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Experimental Verification of Common-Mode Excitation Model for PCB Having Partially Narrow Return Path

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Suppression of common-mode current is important to achieve electromagnetic compatibility of high-speed and high-density electronic circuits. The authors have focused on the common mode current flowing on a printed circuit board (PCB) to explain the excitation mechanism. A narrow ground pattern in microstrip structure excites common-mode current. In the previous paper, the authors explained the mechanism of common mode generation by means of "current division factor" for simple PCBs. The estimated radiation from a simple PCB agreed well with measured one. In this paper, the authors extend the theory to be applied to generalize ground structure. The validity of the theory is confirmed by comparing the measured radiation and the estimated value using the common-mode model for a test PCB. The estimated radiation agrees well with the measured one within 3 dB up to 900 MHz.

1. INTRODUCTION

Electromagnetic compatibility (EMC) aims to prevent interference that disturbs operation of other equipment such as radio or TV sets. In many countries, the import of electronic products is regulated by the governments under regal EMC regulations. Manufacturers must keep the unintentional radiated emission from their products to be less than regulatory limit. So design technique to conform to the EMC specifications is required by product designers.

We have focused on the radiation from a printed circuit board (PCB). In general, the microstrip structure is used for high-speed transmission lines on a PCB. The ideal microstrip structure has an infinite ground plane that can support ideal differential mode transmission, and radiated emission from it is negligibly small. On the other hand, narrower ground pattern on a practical PCB excites common mode that generates stronger electromagnetic radiation[1-6].

In the previous paper the authors explained a mechanism of common-mode generation caused by a narrow ground pattern in a PCB, and developed an estimation method for the common-mode radiation [7]. The ground pattern is treated as a return trace for signal current. Any transmission line has a parameter called "current division factor", which is the ratio of common-mode current flowing on the signal trace to the total common-mode current. In the paper, we discussed common-mode generation on simple PCBs only, and proposed a common-mode excitation model.

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However, the real PCB is more complex, so we will extend the common-mode model to be applied to generalized structure. In this paper we will propose a procedure to generate the common-mode excitation model to calculate the radiation from a PCB. The validity of the model is confirmed by the measurement of a test PCB.

2. THEORY

2.1 Current Division Factor

For any kind of transmission line, the current on each line can be divided into modes. Figure 1 shows two mode currents, normal mode current (I_N) and common mode current (I_C). Signal and the return line current can be divided into two mode currents as following equations.

$$I_S = I_N + h\ I_C \qquad (1)$$

$$I_R = -I_N + (1-h)\ I_C \qquad (2)$$

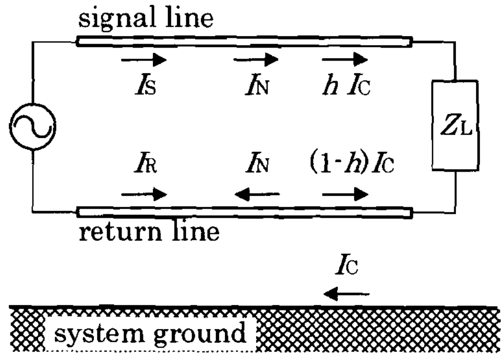


Fig. 1 Two mode currents

Normal mode currents on both lines are the same in magnitude and are opposite in direction. Common mode currents on both lines are the same in direction; however, they are not always the same in magnitude. We denote the ratio of common mode current on the signal line to the total common mode current as h. The parameter 'h' is called "the current division factor".

The parameter h is given in a cross-section of transmission line. Using current density, the current division factor can be calculated. For a microstrip structure with a ground plane of limited width, the current division factor is approximately calculated with the following equation.

$$h = W_S / (W_S + W_R), \qquad (3)$$

where W_S is the width of the signal pattern, and W_R is the width of the ground pattern, respectively. In this case, the 'h' does not depend on the thickness of the substrate.

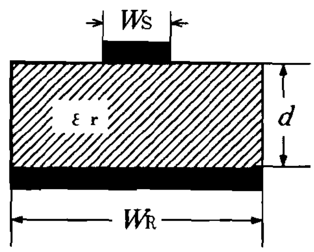


Fig. 2 A microstrip structure with a ground plane of limited width.

2.2 Common Mode Voltage

To calculate common mode radiation from a signal line and its return line, we should treat the two lines as an equivalent line named "a common mode line". And the common mode voltage (V_C) can be defined with the following equation so that transmitted common mode power (P_C) is equal to actual power.

$$P_C = h\ I_C\ V_S + (1-h)\ I_C\ V_R = I_C\ V_C \qquad (4)$$

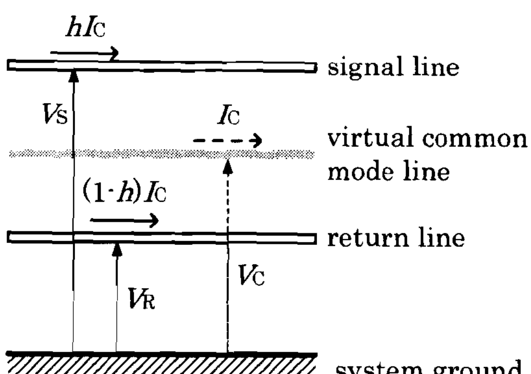


Fig. 3 Common mode voltage

where Vs and Vr are signal and return-line voltages, respectively. The middle part of this equation means transmitted power of common mode. The last part of this equation means the power defined with the virtual line. Normal mode voltage (V_N) is defined as

$$V_N = V_S - V_R. \qquad (5)$$

Substituting Eq. (5) into Eq. (4), we obtain the next relation.

$$V_C = V_R + h\ V_N. \qquad (6)$$

Equation (6) means that common mode voltage depends on current division factor and does not depend on common mode current. Therefore the common mode voltage is determined by ignoring common mode current.

2.3 Connection of Transmission Lines

At a discontinuous point of cross section along the transmission line, the discontinuity is regarded as a connection of different transmission lines. We focus our discussion on the connection point of transmission lines; transmission line A and B as shown in Fig. 4. In general, the reflecting wave is critical for a high-speed circuit. The characteristic impedance of line A must be nearly equal to that of line B. However, the current division factors may not be equal each other.

The current division factors for the transmission line A and B are denoted as h_a and h_b, respectively. The signal line voltage (V_S) is continuous, and the return line voltage (V_R) is also continuous. The common mode voltage is calculated with Eq. (6). If h_b is not equal to h_a, the common mode voltage is not continuous as shown in Fig.4 (b). V_{Ca} is the common mode voltage on the line A near the connecting point. V_{Cb} is that on the line B. ΔV_C is the difference of the common mode voltages.

$$\Delta V_C = V_{Cb} - V_{Ca} = (h_b - h_a)\, V_N. \qquad (7)$$

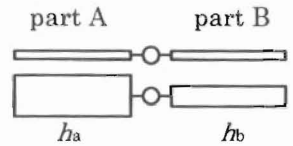
The electromotive force: ΔV_C excites the common- mode circuit to flow common-mode current.

2.4 Common-Mode Excitation Model

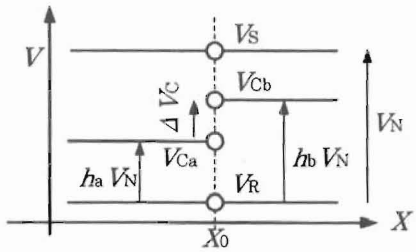
Next, we make a common-mode model for the whole printed circuit board. We discuss the common mode radiation from a printed circuit board, which is located far from other metal objects. In general, a printed circuit board has a lot of transmission lines, and some of these are not synchronous. For simplicity, we will make a model for a printed circuit board that has a signal line with many discontinuous points of cross section. It is easy to extend the model for plural lines that are in phase.

Now we propose a generalized model shown in Fig.5 for calculating common mode radiation. The model is extended for a lot of common-mode electromotive forces with care of those phase. In the previous section, we discussed the common mode voltage and the common mode electromotive force. This mechanism can be applied to whole printed circuit board.

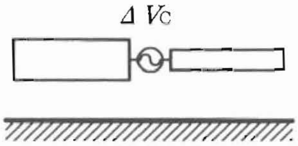
The following is the procedure to make a



(a) Connection of actual transmission lines

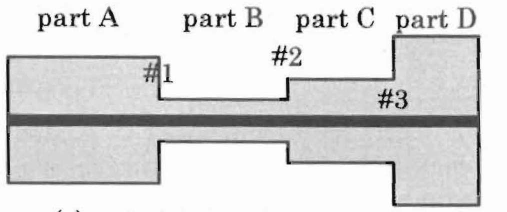


(b) Relation of differential and common mode voltages

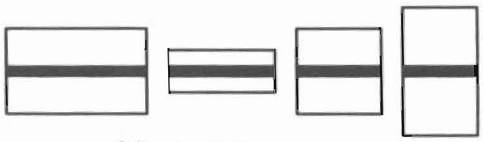


(c) Connected common mode lines

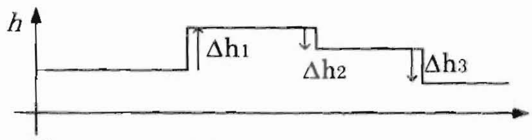
Fig. 4 Connection of transmission lines



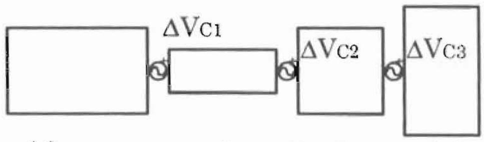
(a) printed ciucuit patterns



(b) divided traces



(c) longtudunal distribution of parameter 'h'



(d) common mode excitation model

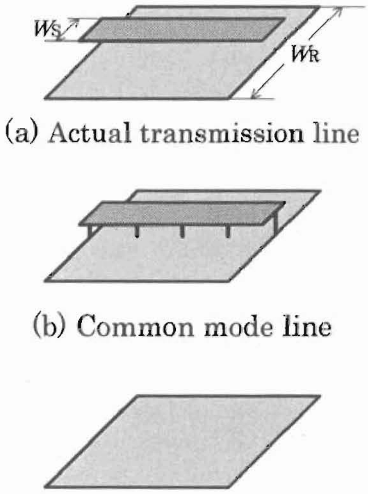
Fig. 5 Generalized common-mode excitation model common mode model.

1. Search the discontinuous points of cross section and mark these points (#m; m=1,2...) as shown in Fig. 5(a).
2. Evaluate the normal mode voltage ($V_N(f)$) at one frequency.
3. Evaluate the delay or phase difference (ϕ_m) at each point marked.
4. Divide the whole patterns into some parts, cutting at marked points as shown in Fig. 5(b). Figure 6(a) shows the structure of a part.
5. Calculate the current division factor for each part by using Eq. (3). The difference of the current division factors between adjacent parts is denoted by Δh_m as shown in Fig. 5(c).
6. Calculate the common mode motive force ($V_{Cm}(f)$) with the next equation at each point marked.

$$V_{Cm}(f) = V_N(f) \exp(-j\omega\, \phi_m)\, \Delta h_m \quad (8)$$

The magnitude of it is product of the normal mode voltage and the difference of the current division factors. The phase of it is the same as that of the normal mode voltage.

7. Connect signal and return patterns to be one signal trace for common-mode current as shown in Fig. 6(b).
8. Insert the common-mode motive force at each cut point (Fig. 5(d))



(a) Actual transmission line

(b) Common mode line

(c) Simplified common-mode line

Fig. 6 Common mode model for a uniform part

If W_R is much lager than W_S, then the signal trace can be eliminated from the common mode line (Fig. 6(c)).

For many signal lines that are in phase, this procedure can be applied.

2.5 Common Mode Radiation

When a printed circuit board is located far from other metal objects, there is no return path for common-mode return current. In this case, the common-mode excitation model does not act as a transmission line but work as an antenna. To calculate the common mode current or radiation from it, we must analyze the common mode model as a multi-point fed antenna.

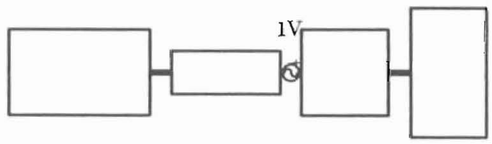


Fig. 7 Extracted common-mode excitation model

The total radiation from the common mode model is the superposition of the radiation from extracted common mode model with single point feeding (Fig. 7), which is made from common mode model Fig. 5(d) and let all V_{Cm}=0 except one point. The extracted common-mode model, which includes one feeding point, is a normal antenna. The radiation from the extracted common-mode model under the condition of unit voltage feeding can be measured or analyzed without common mode electromotive forces. In general, the radiation characteristics of extracted common-mode model, or the 'common-mode antenna', is determined not only by the local cross-section, but by whole structure of ground trace.

When the set of radiation fields from the extracted models driven by a unit source is given as E_m (m=1,2...), the radiation from a PCB is calculated as the following equation.

$$E = \sum_m E_m V_{Cm} \quad (9)$$

Thus the radiation from a PCB can be calculated by using common-mode electromotive forces, which is derived by normal mode voltages and the current division factors, and radiation characteristics of the antenna, which is derived from the whole ground pattern.

3. EXPERIMENT

3.1 Test PCB and Signal Source

In order to verify our theory described in the previous section, we apply the theory to a test PCB described below and compare the estimated radiation and measured one.

Figure 8 shows the test PCB. The test PCB is a double-layered PCB. The substrate is FR-4 (εr=4.3). The thickness of the substrate is 1.6mm. A signal line exists on the top layer. The ground pattern exists on the bottom layer. The signal and the ground pattern form a microstrip structure. The characteristic impedance of it is designed to be 50 ohms when the width of the ground pattern is infinity. A part of signal line, between point B and C, has narrow ground pattern. The feeding point A is connected to the signal source from backside through a SMA connector. The end point D is connected to matched load.

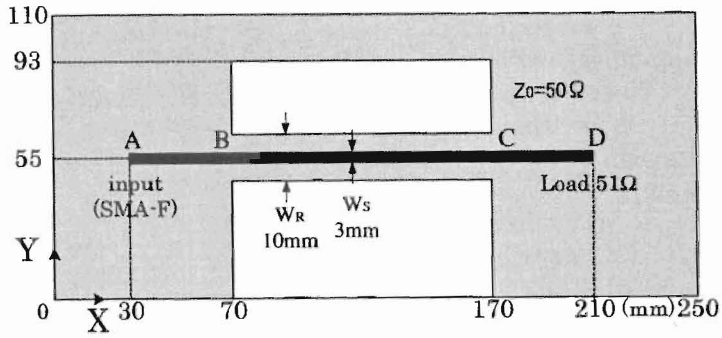


Fig. 8 Test PCB

In this experiment, we use a signal generator as a signal source. The test PCB and the signal generator are connected by a coaxial cable. To suppress the common mode current on the coaxial cable, ferrite cores (Kyoritsu KT-20) are attached to the cable so that the location of the ferrite cores is as close to the SMA connector as possible.

3.2 Common Mode Model of Test PCB

For the test PCB, discontinuous points of cross section are point B and C. The current division factor between B and C is about 0.23 from Eq. (3). The current division factors between A and B, and between C and D are 0.03. Since it is much smaller than that for middle part, so the current division factors for the left and right parts are regarded as 0 in this paper. Thus the difference of current division factor at point B (Δh_1) is 0.23 (-12.7dB), and that at point C is -0.23. Then the common mode model of the test PCB is obtained as shown in Fig. 9. The common mode motive forces are given by following equation.

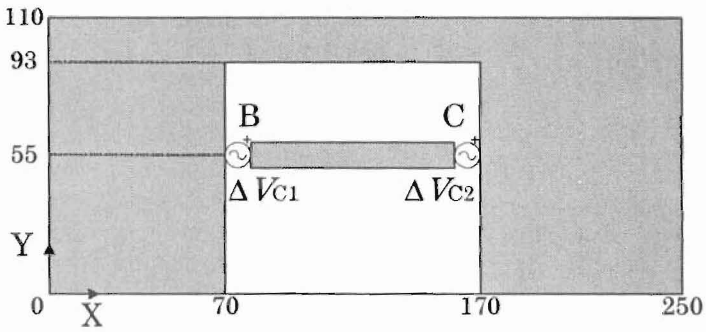


Fig. 9 Common mode model for the test PCB

$$|\Delta V_{C1}| = |\Delta V_{C2}| = |\Delta h_1|\ |V_N|. \quad (10)$$

The phase difference between ΔV_{C1} and ΔV_{C2} is the same as that between normal mode voltages at point B and C.

3.3 Equivalent Antenna

In order to estimate the radiation from the test PCB by applying the common mode model, we can use an equivalent antenna (Fig. 10) instead of a set of extracted common-mode model of Fig. 9. Figure 9 means that the common mode model is 2- point fed antenna.

The magnitude of ΔV_{C1} is equal to that of ΔV_{C2}; however, the phase of ΔV_{C2} is different from that of ΔV_{C1} due to opposite sign of the Δh and signal delay. Fortunately, we can feed two points from one source. A source power is divided equally and distributed to the two feeding points through semi-rigid cables. The feeder to the point C is connected in the opposite direction of that of point B.

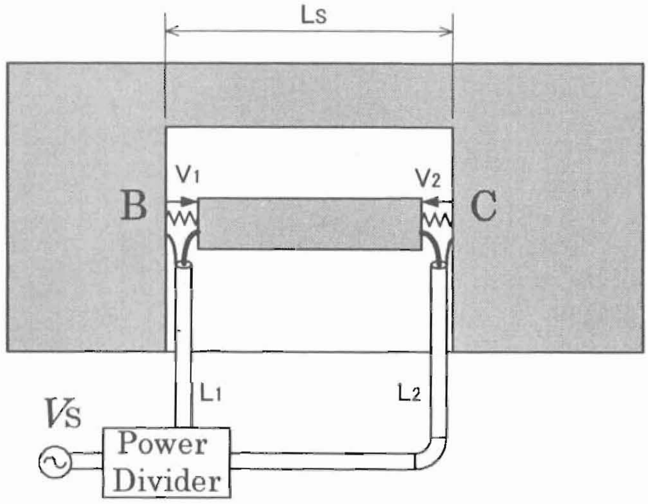


Fig. 10 Equivalent antenna

The phase difference due to the signal delay is adjusted by the difference of feeding line lengths (L_1, L_2 in Fig. 10). The feeding lines are coaxial cables for preventing radiation from the feeding lines. The cables are soldered to the ground pattern for preventing common mode current outside the PCB traces.

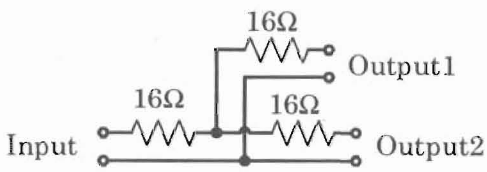


Fig. 11. Power divider

The power divider is shown in Fig. 11. The transmission loss of the divider is 6 dB.

3.4 Measurement of Radiation

The radiation from the test PCB and the antenna model are measured in a semi-anechoic chamber as shown in Fig. 12. The PCB is located above 0.8m from the metal floor. The top layer is faced up. The used antennas are a bi-conical antenna (Schwarzbeck BBA9106) below 300MHz and a log-periodic antenna (Schwarzbeck UHALP9107) above 300MHz. The antennas are set horizontally, because the common mode current flows horizontally, and located above 1m from the floor.

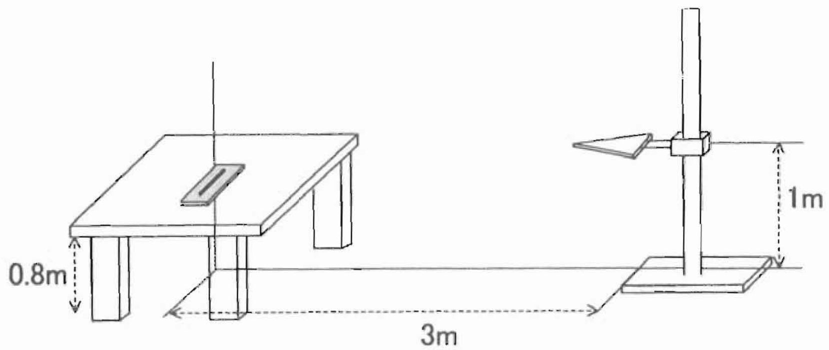


Fig. 12 Measurement setup

The input voltage of the test PCB is 90 dBμV. The magnitude of the common-mode motive force is given with Eq. (8).

$$|\Delta V_{C1}| = |V_N|\ |\Delta h_1| = 77.3[\text{dB}\mu\text{V}]. \qquad (11)$$

Next, we measured the radiation factor of equivalent antenna (E_A) under the condition that V_S

is unit voltage. Considering the loss of divider (L_{dv}), we estimate the radiation from the test PCB (E) as the following equation.

$$E = |\Delta V_{C1}|\ E_A / L_{dv} \qquad (12)$$

The measured radiation from the test PCB and the estimated radiation from measurement of the equivalent antenna are shown in Fig.11. The estimated radiation agrees well with measured one within 3 dB up to 900 MHz.

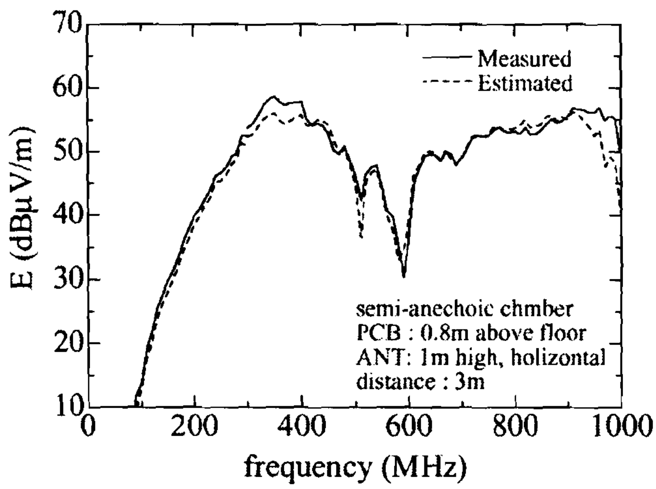


Figure 13. Estimated and measured radiation from test PCB

4. CONCLUTION

In this paper we extend the common-mode excitation model, which we previously proposed, to a PCB having generalized ground structure. The model consists of common-mode electromotive forces and antenna structure. The common-mode electromotive force is generated by the difference of current division factors and normal mode voltage at the discontinuity point of cross section. The antenna structure is constructed by the whole signal and ground traces. The total radiation can be estimated by superposing the fields excited by a set of common-mode electromotive forces located at discontinuous points of transmission lines.

To verify the proposed model, we estimate the common mode radiation from a test PCB having a transmission line with a narrow portion of a ground pattern. As the test PCB has discontinuity of cross section at 2 points, the common mode model has 2 common-mode electromotive forces. The radiation from the test PCB agrees well with the estimated radiation using the common-mode model and the equivalent antenna of the common mode model.

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