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FULL-WAVE MODELING OF MULTIPLE VIAS USING DIFFERENTIAL SIGNALING AND SHARED ANTIPAD IN MULTILAYERED HIGH SPEED VERTICAL INTERCONNECTS

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Abstract—A 3D full-wave approach, based on the Foldy-Lax multiple scattering equations, is successfully extended to model massively-coupled multiple vias using differential signaling and shared antipad in high speed vertical interconnects. For the first time, this method has been used and tested on via-pair with shared antipad in multilayered structure. The magnetic frill current source on the port is calculated by using the finite difference method. Banded matrix iterative method is applied to accelerate the finite difference calculation. Numerical example of 15 signal via-pairs and 20 ground shielding vias in 6-layer board demonstrates that this approach is able to model the via-pair with shared antipad and to include all the coupling effects among multiple vias. The electrical performances of different signal driving schemes are provided and discussed. The coupling crosstalk on various via-pairs is compared. The improvement of signal integrity is shown by using differential signaling and shared antipad for via-pair in multilayered structure. The results are compared with HFSS and SIwave in accuracy and CPU. The CPU using Foldy-Lax approach is three orders of magnitude faster than using HFSS, and two orders of magnitude faster than using SIwave. The accuracy of Foldy-Lax is within 2% difference from HFSS up to 20 GHz, and outperforms SIwave in accuracy.

1. INTRODUCTION

With the ever-rising clock rate of chip-package-board systems, dimensions of interconnect structures become electrically larger as

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frequencies increase. Especially the massively coupled multiple vias behave like efficient radiators, thereby introducing significant electromagnetic interference (EMI), crosstalk and radiation loss [1]. Because of the limited number of ports of network analyzer, the hardware measurement and calibration of the complete network is difficult [2]. On the other hand, simple approximations, such as physical and lumped models, are relative inaccurate due to their incapability of including all the coupling effects among multiple vias.

A 3D full-wave and mostly-analytic approach, based on Foldy-Lax scattering equations and cylindrical wave modal expansions, was adopted to model multiple cylinders in planar waveguides [3, 4]. The magnetic field dyadic Green's functions are expressed in terms of waveguide modes in the vertical direction and vector cylindrical wave expansions in the horizontal direction. The Foldy-Lax approach was modified to model the arbitrary shape of pad and antipad [5] and substrates of layered dielectrics [6]. The finite-sized rectangular board was also modeled using frequency-dependent cylinder layer and mode-matching technique [7]. Recently, we have developed a 3D full-wave interconnect simulator, namely Foldy-Lax Via Tool [8], based on this multiple scattering technique. The simulation results using this tool are within 2% difference of accuracy compared with commercial general-purpose field solver Ansoft HFSS [9]. The CPU of this tool is three orders of magnitude faster than that of the HFSS. The results were also validated using experimental data from hardware measurements in paper [10, 11].

In this paper, we successfully extend this full-wave approach to model the multiple vias using differential signaling and shared antipad in high speed vertical interconnects (Fig. 1). For the first time, this method has been used and tested on via-pair with shared antipad in multilayered structure. The typical shape of shared antipad is oval (Fig. 2). The red frame represents the antipad, also called void, cutting

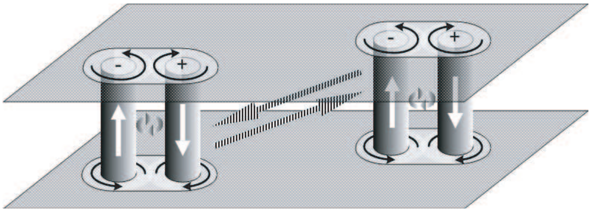

Figure 1. Via pair of differential signaling in shared antipads between two conducting plates.

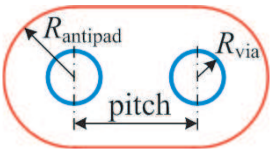

Figure 2. Top view of via pair in shared antipad.

off from the copper plate. The circles are the two cylinder vias going through the shared antipad. Using equivalent principle, we put the port excitation on the antipad and cover the aperture with a perfect electric conductor (PEC). The magnetic frill current source on the port is calculated using the finite difference method (FDM). Banded matrix iterative method is applied to accelerate the finite difference calculation. Numerical examples of 15 signal via-pairs and 20 ground shielding vias in 6-layer board demonstrates that this approach is able to model the via-pair with shared antipad and to include all the coupling effects among multiple vias. The electrical performances of different signal driving schemes are provided and discussed. The coupling crosstalk on various via-pairs is compared. The improvement of signal integrity is shown by using differential signaling and shared antipad for via-pair in multilayered structure.

2. THEORETICAL MODEL

Via cylinders are modeled as conducting cylindrical scatterers between two parallel plates (Fig. 1). In order to capture the coupling effects among the vias (dashed arrows in Fig. 1), we model the via cylinder by using a cylindrical wave expansion of dyadic Green's functions G, which are further expressed in terms of waveguide modal solutions [3]. Based upon the dyadic Green's functions, we excite this parallel-waveguide structure using an equivalent magnetic frill current source M_s at antipad (solid circular arrows in Fig. 1). The surface currents I on the cylinders (white arrows in Fig. 1) are calculated from the magnetic field H. The admittance matrix $\mathbf{Y}$ of the complete network is finally obtained to describe the electrical performance of multiple via interconnects.

$$\bar{H} = -j\omega\varepsilon \iint dx'dy'\overline{\overline{G}}\left(\bar{r},\bar{r}'\right)\cdot\bar{M}_s\left(\bar{r}'\right) \tag{1}$$

$$I = z\cdot\oint_l dl\left(\hat{n}\times\bar{H}\right) \tag{2}$$

The final magnetic field on the pth cylinder is,

$$\bar{H}^{(p)} = \sum_{m,l} w_{lm}^{TM(p)} Rg\bar{H}_m^{TM}(k_{\rho l}, k_{zl}, \bar{\rho}-\bar{\rho}_p, z\pm d/2) \tag{3}$$

where $Rg\bar{H}_m^{TM}$ is the modal solution of TM magnetic field and $w_{lm}^{TM(p)}$ are the field coefficients to be solved by using the Foldy-Lax multiple scattering equations [3].

Then we get the current on the pth cylinder using solved $w_{lm}^{TM(p)}$.

$$I^{(p)} = \sum_{l} \frac{4(-1)^l}{\eta H_0^{(2)}(k_{\rho l} a)} w_{l0}^{TM(p)} \tag{4}$$

The currents are expressed as the summation of contributions from multiple vias scattering in terms of waveguide modes. For modeling multilayered problem, we generate the cascaded transmission matrix **ABCD** by multiplying the transmission matrix of each layer. The transmission matrix is calculated from admittance matrix **Y** using N-port transformation equations [15]. To analyze the case including ground vias, only the **Y** parameters corresponding to the signal vias are extracted from the entire **Y** matrix solved.

3. SHARED ANTIPAD FOR VIA PAIR OF DIFFERENTIAL SIGNALING

In the fabrication of printed circuit boards, electronic packages and sockets, it is quite often that via pair is drilled in the shared antipad. Smaller pitch and shared antipad is designed to enhance the mutual coupling effect within the via-pair. This structure also makes it easy for layout engineer and board vendor to comply with certain fabrication limitation and rules. Since the differential signaling provides out of phase high-speed signals on two vias, the equivalent magnetic current on the port becomes like two frill rings with opposite directions (Fig. 1). In order to calculate this equivalent magnetic current source on the port, we put positive unit voltage on one via and negative on the other. The assigned voltages referenced to the ground plane are only valid for the dominant TM_0 mode assumption on the port excitation, which is equivalent to the cross section of the infinite transmission line model. Thus the simulation can provide the modal solution of differential mode, which is the most desirable data for the differential signaling design.

Based upon the dominant TM_0 mode assumption, we calculate the potential distribution on the antipad by solving electrostatic 2D Laplace equation using FDM up to the second order [16]. Fig. 3 shows the potential distribution for via pair in shared antipad. The potential distribution is then used to calculate the electric field and the magnetic current [5]. In the numerical calculation, banded matrix iterative method is applied to accelerate the FDM calculation [12]. The accuracy and stability of the finite different solution is carefully controlled by optimizing the meshing scheme. Finally, we sample 640 points in ϕ direction and 32 points in ρ direction. The total CPU

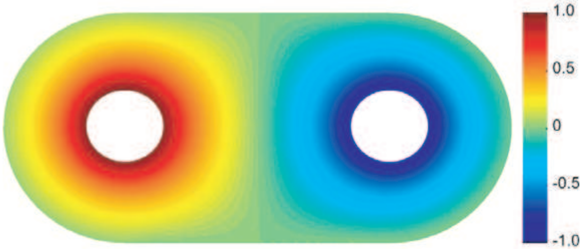

Figure 3. Port potential distribution for via-pair in shared antipad.

time of FDM calculation, including meshing, matrix filling and solving, takes only 2 seconds as the pre-process for our designed example.

Using FDM and the dominant TM_0 mode assumption, we can also generate the modal solution of common mode by assigning both positive voltages on the via-pair and calculating the magnetic source for the port excitation. The modal solution of the single-end case can be calculated by using superposition theorem by combining the differential mode field and the common mode field. For the S parameter normalization, we use the standard reference impedance of 50 Ohm, instead of self-port impedance, to match all the ports.

We have also used the finite element method (FEM) for the waveguide modal analysis on the shared antipad. Using 4768 triangle elements of 2D meshing on the port of dimensions given below, we found the cutoff frequency of the next waveguide mode TE_{11} is 60.8 GHz, which is much larger than the operating frequency range. Thus, the fundamental and dominant TM_0 mode assumption has been verified.

4. RESULTS AND DISCUSSION

The design board uses the following specifications: $\varepsilon_r = 3.5$, $\tan\delta = 0.008$, radius of via drilling $R_{\text{via}} = 4$ mil, radius of antipad $R_{\text{antipad}} = 13$ mil. The pitch within signal via pair is 28 mil. The distance between signal via and ground shielding via is 39 mil. The thickness of every ground plane is 1 mil. Fig. 2 shows the dimensions of the oval shape antipad. Fig. 4 shows the via layout and the stack information. The solid dots represent the ground shielding vias. The circles are the signal via-pair in shared antipad. Vias are drilled through all six layers as well as shared antipads on every ground plane. The S-parameters are measured at the top and bottom of the stack.

Figure 5 shows the insertion loss for the single-ended case on the center via. The results of the Foldy-Lax approach agree well with those

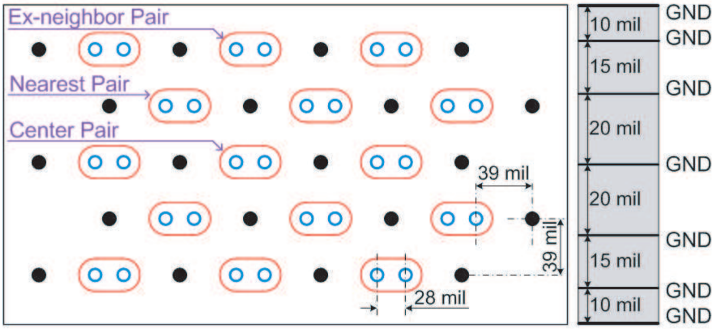

Figure 4. Via layout top view (left) and stack information on vertical cross-section (right).

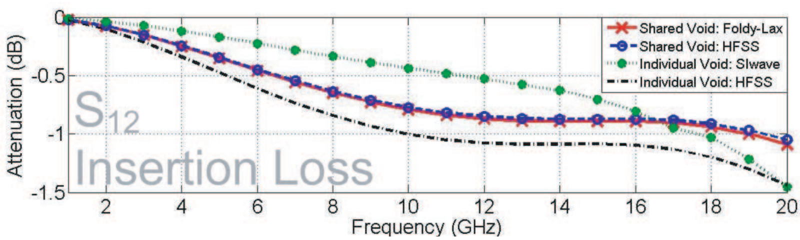

Figure 5. Insertion loss on the center via (single ended case).

simulated by the HFSS, which is a true 3D field solver with adaptive and iterative meshing scheme [9]. The electrical performance of single via in the shared antipad is better than that in the individual antipad. This is because the larger area of the shared antipad leads to less parasitic capacitance between the via and the ground plane. Ansoft SIwave, a 2.5D field solver [13], can only create via component with individual antipad. The results from SIwave are also plotted to show the big difference comparing with the HFSS. Although we have used option of very fine meshing on the SIwave port setup, the SIwave results differ a lot from those of HFSS. Due to fact that the HFSS usually provides the most convincing data and is widely accepted as industrial-standard benchmark, for the following mixed-mode S-parameter plots of higher accuracy, we only focus on the comparison between Foldy-Lax approach and HFSS. The differences are within 2% (< 0.04 dB in mixed-mode) between Foldy-Lax approach and HFSS.

Figures 6 and 7 give the insertion loss on the center via-pair of differential mode and common mode respectively. The electrical performance of via-pair in shared antipad is greatly improved by

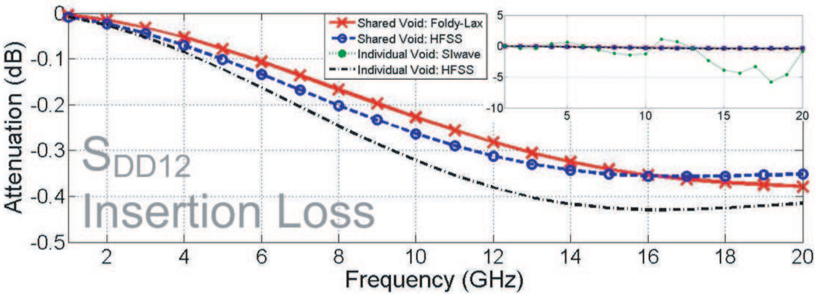

Figure 6. Insertion loss on the center via pair (differential mode).

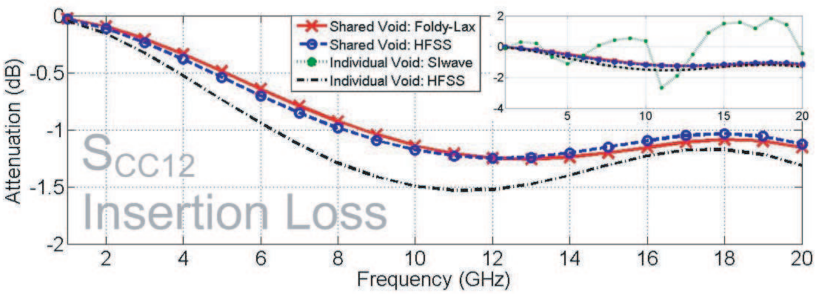

Figure 7. Insertion loss on the center via pair (common mode).

differential signaling scheme, as the insertion loss is less than 0.4 dB at 20 GHz. Instead, the insertion loss of common mode is larger than 1 dB at 20 GHz, even poorer than the single ended case. It shows the enhanced mutual coupling in shared antipad can facilitate the most energy propagate through the via-pair. The SIwave results, which are dramatically inaccurate for the mixed-mode solution, are illustrated on the corner.

Figure 8 shows the far end crosstalk (FEXT) between the center via-pair and the nearest via-pair. FEXT of differential mode is approaching -30 dB at high frequency side. Coupling to the ex-neighbor via-pair is plotted in Fig. 9 and is less than -40 dB up to 20 GHz for differential mode. This indicates that the ground shielding via in between has certain isolation effect by decreasing the crosstalk among different via-pairs. Generally, FEXT of common mode is about 17 dB larger than FEXT of differential mode for the same crosstalk measurement. This is because the common mode signaling scheme has poor immunity to environmental noise, such as the multiple field scatterings from other vias around.

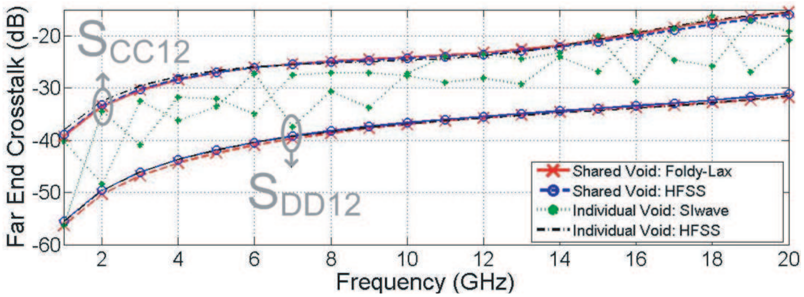

Figure 8. Far end crosstalk between the center via-pair and the nearest via-pair.

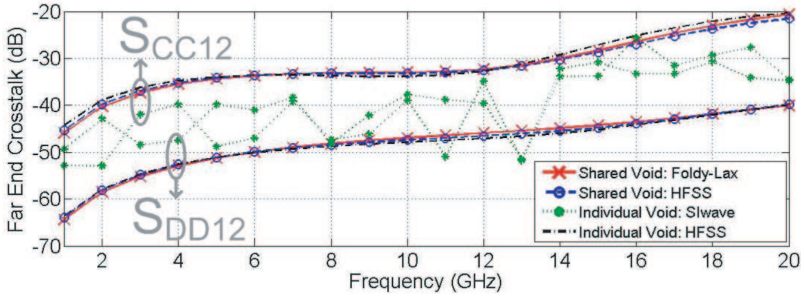

Figure 9. Far end crosstalk between the center via-pair and the ex-neighbor via-pair.

Table 1 shows the CPU time and memory consumption of using different methods to simulate 50 vias in 6-layer board for each frequency point, after taking average of actual simulation on 20 frequency points from 1 GHz to 20 GHz. Therefore, all the pre-processing run time is included in this total CPU report. All these simulations were taken on an Intel Xeon Quad-core 3.0 GHz processor. The CPU using Foldy-Lax approach is three orders of magnitude faster than using HFSS, and two orders of magnitude faster than using SIwave.

In the HFSS setup, we use driven terminal as the solution type. The wave-port excitation is defined on the via-end at the top and bottom of the stack. The wave-port contains two signal conductors and one shared reference conductor on the boundary. Practically this is very similar to the press-fit coaxial-like connector. Then HFSS will find the optimal integration path for the wave-port calculation. For the higher accuracy, the maximum delta S is set as 0.005 in HFSS.

Table 1. CPU time and memory of using different methods to simulate 50 vias in 6-layer board for each frequency point.

Methods	CPU time	Memory
Foldy-Lax	0.25 seconds	13.0 M
SIwave^{TM}	1.15 minutes	27.5 M
HFSS^{TM}	30.5 minutes	2.13 G

S-parameters results are generated on modal solution. The size of rectangular board is 600 mil by 800 mil in HFSS and SIwave simulation.

In the Foldy-Lax approach, the board size is modeled as infinite large, since the edge effect is not a major issue in this paper. All metals are treated as PECs. The metallic loss was studied in paper [14], and is very small compared to the dielectric loss for the vertical interconnects.

5. CONCLUSION

This paper successfully extends the Foldy-Lax multiple scattering approach to model massively-coupled multiple vias using differential signaling and shared antipad in the multilayered high speed vertical interconnects. Numerical example of 15 signal via-pairs and 20 ground shielding vias in 6-layer board demonstrates that this approach is able to model the via-pair with shared antipad and to include all the coupling effects among multiple vias. The CPU using Foldy-Lax approach is three orders of magnitude faster than using HFSS, and two orders of magnitude faster than using SIwave. The accuracy of Foldy-Lax is within 2% difference from HFSS up to 20 GHz. The SIwave results are significantly different from HFSS and Foldy Lax. The improvement of signal integrity is shown by using differential signaling and shared antipad for via-pair in multilayered structure. Other shapes of shared antipad, like rectangular and lemniscate, can also be modeled using same approach presented in this paper. For the larger port structure when fundamental TM_0 wave is not dominant, we can include the higher order modes in future studies.

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