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Increase of Common-Mode Radiation due to Guard Trace Voltage and Determination of Effective Via-Location

Tohlu MATSUSHIMA[†a)], ***Student Member***, **Tetsushi WATANABE**[††], **Yoshitaka TOYOTA**[†], **Ryuji KOGA**[†], ***and*** **Osami WADA**[†††], ***Members***

SUMMARY A guard trace placed near a signal line reduces common-mode radiation from a printed circuit board. The reduction effect is evaluated by the imbalance difference model, which was proposed by the authors, when the guard trace has exactly the same potential as the return plane. However, depending on interval of ground connection of the guard trace, the radiation can increase when the guard trace resonates. In this paper, the authors show that the increase of radiation is caused by the common mode, and extend the imbalance difference model to explain a mechanism of increase of common-mode radiation. Additionally, the effective via location of the guard trace is proposed to reduce the number of vias. The guard trace voltage due to the resonance excites the common mode at the interface where the cross-sectional structure of the transmission line changes since the common-mode excitation is expressed by the product of the voltage and the difference of current division factors. To suppress the common-mode excitation, the guard trace should be grounded at the point where the cross-sectional structure changes. As a result, the common-mode radiation decreases even when the guard trace resonates.

key words: *common-mode radiation, imbalance difference model, printed circuit board, guard trace, ground via*

1. Introduction

Common-mode radiation is a major factor of EMI from a printed circuit board (PCB) [1]. High-speed signal traces running either above a narrow return plane or close to an edge of a ground plane cause common-mode radiation. To suppress EMI below a prescribed level, a scheme for controlling EMI should be deployed at the PCB design stage [2].

A guard trace running along a signal line is conventionally used to reduce common-mode radiation from a PCB [3]–[5]. Placing a guard trace near a signal line enlarges the path of return current and reduces the common-mode radiation. On the other hand, it was reported that the guard trace resonance caused increase of the radiation [6], [7]. However, the mechanism of common-mode increase has been left unclear.

We proposed the "Imbalance Difference Model" [8] to explain a mechanism of the common-mode excitation. In this model, we use a transmission line imbalance determined by the cross-sectional structure of the transmission line to explain the mechanism of common-mode generation. The common mode is excited by a mismatch in the imbalance at a point where the cross-sectional structure of a transmission line changes. Based on this concept, the common-mode generation can be modeled in two phases: evaluation of common-mode excitation source voltage and evaluation of the radiation from a common-mode antenna. The common-mode excitation source voltage is described by a product of difference of the imbalance and voltage between the signal line and the return plane.

In the previous study, we evaluated the common-mode radiation from a PCB with one signal line, which based on the imbalance difference model [8], [9]. To reduce common-mode radiation, the difference of the imbalance is decreased by enlarging the width of the return plane and/or placing a guard trace. We calculated reduction effect of the common-mode radiation using the guard trace [10], [11]. The guard trace running near the signal line is connected to the return plane through vias. We can reduce common-mode radiation when the interval of the vias is short enough so that the guard trace has the same potential as the return plane.

In this paper, We extend the imbalance difference model to explain the mechanism of common-mode increase. The voltage between the guard trace and the return plane occurs due to the resonance when the interval is long, and the voltage excites the common-mode radiation [12]. The authors propose an efficient placement of the vias connecting the guard trace and the return plane to reduce the common-mode radiation.

2. Guard Trace Voltage and Radiation Increase

In this paper, we will discuss a common-mode radiation from a PCB with a narrow return plane, which is depicted in Fig. 1 and Fig. 2. The test board consists of two layers: the top layer for the signal line and the guard trace, and the bottom layer for the return plane. A straight signal line is placed in the x direction and connected to a matched load. The characteristic impedance of the signal line is approximately 75 Ω and the effective relative permittivity $\varepsilon_{\mathrm{eff}}$ [13] is 3.12.

The guard trace on the test board is placed along the signal line and has several ground vias. P_S and P_L are terminal points of the guard trace. P_A is a point on the guard trace

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[†]The authors are with the Graduate School of Natural Science and Technology, Okayama University, Okayama-shi, 700-8530 Japan.
[††]The author is with Industrial Technology Center of Okayama Prefecture, Okayama-shi, 701-1296 Japan.
[†††]The author is with the Graduate School of Engineering, Kyoto University, Kyoto-shi, 615-8510 Japan.
a) E-mail: matsushima@dev.cne.okayama-u.ac.jp

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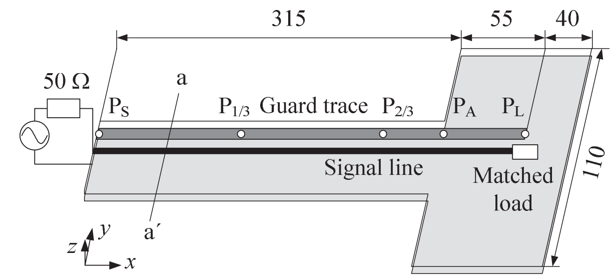
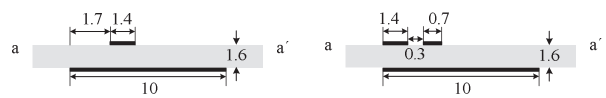


Fig. 1 Structure of a test board with a signal line and a guard trace.



(a) Test board with only signal line (reference board).

(b) Test board with signal line guard trace.

Fig. 2 Cross-sectional structures of test boards.

where width of the return plane changes. $\mathrm{P_{1/3}}$ and $\mathrm{P_{2/3}}$ are the points where the guard trace is divided equally among three. If the guard trace has exactly the same potential as the return plane, placing the guard trace near a signal line is effective method to reduce common-mode radiation [10], [11].

To keep the guard trace voltage 0 V, a lot of ground connections are needed to avoid the guard trace resonance [7]. The guard trace with connections to the return plane resonates at the frequencies where the interval of vias is integer multiple of a half wavelength. The resonance frequencies $f_{\frac{m\lambda}{2}}$ are obtained by the following equation;

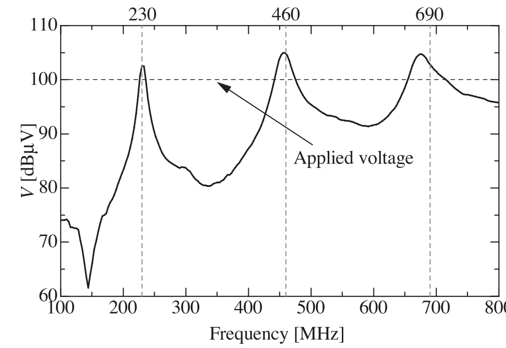
$$f_{\frac{m\lambda}{2}} = \frac{m}{2\ell}\frac{c_0}{\sqrt{\varepsilon_{\mathrm{eff}}}} \qquad (m = 1, 2, \cdots), \tag{1}$$

where c_0 and ℓ are velocity of light in vacuum and interval of vias, respectively.

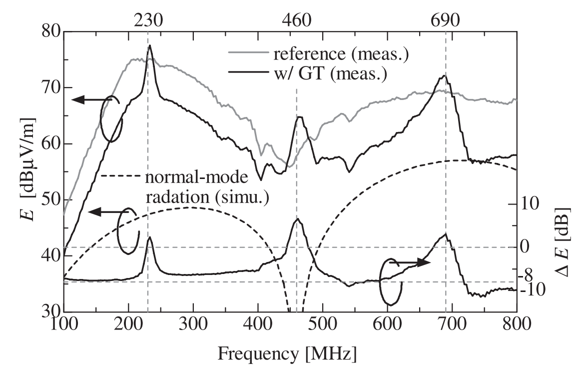
Figure 3(a) shows the guard trace voltage at $\mathrm{P_A}$† when a signal voltage of 100 dBμV is applied to the signal line.

Since the guard trace is grounded at $\mathrm{P_S}$ and $\mathrm{P_L}$, we should consider the guard trace as a resonator. The guard trace voltage can be higher than the applied voltage if the quality factor of the resonator is large. In this situation, the half-wavelength-resonance frequency between $\mathrm{P_S}$ and $\mathrm{P_L}$ is 230 MHz because the distance between $\mathrm{P_S}$ and $\mathrm{P_L}$ is 370 mm; the 230, 460 and 690 MHz are the first-, second- and third-resonance frequencies, respectively.

We measured the radiation†† from the two test boards: the reference board with only signal line and the board with the guard trace grounded at $\mathrm{P_S}$ and $\mathrm{P_L}$. Common-mode radiation from the test boards is essentially equivalent to that from a dipole antenna along x-direction. On the other hand, normal-mode††† radiation is essentially equivalent to that from a loop in the xz plane [14]. Figure 3(b) shows the E-field spectra in the z-direction where we observe the largest radiation. The horizontal polarization, E_x, includes both common-mode and normal-mode radiation. First, we compare the measured E-field strength with the normal-mode



(a) Guard trace voltage at $\mathrm{P_A}$.



(b) Radiation from test boards and di erence with refernce test board.

Fig. 3 Guard trace voltage and radiation from test boards when guard trace is grounded at $\mathrm{P_S}$ and $\mathrm{P_L}$. Resonance frequencies between $\mathrm{P_S}$ and $\mathrm{P_L}$ are 230, 460 and 690 MHz.

radiation from the signal current. As shown in Fig. 3(b), the normal-mode radiation level calculated with a combination of micro dipole antennas [15] is lower and the common-mode radiation is dominant in the frequency range below 700 MHz.

The difference between the radiations from boards with and without the guard trace is also shown in Fig. 3(b). The guard trace reduces the common-mode radiation in wide range except for some frequencies near the resonance of the guard trace.

To suppress the resonance and reduce the common-mode radiation, one possible way is to reduce the interval of vias narrower than the half wavelength at intended frequency. However, placing a large number of vias on a PCB causes restriction in placing other signal lines or electronic components.

In this paper, the authors propose an alternative way

†In this measurement, the voltage between the guard trace and the return plane was measured using an active probe. The ground pin of the probe is connected to a 5-mm-by-5-mm pad near the guard trace on the top layer, which is connected to the return plane.

††The details of measurement setup for the radiation are described in Sect. 3.2.2.

†††In this paper, the differential mode on a single-ended signaling system is called "normal mode" to distinguish it from the differential mode on a balanced transmission line.

to reduce the common-mode radiation even when the guard trace resonates. We will evaluate a common-mode excitation of the guard trace using the imbalance difference model in Sect. 3. In Sect. 4, we will propose an efficient selection of vias location.

3. Common-Mode Excitation

3.1 Current Division Factors and Common-Mode Potential

We consider transmission lines which contain two signal lines and a return plane, as shown in Fig. 4(a). A signal line 1 and 2 are assigned for a signal line and a guard trace in Fig. 1. These transmission lines consist of two parts. In part A, the transmission lines have a narrow return plane. On the other hand, the return plane is wide in part B. The microstrip structure on each part is thin enough and only the TEM mode propagates, so that the effects of higher-order modes are ignored.

We apply signal voltages, V_{N1} and V_{N2}, to the signal line 1 and 2. V_{Nn} $(n = 1, 2)$ is defined as a voltage difference between the signal line potential of line n, V_n, and the return plane potential, V_R.

To evaluate common-mode generation, we use a current division factor (CDF) [9], which represents the degree of imbalance of a transmission line. The CDF is the ratio of the common-mode current flowing on a signal line to the total common-mode current flowing on the transmission lines. For each signal line, the CDF is denoted as

$$h_n = \frac{I_{Cn}}{I_{C1} + I_{C2} + I_{CR}} \quad (n = 1, 2), \tag{2}$$

where I_{C1}, I_{C2} and I_{CR} are common-mode currents flowing on the signal line 1, 2, and the return plane, respectively. Since we assume only TEM mode, the CDFs are obtained by the cross-sectional structure using an 2-D electrostatic-field calculation [9]. Therefore the CDF is independent of frequency. The CDF of part A is higher than that of part B because width of the return plane in part A is narrower.

When we evaluate the CDF of the signal line 1, the signal line 2 is connected to the return plane, therefore the voltage V_{N2} is equal to 0 V as shown in Fig. 4(b). Similarly, for the signal line 2, the voltage V_{N1} is equal to 0 V as shown in Fig. 4(c). As a calculation of the CDF, the CDF of the signal line 2 is higher than that for the signal line 1 because the signal line 2 is placed near the edge of the return plane, as shown in Fig. 4.

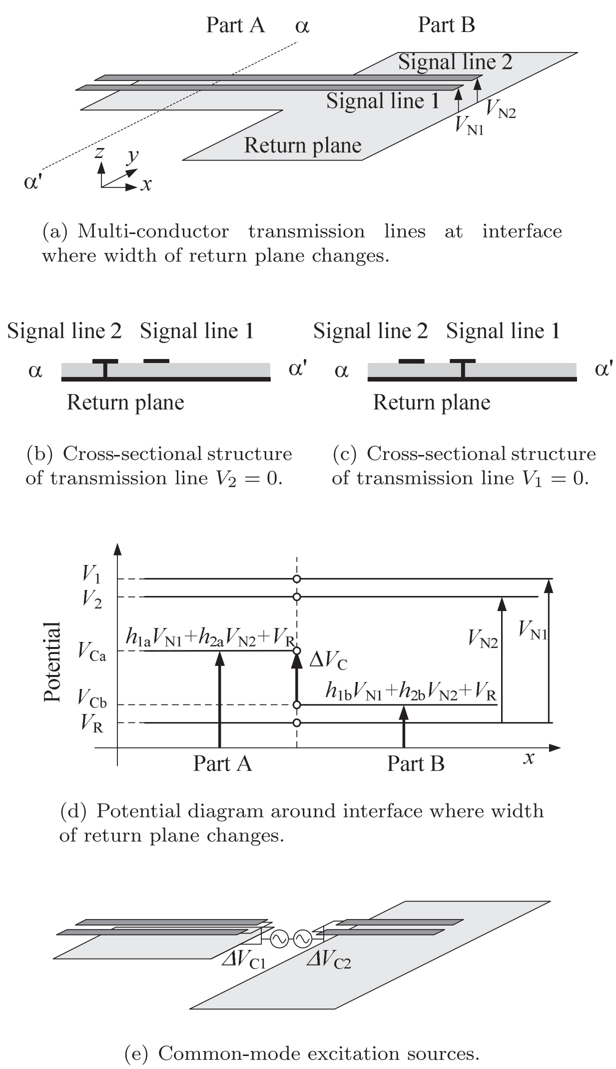
A virtual common-mode potential V_C is derived by using the CDFs as

$$\begin{aligned} V_C &= (1 - h_1 - h_2)V_R + h_1 V_1 + h_2 V_2, \\ &= V_R + h_1 V_{N1} + h_2 V_{N2}, \end{aligned} \tag{3}$$

where V_R is potential of the return plane. At the interface where the cross-sectional structure changes, as shown in Fig. 4(a), the CDFs have different values. We assume an abrupt change in the common-mode potential, as shown in Fig. 4(d). Here, h_{na} and h_{nb} $(n = 1, 2)$ are the CDFs for the signal line n in part A and part B of the transmission line, respectively. Likewise V_{Ca} and V_{Cb} are the common-mode potentials in part A and part B, respectively. According to Fig. 4(d), there is a common-mode potential difference,

$$\begin{aligned} \Delta V_C &= (h_{1b} - h_{1a})V_{N1} + (h_{2b} - h_{2a})V_{N2}, \\ &= \Delta h_1 V_{N1} + \Delta h_2 V_{N2}, \\ &= \Delta V_{C1} + \Delta V_{C2}, \end{aligned} \tag{4}$$

where Δh is the difference between the CDFs in the part A and part B. Thus, the common-mode potential difference ΔV_C appears between two parts, part A and part B, and excites common-mode current. As shown in Fig. 4(e) and Eq. (4), total common-mode excitation is explained by superposition of the common-mode excitation sources ΔV_{C1} and ΔV_{C2}. When a PCB is located far from other metal objects, the PCB acts as an antenna [9]. This antenna is called a "common-mode antenna."



(a) Multi-conductor transmission lines at interface where width of return plane changes.

(b) Cross-sectional structure of transmission line $V_2 = 0$.

(c) Cross-sectional structure of transmission line $V_1 = 0$.

(d) Potential diagram around interface where width of return plane changes.

(e) Common-mode excitation sources.

Fig. 4 Imbalance difference model of microstrip line with two signal lines and a return plane.

Now, for evaluation of the common-mode radiation, the common-mode antenna can be simplified by the following reasons. Most of the common-mode current usually flows on the return plane due to the low impedance of the plane. Moreover the effect of the dielectric is small for the common mode. Therefore we can ignore the signal lines and the dielectric in calculation of common-mode radiation. The common-mode radiation $\boldsymbol{E}(\boldsymbol{r}, f)$ from the common-mode antenna can be calculated by the following equation [9],

$$\boldsymbol{E}(\boldsymbol{r}, f) = \Delta V_{\mathrm{C}} \cdot \boldsymbol{F}(\boldsymbol{r}, f), \tag{5}$$

where $\boldsymbol{F}(\boldsymbol{r}, f)$ is an antenna radiation factor. This factor stays constant when the shape of the return plane is kept unchanged. In this situation, the common-mode radiation depends only on the common-mode excitation source ΔV_{C}.

3.2 Experimental Validation

3.2.1 Test Board Structure

Common-mode radiations from two types of test boards were measured. The test board with only the signal line was designed as reference for the radiation as shown in Fig. 2(a). We call it a "reference board." The other test board had a guard trace running near the signal line, as shown in Fig. 2(b), and the width of the signal line was narrower for matching of characteristic impedance. Placing a conductor, i.e. a guard trace near the signal line, decreased the characteristic impedance of the signal line because it increases the capacitance and decreases the inductance [10], [11]. For matching the load impedance, the width of the signal line was decreased and the inductance of the signal line was increased.

Now let us assign the signal line 1 and signal line 2 in Fig. 4, for the signal line and the guard trace, respectively. Additionally, the voltages V_{N1} and V_{N2} are assigned for the signal voltage V^{sig} and the guard trace voltage V^{GT}, respectively. The CDFs for the signal line and for the guard trace are denoted by h^{sig} and h^{GT} instead of h_1 and h_2, respectively.

Reduction effect on common-mode radiation by placing the guard trace can be evaluated by calculating the CDF for the signal line when the guard trace has exactly the same potential as the return plane [10], [11]. In this case, common-mode excitation source ΔV_{C} consists of only signal line part, as the following equation,

$$\Delta V_{\mathrm{C}}^{\mathrm{sig}} = \Delta h^{\mathrm{sig}} V^{\mathrm{sig}}. \tag{6}$$

The common-mode excitation source voltage is proportional to the difference of the CDFs for the signal line. The CDFs for the signal line and the guard trace are listed in Table 1. The guard trace placed on the test board decreases the difference between the CDFs from (0.157−0.014) = 0.143 with only a signal line to (0.067−0.010) = 0.057 with the signal line and the guard trace. Thus, the common-mode excitation source of the test board having the guard trace should decrease (0.057/0.143) = −8.0 dB from that of the reference board.

When the guard trace voltage V^{GT} is not equal to 0 V, another common-mode excitation source $\Delta V_{\mathrm{C}}^{\mathrm{GT}}$ is generated,

$$\Delta V_{\mathrm{C}}^{\mathrm{GT}} = \Delta h^{\mathrm{GT}} V^{\mathrm{GT}}. \tag{7}$$

This equation corresponds to Eq. (4) when the signal 1 voltage V_{N1} is equal to 0 V. Hence, the guard trace's CDF,

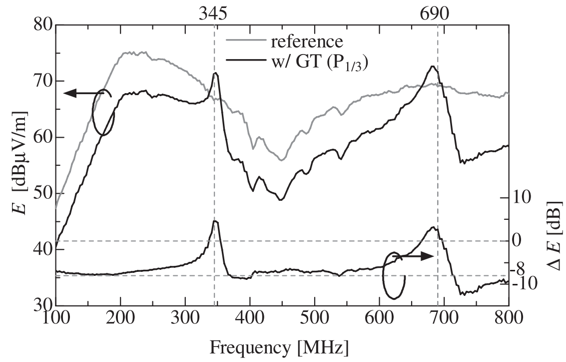
Table 1 Prediction of reduction of common-mode radiation using CDFs.

Test boards	$h_{\mathrm{SA}}^{\mathrm{sig}}$	$h_{\mathrm{AL}}^{\mathrm{sig}}$	$\Delta h^{\mathrm{sig}} = h_{\mathrm{SA}}^{\mathrm{sig}} - h_{\mathrm{AL}}^{\mathrm{sig}}$	ΔE
Reference	0.014	0.157	0.143	0.057/0.143 = −8.0 [dB]
w/ GT	0.010	0.067	0.057	

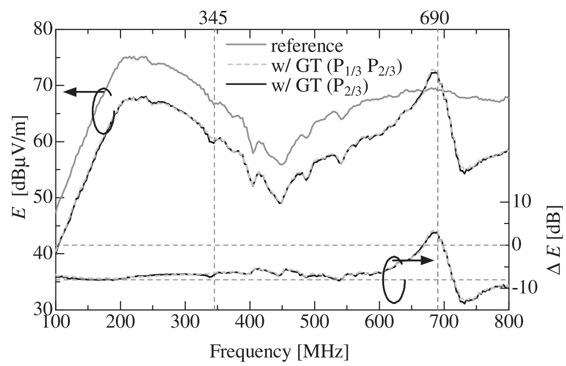
(Note) h_{SA} and h_{AL} are the CDFs where the transmission line with narrow return plane and wide return plane, respectively.

Table 2 Resonance frequencies of grounded guard traces depending on locations of vias (frequency range: 100–800 [MHz]).

Patterns	Location	Intervals of vias [mm]	$f_{\lambda/2}$ [MHz]	f_{λ} [MHz]	$f_{3\lambda/2}$ [MHz]
I	370; P_{S} – P_{L}	370	230	460	690
II	123; P_{S} – $P_{1/3}$ – P_{L}	123	690	(1380)	(2070)
	247; P_{S} – $P_{1/3}$ – P_{L}	247	345	690	(1035)
III	123; P_{S} – $P_{2/3}$ – P_{L}	123	690	(1380)	(2070)
	247; P_{S} – $P_{2/3}$ – P_{L}	247	345	690	(1035)
IV	123; P_{S} – $P_{1/3}$ – $P_{2/3}$ – P_{L}	123	690	(1380)	(2070)
V	55; P_{S} – P_{A} – P_{L}	55	(1550)	(3090)	(4650)
	315; P_{S} – P_{A} – P_{L}	315	270	540	(810)



(a) Via pattern II.



(b) Via pattern III and IV.

Fig. 5 Radiation from test boards and difference between radiations from reference board and test board with guard trace.

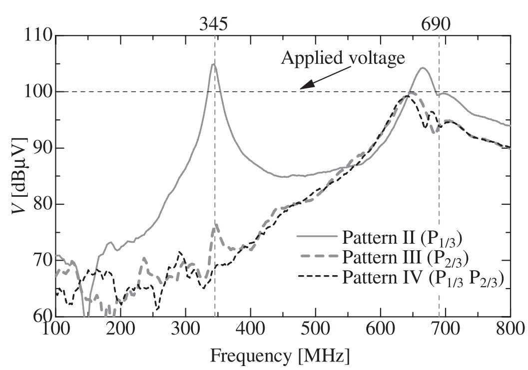


Fig. 6 Guard trace voltages at P_A when guard trace is connected to return plane.

h^{GT}, is evaluated when V^{sig} is equal to 0 V. The excitation source ΔV_C^{GT} causes the degradiation of reduction effect of the guard trace and increase of common-mode radiation.

3.2.2 Experiments

Common-mode radiation from the test boards was measured at a distance of 3 m in a semi-anechoic chamber. Each of the test boards was fixed perpendicular to the floor with the y-axis vertical to the floor on a rectangular block of polystyrene foam of 1 m in height. The receiving antenna was located at a point of 3 m from the test board in the z direction in Fig. 1, and the antenna height was fixed at 1 m above the chamber floor during this measurement. Measurement was carried out for the horizontal polarization with a bi-log antenna (Schaffner, CBL6141A) in the frequency range, 100–800 MHz.

The signal was applied by a tracking generator which was placed outside of the semi-anechoic chamber through a coaxial cable. The coaxial cable connected the test board was held perpendicular to the floor. Additionally this cable was covered with a 0.3-m-long ferrite clamp (Luthi, FTC40X15E) near the test board for reduction of radiation from the cable.

3.2.3 Difference of Radiation Depending on Via Locations

Table 2 shows combinations of grounding positions along a guard trace and the resonance frequencies for each interval of vias. P_A is on the interface where the cross-sectional structure of the transmission line changes. When the guard trace is not grounded at P_A, the guard trace voltage excites the common mode. Additionally, the guard trace on the test board is always grounded at the points P_S and P_L in this experiment in order to simulate most of guard-traces of actual PCBs.

Figure 5 shows the measurement results of radiation from the test boards. The reduction of radiation compared with the reference board is approximately 8 dB except for specific frequencies. These results agree well with prediction using the CDFs which are listed in Table 1.

As previously mentioned in Sect. 2, Fig. 3(b) shows that no reduction of radiation is observed at the frequencies 230, 460 and 690 MHz and it rather increase when the guard trace resonated. The resonance frequencies of the guard trace agree with these frequencies which are listed in Table 2 as Pattern I. This suggests that a loop formed by a guard trace with two vias, P_S and P_L, and the return plane can resonate when the separation between two vias along the trace is equal to $m\lambda/2$.

Via pattern II has two intervals of vias; 123 mm and 247 mm where half wavelength resonance frequencies are 345 MHz and 690 MHz, respectively, as shown in Table 2. The radiation from the test board with the guard trace increases at these frequencies as shown in Fig. 5(a).

We compare the common-mode excitation sources ΔV_C^{sig} and ΔV_C^{GT}. A common-mode excitation source is generally a product of Δh and V. In fact, the guard trace voltage is equal to or larger than the signal line voltage at the particular frequencies as shown in Fig. 6. Hence we compare Δh^{sig} and Δh^{GT}. As denoted in the previous section, the difference of CDF for the signal line of the test board with guard trace, Δh^{sig}, is 0.057. On the other hand, that for the guard trace is calculated as $\Delta h^{GT} = (0.165-0.010) = 0.155$. In the test board, Δh^{GT} is $(0.155/0.057) = 8.7$ dB larger than Δh^{sig} as shown in Table 3. Hence the common-mode excitation due to the guard trace voltage is comparable to or larger than that due to the signal line voltage in the reference board. Consequently, the radiation from the test board with the guard trace is larger than that from the reference board.

Additionally, the common-mode radiation from the test board having the guard trace with the via pattern III, as shown in Fig. 5(b), increased at 690 MHz where the guard trace resonates between $P_{2/3}$ and P_L. On the other hand, the guard trace resonates between P_S and $P_{2/3}$ at 345 MHz. The common-mode radiation, however, reduces 8 dB from the reference board at 345 MHz, as shown in Fig. 5(b) because the resonance between P_S and $P_{2/3}$ did not generate the voltage between the guard trace and the return plane at P_A, as shown in Fig. 6. These results suggest that the increase of radiation is caused by the voltage V^{GT} at P_A.

4. Elimination of Common-Mode Excitation

To suppress the resonance on the guard trace and eliminate the common-mode excitation of the guard trace, the interval of vias should be short enough. As requested frequency is higher, a lot of vias are needed because the interval of vias is inversely proportional to the half-wavelength.

We propose another design rule of ground connection of the guard trace. Via pattern V has only a via at P_A on the guard trace in addition to P_S and P_L. The resonance frequencies between P_S and P_A are 270 MHz, 540 MHz and higher frequencies. Figure 7, however, shows no degradation of radiation reduction at these frequencies.

According to Eq. (4), the common-mode excitation source is described by the product of the guard trace voltage V^{GT} at the P_A and the difference of CDFs as shown in Fig. 6. To suppress the common-mode excitation source caused by the voltage on the guard trace, the guard trace should be grounded at the point where the cross-sectional structure of the transmission line changes, as shown in Fig. 8(b). Although the guard trace resonates, the common-mode excitation source is not generated because the guard trace voltage at the point P_A is approximately equal to 0 V. The common mode is excited by only the signal line voltage and the excitation is decreased by the guard trace. Therefore the radiation can be reduced. Consequently, we can remove unnecessary vias that have no effect on radiation reduction. This is an important design rule for low cost PCB fabrication.

Table 3 Comparison between Δh^{sig} and Δh^{GT}.

	h_{SA}	h_{AL}	Δh h_{SA} - h_{AL}	ΔE
Signal line	0.067	0.010	0.057	0.155/0.057 =
Guard trace	0.165	0.010	0.155	8.7 [dB]

5. Conclusion

In this paper, we discuss the common mode excited by a guard trace voltages. A guard trace to suppress the common-mode excitation on PCB may excite, contrary to the intention, voltage distribution between the trace and PCB. In particular, the guard trace voltage becomes large when the guard trace resonates. In particular, a guard trace for a large PCB is apt to cause resonance and the voltage along the trace causes another common-mode excitation. Hence, total common mode is excited by the signal line voltage and

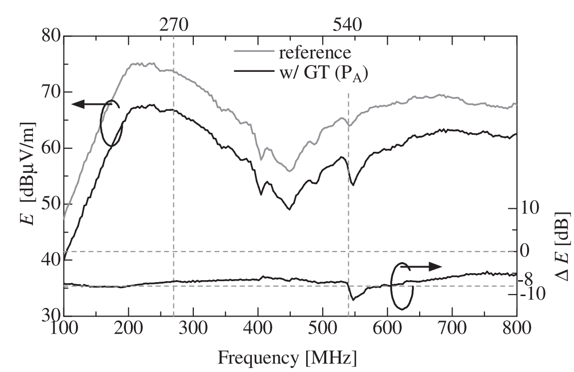
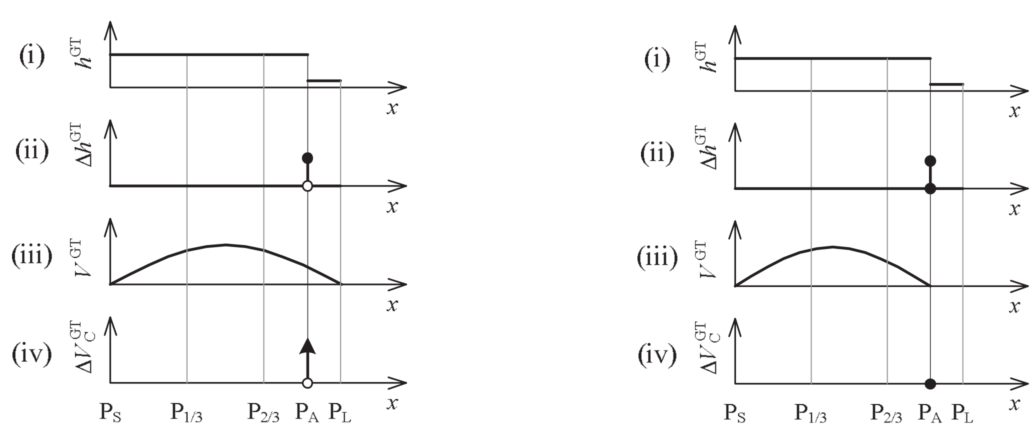


Fig. 7 Radiations and difference of radiations from reference board and test board having guard trace with via at P_A (Via pattern V).



(a) Generation of common-mode excitation source due to voltage of guard trace (Via Pattern I).

(b) Elimination of common-mode excitation source by grounding guard trace at P_A (Via Pattern V).

Fig. 8 Relationship between voltage and difference of CDFs and generation of common-mode excitation source ΔV_C^{GT}.

the guard trace voltage, and the common-mode radiation becomes large.

We also proposed here an effective via location on the guard trace. The guard trace should be connected to the return plane only at the location where the cross-sectional structure of the transmission line changes. In this situation, the common-mode excitation of the guard trace voltage can be eliminated and we can reduce common-mode radiation even when the guard trace resonates. No excess vias are necessary nor effective. We can reduce the number of vias that have no effect on radiation reduction.

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Tohlu Matsushima was born in Hyogo, Japan, on May 5, 1982. He received his M.E., degrees in Communication Network Engineering from Okayama University, Okayama Japan, in 2006. He is currently doctoral student of Okayama University. His research interest is electromagnetic interference problem. He is a member of the Japan Institute of Electronics Packaging.

Tetsushi Watanabe was born in Okayama, Japan, on May 11, 1967. He received his B.E., M.E. and Ph.D. degrees in Electronics Engineering from Okayama University, Japan, in 1990, 1992 and 2004, respectively. Since 1992, he has been with the Industrial Technology Center of Okayama Prefecture. He has engaged in a study of immunity on LAN cables, measurement systems of EMC, and EMI reduction techniques. He is a member of the Japan Institute of Electronics Packaging.

Yoshitaka Toyota was born in Okayama, Japan, on September 17, 1968. He received his Ph.D. degree in electronic engineering from Kyoto University, Japan, in 1996. From 1996 to 1998, he was with Yokogawa Electric Co., Ltd. and in 2005 he worked at Georgia Tech as an overseas research scholar of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. He is currently an Associate professor at Okayama University. His research interest includes EMC design in high-speed digital systems. He is a member of IEEE, Japan Institute of Electronics Packaging, and the Japan Society of Applied Physics.

Ryuji Koga was born in Tokyo on 1945. He got the Doctorate from Kyoto University, and in 1976 he was with Okayama University, starting studies on electronics. On the way of developing a laser-sensing system, he was suffered from EMI from digital system attached it. He has then been engaged in the EMC problem. He is now Professor of Okayama University, and has experienced the chairperson of the Technical Committee of EMC, The Institute of Electronics, Information and Communication Engineers, JAPAN. Now he is the chair of IEEE EMCS Japan chapter. He will also chair the coming symposium EMC'09/Kyoto.

Osami Wada was born in 1957. He received the B.E., M.E. and Dr.E. degrees in electronics from Kyoto University, Japan, in 1981, 1983 and 1987 respectively. Between 1988 and 2005 he was working at the Faculty of Engineering of Okayama University, Japan. Since 2005 he is Full Professor at the Department of Electrical Engineering at the Graduate School of Engineering of Kyoto University, Kyoto Daigaku Katsura, Nishikyoku, 615-8510 Japan. Prof. Wada is a member of IEE of Japan, the Japan Institute of Electronics Packaging, the Japan Society of Applied Physics, and the Optical Society of Japan.