Modeling of Hierarchical Power/Ground Network based on Segmentation Method for Package/Board Co-Design and Simulation

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***Abstract*—Hierarchical power/ground network is the most common structure in system, however it is hard to extract the impedance property of it, because of the interaction between structures in system, such as package and board. With resonant cavity model, segmentation method and two proposed issues on hierarchical network, we can find out the total impedance of system. The result has been verified by comparing with the result of 3D full wave simulation in frequency domain.**

Keywords-hierarchical power/ground network, segmentation method, resonant cavity model, inter-plane effect, fringing effect

I. INTRODUCTION

Nowadays, hundreds of millions transistors are integrated into one chip and the number of transistors are increased rapidly. A large amount of currents and power/ground network for supplying powers make a noise, which is known as simultaneous switching noise (SSN). It is a main factor to deteriorate the reliability and immunity of system. The estimation of impedance in power/ground network is more important to control and guarantee the system performance with high-technology trends.

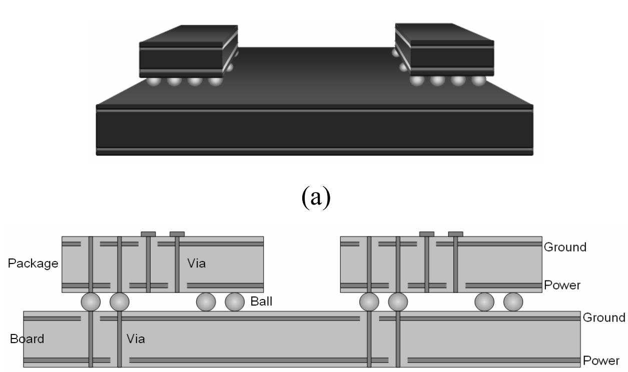


Figure 1. Hierarchical power/ground network which contains one board and two BGA type packages (a) Perspective view (b) Side view

Generally, the power/ground network for system is composed of many independent structures, such as package for interconnection of IC and board for containing many components. Therefore, the power/ground network is a hierarchy from power supply to operation logics, which includes power/ground network of board and package, respectively. Fig. 1 illustrates a simple structure of hierarchical power/ground network which is composed of one board and two BGA packages.

One of the most difficult problems in this condition is that it is hard to predict and to estimate the interaction and co-effect of each power/ground network. Practically, there are many methodologies, such as FEM, FDTD and TLM, for calculating and estimating hierarchical power/ground network, but extremely long elapsed time and a lot of resource are needed. For an accurate result with reduced time, many approaches using analytic modeling method are tried in these days, such as BGA footprints [1], and the isolated power bus [2].

In this paper, the modeling of hierarchical power/ground network based on segmentation method and resonant cavity model for fast acquisition of data and accurate calculation will be proposed. Especially, two modeling issues will be emphasized for the feature in hierarchical structure.

II. BASIC CONCEPT AND PROPOSED ISSUES

A. Resonant Cavity Model and Segmentation Method

The most common power/ground network in a package and board structure is formed by two parallel plates. Impedance matrices of rectangular shaped power/ground network can be represented by a resonant cavity model which is described in [3] and shown in Fig. 2.

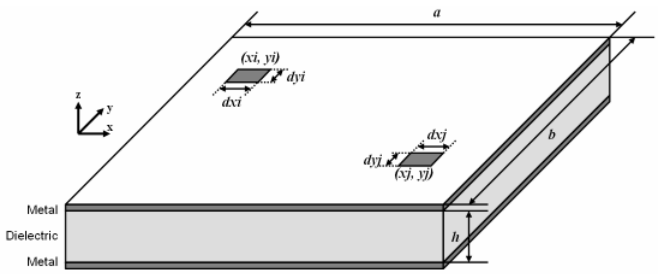


Figure 2. Geometry of a rectangular power/ground planes structure. Each port is defined between power plane and ground plane, and they are located at (xi,yi) and (xj,yj), respectively.

$$Z_{ij} = j\omega\mu h \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{C_m C_n^{\,2}}{ab(k_{xm}^2 + k_{yn}^2 - k^2)} \times \cos(k_{xm}x_i)\cos(k_{yn}y_i)\cos(k_{xm}x_j)\cos(k_{yn}y_j) \times \mathrm{sinc}\left(\frac{k_{xm}dx_i}{2}\right)\mathrm{sinc}\left(\frac{k_{yn}dy_i}{2}\right)\mathrm{sinc}\left(\frac{k_{xm}dx_j}{2}\right)\mathrm{sinc}\left(\frac{k_{yn}dy_j}{2}\right)$$

,where the mode number m represents and m^{th} mode associated with the x dimension, and the mode number n represents an n^{th} mode associated with the y dimension. The terms a, b and h are the metal plane widths in the x and y direction and the dielectric thickness in the z direction, respectively. Two ports are located at (x_i, y_i) and (x_j, y_j) with an electrically small size (dx_i, dy_i) and (dx_j, dy_j), respectively. The constant $C_m^2C_n^2=1$ for m=n=0; $C_m^2C_n^2=2$ for m=0, n≠0 or m≠0, n=0; $C_m^2C_n^2=4$ for m≠0, n≠0.

It is very easy and fast for calculating and finding the impedance matrix in structure of a pair of planes, but it has a limitation can be used only a pair of planes.

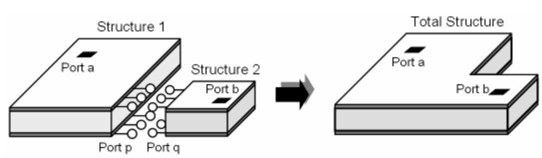


Figure 3. Concept of segmentation method using resonant cavity model for total structure

To merge each structure in system, a segmentation method which manipulates the matrices of impedance of board and package is used [4], [5].

The segmentation method can be accomplished with two kinds of ports. One is an external port for observation of desired signal such as port a and port b, and the other is an internal port for interconnection of each structure such as port p and port q as shown in Fig. 3.

The impedance matrix of structure 1 can be presented as the following.

$$\begin{bmatrix} V_a \\ V_p \end{bmatrix} = \begin{bmatrix} Z_{aa} & Z_{ap} \\ Z_{pa} & Z_{pp} \end{bmatrix} \begin{bmatrix} I_a \\ I_p \end{bmatrix}$$

In similar way, that of structure 2 can also be obtained as the following.

$$\begin{bmatrix} V_b \\ V_q \end{bmatrix} = \begin{bmatrix} Z_{bb} & Z_{bq} \\ Z_{qb} & Z_{qq} \end{bmatrix} \begin{bmatrix} I_b \\ I_q \end{bmatrix}$$

After classifying each matrix, boundary conditions which mean the voltage level at internal ports is equal in the same direction, and the current level is same in the opposite direction are used. Finally, the total impedance of merged structure can be calculated as the following.

$$\begin{bmatrix} V_a \\ V_b \end{bmatrix} = \begin{bmatrix} Z_{aa} - Z_{ap}(Z_{pp}+Z_{qq})^{-1}Z_{pa} & Z_{ap}(Z_{pp}+Z_{qq})^{-1}Z_{qb} \\ Z_{bq}(Z_{pp}+Z_{qq})^{-1}Z_{pa} & Z_{bb} - Z_{bq}(Z_{pp}+Z_{qq})^{-1}Z_{qb} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \end{bmatrix} = \begin{bmatrix} Z'_{aa} & Z_{ab} \\ Z_{ba} & Z'_{bb} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \end{bmatrix}$$

B. Inter-plane Effect

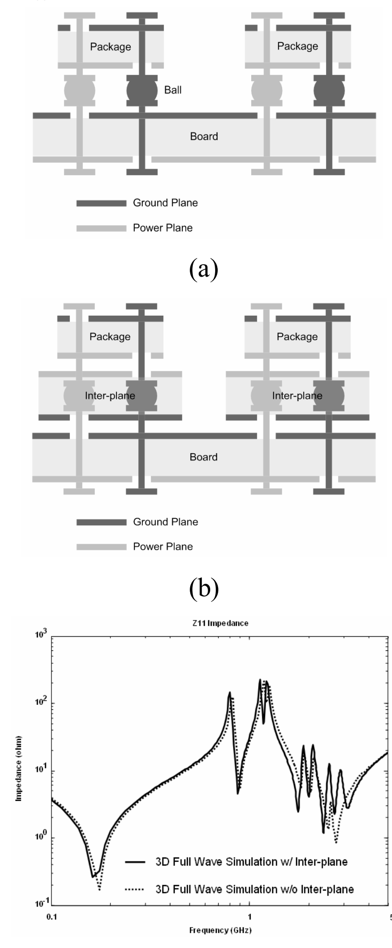
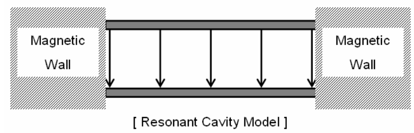


Figure 4. Concept of inter-plane (a) Independent power/ground network (b) New pair of power/ground network with hierarchical situation (c) Impedance plot w/ and w/o inter-plane

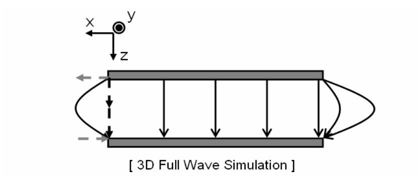
Hierarchical power/ground network includes package structure, board structure, ball interconnections and via interconnections as shown in Fig. 1-(b). In a simple way, total impedance of system can be extracted by using the impedance of package and board from the resonant cavity model and the segmentation method. However, for precise and accurate result, two issues for modeling must be considered.

The first issue is a consideration of inter-plane effect. The impedance of package by the resonant cavity model means the impedance which is made by power plane of package and ground plane of it, and so does that of board as shown in Fig. 4-(a). As we merge two structures to total structure, a new pair of power/ground plane is occurred as shown in Fig. 4-(b). That is made by the power plane of package and the ground plane of board. Therefore, another pair of power/ground plane except package and board themselves, which is called as inter-plane, must be inserted between the package and board. Fig. 4-(c) shows the effect of inter-plane, and resonant peak near 3GHz is not appeared without that.

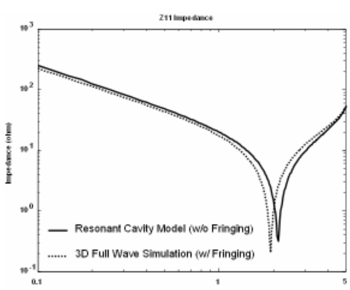
C. Fringing Effect



(a)



(b)



(c)

Figure 5. Concept of fringing (a) Magnetic boundaries in resonant cavity model (b) Air boundaries in 3D full wave simulation (c) Impedance plot considering fringing effect

The other modeling issue is an inherent fringing field of each structure. The resonant cavity model assumes that boundaries at edges are magnetic walls. It means that no electric field can be formed outside of the structure as shown in Fig. 5-(a).

However, the distribution of electric field in 3D full wave simulation, which means air boundaries, has additional fields caused by fringing as shown in Fig. 5-(b). It makes the total capacitance and inductance of structure increased. A change of resonant peak can be occurred as shown in Fig. 5-(c), so the reflection of fringing field is needed for the accurate result.

III. Procedure of Each Strcuture

The total procedure of the proposed model for hierarchical power/ground network is set as shown in Fig. 6. The inter-plane effect and the fringing effect are considered, and the interconnections such as vias and balls are also included as lumped models.

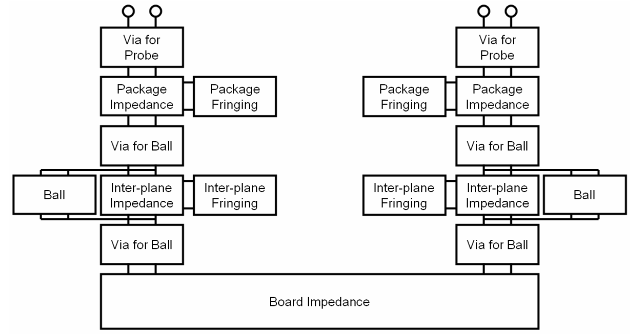


Figure 6. Detailed procedure of proposed model for hierarchical power/ground network.

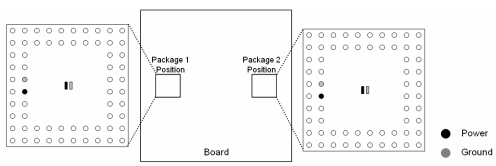
The detailed method to apply the fringing effect to the model is an extraction of equivalent field. The compositions of fringing field which has an elliptical shape as shown in Fig. 5-(b). When we decompose the component of field into two directions, the y and z direction, the total integration of field has only the component in the z direction because the component in the y direction can be cancelled. When the shape of fringing field is uniform in the z direction, we can treat it with the resonant cavity model under an assumption of it. With additional planes at all edges of package for compensating the fringing effects, we can represent it.

The modeling procedure and concept for inter-plane are similar to those of package, but two items are rather different, relative permittivity and the distribution of fringing field. The material in board and package is only dielectric, such as FR-4, whereas that of inter-plane is not homogenous. To use the resonant cavity model, conversion heterogeneous material to homogeneous material is applied, and an effective permittivity of the inter-plane can be found.

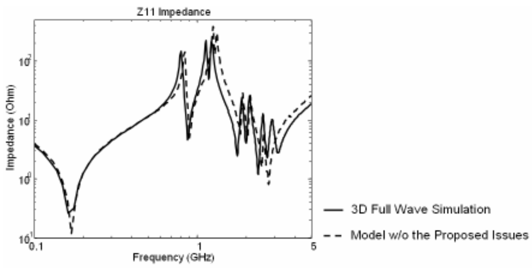
Another difference of the inter-plane is distribution of fringing field. In package, the elliptical-shaped field due to fringing can be treated as the uniform field in z direction caused by equal amount of field in y direction goes to cancel. However, the distribution of fringing field in the inter-plane is not symmetric due to the difference of area in package and board, so an equivalent field in z direction cannot be applied to inter-plane. To solve this problem, an image theory is used, and same method in package is applied again to the inter-plane.

The last items are via structure for the connection of probing and ball pads and ball structure for the interconnection of package and board. By calculating the inductance and capacitance of physical dimension on them, lumped models for them can be set up [6], [7]. Combining raw impedance matrices with the lumped models, total impedance matrix of system is completed.

IV. SIMULATION RESULTS



(a)



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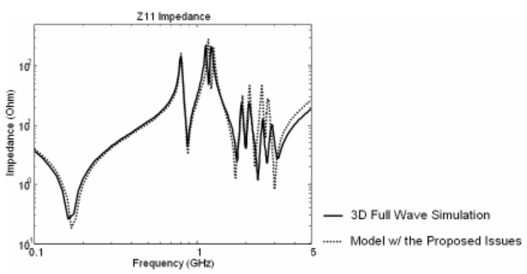

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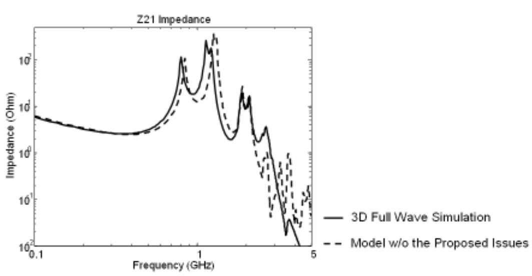
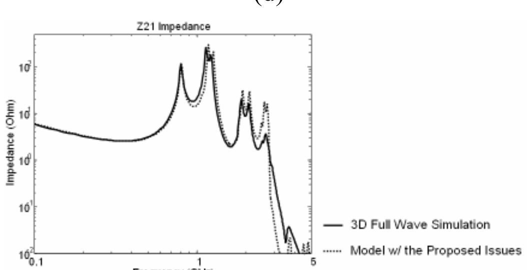


(d)



(e)

Figure 7. Structure for simulation and the results (a) Structure for simulation (b) The self impedance of 3D fullwave simulation and model w/o proposed issues (c) The self impedance of 3D fullwave simulation and model w/ proposed issues (d) The transfer impedance of 3D fullwave simulation and model w/o proposed issues (e) The transfer impedance of 3D fullwave simulation and model w/o proposed issues

Fig. 7-(a) shows the structure for simulating with 3D full wave simulation and the proposed model and Fig. 7-(b), (c), (d), (e) are results of them. A pair of power/ground ball for interconnection between board and package is existed at each package.

A significant difference between the model without the proposed issues and that including the fringing effect and the inter-plane effect is resonance peak near 3GHz in self impedance plot as shown in Fig. 7-(b) and 7-(c). Additionally, the overall shapes of the model with two issues are more accurate than that without items in self impedance as well as transfer one. A similar output is observed in transfer impedance as shown in Fig. 7-(d) and Fig. 7-(e). While resonant peaks are moved without proposed issues, result with them is matched well in resonant peaks, as well as the overall shape. The result of the proposed model is very similar to that from 3D full wave simulation both in self impedance and transfer impedance, and has a remarkable reduction of elapsed time for result. The elapsed time of 3D full wave simulation is 1 hours, 51 minutes and 6 seconds, whereas that of the proposed model is 11 minutes and 47 seconds in same condition. This is only 10.6% portion of 3D full wave simulation.

V. CONCLUSION

In this paper, we used the resonant cavity model for the impedance of a pair of power/ground plane. It is very fast and simple method however a complicated structure such as hierarchical network in system cannot be extracted. To obtain the total impedance of it, the segmentation method for interconnection of each structure was used and the inter-plane effect and the fringing effect were introduced. The proposed model was verified by comparing with the result of 3D full wave simulation, and we can acquire an accurate result in considerably reduced simulation time.

REFERENCES

[1] Selli, G., Drewniak, J.L., Dubroff, R.E., Jun Fan, Knighten, J.L., Smith, N.W., McCoy, D. and Archambeault, B., "Power integrity investigation of BGA footprints by means of the segmentation method," Proc. International Symposium on Electromagnetic Compatibility(EMC) 2005., Vol.2, pp.655-659, Aug. 2005.

[2] Jeong, Y. and Kim, J., "Matrix Substitution Method for Power Bus Analysis With Isolated Power Island in High-Speed Packages and PCBs," IEEE Microwave and Wireless Components Letters, Vol.16, No. 1, pp.31-33, Jan. 2006.

[3] G.T. Lei, R.W. Techentin, and B.K. Gilbert, "High-frequency characterization of power/ground-plane structures," IEEE Trans. On MTT, Vol.47, pp.562-569, May. 1999.

[4] T. Okoshi, Y. Uehara, and T.Takeuchi, "The Segmentation Method – An Approach to the Analysis of Microwave Circuits," IEEE Trans. on MTT, Vol.24, pp.662-668, Oct. 1976.

[5] T.Okoshi, Planar Circuits for Microwaves and Lightwaves, Munich, Germany, Springer-Verlag, 1985, Chapter 2.

[6] D.M. Pozar, Microwave Engineering, 2nd Ed. John Wiley & Sons, Canade, 1998, Chapter 4.

[7] K.L. Kaiser, Electromagnetic Compatibility Handbook, CRC Press, U.S.A., 2005.