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Yoshiki Kayano

Motoshi Tanaka

Hiroshi Inoue

James L. Drewniak
Missouri University of Science and Technology, drewniak@mst.edu

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A Study on the Correspondence of Common-Mode Current in Electromagnetic Radiation from a PCB with a Guard-Band

Yoshiki Kayano, Motoshi Tanaka and Hiroshi Inoue
Dept. of Electrical and Electronic Engineering, Akita University
1-1 Tegata-gakuen-machi, Akita-shi, 010-8502, Japan
e-mail: kayano@venus.ee.akita-u.ac.jp

James L. Drewniak
Dept. of Electrical and Computer Engineering,
University of Missouri–Rolla
Rolla, MO 65409 USA
e-mail: drewniak@ece.umr.edu

***Abstract*— A PCB, in which the ground plane has a finite width and the trace has unbalanced positioning, can result in common-mode (CM) radiation. So far, CM current which is generated by the unbalance of a trace and ground plane has been investigated by experiment and numerical method. It was clarified that CM current is well explained the radiation from PCB up to a few hundred megahertz, and addition of a guard band geometry, which is well connected to the ground plane, can be effective in suppressing the CM current. But it is seemed to be insufficient description for the phenomena observed at higher frequency. This study newly focuses on the correspondence of the CM current in total electromagnetic (EM) radiation from a PCB with a guard band up to 5 GHz. In results, although total radiated power and near electric field up to 1 GHz were related to CM current, the increase in EM radiation in higher frequencies (a few gigahertz) could not be predicted from only the frequency response of CM current. There should suggest two radiation components for a PCB configuration; radiation as a result of a CM current due to the current driven mechanism, and direct radiation from a trace. At the higher frequencies, direct radiation from the trace may be more significant relative to the radiation due to the CM current. This research will be very useful and applicable to estimate the detail of EMC radiation problem from PCBs with attached cables.**

I. Introduction

Recent advancement of the electronics on the down sizing, the high density packaging and high speeding up of the clock frequency require the electronic instruments that have high immunity for the external electromagnetic (EM) noise and undesired EM radiation. Many electronic instruments require feed cables for the operation. The feed cable (*e.g.* coaxial cable) consists of a signal line and a ground line as a return path. In the state of an ideal balance, a signal and a return current are equal. However, for real feed cables, ideal balance can not be established, and, hence, a unbalanced current called common-mode (CM) current exists. CM current is considered as a main source of the radiated electromagnetic interference (EMI) from electronic instruments.

So far some studies on the electromagnetic noise radiated from a printed circuit board (PCB) have been published [1]-[4]. It is necessary to suppress the CM current to reduce the EM radiation [1], [2]. The CM radiation from cables attached to a PCB, as well as radiation from the PCB itself, is a total EMI problem. CM radiation will be the largest at near a resonance frequency of the effective "EMI antenna", one portion of which is the attached cable. Mechanisms by which signal current are converted to CM noise sources resulting in EMI have been demonstrated for lower than the first resonance in Ref. [3].

The authors have discussed the CM current on a feed cable due to a trace near a PCB edge experimentally and with numerical modeling, up to 1 GHz [5]-[7]. As the guard band, copper tape which is connected along the entire edge of the ground plane was proposed to suppress EMI arising from such CM current [7]. So far, it was clarified that the CM current is well explained the radiation from PCB up to a few hundred megahertz. But it is seemed to be insufficient description for the phenomena observed at higher frequency. It is helpful to be able to anticipate at the design stage the EM radiation of PCB configurations. Investigation of the correspondence between CM current and EM radiation from a PCB at a few gigahertz is required.

In this paper, the correspondence of the CM current in total electromagnetic (EM) radiation from a PCB with a guard band is investigated experimentally and with the finite-difference time-domain modeling. First, frequency responses of CM current and EM radiated power are compared up to 3 GHz. The effect of the guard band on EM radiation is also discussed. Second, electric field near a PCB with a guard band is discussed by using a monopole probe. Finally, in order to demonstrate that direct radiation from the trace may be more significant relative to the radiation due to the CM current, results on the variation of the width of a ground plane are also discussed.

II. PCB Geometry

The geometry of the PCB layout under test is illustrated in Fig. 1. The PCB had two layers, with the upper layer for a signal trace and the lower for the reference (ground) plane. The size of PCB was 150 mm length, 100 mm width, and 1.53 mm thickness of the dielectric substrate with ε_r=4.5. The trace, with 2.8 mm width and 50 mm length, was centered lengthwise on a dielectric substrate. A characteristic impedance of approximately 50 Ω was measured with a time domain reflectometry (TDR). In order to match the impedance,

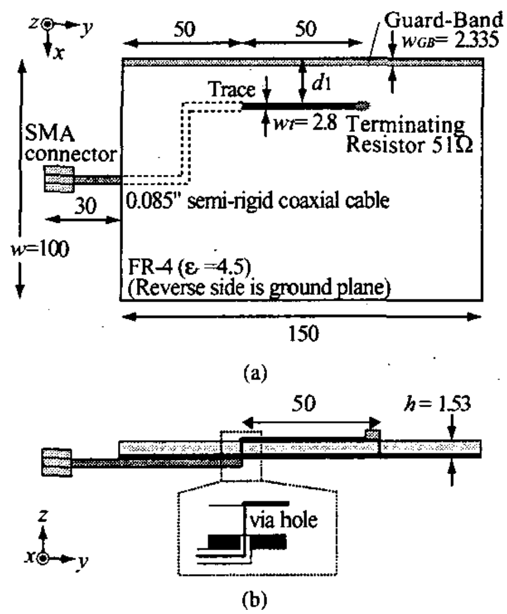

Fig. 1. Geometry of the PCB layout under test (in mm). (a) top view, (b) side view.

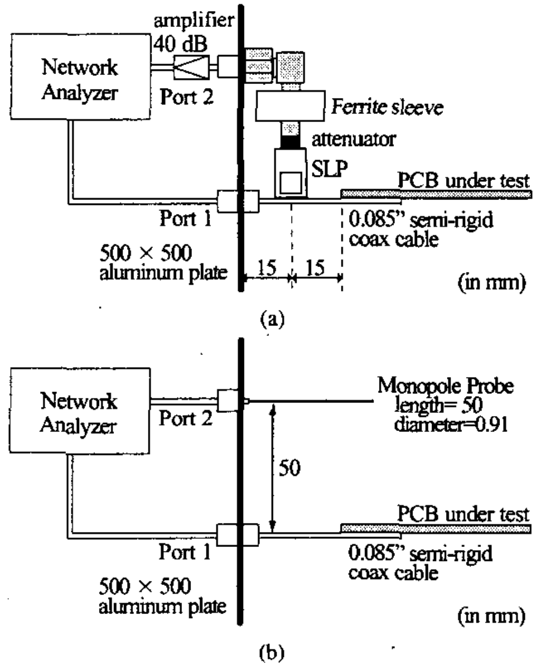

Fig. 2. Experimental setup for the $|S_{21}|$ measurement. (a) CM current measurement, (b) near field measurement.

the trace was terminated with 51 Ω surface-mount technology (SMT) resistor. Several different configurations in which the distance d_1 between the trace and the PCB edge were prepared.

The same configuration of PCBs with a guard band were also prepared. As the guard band copper tape was used and connected along the edge of the ground plane to the upper layer through the side of the PCB. The width w_{GB} of the guard band was 2.335 mm. TDR measurements were worked to compare the characteristic impedance for the cases with and without a guard band, and the results were nearly the same.

The PCB was driven through a 0.085-in semi-rigid coaxial cable running along the center of the PCB on the reverse side. The cable ran the length of the PCB to the feed point of the driven trace, and was soldered to the ground plane along its entire length. The center conductor of the semi-rigid coaxial cable was extended beyond the outer shield and penetrated the PCB through the ground plane to connect to the trace on the top side. The coaxial cable extended 30 mm beyond the PCB edge, and an SMA connector was located at the end of the cable.

III. Experimental and Modeling Method

A. Experimental Method

1) CM Current Measurement: The CM current on the outer shield of the signal feed cable was measured using a shielded-loop probe (SLP) [8], and a network analyzer (Agilent E8358A), as shown in Fig. 2(a). The SLP loop area was 9.2×9.2 mm^2. A 500×500 mm^2 aluminum plate was used to isolate the PCB from the cable leading to the network analyzer. Port 1 was connected to the 0.085-in coaxial cable to drive the signal line, and Port 2 was connected to the SLP. The 10 dB attenuator was used to match the impedance of a SLP to a coaxial cable. The SLP signal was amplified by 40 dB. A ferrite sleeve was mounted around the probe connector to reduce coupling to the SLP. The $|S_{21}|$ at the location of Port 1 (the voltage source for the signal trace) and Port 2 (SLP on the semi-rigid coaxial cable) was measured in the frequency range from 100 MHz to 3 GHz.

The calibration of the network analyzer and removal of the frequency response of the SLP were implemented [7]. In this procedure, a microstrip line as the standard magnetic field source was prepared and employed as a means of calibrating the SLP [9]. Consequently, the relationship between the $|S_{21}|$ and CM current is given by

$$|S_{21}| = \frac{100|I_{CM}|}{|V_S|}, \qquad (1)$$

where the V_S is the RF source voltage of the network analyzer.

2) Near Field Measurement: Near field for PCB was measured using a monopole probe [10], [11], and a network analyzer, as shown in Fig. 2(b). The setup for the experiment was identical to that in Fig. 2(a), except the SLP was replaced with a 50 mm monopole probe. The distance between the monopole probe and the PCB was 50 mm. The electric field detected by the monopole probe contains the frequency response of the probe, and is not direct indication of the absolute electric field. Nevertheless, this method is used to understand the behavior of EM radiation at the higher frequencies.

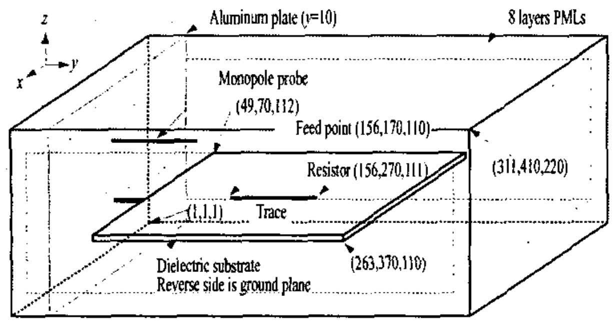

Fig. 3. Computational domain for the FDTD simulation.

The $|S_{21}|$ is a ratio of the received voltage V_p at the monopole probe to the forward voltage on the Port 1. Since the source impedance is matched to the characteristic impedance of the cable, the forward voltage is $V_s/2$. The voltage V_p induced on the monopole probe is proportional to the product of the effective antenna length and the incident electric field. Consequently, the $|S_{21}|$ is related to the near electric field;

$$|S_{21}| = \frac{|2V_p|}{|V_S|}. \tag{2}$$

Equations (1) and (2) are used to compare experimental and numerical results.

B. Method of FDTD Modeling

The FDTD method [12] is used for simulating CM current on a feed cable attached to the PCB, total EM radiated power, and near field for the PCB. Figure 3 shows the computational domain for the FDTD simulation as a typical example. For the FDTD modeling and calculation, the unit cell size was Δx=0.467, Δy=0.5 and Δz=0.765 mm respectively. The time step was Δt=1.0 ps from Courant's stability condition. The trace was modeled as perfect electric conductor (PEC) with six cells wide. The ground plane and aluminum plate were also modeled as PEC. The aluminum plate used in the experiments was included as an infinite ground plane. An SMT resistor was modeled as one cell lumped element in the PCB substrate. The PCB substrate was modeled as a dielectric two cells deep with relative permittivity ε_r=4.5. Dispersion characteristic and dissipation for the substrate were disregarded. A resistivity of copper as the trace and ground was also disregarded. The source was modeled as the source with source resistance 50 Ω to account for the 50 Ω measurement system. The via connecting the trace to the ground plane was modeled as a thin wire, and the source was modeled in one cell of the dielectric under the trace. The cylindrical outer shield (ground) of the semi-rigid coaxial cable was modeled as cuboidal PEC boxes. The monopole probe was modeled as a thin wire. A 50 Ω resistor was placed between the monopole probe and the aluminum plate to account for the 50 Ω measurement system. A sinusoidally modulated Gaussian pulse voltage whose frequency range was from 100 MHz to 5 GHz was applied as signal source. To shorten the calculation time, the vector and parallel computation method for a super computer (NEC SX-7) was used in FORTRAN 90.

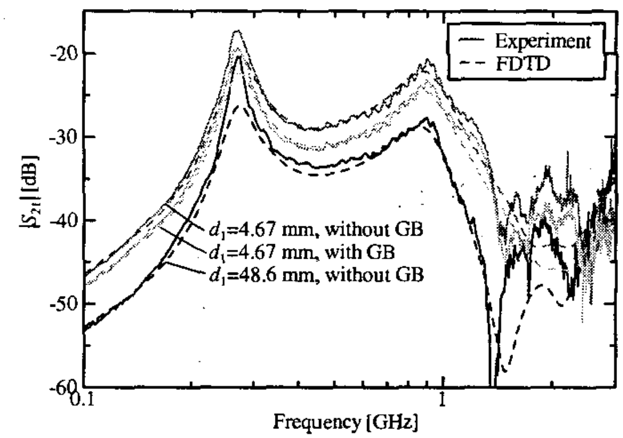

Fig. 4. Frequency response of $|S_{21}|$ related to CM current.

The CM current (I_{CM}) was calculated from the average magnetic field strength H_x in the SLP. The total radiated power P_r was calculated by the surface integral of the real part of the Poynting vector on the closed-surface surrounding the PCB as the following equation [13]

$$P_r = \frac{1}{2}\mathrm{Re}\left[\iint_S (\boldsymbol{E} \times \boldsymbol{H}) \cdot d\boldsymbol{s}\right]. \tag{3}$$

The voltage V_p induced on the monopole probe was calculated from the voltage dropped across the resistor connected to the monopole probe.

IV. Effect of Trace Position

A. CM Current on Feed Cable and Total Radiated Power

The measured and calculated results for $|S_{21}|$ related to CM current are shown in Fig. 4. First and second resonance frequencies due to an antenna type resonance are 273 MHz and 860 MHz, respectively. As the trace is moved close to the PCB edge, the $|S_{21}|$ increases. On the other hand, guard band suppresses CM current. Further, the curve is shifted nearly uniformly in magnitude below 1 GHz. Comparison between the calculated and measured results shows good agreement, which indicates that the FDTD modeling is applicable for radiated power calculations.

Frequency responses of calculated P_r are shown in Fig. 5, where the P_r is normalized to the incident power P_{inc} at the signal trace input. Symbols are calculated results, and solid lines are least squares curves. In the case of finite ground plane, the P_r has a peak at 273 MHz identical to the $|S_{21}|$ related to CM current. Although $|S_{21}|$ decreases above 1 GHz, P_r increases as the frequency increases.

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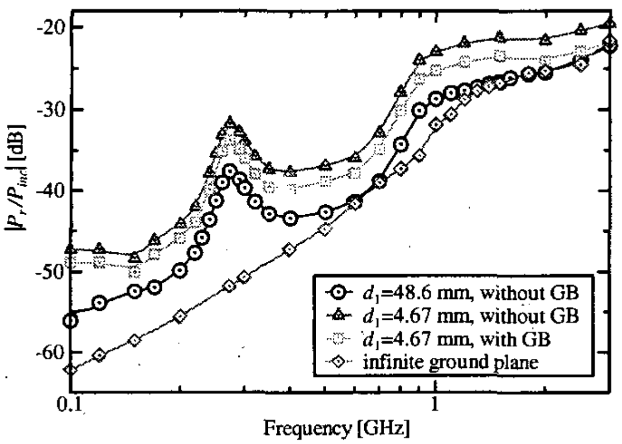


Fig. 5. Frequency response of $|P_r/P_{inc}|$. (Calculated and least squares curves.)

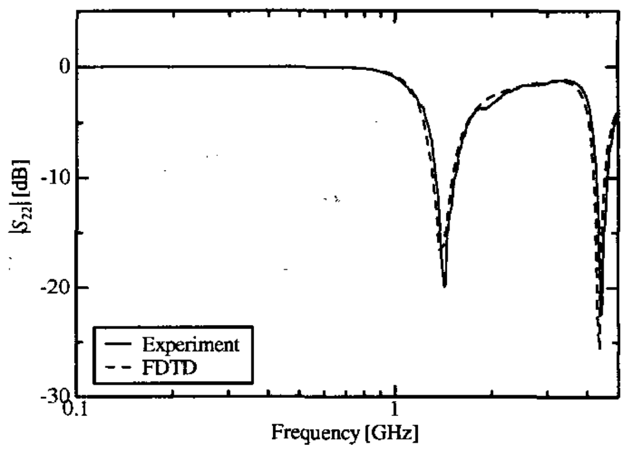


Fig. 6. Reflection coefficient $|S_{22}|$ for the monopole probe.

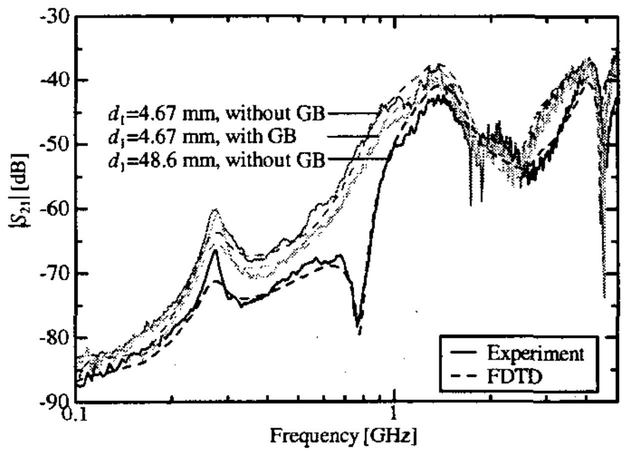


Fig. 7. Frequency response of near field for PCB.

There should suggest two radiation components for the present PCB configuration; radiation as a result of the CM current due to the current driven mechanism [3], and direct radiation from the trace. The total radiated power P_r does not allow for distinguishing between these two components. In order to distinguish these two components, the total radiated power P_r from a PCB with an infinite ground plane which means direct radiation from the trace was calculated. At the higher frequencies, direct radiation from the trace may be more significant relative to the radiation due to the CM current.

B. Near Field for PCB

Figure 6 shows the reflection coefficient $|S_{22}|$ for the monopole probe. The resonances corresponding to 1/4 and 3/4 wavelength are observed. The measured and calculated results for $|S_{21}|$ related to near field for PCB are shown in Fig. 7. The calculated and measured results are in good agreement. The $|S_{21}|$ has a resonance at 273 MHz which is identical to resonance in frequency response of CM current. The resonances at 1.5 GHz and 4.5 GHz are caused by the monopole probe.

The effect of the guard band to suppress the near electric field at the 273 MHz was 2.5 dB. The effect is almost the same as that on CM current.

Although CM current decreases above 1 GHz, $|S_{21}|$ related to near field for PCB increases. This phenomenon corresponds to the frequency response of total power of EM radiation. At the higher frequencies, direct radiation from the trace may be dominant rather than the radiation due to the CM current. The results indicate that the increase in EM radiation in higher frequencies could not be predicted from only the frequency response of CM current.

C. Relationship between Distance d_1 and the CM Current and Total Radiated Power

The $|S_{21}|$ and P_r as a function of distance d_1 between the trace and the PCB edge are shown in Fig. 8, where the $|S_{21}|$ and P_r are normalized to a "centered trace (d_1=48.6 mm) without guard band" case. $|S_{21}|_{norm}$ and $|S_{21}|_{GBnorm}$ are for the cases without and with a guard band, respectively. Symbols are FDTD calculated results, and the lines are calculated by the empirical equation for normalized $|S_{21}|$ [7]. The effect of the guard band to suppress the EM radiation is almost the same as that on CM current. This result indicates that the effect of the guard band to suppress the EM radiation can be estimated using previous results given in Ref. [7]. However, the guard band is effective in suppressing the EM radiation due to CM current. Therefore, above a few gigahertz effect of the guard band and position of the trace may not correspond to these results.

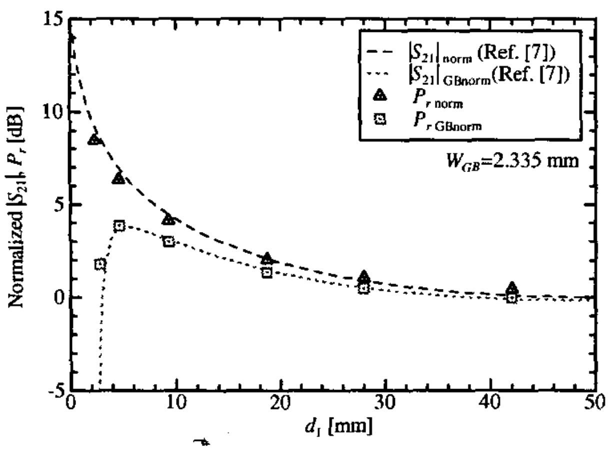
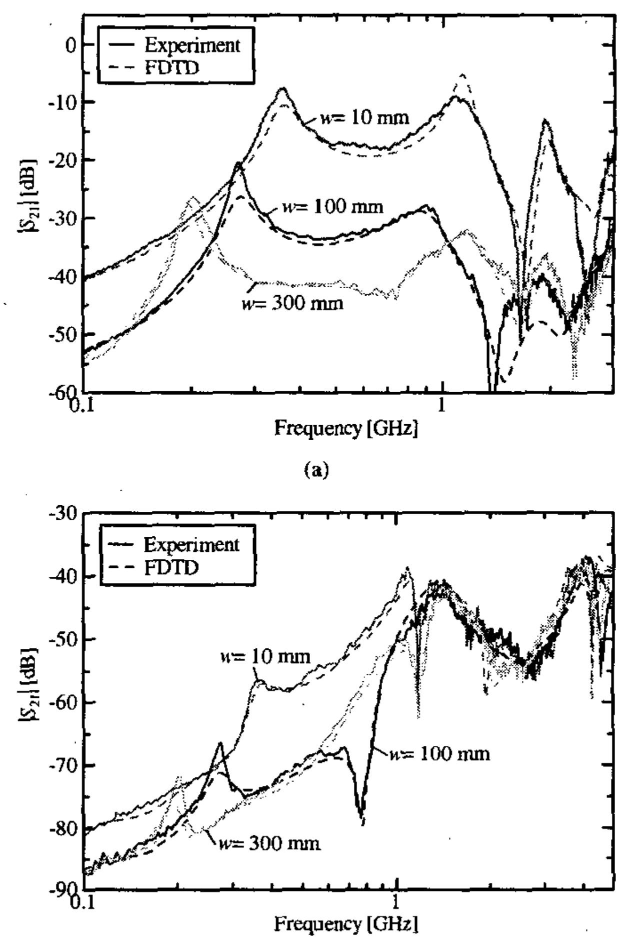


Fig. 8. $|S_{21}|$ and P_r (normalized for the center trace case) at 273 MHz vs. d_1.

V. Effect of Width of a Ground Plane

In order to experimentally distinguish two radiated emission components, the results on the variation of the width of a ground plane are discussed in this section. The CM current and near field for a PCB are investigated. The PCB dimensions are the same as Fig. 1 except width w of a ground plane. A trace was centered on a PCB. The CM current on a semi-rigid coaxial cable and near field for a PCB are shown in Fig. 9(a) and (b), respectively. As the width of a ground plane is narrower, the CM current increases significantly [14]. Since return current concentrates on the edge of the ground plane, the shift of resonance frequencies are due to increasing of the return path.

On the other hand, near field for a PCB above 1 GHz are independent on the width of the ground plane. Since the position of the trace is fixed, the electric field due to direct radiation from the trace picked up by the monopole probe is independent on the width of the ground plane. Therefore, these results indicates that direct radiation from the trace is more significant relative to the radiation due to the CM current at a few gigahertz.



(b)

Fig. 9. Effect of width of a ground plane. (a) CM current, (b) Near field for PCB.

VI. Conclusion

The correspondence between CM current and radiated electric field from a PCB with a guard band was investigated experimentally and with FDTD modeling. First, frequency responses of CM current and EM radiated power were compared up to 3 GHz. Second, electric field near a PCB with a guard band was discussed by using a monopole probe. The effect of the guard band on EM radiation was also discussed. In results, although CM current decreases above 1 GHz, EM radiated power and near electric field for a PCB increase as the frequency increases. There should be two radiation components for the present PCB configuration; radiation as a result of the CM current due to current driven mechanism, and direct radiation from the trace. The total radiated power from a PCB with an infinite plane which means direct radiation from the trace was calculated to distinguish these two components. At the higher frequencies, direct radiation from the trace may be dominant rather than the radiation due to the CM current. Finally, in order to demonstrate that direct radiation from the trace may be more significant relative to the radiation due to the CM current, results on the variation of the width of a ground plane were also discussed. The results indicate that the increase in EM radiation in higher frequencies (above a few gigahertz) could not be predicted from only the frequency response of CM current. This research will be very useful and applicable to estimate the detail of EMC radiation problem from PCBs with attached cables.

The experiments to support calculated results of total radiated power from a PCB and comparison in far-field should be the further studies.

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