# Coupling of large number of vias in electronic packaging structures and differential signaling

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*Abstract*— **A method is presented for modeling multi-interaction among large number of vertical vias in densely packaged integrated circuits. The analysis of the interior problem is based upon the cylindrical wave expansion of the magnetic field Green's function and the foldy-lax multiple scattering formula. The exterior problem of bent traces is analyzed using MOM approach. A system matrix equation is obtained by combining the exterior and interior problem of which the solution gives the propagation characteristics of the entire structure. Using iterative solver, results are illustrated for problems of several thousand vias with moderate CPU and memory requirement. Also illustrated are the results for common and differential mode in differential signaling, including the effects of surrounding idle vias and shorting vias.**

## I. Introduction

Via structure is one common type of interconnect that has been extensively used in electronic package. Because of the impedance difference with signal traces, vias can cause significant signal integrity problem in high-speed circuit design. Moreover, the nature of the multi-layered circuit geometry introduces parallel plate waveguide effect, which means the signal on the active via cylinders will excite waveguide modes along the plane and thus affect other active or passive vias. The induced current/voltage on other via cylinders will in turn affect the original active vias. The coupling of vias within waveguide decays only as square root of distance from the via. Multiple scattering exist among many vias in the region. This poses a significant challenge to reliable, high-speed IC operation.

In the past, different types of vias have been investigated using various methods. The inductance of a via connection of two striplines was analyzed [1] by using the partial electric element circuit (PEEC) model [2]. The capacitance and inductance of a through hole via has been analyzed using quasi-static approach [3][4]. The Method of Moment (MOM) full wave analysis has been applied to through hole via geometry [5][6]. Although both the MOM and FDTD (Finite Difference Time Domain) approach [7] can be used to theoretically solve the coupling problem accurately, these techniques have large computational time and memory overheads and thus have, in practice, been used to model only small sections of the complete package. A semi-analytical approach attempt to account for coupling noise between coupled vias is shown by Gu, et al in [8][9]. Coupling between two adjacent vias was analyzed using equivalent magnetic frill array models and capacitor plate antenna based on Otto's approach [10]. This method assumes symmetry of the two vias and neglects the influence of other vias. Another approach is combining lumped circuit model of single vias with TEM mode propagation [11].

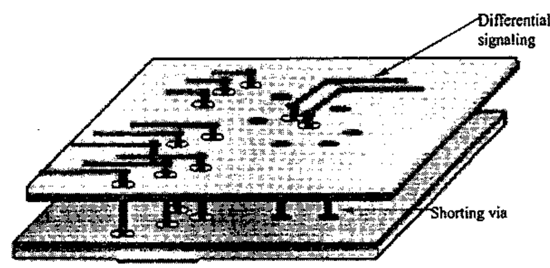


Fig. 1. Multi-via structure

The analysis of multiple interaction among all vias in a certain region could be quite important in some applications. For example, the analysis of the effect of shoring vias, which are used to reduce radiation loss and eliminate resonance effect. Recently, we employ a semi-analytical technique to study the multiple scattering among large number of vias by using the Foldy-Lax equations [12][13]. The multi-via structure (figure 1) is decomposed into exterior and interior problem by using equivalent magnetic sources. For the interior problem, the Foldy-Lax equations of multiple scattering among vias are derived based on the vector cylindrical waves expressed in terms of waveguide modes. The waveguide modes are decoupled in the Foldy-Lax equations so that the solution can be calculated for each waveguide mode separately. In this paper, the exterior problem of coupling signal traces is solved based on MOM by extending the approach of reference [5]. Furthermore, a single matrix equation is obtained from the combined interior and exterior problem and solved by bi-conjugate gradient method. The procedure can give the solutions of cases of several thousand vias with moderate CPU and memory requirements. Also illustrated are the results for common and differential mode in differential signaling with up to thousands of adjacent idle vias and shorting vias. The differential mode provides a return path for the via currents and shows less transmission loss than the common mode.



 

## II. Formulation

### A. Interior problem:

Consider N via cylinders between the two parallel plates centered at $\overline{\rho}_1, \overline{\rho}_2 ........ \overline{\rho}_N$. The multiple scattering can be formulated in terms of Fold-Lax equations [13].

$$w_{\ell n}^{TM(q)} = a_{\ell n}^{TM(q)} + \sum_{\substack{p=1 \\ p\neq q}}^{N} \sum_{m=-\infty}^{\infty} H_{n-m}^{(2)}(k_{\rho\ell} |\overline{\rho}_p - \overline{\rho}_q|) e^{j(n-m)\phi_{\overline{\rho}_p\rho_q}} T_m^{(N)} w_{\ell m}^{TM(p)} \quad (1)$$

$$w_{\ell n}^{TE(q)} = a_{\ell n}^{TE(q)} + \sum_{\substack{p=1 \\ p\neq q}}^{N} \sum_{m=-\infty}^{\infty} H_{n-m}^{(2)}(k_{\rho\ell} |\overline{\rho}_p - \overline{\rho}_q|) e^{j(n-m)\phi_{\overline{\rho}_p\rho_q}} T_m^{(M)} w_{\ell m}^{TE(p)} \quad (2)$$

where $a_{\ell n}^{TM(q)}$, $a_{\ell n}^{TE(q)}$ are the incident field onto cylinder q, $w_{\ell m}^{TM(p)}$ and $w_{\ell m}^{TE(p)}$ are the exciting field coefficients to be solved using Foldy-Lax equations. Notice that with magnetic frill current sources, the TE excitation is zero.

Suppose we have N vias, and we keep to $\ell = L_{\max}$ and multipoles up to $n = \pm N_{\max}$. Then the dimension of $\overline{w}_\ell$ is $(2N_{\max}+1) \times N$. Using a combined index of cylinder index $q$ and multipole index $n$, we have a combined index of $\alpha(q,n) = (2N_{\max}+1) \times (q-1) + n + N_{\max} + 1$. Thus $\alpha = 1, 2, ....M$ where $M = N \times (2N_{\max}+1)$. The Foldy-Lax matrix $\overline{\overline{F}}_\ell$ is of dimension $M \times M$.

$$\left[\overline{\overline{F}}_\ell\right]_{qn,pm} = \delta_{nm}\delta_{qp} - (1-\delta_{pq}) H_{n-m}^{(2)}\left(k_{\rho\ell}|\overline{\rho}_p - \overline{\rho}_q|\right) e^{j(n-m)\phi_{\overline{\rho}_p\overline{\rho}_q}} T_m^{(N)} \quad (3)$$

The Foldy-Lax equation can be written in matrix form:

$$\overline{\overline{F}}_\ell \overline{w}_\ell = \overline{\overline{E}}_\ell \overline{V} \quad (4)$$

where $\overline{V}$ are port voltages and $\overline{\overline{E}}_\ell$ is exciting matrix.

Solving equation (4), we can find currents on the via cylinders using the exciting fields $\overline{w}_\ell$ [13].

### B. Exterior problem

In general, the exterior problem consists of large number of transmission lines bent to connect to the sections of vias outside the parallel plate waveguide. The exterior problem can be solved by the usual MOM approach. In this paper, we consider the case of two coupled transmission lines (which is commonly the case for differential signaling). For the general case of $N$ transmission lines/wires in the exterior problem, we have:

$$\overline{B} = \overline{\overline{\Gamma}}_{sc}\overline{A} - \overline{\overline{T}}_{ant}\overline{V} \quad (5)$$

$$\overline{I} = \overline{\overline{I}}_{sc}\overline{A} - \overline{\overline{Y}}_{ant}\overline{V} \quad (6)$$

where $\overline{A}$ and $\overline{B}$ are the incident and reflected wave on the lines, $\overline{V}$ and $\overline{I}$ are the port voltages and currents.

We solve the exterior problem using MOM and the matrix elements $\Gamma_{sc}$, $T_{ant}$, $I_{sc}$ and $Y_{ant}$ can be calculated using the matrix-penciled method [14][5]. We assume that coupling only exists among a small number of lines/wires where the rest are uncoupled. Then $\overline{\overline{\Gamma}}_{sc}, \overline{\overline{T}}_{ant}, \overline{\overline{I}}_{sc}$ and $\overline{\overline{Y}}_{ant}$ are $N \times N$ sparse matrices in block form with no coupling among the blocks.

## III. Combination of interior and exterior problem into a system of matrix equation

We consider two coupled transmission lines and the rest $N-2$ lines are uncoupled for the exterior problem and $N$ vias coupling for the interior problem. In the interior problem, we include TEM mode ($\ell = 0$) coupling for all vias because it decays only as square root of distance. For small layer thickness, the higher order modes ($\ell \geq 1$) are evanescent so we assume that they are coupled in the near-field only. Combining the interior and exterior matrix equation and rearranging the terms, we have:

$$\begin{bmatrix} \overline{\overline{F}}_0\left(-\overline{\overline{Y}}_{ant} + \overline{\overline{Y}}_{extra}^{uu} + \overline{\overline{Y}}_{extra}^{ub}\right) \\ +(B_0+D_0)\overline{\overline{E}}_0 \end{bmatrix} \overline{\overline{T}}_{ant}^{-1} \cdot \overline{B}^u = \begin{bmatrix} -\overline{\overline{F}}_0\left(\overline{\overline{I}}_{sc} + \overline{\overline{Y}}_{ant}\overline{\overline{T}}_{ant}^{-1}\overline{\overline{\Gamma}}_{sc}\right) \\ -\left(B_0\overline{\overline{E}}_0 + \overline{\overline{F}}_0\overline{\overline{Y}}_{extra}^{uu}\right)\overline{\overline{\Gamma}}_{sc} \\ -\left(D_0\overline{\overline{E}}_0 + \overline{\overline{F}}_0\overline{\overline{Y}}_{extra}^{ub}\right)\overline{\overline{T}}_{ant}^{-1}\overline{\overline{\Gamma}}_{ratio} \end{bmatrix} \cdot \overline{A}^u + \left(D_0\overline{\overline{E}}_0 + \overline{\overline{F}}_0\overline{\overline{Y}}_{extra}^{ub}\right)\overline{\overline{T}}_{ant}^{-1}\left[\overline{\overline{\Gamma}}_{sc} - \overline{\overline{\Gamma}}_{ratio}\right] \cdot \overline{A}^b \quad (7)$$

here the superscripts $u$ and $b$ stand for upper ports and bottom ports and

$$B_\ell = \frac{4(-1)^\ell}{\eta H_0^{(2)}(k_{\rho\ell}a)}; \quad D_\ell = \frac{4}{\eta H_0^{(2)}(k_{\rho\ell}a)} \quad (8)$$

$$\overline{\overline{P}}_\ell = \overline{\overline{F}}_\ell^{-1}\overline{\overline{E}}_\ell \quad (9)$$

$$\overline{\overline{Y}}_{extra}^{uu} = \sum_{\ell=1}^{\infty} B_\ell \overline{\overline{P}}_\ell; \quad \overline{\overline{Y}}_{extra}^{ub} = \sum_{\ell=1}^{\infty} B_\ell \overline{\overline{P}}_\ell \quad (10)$$

$$\overline{\overline{\Gamma}}_{ratio} = \overline{\overline{T}}_{ant}\left[\overline{\overline{Y}}_{ant} + (\overline{\overline{Y}}_{extra}^{uu} - \overline{\overline{Y}}_{extra}^{ub})\right]^{-1} \left[\overline{\overline{I}}_{sc} + (\overline{\overline{Y}}_{ant} + \overline{\overline{Y}}_{extra}^{uu} - \overline{\overline{Y}}_{extra}^{ub})\overline{\overline{T}}_{ant}^{-1}\overline{\overline{\Gamma}}_{sc}\right] \quad (11)$$

Equation (7) has only $N$ unknowns and represents combined matrix equation incorporating both the interior and exterior problem. Note that only $\overline{\overline{E}}_0$ and $\overline{\overline{F}}_0$ are dense full matrices in the equation. Equation (7) is of $\overline{B}^u$ in terms of $\overline{A}^u$ and $\overline{A}^b$. We solve it for $\overline{B}^u$ using iterative method and similarly for $\overline{B}^b$.

## IV. Results and Discussion:

Because of the compact form that we arrange the coupling equations, the final matrix equation only has N unknowns for the N via problem and it is well conditioned. The matrix equation is solved by the bi-conjugate gradient method. The CPU time for a problem of 2500 vias only takes less than 1 minutes (56 seconds) on a PC of PIII 866 MHz with 512 Mb memory.

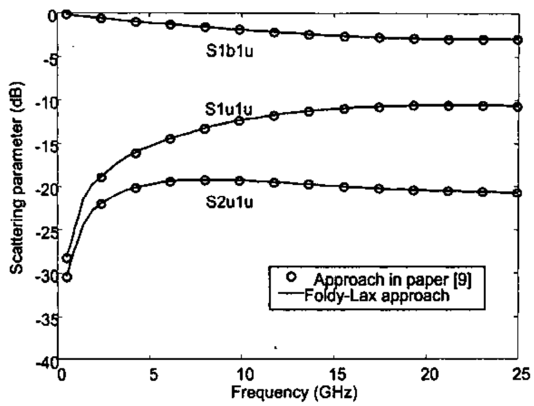


Fig. 2. The scattering parameters of two coupled vertical vias. Comparison with reference [9].

We first made a comparison with the result of paper [9]. Figure 2 shows the scattering parameters of two coupled vertical vias. In figure 2, for the sake of comparison, we use the same coaxial cable feed-in and the same parameters as used in paper [9], which are: via inner radius $a = 0.457mm$, via outer radius $b = 1.524mm$, separation of two vias $s = 4mm$, layer thickness $h = 1.524mm$, layer relative dielectric constant of $\varepsilon_r = 2.2$.

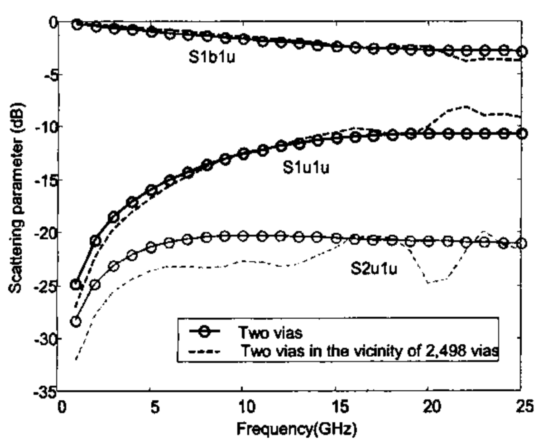


Fig. 3. The scattering parameter of two coupled vertical vias in the vicinity of 2498 other vias. Comparison with two via coupling

Next we illustrate the results of two active vias in the presence of 2498 matched idle vias. Figure 3 shows the scattering parameters of this two active vias with and without considering the surrounding 2498 idle vias. The figure shows clearly that the coupling effect from the surrounding vias could affect the original scattering parameter of the two vias, especially the coupling coefficient. Thus in densely packaged electronic circuits, where the number of vias could be large in certain region, this simulation technique will give accurate modelling of coupling effect and circuit behavior. Figure 4 gives the geometry of these 2498 randomly distributed vias and the two active signal vias that we are considering.

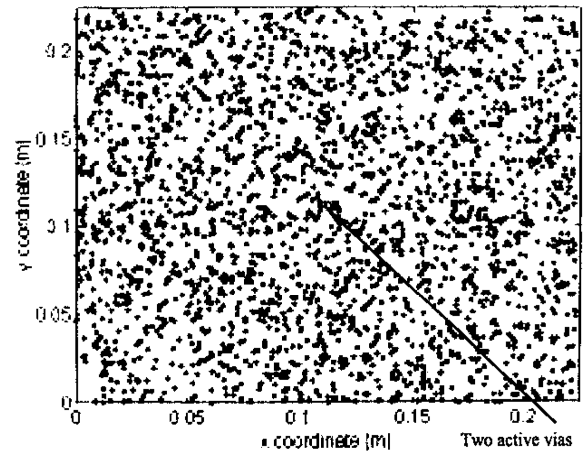


Fig. 4. Geometry of 2500 randomly distributed via, with two active vias marked

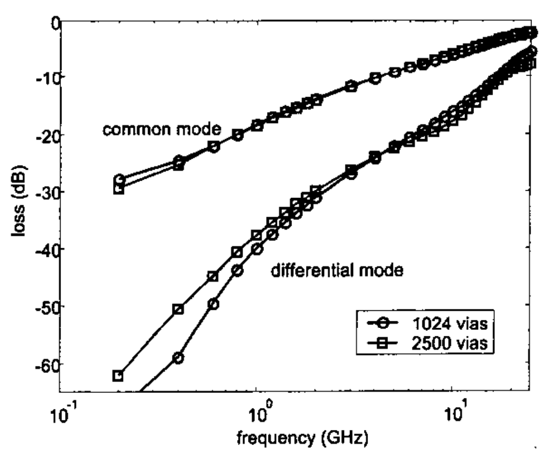


Fig. 5. Differential signaling with surrounding idle vias

To reduce power loss and deliver the most of power into destination at high frequency, differential signaling is used to achieve the purpose. In figure 5, we show the capability of the proposed approach to handle the interactions among large number of vias. Figure 5 shows the transmission loss of two active vias surrounded with randomly distributed 1022 and 2498 idle vias, respectively, for the common and

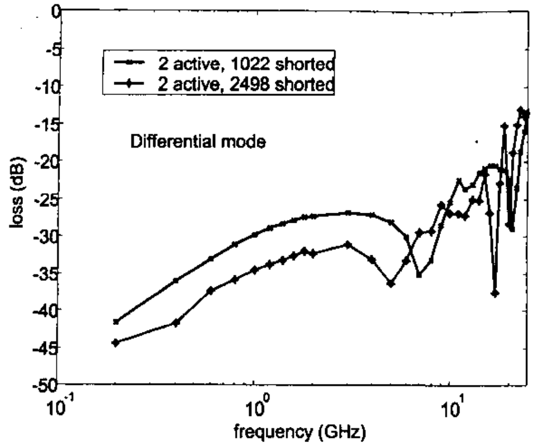


Fig. 6. Differential mode with surrounding shorting vias

differential mode. It can be seen that the increase of number of idle vias will not affect the loss of active vias very much and the loss of differential mode is significantly less than that of the common mode.

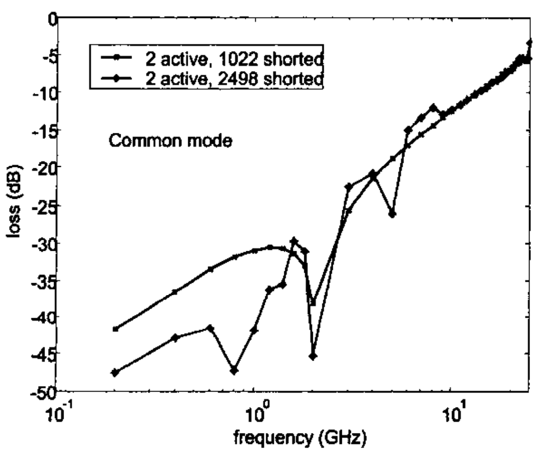


Fig. 7. Common mode with surrounding shorting vias

The same cases are plotted in figure 6 and 7 with all the idle vias substituted by shorting vias. Comparing with figure 5, the power loss is greatly reduced for both common and differential mode, proving the use of shorting vias can reduce power loss by producing additional return paths.

## V. Conclusion:

The method presented in this paper can be applied to a common discontinuity in high-speed circuit with accuracy and modest CPU and memory. It solves multiple scattering among vias by relating the exciting, incident and scattered waves from each cylinder using Foldy-Lax equations. A compact system matrix is obtained by combining the interior and exterior problem and is solved efficiently by bi-conjugate gradient method.

The result of 2500 randomly distributed vias shows clearly that in order to accurately model the via coupling effect, the surrounding passive vias must be considered together with the active signal vias. The simulation of surrounding shorting vias in the application of reducing radiation loss further confirms this point. This simulation technique can be used to solve the coupling problem in multi-via structure which is quite common in high-speed printed circuit board.

## References


[1] A. Djordjevic and T.K. Sarkar, "Computation of inductance of simple vias between two striplines above a ground plane", IEEE Trans. Microwave Theory and Techniques, Vol. 33, pp. 268-269, Mar. 1985.

[2] A.E. Ruehli, "Equivalent circuit models for three-dimensional multiconductor systems", IEEE Trans. Microwave Theory and Techniques, Vol. 22, pp. 216-221, Mar. 1974.

[3] T. Wang, R.F. Harrington and J.R. Mautz, "Quasi-static analysis of a microstrip via through a hole in a ground plane", IEEE Trans. Microwave Theory and Techniques, Vol. 36, No. 6, pp. 1008-1013, 1988.

[4] A.W. Mathis, A.F. Peterson and C.M. Butler, "Rigorous and Simplified Models for the Capacitance of a Circularly Symmetric Via", IEEE Trans. Microwave Theory and Techniques, Vol. 45, No. 10, pp. 1875-1878, 1997.

[5] S.G. Hsu and R.B. Wu, "Full wave characterization of a through hole via using the matrix-penciled moment method", IEEE Trans. Microwave Theory and Techniques, Vol. 42, No. 8, pp. 1540-1547, 1994.

[6] S.G. Hsu and R.B. Wu, "Full-wave characterization of a through hole via in multi-layered packaging", IEEE Trans. Microwave Theory and Techniques, Vol. 43, No. 5, pp. 1073-1081, 1994.

[7] B. Archambeault, C. Brench, and O.M. Ramahi, "Emi/Emc Computational Modeling Handbook, Kluwer International Series in Engineering and Computer Science", 2001

[8] Q. Gu, Y.E. Yang and M.A. Tassoudji, "Modeling and analysis of vias in multilayered integrated circuits", IEEE Trans. Microwave Theory and Techniques, Vol. 41, No. 2, pp. 206-214, 1993.

[9] Q. Gu, A. Tassoudji, S.Y. Poh, R.T. Shin and J.A. Kong, "Coupled noise analysis for adjacent vias in multilayered digital circuits", IEEE Trans. Circuits and Systems, Vol. 41, No. 12, pp 796-804, 1994.

[10] D.V. Otto, "The admittance of cylindrical antennas driven from a coaxial line", Radio Science, Vol. 2, No. 9, pp. 1031-1042, 1967.

[11] R. Ito, R.W. Jackson, and T. Hongsmatip, "Modeling of interconnections and isolation within a multilayered ball grid array package", IEEE Transactions on Microwave Theory and Techniques, vol. 47, pp1819-1825, 1999.

[12] L. Tsang, J. A. Kong, K. H. Ding, and C. Ao, "Scattering of Electromagnetic Waves: Vol. 2 Numerical Simulations", Wiley Interscience, New York, 2001.

[13] L. Tsang, H. Chen, C. Huang and V. Jandhyala, "Modeling of multiple scattering among vias in planar waveguide using foldy-lax equations", Microwave and Optical Technology Letters, Vol. 31, No. 3, November 2001, pp 201-208

[14] Y.B. Hua, T.K. Sarkar, "Generalized pencil-of-function method for extracting poles of an EM system from its transient response", IEEE Trans. Antenna Propagat., vol. 37, pp. 229-234, Feb. 1989.