Time Domain Electromagnetic Analysis of a Via in a Multilayer Computer Chip Package

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Abstract

The determination of an equivalent circuit to approximate the behavior of an interconnect in a computer package is an important step in the evaluation of the computer's performance. This paper presents a methodology for deriving an equivalent circuit of a via using a time-domain full-wave solution of Maxwell's equations.

1. Introduction

The design of present day digital computers requires the electrical characterization of the interconnection circuits that exist in the computer package to ensure reliable and predictable performance of the computer. Accurate timing analysis of the electrical signals and accurate determination of the minimum logic levels at a receiver are two important parameters that need to be determined when designing the computer. Discontinuities along the interconnect path cause reflections that affect the signal delay and the transient logic levels of a digital circuit, possibly causing erroneous behavior of the computer [1].

This paper investigates the reflection from a via in a multilayer computer package environment and presents a methodology for determining an equivalent circuit that may be used in general circuit analysis software. Two via geometries are presented: a rectangular via passing through a pair of ground planes, and a cylindrical via passing through a hole in a ground plane coated on both sides by a dielectric slab. The rectangular via is analyzed using two time-domain electromagnetic field algorithms: finite-difference time-domain (FDTD) [2] and transmission line matrix (TLM) [3]. The cylindrical via is analyzed using a FDTD nonorthogonal grid formulation [4,5]. The electromagnetic waveforms obtained using these solvers are used to determine the scattering parameters of the vias from which equivalent circuits are derived.

The use of FDTD or TLM provides a full-wave analysis tool for determining the electromagnetic field behavior of a discontinuity. The FDTD and TLM algorithms allow the modeling of arbitrarily shaped material regions which compose an interconnect path since the computational space is discretized into cells where the material properties of each cell can be specified. Time-domain analysis allows the efficient determination of frequency-dependent parameters through the use of the Fourier transform.

The equivalent circuit allows the circuit designer to approximate the behavior of the discontinuity in a circuit simulator where complex transmission line circuits with nonlinear terminations can be included. An interconnect with numerous path discontinuities and distributed nonlinear loads can then be analyzed in a general circuit simulator.

2. Approach

The first step in determining the equivalent circuit parameters for the via is to employ a time domain Maxwell solver, e.g., TLM or FDTD, using a Gaussian pulse excitation to obtain the total voltage and current waveforms at the input and output ports from which the scattering parameters are determined. The voltage is determined by integrating the electric field from the strip to the adjacent reference plane. In view of the symmetry of the stripline cross-section, the choice of reference plane is arbitrary. A convenient choice for this path is to extend it perpendicularly from the center of the strip to the reference plane. However, numerical experiments have shown that the final result for the voltage or current is relatively insensitive to the choice of integration path.

The line current is determined by performing a closed line integral of the magnetic field around the strip. The path of the line integral forms a rectangle whose edges coincide with the magnetic field components parallel to the strip one-half cell distance away. Integration in FDTD and TLM is performed by the trapezoidal rule. This entails a summation of the electric or the magnetic field components followed by a multiplication by the cell length along the path of integration.

The TEM mode of the stripline is excited near the input port using a spatial distribution of the electric field determined by the solution of Laplace's equation on a finite-difference grid. As outlined below, the calculation of the scattering parameters requires the knowledge of the incident field which is easily determined by exciting a uniform stripline.

The time-domain solver is run for the via structure to obtain the total voltage and current at the input and output ports. The scattering parameters are then determined by a DTFT (discrete-time Fourier transform, denoted below by the $\mathcal{F}[\cdot]$ operator) of the current or voltage waveforms,

$$\tilde{G}_i(e^{j\omega}) = \mathcal{F}[g_i(k)] = \sum_{k=0}^{N-1} g_i(k)\cdot e^{-j\omega k} \qquad (1)$$

where $g_i(k)$ is the time series output of the current or voltage at port i (i = 1 (input) or 2 (output)) and $\tilde{G}_i(e^{j\omega})$ is the Fourier transform of $g_i(k)$. The frequency-dependent scattering parameters are then calculated by

$$S_{11}(\omega) = \frac{\tilde{G}_{refl}(e^{j\omega})}{\tilde{G}_{inc}(e^{j\omega})} \qquad (2)$$

$$S_{21}(\omega) = \frac{\tilde{G}_2(e^{j\omega})}{\tilde{G}_{inc}(e^{j\omega})} \quad (3)$$

where $\tilde{G}_{inc}(e^{j\omega})$ is the transform of the incident voltage or current as computed using (1), and $\tilde{G}_{refl}(e^{j\omega})$ is the Fourier transform of the reflected waveform given by

$$\tilde{G}_{refl}(e^{j\omega}) = \mathcal{F}[g_1(k) - g_{inc}(k)]. \quad (4)$$

Once the scattering parameters for the via are determined, an equivalent circuit model may be obtained by using TouchStone[6]. TouchStone has an optimizing feature that allows the elements of a given circuit to be fitted to a set of given scattering parameters.

To complete the analysis, the circuit model is analyzed by the time domain circuit simulator, Multiple Transmission Line Time Domain Analysis (MTLTDA), which is described by Blazeck and Mittra [7]. MTLTDA is a circuit simulator that allows multiple lossy transmission lines with frequency-dependent inductance and capacitance matrices and nonlinear terminations. For this via structure, however, only a single lossless transmission line with linear discrete elements is needed.

3. Numerical Results

3.1. Rectangular Via.

The via chosen for analysis is shown in Fig. 1. The stripline cross-section measures 0.25 millimeters by 1.25 millimeters and the reference planes are placed so the impedance of the stripline is approximately 50 ohms. The via has a rectangular cross section of 0.50 millimeters by 0.75 millimeters which fits the rectangular grid used in the time-domain analysis. The fields on the walls at the input and output ports are determined using an absorbing boundary condition.

The FDTD and TLM mesh is comprised of cells 0.250 millimeters (δL) on a side, and a time step (δt) of 0.417 ps ($\delta t = \delta L/2c$) where c is the speed of light in free space. The temporal variation of the excitation pulse is a Gaussian distribution with a width of 60 time steps (25 ps). This pulse has a 3 dB cutoff frequency of approximately 20 GHz.

After the time-domain solvers are run, the time variation of the voltages and currents at the input and output ports are available. The voltages from the TLM analysis at the input and output port are shown in Fig. 3.

The scattering parameters are then calculated as outlined in the previous section. The magnitudes of the scattering parameters, $S_{11}(\omega)$ and $S_{21}(\omega)$, are shown in Fig. 4 for frequencies up to 40 GHz as calculated using both the voltage and current waveforms from TLM and the voltage waveform from FDTD. Note the sharp breaks above 30 GHz because the TE_{10} mode of the enclosure is excited. The side walls and power planes form a wave guide with dimensions 4.25 mm by 1.25 mm. At 35.3 GHz, $\lambda/2$ = 4.25 mm and the TE_{10} mode is excited. The effects observed between 30 and 35 GHz are due to the perturbation of the waveguide mode because of the strip, via, openings in the ground planes, and the close proximity of measurement port 1 to the discontinuity where an evanescent mode with slow attenuation may be excited.

The circuit model shown in Fig. 2 represents the via structure of Fig. 1. Note that the striplines have been modeled as ideal transmission lines; the stripline to via transition regions have been represented by a lumped Π-circuit consisting of C1, C2 and L1; and the via portion between the middle two planes has been modeled by L2.

In TouchStone the scattering parameters of the circuit in Fig. 2 are matched to the Fourier-transformed time domain results for the frequencies ranging from 0.48 GHz to 20 GHz. The element values to achieve this fit are: C1 = 0.119 pF, C2 = 0.075 pF, L1 = 0.47 nH, L2 = 0.062 nH. TouchStone matches S_{11} well in the middle of the 0.48 to 20 GHz spectrum, but some error arises at the low and high end of that frequency spectrum. S_{21} is well-matched throughout the spectrum.

The final step is to place the equivalent circuit model into the time domain transmission line simulator MTLTDA [7]. The excitation of the TE_{10} waveguide mode is not taken into account in the equivalent circuit, and the Gaussian waveform is approximated by a trapezoidal pulse in MTLTDA so a direct comparison between the two waveforms does show some discrepancies. However, by passing the time-domain waveforms through a Hanning low-pass filter to remove the frequency components above 20 GHz, the equivalence of the voltage response becomes apparent as shown in Fig. 5 where the filtered TLM waveforms of Fig. 3 are compared to the filtered waveforms from MTLTDA.

3.2. Cylindrical Via

An equivalent circuit model of a cylindrical via discontinuity is obtained using the same procedures as for the rectangular via; however, due to the complicated geometry, only the nonorthogonal FDTD analysis [4,5] is employed to perform the time-domain analysis. In this section, the results of the FDTD analysis will be compared with measurements taken from Maeda, *et al.* [8], and an equivalent circuit of the via will be given.

The cylindrical via discontinuity [8] is shown in Fig. 6. The via diameter is 0.7 mm, its length is 3.2 mm, the pad diameter is 3.9 mm, and the width of the connecting microstrip is 3.3 mm. The dielectric slab is 3.2 mm thick, and its permittivity is 3.4. The ground plane, which is in the center of the slab, has a circular cutout of 3.9 mm in diameter for the via.

The cylindrical via is discretized with a nonorthogonal grid, providing a piecewise linear model of the entire structure. The via was enclosed in a rectangular box with four perfectly conducting side walls and two absorbing end walls. The absorbing walls were at the near- and far-end of the discontinuity, respectively. The enclosure was 42.04 mm in length by 19.5 mm in width by 16 mm in height. This region was discretized with 8,000 nonorthogonal FDTD cells, providing a 79% reduction over the number of cells required by a grid based on the conventional Yee cell [3] of 0.7 mm in width. A Gaussian pulse with a quasi-TEM modal spatial distribution was used as the excitation for the nonorthogonal FDTD analysis.

The scattering parameters were computed from the nonorthogonal FDTD results using the FFT and compared with measurements from reference [8]. Figs. 7 and 8 show good agreement between the computations and the measurements. The discrepancies are attributable to two main factors other than the errors in reading the measured results from reference [8]. One is that the average cell size in the nonorthogonal mesh is too large for frequency components above approximately 13 GHz and introduces error in the high-frequency behavior of the scattering parameters. The other is that waveguide modes occur due to the presence of the perfectly conducting side walls around the via discontinuity and introduce errors in the computed results. In spite of these problems, the nonorthogonal results agree well with the measurements below 7 GHz, and show similar behavior to the measurements up to 16 GHz.

The equivalent circuit of the cylindrical via discontinuity shown in Fig. 9 was developed from the scattering parameter results obtained from the nonorthogonal FDTD analysis by using the same procedure given for the rectangular via. The equivalent circuit consists of ideal transmission lines for modeling the microstrip lines and a lumped L-C network for modeling the pads and via. This circuit model accurately reproduces the scattering parameter results up to approximately 6 GHz.

4. Conclusions

A methodology for determining the equivalent circuit of a via in a multilayer computer package has been demonstrated. The approach is general and its applicability is limited by the ability of the circuit simulator to model frequency dependent elements.

To accurately model the curved geometry, the nonorthogonal FDTD algorithm was employed instead of the conventional FDTD method because it provides a piecewise linear model of curved surfaces, and with the variable mesh density, it can represent complicated structures without an excessive number of unknowns. The nonorthogonal FDTD results were validated with measurements, [8] and an equivalent circuit model was developed from the results.

Acknowledgment

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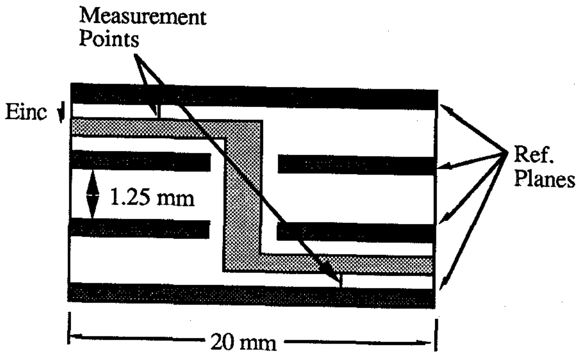

Figure 1. A side view of a rectangular via connecting two striplines on different levels in a multilayer circuit board configuration. The striplines are 0.25 mm by 1.25 mm, the via is 0.5 by 0.75 mm, and the reference planes are separated from the via by 0.25 mm.

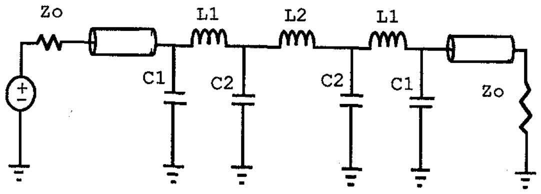

Figure 2. The equivalent circuit chosen to represent the rectangular via discontinuity. The transmission lines represent the stripline portions and the inductors and capacitors represent various parts of the via. The element values are Zo = 48.5, C1 = 0.119 pF, C2 = 0.075 pF, L1 = 0.470 nH, L2 = 0.062 nH as determined by TouchStone.

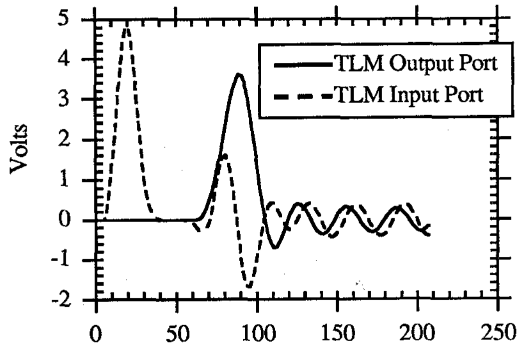

Figure 3. The time domain TLM voltage waveform of the rectangular via at the input and output ports.

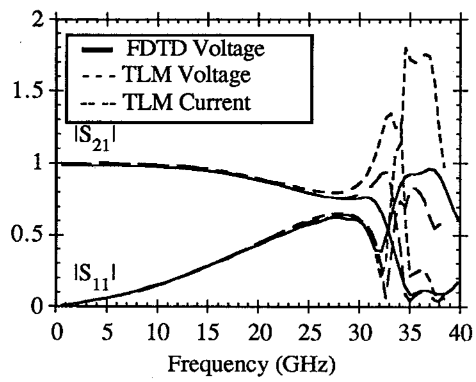

Figure 4. The rectangular via scattering parameter magnitudes as determined by FDTD and TLM.

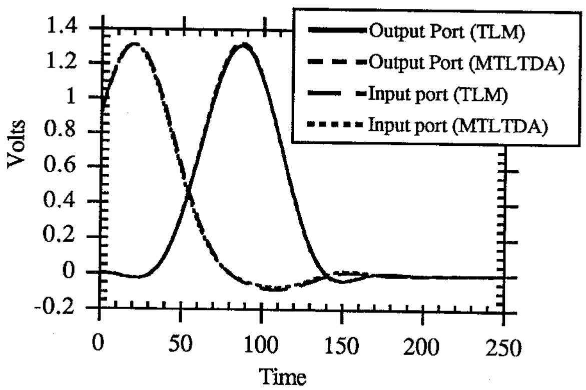

Figure 5. The time domain TLM and MTLTDA circuit waveforms filtered by a Hanning window with a 20 GHz cutoff frequency.

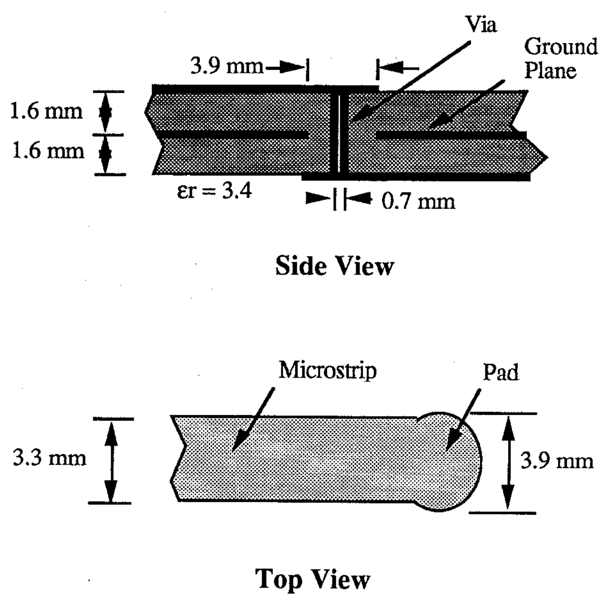

Figure 6. The geometry of the cylindrical via discontinuity.

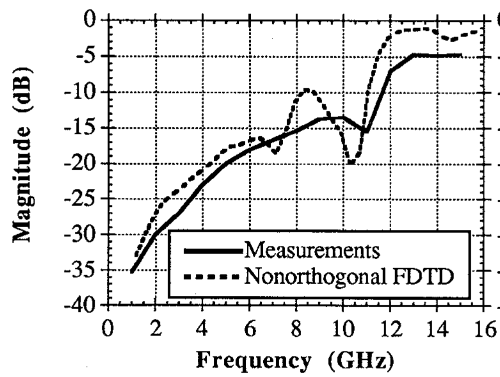

Figure 7. A comparison of the magnitude of S11 computed with the nonorthogonal FDTD time-domain waveforms to the measurements of S11[8].

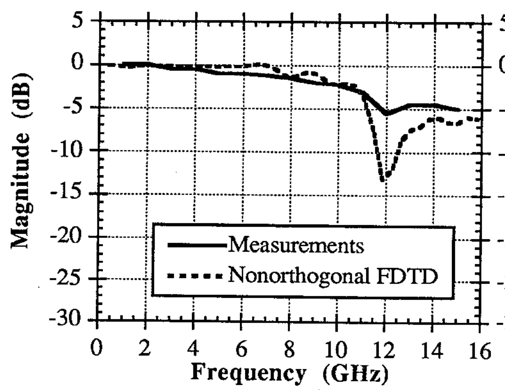

Figure 8. A comparison of the magnitude of S21 computed with the nonorthogonal FDTD time-domain waveforms to the measurements of S21 [8].

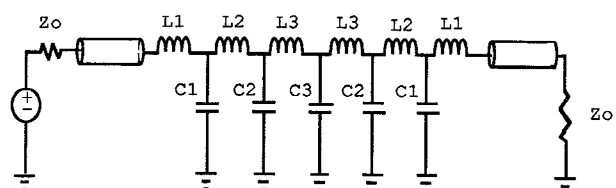

Figure 9. An equivalent circuit of the cylindrical via discontinuity. The transmission lines have an impedance of 55 ohms, and a effective dielectric constant of 2.76. L1 = 369.7 pH, L2 = 5.915 pH, L3= 723.17 pH, C1=.25283 pF, C2 = 0.00118 pF and C3 = 0.3393 pF.