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FDTD Analysis of Printed Circuit Boards Containing Wideband Lorentzian Dielectric Dispersive Media

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Abstract

A Lorentzian model as the general case of a frequency-dependent behavior of a dispersive dielectric material is considered in this paper. Recursive convolution algorithms for the finite-difference time-domain (FDTD) technique for two cases of a Lorentzian medium, narrowband and wideband, depending on the ratio of a resonance line half-width at –3 dB and the resonance frequency of the material, are detailed. It is shown that a wideband Lorentzian model of a dielectric FR-4 used in printed circuit boards is more flexible and gives good agreement with experimental curves, and may be preferable as compared to a Debye model.

Keywords

Dispersive dielectric media, Lorentzian model, Debye model, FDTD technique, recursive convolution.

INTRODUCTION

In recent years many new composite dielectric and magnetic materials have been designed for application in various electronic devices [1]. FDTD modeling of electromagnetic structures containing linear dispersive materials, both Debye and Lorentzian, can use a comparatively efficient recursive convolution procedure [2-4]. FDTD modeling of Lorentzian materials has its peculiarities as compared to the Debye case. For a Debye model the function of susceptibility and field convolution is real, so that the recursive convolution procedure is straightforward. In the Lorentzian model, a similar convolution function is complex. In paper [5], it is shown that depending on the ratio of a resonance line half-width (at –3 dB level) and the resonance frequency, different recursive convolution equations and coefficients for field updating are obtained. At $\delta / \omega_0 \geq 1$, where δ is a resonance line half-width, and ω_0 is the resonance frequency, it is a wideband Lorentzian material, and its behavior resembles, but does not coincide with that of the Debye model. The wideband Lorentzian model has an analog in linear circuit theory with constant parameters as an RLC-circuit with low Q-factor ($Q \leq 1$). At $\delta / \omega_0 < 1$, it is a narrowband Lorentzian material suitable for resonance effects modeling, and its analog is a high-Q RLC-circuit. As for a Debye model, its analog is an RC or RL circuit with an impulse response that is a damped exponential function.

A Debye model is suitable for materials with dispersion at comparatively low frequencies and with comparatively low loss, and it is successfully used for the description of the behavior of such dielectrics as FR-4 in printed circuit boards in the low gigahertz range [6,7]. Both narrowband and wideband Lorentzian material models can be used for the description of more pronounced dispersion and resonance effects. These three types of material models encompass all the types of linear non-parametric media that can be described canonically by a rational-fractional function of frequency and a corresponding series of damped exponentials in the time domain. This allows recursive convolution being applied in the FDTD modeling of such media, since the recursive convolution procedure is based on the time-shift property of an exponential function.

All other material models, such as modified Debye and Drude [2,3], are particular cases of a more general Lorentzian media. Therefore, introducing into FDTD the Lorentzian model with two different cases - wideband and narrowband, allows for general analysis of a broad variety of dielectric, magnetic, magneto-dielectric materials (including composites), and their combinations in a wide frequency range using a unified software tool.

Below the numerical results for a wideband Lorentzian model applied to an FR-4 dielectric in a printed circuit board are presented. For verification, these modeling results are compared with experimental data and the corresponding Debye model.

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NUMERICAL AND EXPERIMENTAL RESULTS

The schematic of a test board used in the measurements and for FDTD modeling is represented in Figure 1.

The board was the double-side copper-clad printed circuit board with an FR-4 substrate populated with a set of lumped decoupling capacitors, similar to that described in paper [6]. The decoupling capacitors were distributed uniformly over the test board, and their location (all dimensions are in mm) is indicated in Figure 1. One end of each decoupling capacitor was soldered directly to the top copper plane, the other end being connected to the bottom plane by a short piece of *AWG 24* wire. Sixteen *2 mm x 2 mm* square apertures were cut in the upper plane to allow the *AWG 24* wires to penetrate the plane without electrical contact.

The computational domain used in the FDTD simulations was discretized by a uniform mesh of *1 mm x 0.165 mm x 1 mm*, with the short dimension for the board thickness. There were five FDTD cells within the board thickness, eight PML cells were placed at each boundary plane of the computational domain, and seven white space layers were placed between the PML and the test board.

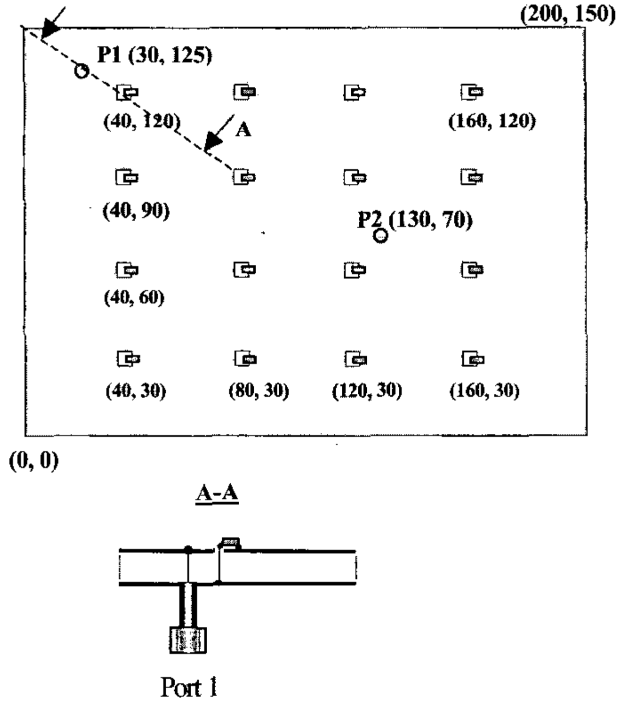
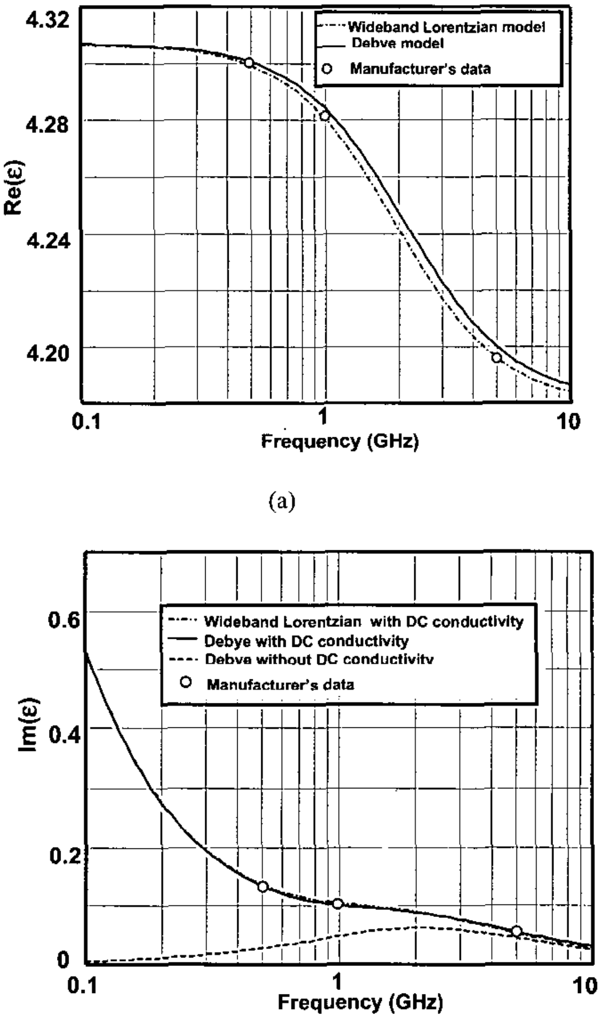


Figure 1. Test board with decoupling capacitors (all the dimensions are in millimeters).

The parameters of the FR-4 dielectric were known (without high accuracy) from the manufacturer's data, and were approximated by Lorentzian and Debye curves using the approach described in [8]. This approach is based on an analytical solution of a system of non-linear equations with restrictions following from the fundamental causality principle, and allows restoring a Debye or a Lorentzian curve by data of real and imaginary parts of permittivity at a few frequency points. These restored Lorentzian and Debye dependencies were then used for FDTD modeling, and the input Lorentzian and Debye parameters then were modified until the best match of the FDTD-simulated results with measured data was achieved. The frequency dependence of the real and imaginary part of the FR-4 permittivity used for the final simulations are shown in Figures 2 (a, b).



(a)

(b)

Figure 2. Real (a) and imaginary (b) parts of permittivity in Debye and Lorentzian dielectric models of an FR-4 substrate.

The parameters of the dispersive dielectric for the Lorentzian model

$$\varepsilon = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)\cdot f_p^2}{f_0^2 - f^2 + jf\cdot\Delta f} \qquad (1)$$

are $\varepsilon_s = 4.307$; $\varepsilon_\infty = 4.181$; $\sigma_e = 2.93\cdot10^{-3}$ S/m; $f_0 = f_p = 17$ GHz; $\Delta f = 150$ GHz, and for the Debye model

$$\varepsilon = \frac{\varepsilon_s - \varepsilon_\infty}{1 + j2\pi f\cdot\tau_r} \qquad (2)$$

the parameters of the dielectric are $\varepsilon_s = 4.307$; $\varepsilon_\infty = 4.181$; $\sigma_e = 2.93\cdot10^{-3}$ S/m, $\tau_r = 7.50\cdot10^{-11}$ s.

The two-port measurements were made using an *HP8753 D* vector network analyzer.

There is good agreement between the experimental and computed results for these two models with the parameters mentioned above. However, the FDTD modeled $|S_{11}|$ is slightly better for the wideband Lorentzian model shown in Figure 3 than for the corresponding Debye model in Figure 4, as seen in the frequency range of 2 – 3.5 GHz and above.

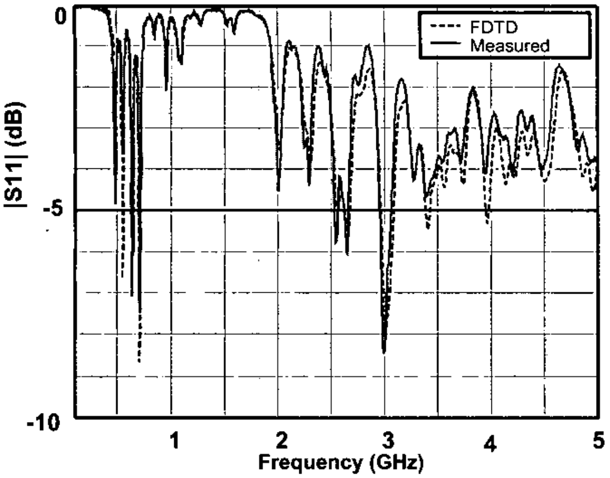


Figure 3. Measured and FDTD modeled $|S_{11}|$ of the PCB with 16 decoupling capacitors and Lorentzian wideband dielectric.

This might be explained by the increased influence of the decoupling capacitors on the "effective" dielectric constant of the PCB substrate (since it has apertures and inhomogeneities in the form of capacitors). While the Debye model analogue is a two-element (RC or RL) linear circuit, for the case of the populated PCB the analog of the resultant "media" will be a three-element RLC circuit, where the Q-factor approaches unity, and the behavior of a Debye and wideband Lorentzian media become distinctly different. Then the wideband Lorentzian model of the dielectric at higher frequencies is preferable to the Debye case.

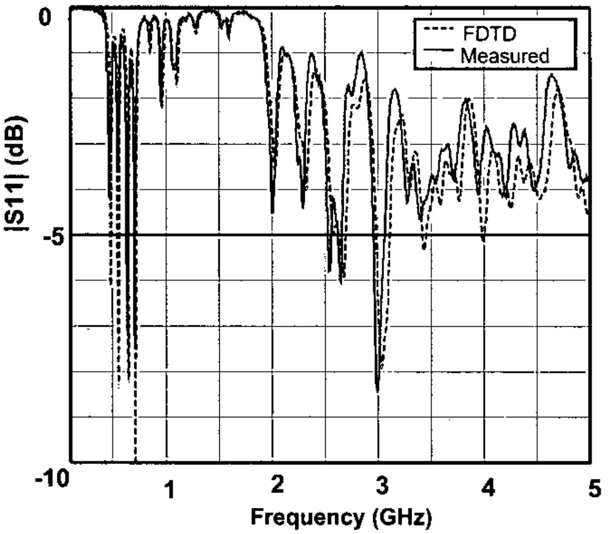


Figure 4. Measured and FDTD modeled $|S_{11}|$ of the DC power-bus with sixteen decoupling capacitors and Debye dielectric.

CONCLUSIONS

A Lorentzian material model is more general as compared to a Debye one (and other models, such as modified Debye and Drude [2,3]). A wideband Lorentzian model may be preferable as compared to the Debye one, since it takes into account different frequency behavior of the material, especially at higher frequencies where resonance effects in the material can be noticeable. Though more memory consuming as compared to the Debye model, the Lorentzian model with two different cases - wideband and narrowband, introduced into the FDTD method, allows analyzing a broad variety of dielectric, magnetic, magneto-dielectric materials (including composites), and their combinations in a wide frequency range using a unified software tool.

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REFERENCES

[1] P.S.Neelakanta, *Handbook of Electromagnetic Materials. Monolithic and Composite Versions and Their Applications,* CRC Press. 1995.

[2] K.Kunz, R.Luebbers, *The Finite Difference Time Domain Method for Electromagnetics*, CRC Press, Inc., 1993.

[3] A.Taflove, *"Computational Electrodynamics. The Finite-Difference Time-Domain Method"*, Artech House, Inc., 1995.

[4] R.Luebbers, F.P.Hunsberger, K.S.Kunz, R.B.Standler, M.Schneider, "A frequency-dependent finite-difference time-domain formulation for dispersive materials", *IEEE Trans. on EMC,* v.32, No 3, August 1990, pp. 222-227.

[5] M.Y.Koledintseva, J.L.Drewniak, X.Ye, "Representation of Gyromagnetic Composite Media for FDTD Modeling". *Proc. IEEE EMC Symp. Montreal '2001*, V. 1, p. 555-558.

[6] X.Ye, M.Y.Koledintseva, M.Li, J.L.Drewniak, "DC Power-Bus Design Using FDTD Modeling with Dispersive media and Surface Mount Technology Components", *IEEE Trans. on EMC,* v.43, No 4, November 2001, pp. 579-587.

[7] X.Ye, J.Fan, M.Koledintseva, J.L.Drewniak, "DC Power Bus Design with FDTD Modeling Including a Dispersive Media", *Proc. IEEE Conf. On Electrical Performance on Electronic Packaging,* 2000, USA, p.55-58.

[8] M.Y. Koledintseva, G. Di Fazio, "Extraction of the Lorentzian and Debye parameters from measurement data in a few frequency points", *Proc. 10th Int. Conf. On Spin Electronics,* November, 2001, Firsanovka (Moscow Region), Russia, pp. 530-542.