Wideband Propagation Constant Characterization for Printed Circuit Board Interconnects

Kuen-Fwu Fuh [1], Tsung-Wen Chen [2]

[1]Department of Electronic Engineering, National United University

1 Lien-Da, Kung-Ching Li, Miaoli 360, Taiwan. kffuh@nuu.edu.tw

[2] Material & Chemical Research Laboratories, Industrial Technology Research Institute (ITRI)

Bldg. 77, 195-5 Chung Hsing Rd., Section 4, Chutung, Hsinchu 310, Taiwan

1. Introduction

The issues of signal distortion and electromagnetic interference (EMI) deteriorate as the rise time of signals in printed circuit board (PCB) decreases. Therefore signal integrity (SI) becomes an important topic in modern wideband and high-speed applications for PCB manufacturers and designers [1-2]. The dispersion propagation and frequency-dependent attenuation of PCB interconnects or transmission lines contribute significantly to the SI issues; the propagation characteristics of interconnects or transmission lines in PCB are required by designers to estimate the qualities of communication signals, e.g., eye-diagram evaluation [3]. 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 [4].

Propagation constant $\gamma=\alpha+j\beta$ is an eigenvalue of the transmission matrix of uniform transmission line; it can also be viewed as the transfer function of the uniform transmission line. Therefore it contains all the signal transfer characteristics of an interconnect. It is well known that TRL calibration method can extract propagation constant from the measurement of S-parameters of two lines with different lengths [5-6]. Various authors apply this methodology to characterize instrinsic parameters of transmission lines and permittivities of materials [7-10]. Based on the same algorithm and proper numerical process, we have shown that this method can characterize propagation constant of PCB interconnect till 40 GHz. This methodology can help manufacturers and designers to evaluate propagation properties of TEM or quasi-TEM transmission line in real application scenario.

In section 2 the mathematical model is derived; the model is examined in section 3 by the aids of commercial circuit and field solvers. Then the propagation characteristics of microstrip lines fabricated on thin PCB substrates are measured. The measured data shows that this methodology can help manufacturers and designers to clarify the issues of dispersive and anisotropic propagations.

2. Theory of Methodology

As shown in figure 1, $\bar{\bar{T}}$ represents the transmission matrix of transmission line and transmission matrices $\bar{\bar{A}}$ and $\bar{\bar{B}}$ represent the combined responses of fixture, cables, and vector network analyser at port one and port two, respectively. The measured response embeds the effects of both $\bar{\bar{A}}$ and $\bar{\bar{B}}$. Based on TRL calibration theory, propagation constant γ can be extract out from the measured S-parameters of two transmission lines with different lengths (L_1 and L_2). $\bar{\bar{M}}_1$ and $\bar{\bar{M}}_2$ are the measured transmission matrices of line 1 and 2 in figure 1 and they can be expressed by $\bar{\bar{T}}$, $\bar{\bar{A}}$, and $\bar{\bar{B}}$ as

$$\bar{\bar{M}}_1 = \bar{\bar{A}}\bullet\bar{\bar{T}}_1\bullet\bar{\bar{B}};\quad \bar{\bar{M}}_2 = \bar{\bar{A}}\bullet\bar{\bar{T}}_2\bullet\bar{\bar{B}}\,. \qquad (1)$$

The following two equations can then be derived from (1).

$$\left(\bar{\bar{M}}_2 \bullet \bar{\bar{M}}_1^{-1}\right) \bullet \bar{\bar{A}} = \bar{\bar{A}} \bullet \left(\bar{\bar{T}}_2 \bullet \bar{\bar{T}}_1^{-1}\right) \quad (2)$$

$$\bar{\bar{T}}_2 \bullet \bar{\bar{T}}_1^{-1} = \begin{bmatrix} e^{-\gamma(L_2-L_1)} & 0 \\ 0 & e^{\gamma(L_2-L_1)} \end{bmatrix} \quad (3)$$

Equation (2) is an eigen equation and the eigenvalues of $\bar{\bar{M}}_2 \bullet \bar{\bar{M}}_1^{-1}$ are $e^{\pm\gamma(L_2-L_1)}$ and $\bar{\bar{A}}$ is the engenvector matrix.

3. Verifications

The Agilent ADS and Ansoft HFSS are used as numerical experiment platforms to verify the capability of the developed model and revise unexpected numerical errors. S-parameters of two microstrip lines with different lengths are generated by ADS and their propagation constant $\gamma=\alpha+j\beta$ is numerically extracted out to compare with those calculated by LineCalc of ADS and HFSS. The associated parameters of the verification microstrip line are:

Substrate permittivity: ε_r=9.6 tanδ=0.002; Substrate thickness: 0.65mm; Conductor width:0.63 mm copper; Conductor thickness:0.1 mm

Figure 2 exhibits the comparisons between the numerically extracted propagation constant from S-parameters generated by ADS and those calculated by LineCalc and HFSS with frequency ranges from 0.1 GHz to 20 GHz. Fig. 2a shows very well match of the phase constant (β, beta) among these numerical platforms and the developed methodology within the whole frequency range. For attenuation constant (α, alpha), the data obtained from the three platforms also match well till 10 GHz; but larger discrepancy occurs as frequency increases further. However the numerical model do accurately recover the propagation constants from the same software set, ADS and LineCalc. The discrepancy with HFSS may results from the numerical convergence problem of the field solver or the inaccuracy of the model employed by ADS.

4. Print Circuit Board characterization

New–generation communication system requires wide operation bandwidth and low hardware profile to enhance performance and function density. Therefore the developed numerical methodology is applied to characterize the propagation constants of interconnects fabricated on thin FR4 PCB till 40GHz. PCB is a combination with resins and woven fibreglass fabrics; there may exist anisotropic propagation property. In this paper we examine this issue by manufacturing the microstrip lines along latitude direction (denoted by H), longitude direction (denoted by V), and 45-degree direction (denoted by S). The microstrip lines under test are fabricated on a PCB substrate with 0.127 mm thickness and clad with half ounce copper foil. The line width is arbitrarily designed to be 0.245 mm and samples with various lengths are fabricated. S-parameter measurements from 40 MHz to 40 GHz of two test samples with different lengths are measured. Then the numerical model extracts the propagation constant through the measured S-parameters. Data in figure 3a shows that the measurement uncertainty of beta is small and the effect of propagation dispersion is weak. It also shows that the thin PCB substrate cause no anisotropic propagation problem till 40 GHz. Figure 3b indicates that the measurement fluctuations of attenuation increase with increasing frequencies; but it behave good below 30GHz. Data in figure 3b indicates that the dispersion loss mechanism of interconnects is significant and it should be considered for signal integrity. Finally the loss mechanism of this thin PCB interconnect is independent on the propagation orientation.

5. Conclusions

Measurement-based numerical methodology for propagation constant characterization of interconnects or transmission lines has been established and verified by the commercial circuit and field solvers. It requires only preparing two test transmission lines with different lengths and measuring their S-parameters. Calibration of network analyser is not required because the model is derived from TRL calibration algorithm. Wideband propagation constant characterization is performed on interconnects fabricated on thin PCB substrate that meets the needs of future high-performance and high-speed circuit applications. Measurement data indicates that interconnect on thin PCB substrate propagate with no dispersion over wide frequency range and suffers no anisotropic propagation problems. The frequency-dependent loss mechanism may contribute to signal integrity problem.

Acknowledgments

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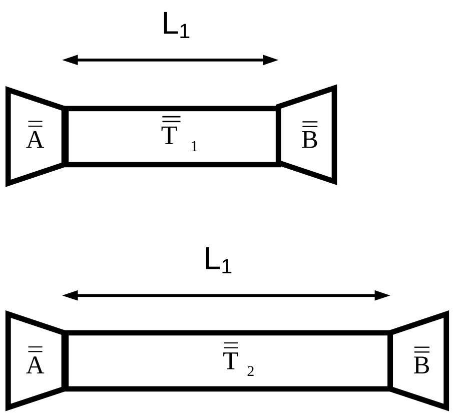
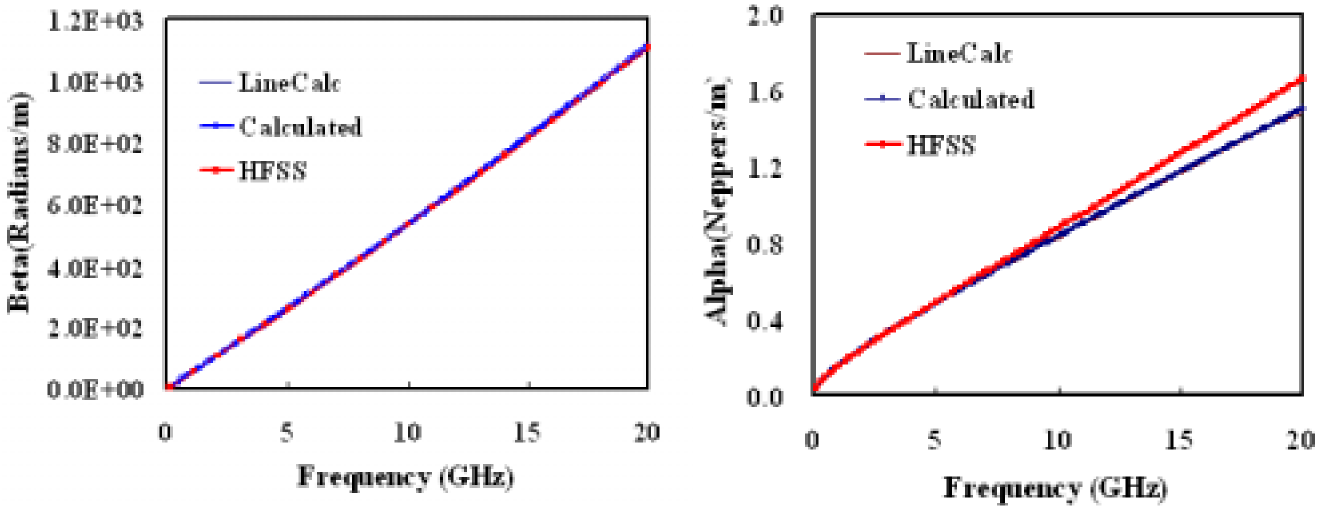
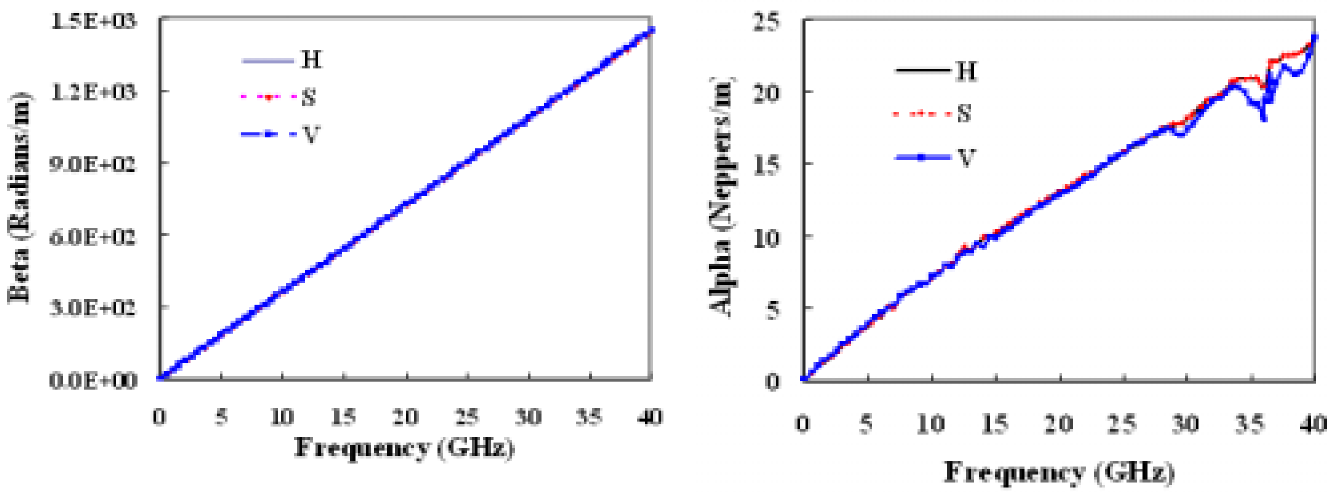


Figure 1: Transmission matrices related to transmission lines



(a) (b)

Figure 2: Comparison between the developed model and the commercial circuit and field solvers. (a) Beta (β) comparison, (b) Alpha (α) comparison.



(a) (b)

Figure 3: Wideband propagation properties characterization of microstrip line fabricated on thin FR4 PCB substrate. H: microstrip in latitude direction, V: microstrip in longitude direction, S: microstrip in 45-degree direction. (a) Beta (β) measurement, (b) Alpha (α) measurements.