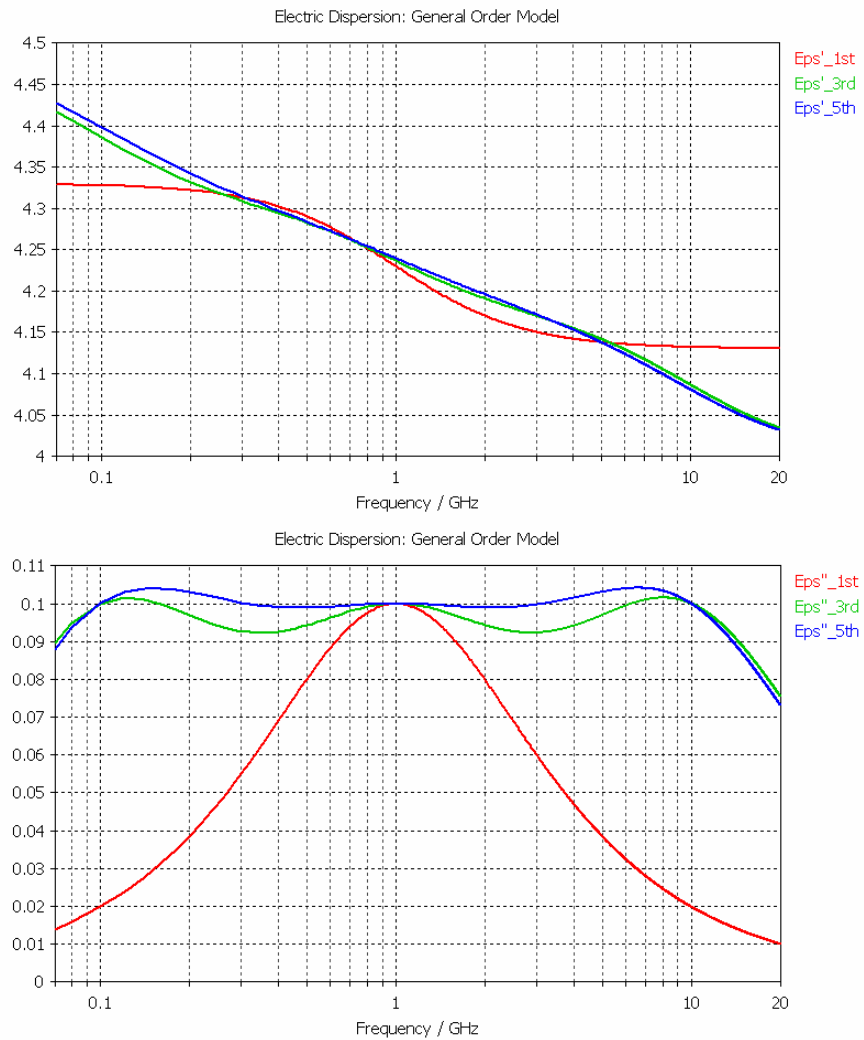

Figure 9: Constant loss approximation using 1st,3rd and 5th-order Debye models

In order to reduce the unknowns of the higher-order Debye model for FR4-type materials, a 1st, 3rd and 5th order approximation was developed. As in the band limited infinite order Debye model, the requirement of a constant loss is incorporated. The poles in this case are equally split over two decades, e.g. 1GHz to 100 GHz. In this case we force the loss values at the sample frequencies to be identical – therefore reducing the number of unknowns to two: loss tangent and real part of the permittivity at a given frequency. After setting up the equation systems and solving it, we determine the following β values:

Table 1: Frequency samples for 1st, 3rd and 5th order Debye model. The goal was an equidistant sampling on the logarithmic axis

Order	ω1	ω2	ω3	ω4	ω5
1st	ω0				
3rd	ω0	10 ω0	100 ω0		
5th	ω0	3.162 ω0	10 ω0	31.62 ω0	100 ω0

Table 2: Pole strength of 1st, 3rd and 5th order Debye model in order to produce an almost constant loss vs. frequency

Order	β0,1/eps''(ω0)	β0,2/eps''(ω0)	β0,3/eps''(ω0)	β0,4/eps''(ω0)	β0,5/eps''(ω0)
1st	2 ω0				
3rd	1.70349 ω0	13.2535 ω0	170.349 ω0		
5th	1.5197 ω0	1.33303 ω0	9.13338 ω0	13.3311 ω0	151.973 ω0

These of course need to be scaled by the loss or loss tangent at the known frequency, ω0. Figure 9 illustrates, how additional poles contribute to the imaginary part of the permittivity and allow it to be almost flat.

Figure 7 shows an example of a structure from the PLRD board and figure 8 the correlation of the insertion loss after optimization of a 2nd order and band limited, infinite order Debye model.
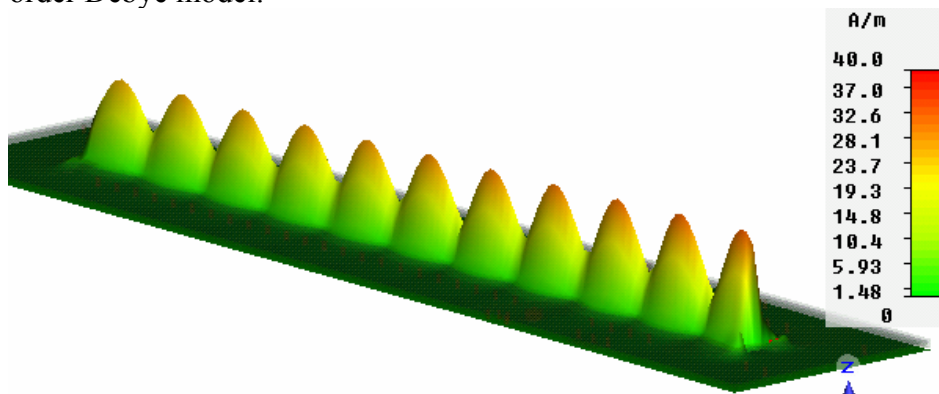
Figure 10: Overlaying pulse propagation at various times. The amplitude degradation as well as the pulse widening due to the material dispersion, can be clearly seen.

Summary

This paper proposed a consistent workflow of extracting material properties from measured data. Key in this extraction is the material modeling, which needs to be flexible, otherwise the accuracy will be limited. The proposed optimization as well as the least square fitting to given material properties allow an automatic procedure with no user interaction required. With a summation of N general 1st and 2nd order models this flexibility has been demonstrated using the case of a laminate material that is well represented by a band limited infinite order Debye model. In addition to this general fitting scheme a low order approximation of a constant imaginary part of the permittivity for FR4 – type material has been developed. This significantly reduces the number of unknowns during the fitting algorithm.

References

[1] T. Weiland, "A discretization method for the solution of Maxwell's equations for six-component fields": Electronics and Communication, (AEÜ), Vol. 31, pp. 116-120, 1977.

[2] T. Weiland, "Time domain electromagnetic field computation with finite difference methods." International Journal of Numerical Modelling, Vol. 9, pp. 295-319, 1996.

[3] B. Krietenstein; R. Schuhmann; P. Thoma; T. Weiland: "The Perfect Boundary Approximation technique facing the challenge of high precision field computation": Proc. of the XIX International Linear Accelerator Conference (LINAC'98), Chicago, USA, pp. 860-862, 1998.

[4] P. Debye. *Polar Molecules*, Chemical Catalog Co., New York, 1929

[5] K. E. Oughstun, *Electromagnetic and Optical Pulse Propagation 1*. Springer 2006

[6] K.S. Cole and R.H. Cole: "Dispersion and absorption in dielectrics. I. Alternating current characteristics", J. Chem. Phys, Vol9, pp341-351, 1941

[7] A.R. Djordjević, R.M.Biljić, V.D. Likar-Smiljanić, T.K. Sarkar, Wideband "Frequency-Domain Characterization of FR-4 and Time-Domain Causality", IEEE Trans. EMC, Vol. 43, No. 4, November 2001

[8] C. Svensson, G.E. Dermer, "Time Domain Modeling of Lossy Interconnects", IEEE Trans. Advanced Packaging, Vol. 24, No. 2, May 2001

[9] CST STUDIO SUITE™ 2009, www.cst.com

[10] Personal Communication, Holm Krüger, CST AG, Oct. 2009

[11] Y. Shlepnev, A. Neves, T. Dagostino, S. McMorrow, "Measurement-Assisted Electromagnetic Extraction of Interconnect Parameters on Low-Cost FR-4 boards for 6-20 Gb/sec Applications", Proceedings of Design Con 2009