Simulation and Design of a PCB-Chassis System for Reducing Radiated Emissions

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Abstract **─** The effects of the design parameters for a printed circuit board (PCB)-chassis system such as the slots on the chassis, the decoupling capacitors on the PCB, and the grounding posts (screws) connected between the PCB and the chassis are investigated using numerical analysis. These design parameters can affect the radiated emissions of the PCB-chassis system by changing or removing the resonances of the PCB and chassis. This numerical investigation represents a promising guideline for optimizing the number and location of grounding posts with regard to the placement of slots on a chassis and of decoupling capacitors on a PCB. The simulated results are shown to be consistent with the corresponding theoretical interpretations. Several design guides are summarized in the conclusion.

Index Terms **─** Chassis, decoupling capacitors, grounding posts, printed circuit boards, radiated emissions, resonance frequency, slots.

I. INTRODUCTION

Owing to the continually increasing speed of digital devices, it is becoming more difficult to solve electromagnetic interference (EMI) problems. Accordingly, EMI design is emphasized gradually in the development of electric devices at the early stage. Up until now, various studies and techniques aimed at reducing radiated emissions from high-speed digital systems have been conducted over a long period of time. The noise mitigation effect of local decoupling capacitors for the power bus designs of printed circuit boards (PCBs) was demonstrated in [1, 2]; the impact of ground plane stitching on the radiated EMI of a multilayer power-bus stacked PCB was studied in [3]; and the shielding characteristics of a rectangular chassis were investigated in terms of the shape of multiple apertures or slots in [4, 5]. However, most of the previous works were focused on modeling the PCB or chassis (enclosure) itself. Recently, more analytic approaches have been conducted to electrically and optimally model the grounding post as simple closed-form expressions, and then to rigorously investigate PCB-chassis cavity resonant emissions, even though the chassis was merely modeled as a conducting plane [6, 7]. Nevertheless, there have not been enough studies on system-level EMI countermeasures and improvements that consider PCB and chassis simultaneously.

To clearly perceive why the system-level EMI analysis including PCB and chassis together is very important, it is necessary to mention our real-world experience. Due to design simplicity and cost efficiency, the plastic back-cover of liquid crystal display (LCD) TV was once replaced by metal case. Most EMI engineers expected that the radiated emission from the LCD TV would decrease more than before because of the metallic back-cover. However, the radiation peaks which were never occurred when using plastic mold cover took place due to additional resonance by the metal case. To remedy this problem, the position of some screws was adjusted to avoid resonance phenomena. This real experience motivated us strongly to investigate the design method for the PCB-chassis system.

In this paper, from the EMI point of view, we present practical design methods or optimal guidelines of the PCB-chassis structures which can be directly available to every engineer involved in the design of realistic and complicated high-speed digital system. This paper, taking into account the

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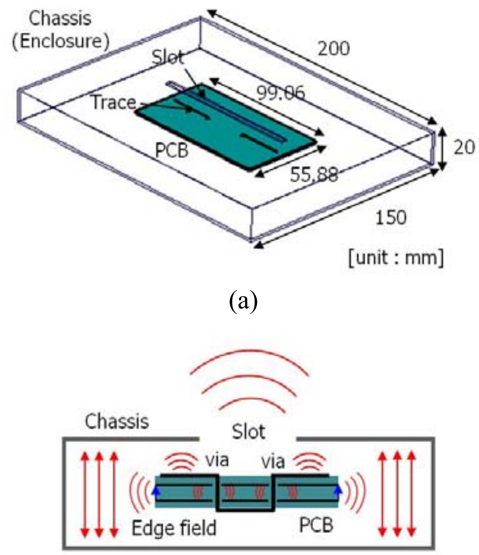
previous experience in modeling and measuring the PCB-chassis system, makes a step forward, by proposing a more detailed design approach for the optimization of the PCB-chassis system, based on numerical analysis. Our study focuses on bringing about a reduction of radiated emissions from the PCB-chassis system by using a combination of slots on the chassis, grounding posts, and decoupling capacitors on the PCB. Valuable design guidelines were inferred and provided from an investigation by numerical analysis.

II. GEOMETRY OF THE PROBLEM

Generally, the PCBs of electronic devices are mounted on a metallic enclosure or chassis. This metallic chassis serves both as a shield and as an electrical ground. The chassis commonly has a slot or array of slots in order to ventilate the system. Slot design is an important factor in reducing the radiated emissions from PCBs with a chassis. When the PCB with power and ground planes is mounted near and parallel to the metal chassis, there are two types of resonances: power/ground plane resonance and chassis cavity resonance [8]. Grounding posts or screws are used to make an electrical connection between the PCB's ground and chassis. The number and location of them may have an influence on changes of resonance, which in turn affect the radiated emissions over a wide frequency range [8-10]. Most PCBs also comprise a couple of decoupling capacitors to have a qualified power supply system. The number and location of the decoupling capacitors may also have an influence on changes of the resonances.

A PCB-chassis system consisting of a four-layered PCB and chassis with a slot was simply modeled, as depicted in Fig. 1. The PCB featured a microstrip-type trace extending to the top and bottom planes with two through-hole vias. The PCB has width of 55.88 mm, length of 99.06 mm, and thickness of 1 mm with the dielectric substrate of ε_r = 4.5. A metallic chassis has the dimensions of 200 mm × 150 mm ×20 mm and a slot (100 mm × 4 mm) placed at the center of the upper side. The walls of the chassis were assumed to be perfect electric conductors and their thickness is 1 mm. The PCB was located at the center of the chassis.

The radiation mechanism of the PCB-chassis system is shown in Fig. 1(b). The PCB could generate radiation not only from the signal traces but along the edges of the power and ground planes due to the via transitions of high-speed signals [11, 12]. The edge radiation from the PCB was maximized at the resonance frequencies of its power and ground planes. The radiated field from the PCB's edge caused resonance of the chassis. The resonance field of the chassis was radiated through the slot.



(b)

Fig. 1. (a) Simulation geometry and (b) radiation mechanism of the PCB-chassis system.

In this paper, numerical analyses were carried out using a full-wave finite integration technique (FIT) simulator, the CST Microwave Studio (MWS) [13]. The accuracy of the CST MWS in analyzing the PCB within a chassis with apertures has been demonstrated in [5, 10, and 14], where strong agreement with measurements and other numerical methods was obtained. When we calculated the radiated emissions from the PCB-chassis system using the CST MWS, a macro function named EMC-Norm was used to evaluate the broadband behavior of the maximum electric field strength (μV/m) at a distance of 3m from the structure.

III. NUMERICAL ANALYSIS

A. Resonances of PCB and PCB-chassis system

The resonances of the PCB and chassis are determined according to their size and their material properties. When the power and ground planes of the PCB and the material of the chassis are perfect conductors, the resonance frequencies of the PCB and chassis can be represented by equations (1) and (2), respectively,

$$f_{mn}^{PCB} = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0\varepsilon_r}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}, \quad (1)$$

$$f_{mnp}^{Chassis} = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0}}\sqrt{\left(\frac{m\pi}{L}\right)^2 + \left(\frac{n\pi}{W}\right)^2 + \left(\frac{p\pi}{H}\right)^2}, \quad (2)$$

where m, n, p = 0, 1, 2, ⋯, and a, b are the sizes of the PCB, ε_r is the permittivity of the PCB's substrate, and L, W, H are the sizes of the chassis. Table 1 shows the resonance frequencies calculated by theoretical equations (1) and (2) for the PCB and chassis of the simulated model. Figure 2 shows the radiated emissions from the PCB alone and PCB within the chassis. The radiated emission from the PCB alone has peaks at resonance frequencies of around 730 MHz, 1.48 GHz, 2.5 GHz, and 2.9 GHz, which are almost identical to the theoretical calculation shown in Table 1. Radiation peaks from the PCB-chassis system occur at the frequencies of around 749.5 MHz, 1.25 GHz, and 1.8 GHz, which are also consistent with the theoretical calculation. As shown in Fig. 2, the radiated field of the PCB within the chassis is around 40 dB less than that of the PCB alone, which means that the metallic chassis is explicitly effective to electromagnetic shielding. For validation, the results of HFSS simulation based on finite-element (FE) method [15] are also plotted in Fig. 2. Good agreement can be observed between the results of CST and HFSS simulations.

Table 1: Resonance frequencies of the PCB and chassis

PCB's resonance frequencies calculated by (1)				
		m=0	*m=1*	*m=2*
n=0			713.3 MHz	1.427 GHz
n=1		1.265 GHz	1.452 GHz	1.906 GHz
n=2		2.529 GHz	2.628 GHz	2.904 GHz
Chassis's resonance frequencies calculated by (2)				
		m=0	*m=1*	*m=2*
p=0	*n=0*		749.5 MHz	1.499 GHz
	n=1	999.3 MHz	1.249 GHz	1.802 GHz
	n=2	1.009 GHz	2.135 GHz	2.498 GHz

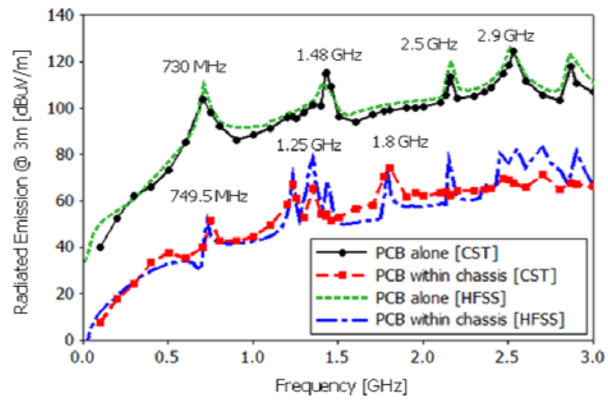
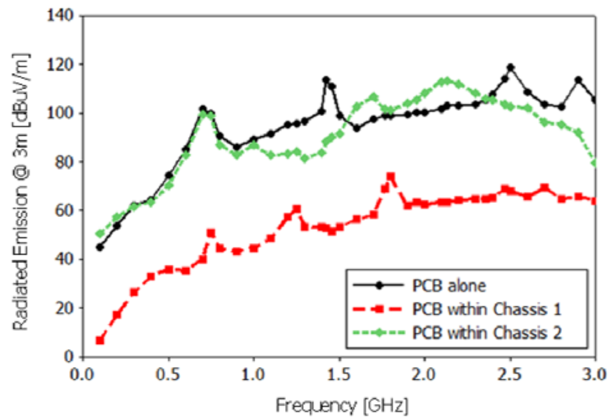


Fig. 2. Radiated emissions from the PCB alone and PCB within the chassis.

B. Effect of slot on radiated emissions from the PCB-chassis system

The slot on the chassis is an important factor with respect to the EMI radiation of electronic systems. Figure 3(a) shows the radiated emissions according to two kinds of slot placement. The radiated EMI level shows obvious differences between Chassis 1 and Chassis 2 of above 30 dB throughout the entire frequency range. In the case of Chassis 2, the radiated emission is almost at the same level as that of the PCB alone. The chassis became useless in terms of the shielding property of the system. The reason why the radiated emission of Chassis 2 is greater than that of Chassis 1 can be explained by examining the surface current on the chassis, as shown in Fig. 3(b). The surface current is induced on the inner side of the chassis by the current on the trace of the PCB. When the long direction of the slot coincides with the direction of the surface current on the chassis (as in the case of Chassis 1), the surface current is only slightly perturbed by the slot. Otherwise, when the long direction of the slot is perpendicular to the direction of surface current on the chassis (as in the case of Chassis 2), the surface current on the chassis is seriously perturbed by the slot. This perturbed surface current flows out over the chassis through the slot, resulting in serious radiation. Therefore, it is important to minimize the surface current so as to reduce radiated emission at the slot design stage. To decrease the surface current on the inner side of the chassis, the long direction of the slot should be parallel to the critical traces flowing high-speed signal current.



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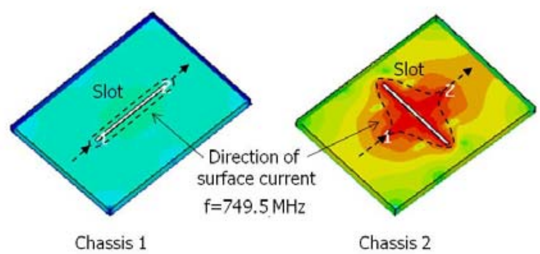


(b)

Fig. 3. (a) Radiated emissions from PCB-chassis systems with different placements of slot and (b) surface current on the chassis at 749.5 MHz.

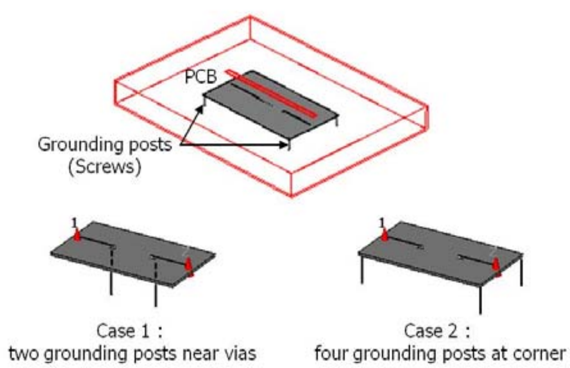
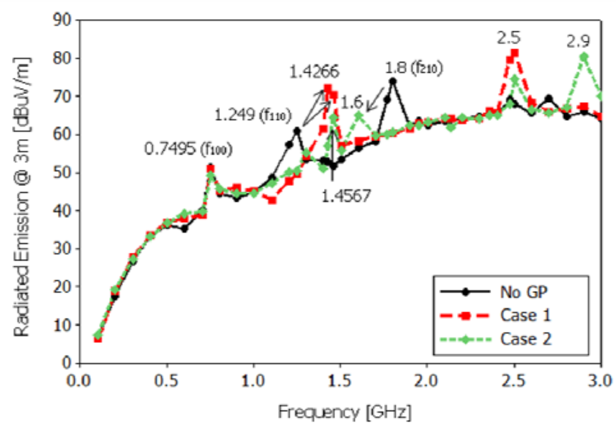


Fig. 4. Two simulation models of the PCB-chassis system with grounding posts.

C. Effect of grounding posts on radiated emissions from the PCB-chassis system

Grounding posts (GPs) are commonly used to connect electrically with the PCB ground and chassis ground, and can change the resonance frequency of the PCB-chassis system.

To investigate the effect of the GPs on radiated emissions from the PCB-chassis system, we considered two simulation models as illustrated in Fig. 4. The radiated emissions from the PCB-chassis system with two GPs situated near the via-hole (Case 1) and four GPs located at the corner (Case 2) were numerically analyzed. For the simulation, the GPs were modeled as conducting pillars with a radius of 0.6 mm. As shown in Fig. 5(a), the GPs did not have any effect on radiated emissions at 0.7495 GHz, which is the f_{100} resonance frequency of the chassis. However, the EMI peak at 1.249 GHz, which corresponds to the f_{110} resonance frequency of the chassis, disappeared by GPs.



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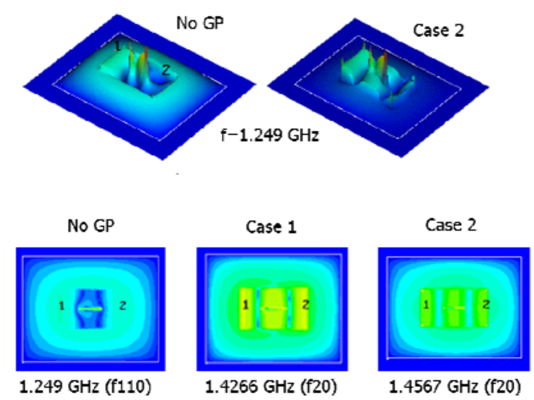
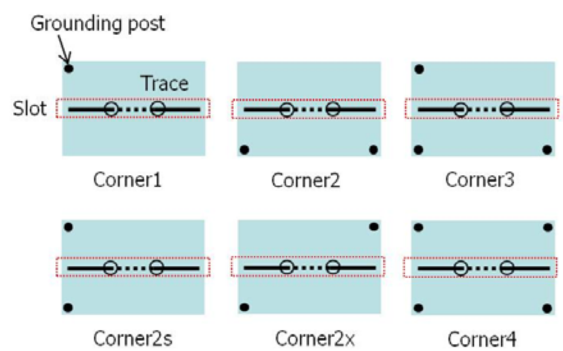


(b)

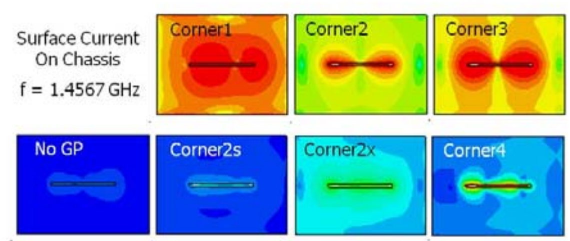
Fig. 5. (a) Radiated emissions from the PCB-chassis systems with differently positioned grounding posts and (b) 3D/2D electric field distributions inside the chassis.

This phenomenon can be clearly seen in the 3D electric field distributions inside the chassis at 1.249 GHz, as depicted in Fig. 5(b). In Case 1, the EMI peak was moved from 1.249 GHz to 1.4266 GHz, which is identical to the f_{20} resonance frequency of the PCB. The EMI peak of Case 2 turned up at 1.4579 GHz, which is close to the f_{20} resonance frequency of the PCB. The 2D electric field distributions shown in Fig. 5(b) support these results. They show the resonances of the PCB and chassis at the f_{20} mode and f_{110} mode, respectively. Lastly, the EMI peak at 1.8 GHz was removed in Case 1, and was moved to 1.6 GHz in Case 2. From these results, it was observed that the EMI peaks from the resonances can change considerably due to the position of the GPs connected between the PCB and chassis.

Next, in order to investigate the effect of changing the number and position of the GPs on radiated emissions, we considered six cases of PCB-chassis system, as shown in Fig. 6(a). These simulated structures can be divided into two groups by symmetry along the direction of the slot. Corner 2s and Corner 4 (also including no GP) have symmetrical GPs with respect to the slot. On the other hand, Corner 1, Corner 2, Corner 2x, and Corner 3 have asymmetrical GPs with respect to the slot. The microstrip on the PCB and the slot on the chassis were placed in the same direction in both groups. Figure 6(b) shows the surface current on the inner side of the chassis in each case at a frequency of 1.4567 GHz. As the asymmetry of the GPs increased, more surface currents were induced on the chassis with the slot. This can be seen clearly in the radiated emissions of each case, as shown in Fig. 7. The radiated emission levels were lower in the symmetric group than in the asymmetric group by as much as 30 dB. Increasing the number of GPs may not be the primary factor in the decrease of the radiated emission level. Although Corner 3 has more GPs than Corner 2s, its radiation level was 30 dB higher than that of Corner 2s due to the asymmetric placement of the GPs. This can be explained by investigating the ***E***-field vector on the slot, as shown in Fig. 8. In the cases of the symmetric group (No GP and Corner 4), E_z component electric field which is normal to the slot surface was dominant. The E_y component canceled out on the slot when the PCB had symmetrically positioned GPs. Therefore, the magnitude of the E_y component became smaller. But, in the cases of the asymmetric group (Corner 3 and Corner 1), the E_y component didn't cancel out on the slot when the PCB had asymmetrically positioned GPs. The E_y component electric field was dominant on the slot. This tangential component made radiated emissions from the slot easily. If the E_y component is higher on the slot, the radiated field also increases. Consequently, it is important to note that GPs should be placed symmetrically with respect to the long direction of the slot on the chassis so as to reduce the level of radiated emission.



(a)



(b)

Fig. 6. (a) Simulation geometries with respect to the number and position of grounding posts and (b) their surface current distributions at 1.4567 GHz.

D. Effect of decoupling capacitors on radiated emissions from the PCB-chassis system

Traditionally, the use of a decoupling capacitor is intended to mitigate switching noises between the power and ground planes by providing a low impedance path for the signal return current. Placing decoupling capacitors on a PCB can reduce or even eliminate the PCB's resonant mode, and that also affects the edge radiation along the PCB and the radiated emission of the PCB-chassis system [16]. Figure 9 shows two

PCBs with different numbers of decoupling capacitors placed in different locations. One, called Decap 1, features 30 decoupling capacitors mounted along its edge like a fence. The decoupling capacitor fence replaces the open edge boundary with a short boundary condition. In [11], as the number of decoupling capacitors per unit length of the fence is increased, the amount of the edge radiation field emission is diminished. Another PCB, called Decap 2, consists of 4 decoupling capacitors placed symmetrically around each via (i.e. a total of 8 decoupling capacitors were mounted on the PCB). Each decoupling capacitor has 10 nF. Simulations were conducted to examine the radiated emissions from these two PCB-chassis systems. As shown in Fig. 10(a), there were some changes in the resonance frequency of the PCB-chassis system in both cases compared with the case of the PCB without decoupling capacitors. The EMI peak at 0.7495 GHz, which corresponds to the f_{100} resonance frequency of the chassis, was removed in both cases. This was due to the degeneration of the f_{10} resonance frequency (713.3 MHz) of the PCB, which can be seen clearly in the 3D electric field distributions, as depicted in Fig. 10(b). In the case of No Decap, i.e. the PCB without decoupling capacitors, the f_{10} resonance mode is clearly seen on the PCB at 0.7495 GHz. But, in the case of Decap 1, the f_{10} resonance mode of the PCB was degenerated by the decoupling capacitors. This means that the decoupling capacitors eliminated lower frequency resonance inside the PCB, regardless of the placement of the decoupling capacitors. However, the other resonance frequencies over 1 GHz were changed slightly. From the EMI point of view, little difference was observed between Decap 1 and Decap 2. Consequently, the use of the decoupling capacitor is an effective way to reduce radiated emissions from the PCB-chassis system in the MHz range, although its influence is scant in the GHz range.

Finally, we investigated the combined effect of grounding posts and decoupling capacitors on radiated emissions from the PCB-chassis system. As indicated in the previous results, each grounding post and decoupling capacitor is an effective element in changing the radiation peaks or in reducing the EMI level of the PCB-chassis system.

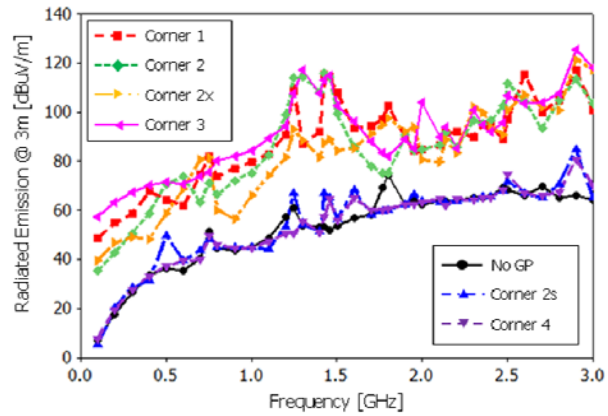


Fig. 7. Radiated emissions from PCB-chassis systems with different grounding post structures.

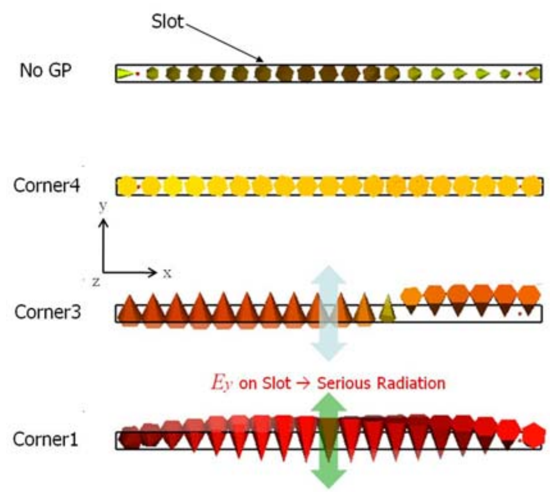


Fig. 8. Vector plotting of the electric field within the slot.

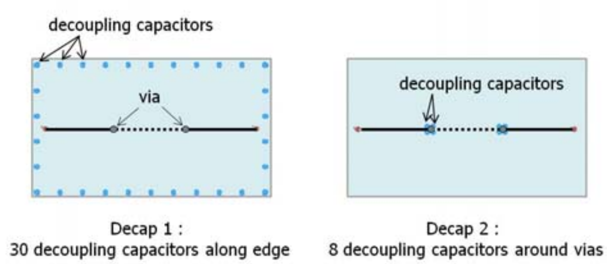
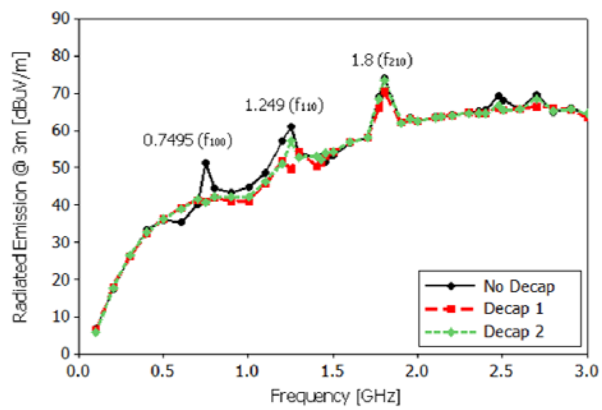
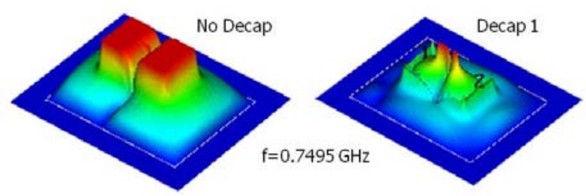


Fig. 9. Two PCBs with decoupling capacitors.



(a)



(b)

Fig. 10. (a) Radiated emissions from the PCB-chassis systems with different placement of decoupling capacitors and (b) 3D electric field distributions inside the chassis at 0.7495 GHz.

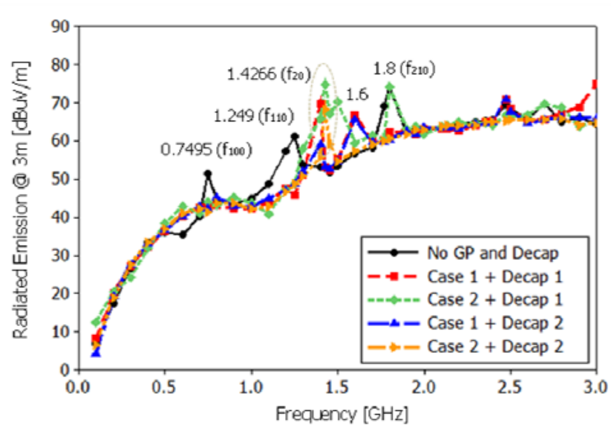


Fig. 11. Radiated emissions from the PCB-chassis systems for the combined placements of grounding posts and decoupling capacitors.

In reality, both elements are used at the same time when designing the PCB-chassis system. Therefore, it is important to consider the correlation between the grounding post and the decoupling capacitor in reducing the radiated emissions.

From Figs. 4 and 9, we can make four combined placements of grounding posts and decoupling capacitors. Figure 11 represents the simulated results of radiated emissions. As mentioned previously, the f_{100} resonant mode of the chassis at 0.7495 GHz was removed from the EMI peaks by placing decoupling capacitors, and also the resonance peak at 1.249 GHz was moved to around 1.4266 GHz by the grounding posts. In Case 1, a resonant peak was newly brought into being at 1.6 GHz by adding decoupling capacitors, when we compared with Fig. 5(a). In Case 2, the moved resonant peak at 1.6 GHz shown in Fig. 5(a) returned to 1.8 GHz due to the decoupling capacitors. From these results, the structure of Case 2 combined with Decap 2 shows a lower level of radiated emissions and fewer EMI peaks than the others, with the exception of the EMI peak at 1.4266 GHz. Consequently, proper placement of the grounding posts and decoupling capacitors can eliminate or change the EMI peaks effectively.

IV. CONCLUSION

To reduce radiated emissions from the PCB-chassis system, the design parameters such as a slot on the chassis, decoupling capacitors on the PCB, and grounding posts (screws) connected between the PCB and chassis were investigated using numerical analysis. The results of simulation demonstrate that the shape of the slot, the placing of decoupling capacitors, and the number of grounding posts and their locations can have a significant influence on the level of radiated emissions of the PCB-chassis system. Several design guidelines are summarized as follows:

- The long direction of the slot should be parallel to the critical traces on the PCB.
- The number and location of grounding posts influence changes in the resonant frequencies of the PCB-chassis system.
- The grounding posts should be placed symmetrically with respect to the long direction of the slot on the chassis.
- The placing of decoupling capacitors is an effective way to reduce radiated emissions from the PCB-chassis system in the MHz range, but it has little influence in the GHz range.

- Proper placement of the grounding posts and decoupling capacitors together can eliminate or change the EMI peaks effectively.

These guidelines are considered helpful in reducing radiated emissions from the PCB-chassis system at the design stage.

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