Analysis of a PCB-Chassis System Including Different Sizes of Multiple Planes Based on SPICE

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Abstract— **This paper describes the SPICE modeling of multiple plane structures where the inner layers planes have different shapes than the outer layer planes. These structures are often seen in a printed circuit board (PCB), or the space between a PCB and metal chassis. First, a SPICE model is proposed for these structures using 2-dimensional ladder networks and ideal transformers. Next, the model is expanded to structures including vertical connecting conductors, such as vias in a PCB and grounding posts connecting a PCB to a metal chassis. Coupling properties inside a PCB are calculated using the SPICE model and shown to be consistent with experimental data. Furthermore, radiated emissions from a PCB-chassis system are also calculated based on the SPICE and equivalent magnetic current source models. The results are consistent with experimental data to show the changes in radiated EMI due to the locations of grounding posts.**

Keywords-component; SPICE models; multiple planes; 2-dimensional ladder network; ideal transformer; powr bus resonance; chassis connections; grounding postrs; equivalent magnetic current source; radiated EMI from PCBs

I. INTRODUCTION

PCB-chassis systems include several cavity configurations sandwiched by facing metal planes (e.g. the power bus in a PCB or the space between a PCB and metal chassis) [1]. Injected noise may resonate in the cavity or couple to neighboring cavities resulting in radiated emissions. Therefore, it is desirable to be able to model the cavity configurations and the coupling between them.

In previously published works, analytical SPICE models of vertical connecting conductors penetrating various cavities (e.g. via structures in a PCB or grounding posts connecting a PCB to a metal chassis) were proposed to investigate coupling inside a PCB or radiated emissions from PCB-chassis systems [1][2][3]. Although the calculated results from these models were shown to be consistent with the corresponding experimental data, these models only handle multiple plane structures where the sizes of the inner layer planes are the same as the outer layer planes. When the inner layer planes are sandwiched by larger outer layer planes, additional cavities are formed by the space between the upper and lower planes [4]. In this case, the edge coupling between the cavities can affect the resonant properties and radiated emissions.

This paper models structures with different sized planes where additional cavities are formed by the space between the upper and lower layer planes due to the missing areas of inner layer planes. Furthermore, the paper expands the proposed model to include structures with vertical connection conductors such as the vias in PCBs or the grounding posts connecting a PCB to a metal chassis. The paper also investigates the radiated emissions from these structures and compares calculated results to experimental data.

II. DESCRIPTION OF THE METHOD

This section describes a SPICE modeling procedure for a PCB or PCB-chassis system including multiple metal planes of different sizes where additional cavities are formed by the space between the upper and lower planes due to the missing areas of the inner planes. First, the SPICE model for these structures is developed using ideal transformers and 2-dimensional ladder networks. Next, the SPICE model is expanded to include systems that have vertical connecting conductors.

A. SPICE modeling of multiple planes

Fig. 1(a) shows one part of a simple printed circuit board consisting of multiple metal planes of different sizes. Notice that a cavity is formed in an area where dielectric material is sandwiched by facing metal planes. In Fig. 1(a), Cavity-1 and Cavity-2 are the spaces sandwiched by the upper and middle layer planes, and by the middle and lower layer planes, respectively. Cavity-3 is the space sandwiched by the upper and lower planes where the middle plane is missing.

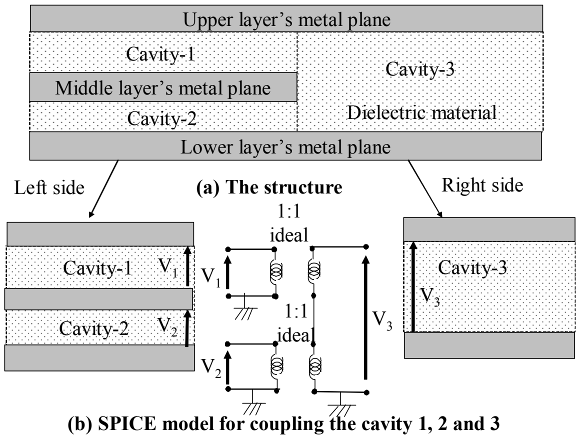

Figure 1. Cavity configurations formed by facing metal planes inside a PCB and the SPICE model representing the coupling between the left and right sides of the cavities.

Each cavity structure can be modeled using a 2-dimensional ladder network if the height of the cavity is very small compared to the wavelength [5]. The connecting parts between the cavities can be modeled as bifurcated waveguides [6]. If higher-order modes in the vertical direction are neglected, the relation between the voltages at the connecting parts can be represented as follows:

$$V_1+V_2=V_3 \quad (1)$$

where V_1, V_2 and V_3 represent the voltages in the vertical direction at the intersection of cavity 1, cavity 2 and cavity 3. Equation (1) can be simply enforced in a SPICE model using ideal transformers as shown in Fig. 1(b).

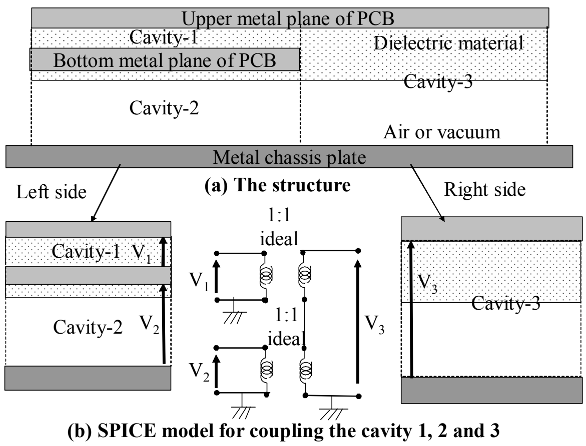

Figure 2. Cavity configurations formed by facing metal planes in a PCB-chassis system and the SPICE model representing the coupling between the left and right sides of the cavities.

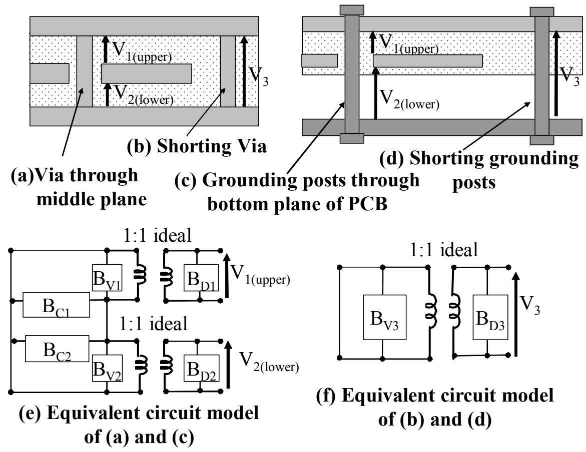

Figure 3. Configurations of vertical connecting conductors such as vias and grounding posts and the corresponding SPICE models.

Fig. 2(a) shows the space between a PCB and metal chassis when the PCB is mounted parallel to the chassis. Three cavities are formed by the spaces between facing metal planes similar to those in Fig. 1(a). Cavity-2 and Cavity-3 are filled with inhomogeneous materials, such as FR-4 and air. However, when the distance between the PCB and chassis is much greater than the thickness of the PCB, these cavities are well approximated by homogeneous structures and have the approximate permittivity of air. These cavities can also be represented using 2-dimensional ladder networks if the space between the planes is very small compared to the wavelength [1][3]. Equivalent circuits between the left and right sides of the cavities can be introduced in Fig. 2(b) that are similar to those in Fig. 1(b). Therefore, a PCB-chassis system consisting of multiple planes of different sizes can be modeled using SPICE even when additional cavities are formed by the spaces between the upper planes of a PCB and a chassis due to missing areas of the bottom planes of the PCB.

B. Vertical connecting conductors

Procedures for modeling multiple planes with vertical connecting conductors (vias or grounding posts) are introduced in [1][2][3]. These procedures are based on a radial/coaxial line junction model [7]. These models can be easily incorporated into configurations with different sizes of planes. Fig. 3 shows the outline of the model. It is interesting to note that in the via or grounding post models (a), (b), (c) and (d) of Fig.3, the susceptances for the planar cavity sides, B_{Di} (i=1, 2 or 3), can be represented by frequency independent negative inductances and the susceptances for the via or grounding post sides, B_{Vi} (i=1, 2 or 3), can be represented by frequency independent positive inductances when the physical dimensions are very small compared to a wavelength [2]. Furthermore, the negative and positive inductances cancel each other since they have the same amplitude through the ideal transformers with a ratio of 1:1. Therefore, these susceptances can be omitted and the relations between the upper and lower voltages, $V_{1(upper)}$

and $V_{2(lower)}$, in (a) and (c) of Fig. 3, are simply represented as follows:

$$V_{1(upper)} = -V_{2(lower)}$$

This relation is easily implemented in SPICE by connecting the upper and lower cavities with an ideal transformer with a ratio of 1: -1. The voltage at shorting vias and grounding posts, [e.g. V_3 in (b) and (d) of Fig.3] can be simply set to zero. Notice that the susceptances, B_{Ci}, (i=1 and 2), correspond to the capacitances of clearance holes and are likely to have a negligible effect on the total calculated results at low frequencies.

C. Estimating radiated emissions from the system

If the resonant cavities are dominant sources of radiated emissions, the radiated EMI for multiple plane configurations can be approximated by applying equivalent magnetic current sources along the cavity walls [3]. The mathematical formulation for the radiated electric field, **E**, can be obtained using the calculated voltages, V_{edge}, along the cavity walls, as follows:

$$\mathbf{E} = -\nabla \times \frac{e^{-jk_0 r}}{4\pi r} \int_S \frac{V_{edge}}{h} e^{jk_0 r' \cos\psi} d\mathbf{S}$$

where j is a unit of imaginary number and k_0 is the free-space wave number. **S** represents the area element vector along the outer walls of the cavity with height, h. r represents the distance from the origin of the coordinate system to an observation point in the far field. r' represents the distance from the origin to an infinitesimal area element inside the integral. ψ is the

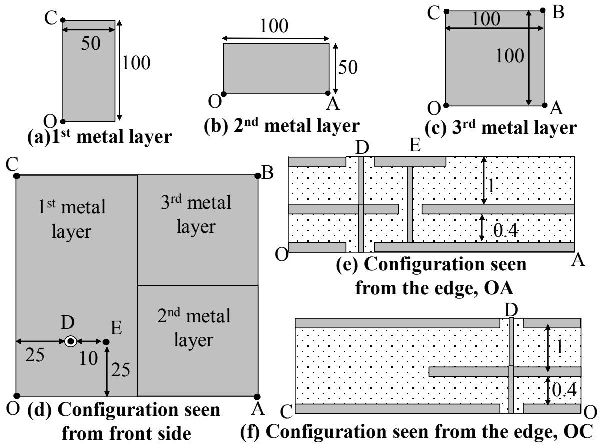

Figure 4. Test Board 1.

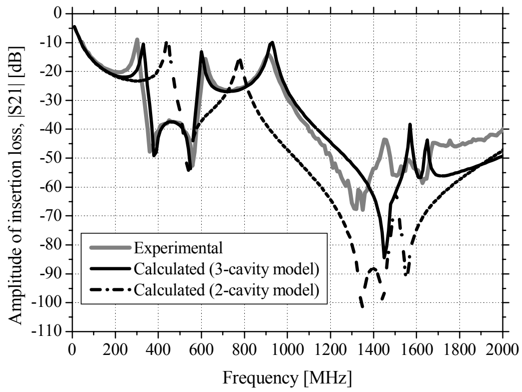

Figure 5. Comparison of the calculated results with corresponding experimental data from Board 1 (|S21|: coupling from input port on the 1st layer to output port on the 3rd layer).

angle between the 2 line segments, the former of which is from the origin to the observation point and the latter is from the origin to the infinitesimal area element inside the integral [8]. Notice that the cavity walls are corresponding to the edges of the 2-dimensional ladder networks, which are included in the SPICE model.

III. COMPARISONS WITH MEASUREMENTS

The SPICE model for multiple planes of different sizes was validated by comparing calculated results to experimental data. First, a three-layer test board (Board 1) consisting of copper planes and FR-4 material was built to investigate the coupling properties inside a PCB. A 2-port network analyzer was used to measure the S-parameters at ports located between the upper and lower layers. Fig. 4 shows the configuration of the test board. The test board has three metal layers of different rectangular shapes, as shown in Fig. 4 (a), (b) and (c). The left and bottom corner, O, of these rectangles overlap as seen from the front side, as in Fig. 4 (d). The 1st and 3rd layers are electrically connected with a via through clearance hole in the 2nd layer, at the point E, as shown in Fig. 4 (d) and (e). The point D, as shown in Fig. 4 (d), (e) and (f), is the location of the input or output ports for the network analyzer. The positions corresponding to the 1st and 3rd layer were set as the input and output ports, respectively. SMT connectors were attached to the ports and $|S_{21}|$ was measured from 50 MHz to 2 GHz.

In SPICE, the test board was modeled as a system of 3 cavities since there are 3 regions sandwiched by the facing metal planes. To investigate the importance of the cavity formed by the space between the 1st and 3rd metal layer, a model neglecting the corresponding cavity was also evaluated and compared with the 3-cavity model.

Fig. 5 shows the amplitude of the transfer coefficient, $|S_{21}|$, for the experimental results and the 2 calculated models. The calculated results for the 3 cavity model are consistent with the experimental data up to 1.0 GHz. At higher frequencies, the frequency-dependencies of the connectors and materials become more important and these factors are neglected in the SPICE model. The results from the 2-cavity model, which neglect the cavity formed by the 1st and 3rd layer, are rather inconsistent with the experimental results in the lower frequency range. The results imply that the additional cavities due to the missing areas of middle planes can affect the coupling in multi-cavity systems.

Next, the validity of the method for EMI estimation using the SPICE model and equivalent magnetic current sources was examined for a PCB-chassis system. Another four-layer test board (Board 2) was built and the radiated emissions from the test board mounted on a chassis were measured in a 3-meter anechoic chamber.

Figs. 6 and 7 show the test board configuration. The test board has two signal traces on the 1st and 4th layers, a ground plane on the 2nd layer and clearance holes for the attachment of grounding posts at 30-mm intervals. The board has 2 separate power planes, Power bus-1 and Power bus-2, on the 3rd layer as shown in Fig. 7(a). Each of the power buses is connected to a 20-MHz clock oscillator and driver mounted on the 1st layer. These drivers are connected to one end of 10-mm microstrip traces. The other ends are connected to 50-mm segments of microstrip trace on layer 4 through via structures. The far ends of these traces are also connected to other 10-mm microstrip traces back on layer 1 through via structures. The characteristic impedances of the microstrip configurations were 50 ohms and the traces were terminated with 50-ohm resistors on the 1st layer.

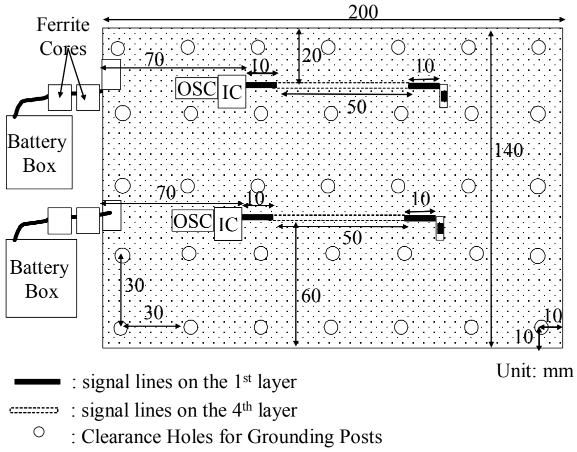

Figure 6. Test Board 2 trace configuration.

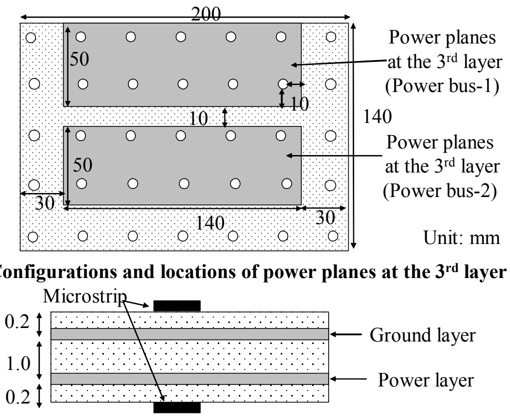

Figure 7. Test Board 2 plane configuration.

In the evaluations of Board 2, the board was mounted over a 50.0-cm x 40.0-cm flat metal chassis using 1-cm grounding posts. A battery box was attached to one of the two power buses, Power bus-1 or Power bus-2, at the edge of the PCB through an 8-cm cable with ferrite cores to suppress common-mode currents. The 2nd layer's ground plane and the metal chassis were connected by the grounding posts. The radiated EMI was evaluated for the two grounding post locations and two power bus switching conditions. Fig. 8 shows these conditions: (a) 4 corner grounding post locations while Power bus-1 was switched on and Power bus-2 off, (b) 4 corner grounding post locations and one additional grounding post at the center of the board while Power bus-1 was switched on and Power bus-2 off, (c) 4 corner grounding post locations while Power bus-2 was switched on and Power bus-1 off, and (d) 4 corner grounding post locations and one additional grounding post at the center of the board while Power bus-2 was switched on and Power bus-1 off. The radiated emissions from the board were measured from 30 MHz to 1 GHz. The vertical electric field was measured in the plane of the PCB and the maximum emissions at each frequency were reported. This orientation was selected because it is most likely to exhibit the effect of addition or cancellation of the fields along the edges of the PCB and the chassis cavity. As references, the radiated emissions from the board without a chassis and grounding posts were also evaluated with either Power bus-1 or Power bus-2 switched on. Fig. 9 shows the measured emissions when Power bus-1 was switched on while Fig. 10 shows the emissions when Power bus-2 was switched on. Both results show that the 1st EMI peaks around 200 MHz are attenuated by the grounding posts while the emissions are increased at the other frequencies. The increases due to the grounding posts are seen around 550 MHz and 750 MHz. These peaks correspond to the PCB-chassis resonances with the grounding posts [1][3]. The center point ground in addition to 4 corner grounds shifts the first resonant frequency higher.

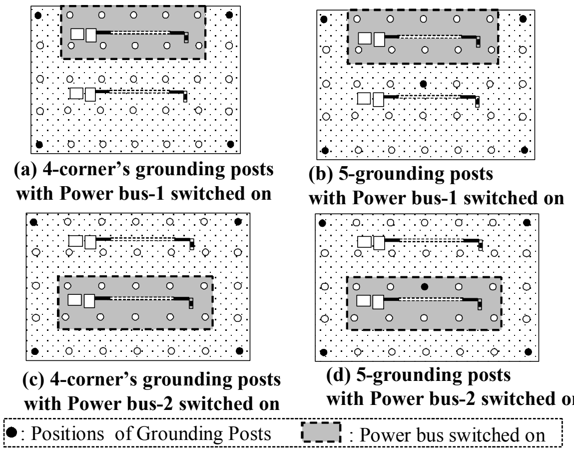

Figure 8. Test configurations.

In the calculations, the SPICE model was used to obtain the radiated EMI from the PCB-chassis system as described previously. The model incorporated the multiple planes with the additional cavity formed by the space between the 2nd layer's ground plane and chassis plate due to the missing area of the 3rd layer's power planes. The signal lines (microstrips) and via structures were modeled as transmission lines and via models using the procedure developed in [3]. The coupling between the signal line on the 4th layer and chassis plate was neglected since it is likely to be small compared to the direct coupling through the grounding posts or edges of the power planes. A 1-amp current source with a 50-ohm shunt resistor was located at the corresponding input of the transmission lines when either Power bus-1 or Power bus-2 were switched on.

The radiated emissions were calculated using the equivalent magnetic current source models described in the previous section.

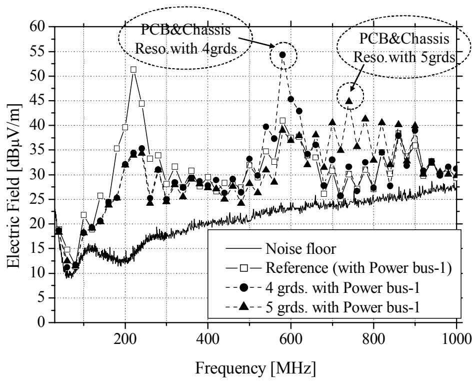

Figure 9. Radiated emissions from Board 2 with Power bus-1 switched on.

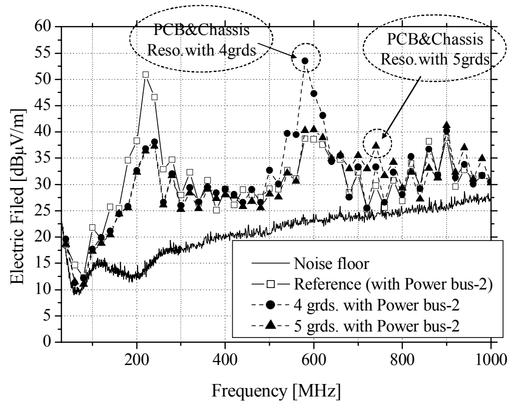

Figure 10. Radiated emissions from Board 2 with Power bus-2 switched on.

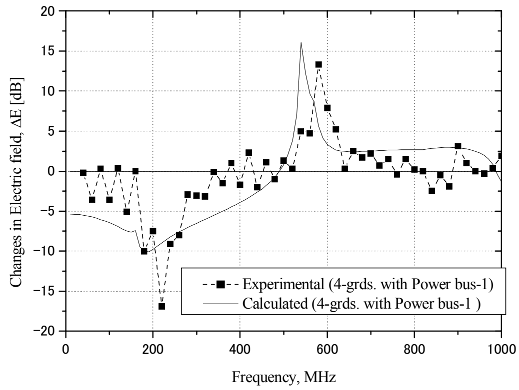

Figure 11. Differences of the radiated EMI from the reference values (Experimental and Calculated), 4 grouding posts with Power bus-1 switched on.

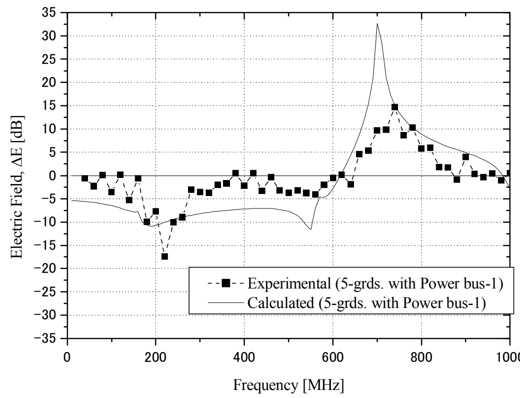

Figure 12. Differences of the radiated EMI from the reference values (Experimental and Calculated), 5 grouding posts with Power bus-1 switched on.

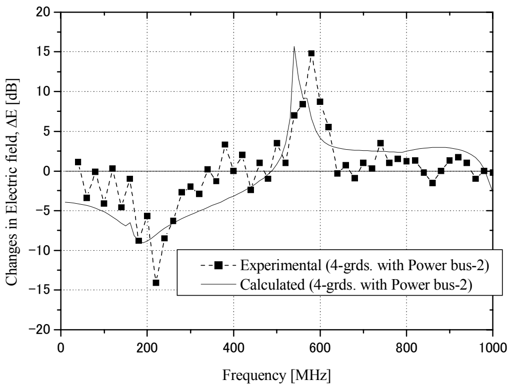

Figure 13. Differences of the radiated EMI from the reference values (Experimental and Calculated), 4 grouding posts with Power-bus-2 switched on.

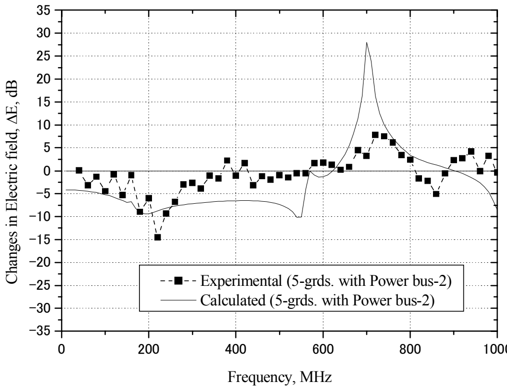

Figure 14. Differences of the radiated EMI from the reference values (Experimental and Calculated), 5 grouding posts with Power bus-2 switched on.

As references, the radiated emissions from the single board without chassis and grounding posts were also calculated. The change in radiated emissions relative to the references are plotted.

Figures 11 and 12 show the results for 4 and 5 grounding locations, respectively, when Power bus-1 was switched on. Figures 13 and 14 show the results for 4 and 5 grounding locations, respectively, when Power bus-2 was switched on. The calculated results are generally consistent with the measured data. The frequency-shifts of the PCB-chassis resonances due to the 5th grounding posts are evident in both the measured and calculated results. The differences between the calculated and experimental data may be due to other emission sources, such as the cable and signal lines. For the PCB-chassis cavities with grounding posts, the calculated results exhibit slightly lower resonant frequencies than the measured data since some detuning factors, such as fringing fields near edges of the cavities, coupling due to the cable and signal lines, and clearance holes on the metal chassis plate, are neglected in the calculated model.

IV. CONCLUSION

SPICE modeling procedures for analyzing a PCB-chassis system with multiple planes of different sizes have been proposed. First, the multiple plane structure where additional cavities are formed due to the missing areas of mid-layer planes was modeled and applied to a PCB with or without a chassis. Next, the model was expanded to a system with vertical connecting conductors, such as grounding vias and posts. The calculated results for a test board using the model were shown to be consistent with the experimental data obtained using a network analyzer. Furthermore, radiated emissions were calculated based on the SPICE model and equivalent magnetic current sources for a PCB-chassis system. The calculated results are generally consistent with the experimental data and show that a center-point ground in addition to 4 corner grounds shifts the first PCB-chassis resonance to higher frequencies.

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