Predicting and Mitigating Techniques of the PCB Rectangular Power/Ground Planes' Resonance Modes

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ABSTRACT

The pair of metalized plates so called ‘power/ground planes’ or ‘Power-Bus Structure’ in the layered PCB architecture is known for causing the resonance phenomena that lead to increasing the impedance of the ground and finally becoming the noise in digital signal transfer in the PCB. In line with the signal integrity, it is necessary to predict the exact resonance behavior in the impedance as well as electromagnetic fields from the structure. For accurate evaluation of the electromagnetic properties due to the resonance, an efficient way of calculation ‘series expansion’ is used for the basic geometry and it is extended to the power-bus structure loaded with SMT(surface mounting technology) components for considering the resonance-mitigation by lumped elements. Besides, in an attempt to lower the impedance level of the ground, multiple feeds such as differential modes are adopted to provide the artificial return current path, and numerous cases of this particular feeding scheme are investigated with and without SMT loads. Finally, the radiated emission(RE) levels from the structure will be dealt with to see how the resonance mode ends up with the fields propagated from the edges of the power-bus geometry and what approaches can lower the RE level.

Keywords : PCB power/ground planes, Series Expansion, SMT component, RE, Resonance

1. INTRODUCTION

To facilitate the components and circuits for numerous essential functions in one body, modern communication systems are designed to have layers of PCBs. Standard layering of the PCBs has a pair of metal planes facing each other for DC-power supply and grounding. They are called power/ground planes.

The PCB power/ground planes form a cavity, composed of the top and bottom planes as the PEC boundary condition and the PMC walls[1-6]. These boundary value problems can be treated by a number of numerical techniques such as Method of Moment, Finite Difference Time Domain, Finite Element Method, etc. to examine physics on the structure generating resonance modes, impedance rise and interference problems. Among the computational techniques, a modal sum or series expansion analysis method is considered convenient to use when there is no problem in assuming the geometry as a cavity[1, 4-5].

Once we are convinced of the validity of the analysis method for the structure of this interest, we can move on to coping up with the resonance. In practice, SMT loads such as decoupling capacitors are placed on the plate on which PCB components reside. For the local elements to be included in the process to remove the resonance and prediction, a number of times of linear algebraic manipulations are employed to carry out the Kirchhoff current and voltage laws. However, a simple expression is introduced later with the SMT application to reduce the impedance levels of resonance points. Furthermore, if multiple feeds are used to guarantee the return current path with respect to the original signal line, we will possibly improve the solution. This can be numerically characterized using the superposition principle without any difficulty and will show the differential multiple feeds can make things better

Along with the impedance watch and fields in the vicinity of the power-bus structure, it is important to check out the electromagnetic waves in the far zone from the cavity as Radiated Emission(RE) level, an indicator of electromagnetic interference toward adjacent circuits. This RE level can be predicted by the radiation integral, using the structure's magnetic currents induced along the walls.

This paper is organized as follows. First, the modal analysis method to meet the boundary conditions of the power/ground planes results in the series expansion to calculate the fields and impedance of the unloaded power/ground planes and then it is modified to the geometry with lumped elements. Second, two feeding techniques with differential mode and common-mode are addressed and applied to reduce the impedance projections at resonance modes, with the aforementioned mathematical expression developed to the multiple cases by way of the superposition principle. Finally, we deal with the RE level which is a yardstick about the interference due to the resonance and discuss the lumped element loading and multiple feeding schemes for mitigating the RE levels.

2. THEORY

2.1 Series Expansion Form for a Cavity Structure Analysis

Lately, the PCB level EMC problems have drawn much attention for many reasons. One is that a variety of potential noise sources around the RF systems are formed by way of the layers in the PCB. The main noise maker is the power-bus structure which has resonance modes, illustrated as in Figure 1

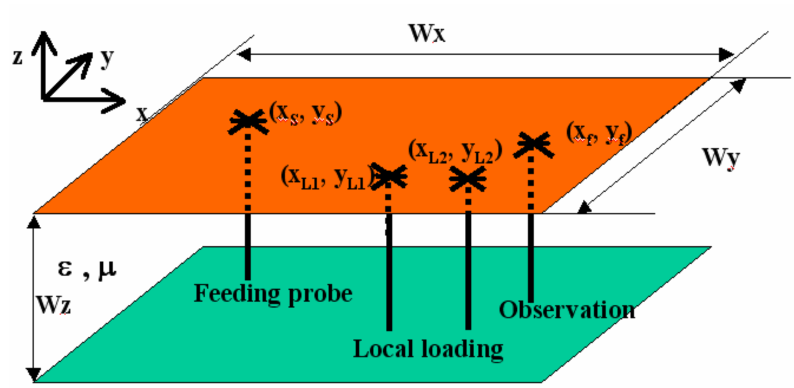


Fig. 1. Cavity model for a power/ground plane structure with ports and loads

The top as the ground and the bottom as the power-metal plane are identical in size with $Wx \times Wy \times Wz$. The DC current is carried along the feeding probe situated at (X_s, Y_s). And it is used as port 1. Port 2 is any arbitrary observation point at (X_f, Y_f) where induced voltage is observed. The impedance from port $\boldsymbol{s}$ to port $\boldsymbol{f}$ is given as

$$Z_{sf} = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{\gamma_{mn} \cdot c_{mn}(X_s, Y_s) \cdot c_{mn}(X_f, Y_f) \cdot W_z /(W_x W_y)}{\varepsilon\omega / Q + j(\varepsilon\omega - \dfrac{k_{xm}^2 + k_{yn}^2}{\omega\mu})} \tag{1}$$

The intermediate region between the two planes is the dielectric substrate and 4.2 and 0.02 are given as its relative dielectric constant and loss tangent, respectively. Referring to the structure's boundary conditions again, the two planes are the PEC and the walls are the PMC. Then, the impedance, when lumped elements are placed at (X_L, Y_L), is expressed as[5]

$$Z_{Ld} = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{\gamma_{mn} \cdot c_{mn}(X_s, Y_s) \cdot c_{mn}(X_f, Y_f) \cdot W_z /(W_x W_y)}{\varepsilon\omega / Q + j(\varepsilon\omega - \dfrac{k_{xm}^2 + k_{yn}^2}{\omega\mu}) + \dfrac{\gamma_{mn} \cdot W_z}{W_x W_y} \sum_{Lu=1}^{NLu} c_{mn}^2 (X_{Lu}, Y_{Lu}) \cdot \widetilde{Y}_{Lu}} \tag{2}$$

where

$c_{mn}(X_i, Y_i) = cos(k_{xm}X_i) \cdot \cos(k_{yn}Y_i) \cdot sinc(k_{xm}P_{xi}/2) \cdot sinc(k_{yn}P_{yi}/2)$

$$k_{xm} = m\pi / W_x, \quad k_{yn} = n\pi / W_y, \quad \omega = 2\pi f, \quad Q = [\tan\delta + \sqrt{2/\omega\mu_0\kappa W_z^2}\,]^{-1} \tag{3}$$

γ_{mn} is 1 and 4 for (m =0, n =0) and ($m \neq 0$, $n \neq 0$) each. When ($m \neq 0$, n=0) or (m=0,$n \neq 0$), γ_{mn} takes 2. $tan\delta$, ε , μ, f, P_i and j denote loss-tangent, permittivity, permeability, frequency, port's width and $\sqrt{-1}$, respectively. Eqn. (1) considers NL_u loads with the series equivalent circuit of the Lu-th load

$$\widetilde{Y}_{Lu} = [R_{Lu} + j(\omega L_{Lu} - 1/(\omega C_{Lu}))]^{-1} \tag{4}$$

2.2 Structure with Multiple Feeds

By now, the things were about the one feed structure. Now let us talk about the multiple feeds.

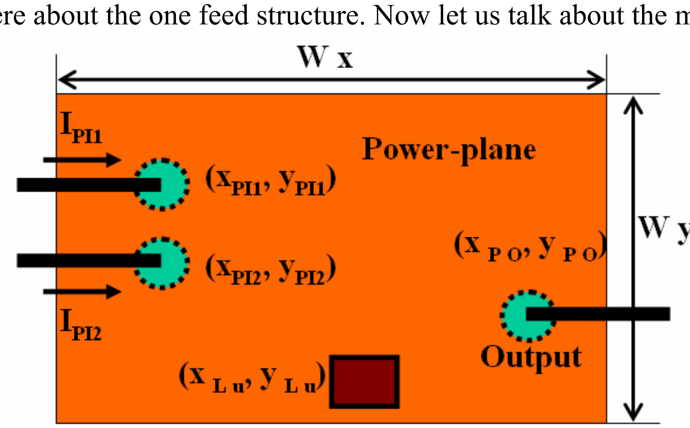


Fig. 2. Top-view of a power/ground plane structure with two feeds

Based upon the one-feeding line case, the differential signaling can be characterized with no difficulty, since the superposition principle also works in this structure. Therefore, the common-mode impedance and the differential-mode impedance are calculated by using the Eqn.'s (8) and (9) in [6].

2.3 Radiated Emission Characterization

Employing of the evaluation above, the eletromagnetic field strength is shown to be maximum at resonance modes, and they propagate past the edges of the planes to the external region. This radiated emission(RE) from one cavity reaches its upper and lower PCB layers and nearby systems.

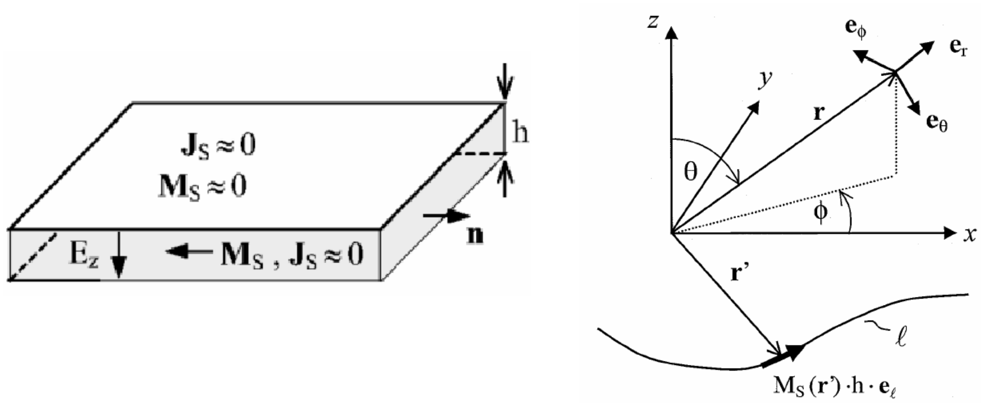


Fig. 3. Geometric configuration and coordinates of radiated emission[6]

The radiation can be explained as that of magnetic currents due to E_z is induced on the walls first, and then this fictitious current radiates. As for this, the radiation integral in the following is employed[6].

$$\underline{E} = (jk_0 W_z e^{jk_0 r}/(4\pi r)) \oint_{Rim} \underline{M}_s(\underline{r}') e^{jk_0 \underline{r}' \cdot \hat{e}_r} (\hat{e}_r \times \hat{e}_l) d\underline{l} \qquad (5)$$

$\underline{M}_s(\underline{r}')$ is the induced magnetic current at $\underline{r}'$ on the walls, and $\hat{e}_r$ and $\hat{e}_l$ are the normalized position vectors of the observation and source points. k_o is the free-space wave-number. Given that W_z is far less than W_x or W_y Eqn (5) takes a line integral along the periphery instead of a surface integral. Also, the above equation can be approximated as the far-zone field for simplicity.

3. RESULTS OF EXPERIMENTS

Firstly, the input impedance evaluation is performed using Eqn.(1) with respect to the power/ground planes of 220mm by 150mm by 1.5mm. And the DC current is fed at (X_s=0, Y_s=0) from bottom to top. The observation is made at the same as the source position, whose impedance is called 'self-impedance'. The frequency of interest for simulation ranges from 0 through 1GHz.

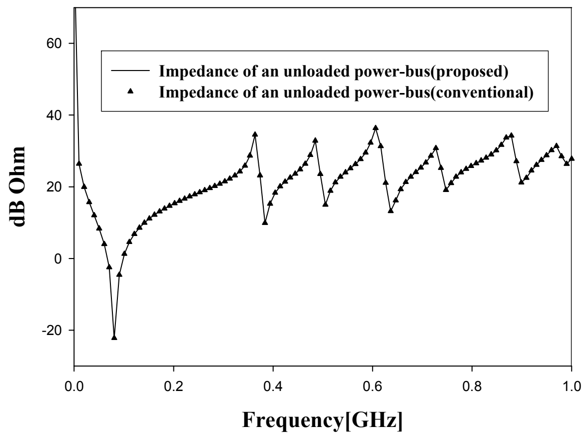


Fig. 3.Comparing the measurement and calculation for an unloaded structure's input impedance

The two methods produce the overlapping results. The series expansion was truncated at (m=400, n=400) and it can be made faster if a transformation(one-sided fourier transformation) is used . Seeing the result, beyond 200 MHz, peaks of resonance modes (1,0), (0,1), (1,1), (2,0), (2,1) and (0,2) occur in order.

Next, the power/ground plane structure is loaded with components. DeCaps are used in the structure. Resonance modes at 370MHz and 730MHz are targeted for damping by DeCaps. Using optimization techniques considering two DeCaps, the followings are obtained. DeCaps 1 and 2 have (1Ω,4.6nH, 47pF) at (220mm,75mm) and (12Ω,1.5nH,47pF) at (0,75mm), respectively. In the second place, Eqn.(4) is used with those input parameters for Y_{NLoads} to present the damping performance on the desired resonance modes. In addition to the input impedance evaluation, the maximum of $|\underline{E}|$ as RE level is calculated with respect to the original resonance modes. In particular, the RE levels of the power/ground planes before and after damping the specified resonance modes are compared along with the impedance profiles.

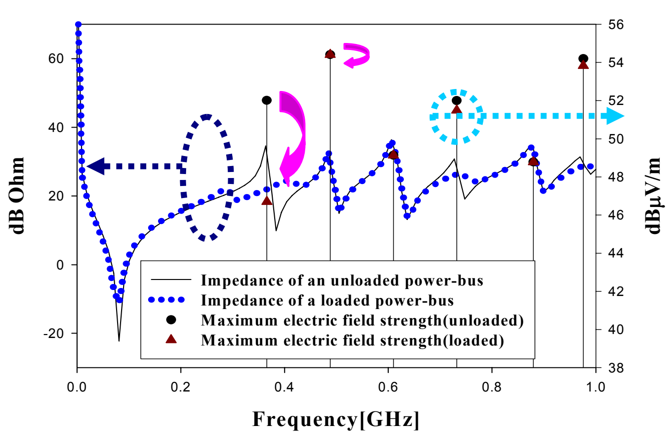


Fig. 4. Impedance and RE before and after loading DeCaps in the power/ground planes

Seeing the solid and dotted lines as the original power/ground planes and loaded case, the impedance levels at the aforementioned resonance modes are reduced by 13dB and 4dB as desired. This can be confirmed by the fact that the RE levels at 370MHz and 730MHz come down from 52 dBμV/m and 52 dBμV/m to 47 dBμV/m and 51dBμV/m, respectively. It is proven that the damping of the resonant impedance point can reduce the RE level out of the power/ground planes.

Now, the calculation of the impedance is carried out on the power-bus structure with the differential signals. Through this experiment, we will have an idea how accurate the proposed single-sum calculation is, when examined by the comparison with the results of the double-sum and the FDTD application for the same environment for simulation[7].

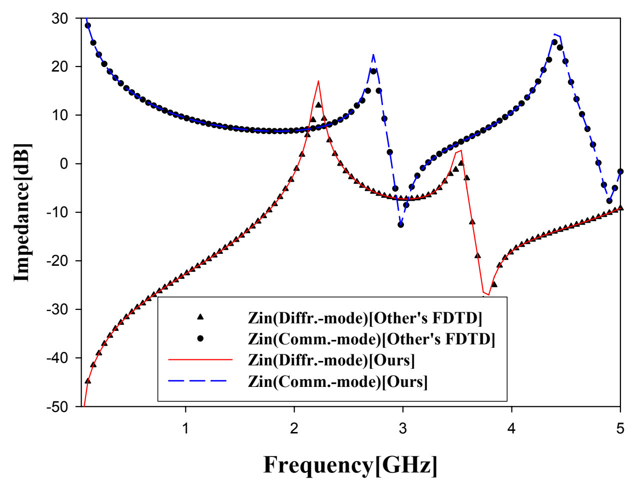


Fig. 5. Differential- & common-mode feeding results on the power/ground planes

The structure and frequency range are the same as [7], where 54mm×33.5mm×1.1mm, (27.0mm, 17.2mm), (27.0mm, 16.3mm), (41.8mm, 27.4mm) are given to $W_x \times W_y \times W_z$, ($X_{P0}$, Y_{P0}), (X_{N0}, Y_{N0}), and (X, Y). Fig. 5 shows the good agreement between the present method and the FDTD in [7] except for negligible discrepancies at some peaks. Seeing the compared curves of the two feed signals, the differential mode has lower impedance than the common-mode, and is superior to the one-feed case when good conditions are met such as right placement and proper distance between the feeds in practice The following is the RE prediction with the differential feeding as well as common-mode feeding

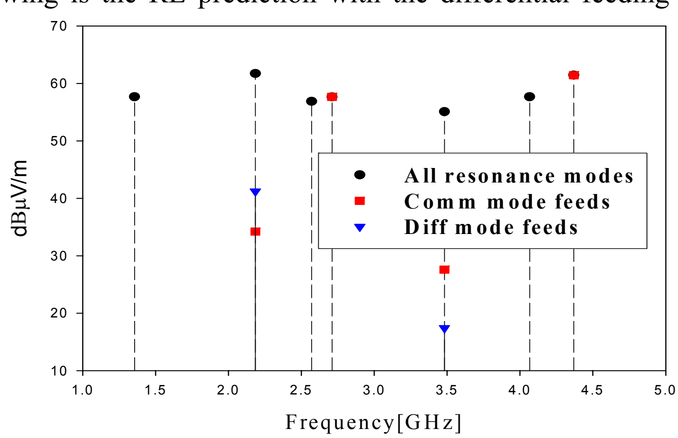
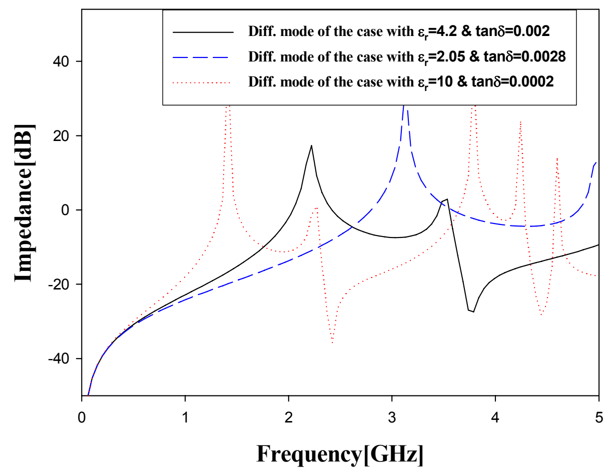


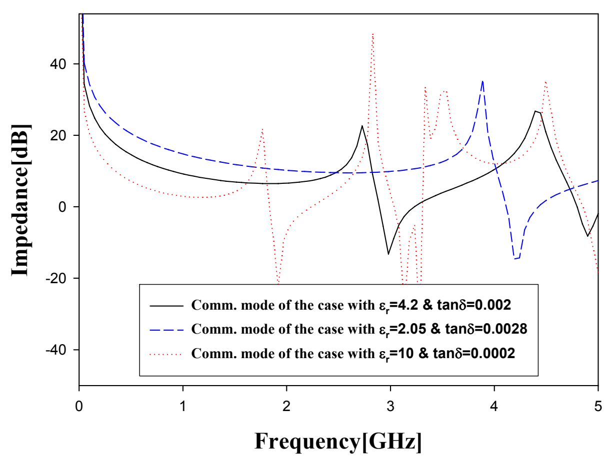
Fig. 6. Differential- & common-mode feeding V.S. RE levels

Examining the comparison, the improvement is found at the resonance frequencies of the original one feed structure to the reduced RE level introduced by the two freed system..

Finally, we will observe the trend of the impedance profile according to the different conditions on the multiple feeding. Different kinds of substrate materials will be input.



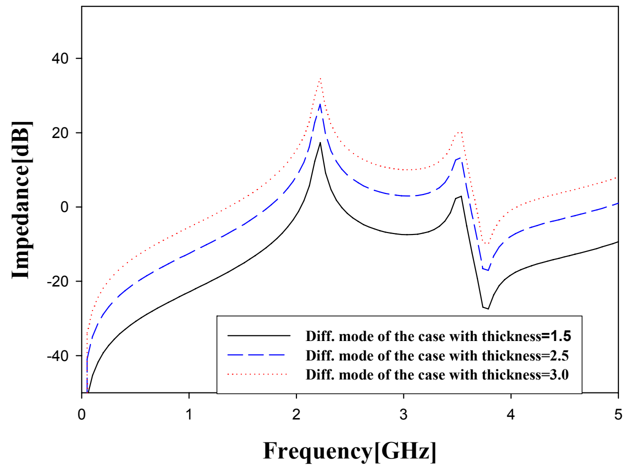
(a) Differential mode signals



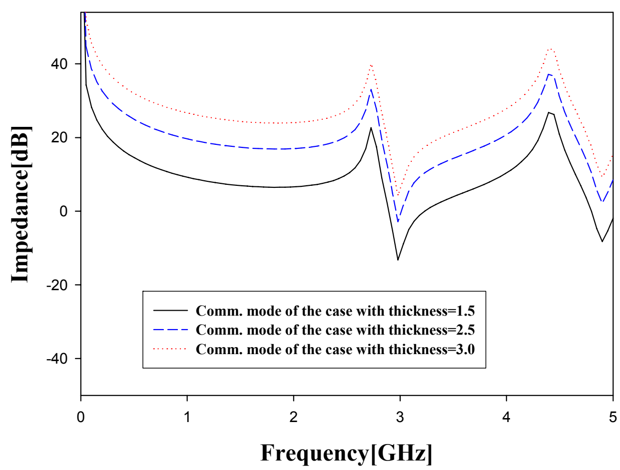
(b) Common-mode signals

Fig. 7. Effects of the different dielectric constants and loss tangent values

The solid lines in Fig.'s 6 (a) and (b) correspond to the differential and common mode signals in Fig. 8 used as the reference toward the change. As is seen, the change in the dielectric constant gives rise to a noticeable frequency shift. Regarding the differential mode signaling, the main peak (2 GHz) of the impedance moves from 3 GHz through 2GHz to 1 GHz, as the magnitude of the complex relative permittivity increases. On the contrary to the former(out-of-phase) signaling, the common-mode(in-phase) signaling does not show a fixed pattern. What comes next is the influence of the change in the thickness of the spacing between the power- and ground planes.



(a) Differential mode signals



(b) Common mode signals

Fig. 8. Effects of the different spacing between the power/ground planes

In Fig. 8, the thicker substrate causes the impedance profiles to increase in both common mode as well as differential mode. As is addressed before, the varied spacing between the two plates fixes the resonance modes with lowered capacitance and increased inductance of the structure, but extends current paths on the metal planes.

4. CONCLUSION

PCB power/ground planes have been rigorously characterized by the modal summation expansion. In particular, the resonance modes have been predicted with the impedance and fields in the structure. Given a valid method of calculation, the formula could be extended to the loaded structure and differential mode and common-mode feeding in an effort to decrease the impedance peaks at the resonance modes. Besides, the interference due to the radiated emission has been investigated by another simple computational method and validated by measurement. These things are very important to get the idea on how to cope with the damping of the resonance and leave the door open to find the best answer for a determined geometry for practical work.

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