Three-dimensional Noise Current Distribution on Power and Ground Planes in Printed Circuit Boards

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Abstract: Radiation noise currents on power and ground planes in multilayer printed circuit boards are shown three-dimensionally, combining the moment method simulation with far electric and near magnetic field measurements. The power and ground layers are modeled into four metal planes, considering the skin effect. The analysis shows that the main noise current flows only on the two facing planes (the inner planes) of the layers in the differential-mode. The current distributions on the inner planes are shown for various resonance modes. Methods of reducing the noise radiation are also discussed.

INTRODUCTION

Printed circuit boards (PCBs) are essential sources of the electromagnetic noise radiation from electronic equipment. The main noise source in PCBs has been considered to be currents on signal traces. In the case of the microstrip structure with a trace and a perfect metal plane, noise sources are a signal current on the trace and a image current induced on the metal plane [1]. But in actual boards, extra noises such as delta-I noise are generated because real metal planes are imperfect. In particular, delta-I noise on power and ground planes is very important as the actual noise source in recent multilayer boards [2], [3]. The power and ground planes have been identified as a kind of resonators by the S-parameter and near magnetic field measurement [4], and the transfer impedance analysis [5]. However, these works did not analyze the noise current directly. In other report, the noise currents on the power and ground planes were simulated directly at 10 GHz, but the calculated frequency was extremely high [6]. Thus, the noise currents on power and ground planes have not been analyzed clearly.

In this report, the radiation noise current distributions in the power and ground layers are described three-dimensionally, considering the difference between the front and back planes of metal layers by far electric and near magnetic field measurements and the moment method simulation. Noise reduction methods against the current distributions are also discussed.

METHODS

Test Board Configuration

The test board for analysis consists of four layers, which are trace, power, ground and device layers, as shown in Figure 1. Driver and receiver ICs are mounted on the board. TTL and CMOS devices were used for the ICs. A clock generator board with a power supply battery, which is not shown in Figure 1, was attached to the board. The ICs and the battery were shielded perfectly by metal cases on the reverse side to signal traces. The trace lengths were varied in the range from 100 to 400 mm at an interval of 100 mm. The board size was 420 mm X 420 mm. Power and ground layers of 70 μm thick were spaced at a distance of 0.8 mm.

Figure 1. Cross sectional view of the test board used for the measurements. The noise is radiated only from the traces, the power and ground layers.

Radiation Noise Measurement

Radiation noise was measured at several fixed positions to discuss the effect of relative position between the board and a detection antenna. The board was placed on a 0.8 m height table at a distance of 3 m from the 1.1 m height antenna. The board was placed on the table vertically and horizontally.

Near Field Noise Measurement

Magnetic near field around the board was measured by an antenna array system (EMSCAN of Northern Telecom). The detected signal by the array system was input to a spectrum analyzer after the amplification of 45 dB for detecting weak field by currents on the power and ground planes. Using the directivity of the antenna arrays, we are able to know the direction of the current which produces the magnetic field. The relative position between the antenna array and the board under test was aligned to the proper position for detecting the current direction.

Simulation

Noise currents on the power and ground planes were simulated by a moment-method simulation tool
Three models shown in Figure 2 were extracted from the actual board structure to simulate the power and ground layer radiation. In all models, metal planes were modeled as the perfect conducting planes with zero thickness. At the driver IC position, a sine wave signal of 1 Vp-p was applied to the power and ground layers as the noise signal.

In Model A, the relative permittivity in space was replaced by the relative permittivity of the board material $\varepsilon_r$. This model is a good approximation only for the noise current which flows between the power and ground layers except for the board edge, because the current feels $\varepsilon_r$ as the net relative permittivity. As a preferable model for the edge current, capacitors corresponding to the relative permittivity were inserted between the power and ground layers in Model B. This model is able to represent the difference of the relative permittivity between the inside and the outside of the layers.

However, the thickness of metal layers is not taken account in these models. The thickness of metal layers in the test board is rather thicker than the skin depth of the metal material, which is about 5 $\mu$ m at 200 MHz. Therefore, the metal layer is completely divided into two planes due to the skin effect in the frequency range of our interest. In the last model, Model C, a metal layer was modeled as two zero-thickness metal planes spaced at a distance of the layer thickness to consider the metal layer thickness. Finally Model C has four metal planes consisting of two facing planes (the inner planes) and two non-facing planes (the outer planes). The inner and outer planes in a layer were connected electrically at the noise source position and the board edges.

**RESULTS**

Radiation Noise Measurement

The radiation spectra from the test board were measured in various positions and from various directions. The strongest field was detected when the board was placed vertically in front of the horizontal antenna. Following results were obtained in this arrangement.

Figure 3 shows the radiation spectra from the test board. Each spectrum has a radiation peak around 170 MHz. The peak frequency and the peak intensity do not change when the trace length varies from 100 mm to 400 mm. The Figure 3 is the result for LS ICs. In the case of other TTL or CMOS devices, the spectrum shapes around the main peak did not change but the intensity varied. Also in the case of the board without signal trace, the spectrum shape around the peak was almost the same as the spectra from the board with traces, as shown in Figure 4. This result indicates that the radiation peak at 170 MHz comes from the power and ground layers because other noise sources are removed or perfectly shielded.
Near Field Noise Measurement

To determine the current distribution on the power and ground planes experimentally, we measured the near magnetic field distribution on the board without signal trace at the radiation peak frequency of 170 MHz.

Figure 5 shows a typical data. The strong field was detected outside and near the board edge. The maximum field was detected at the center of the board side. When the board edge was placed at 45 degrees to the arrayed antennas, the maximum and minimum fields were detected by even row antennas and odd row antennas, respectively, as shown in Figure 5. Considering the directivity of even and odd row antennas, it was found that the noise current creating the near field flowed along the board edge.

The whole view of the near field was obtained as shown in Figure 6. The strongest fields except for IC position distributed along the outside of the upper and lower edges. The second strongest fields were detected along the outside of the left and right edges. These fields were stronger than the field detected under the board. The result indicates the main noise current flows not on the surface of the board but in the inside of the board.

Moment Method Simulation

Next we discuss the results of the moment method simulation to elucidate the current distribution on the power and ground planes. Figure 7 is the simulated spectrum of Model A. The peak frequency and the spectrum shape agree well with the measured data shown in Figure 4, although the intensity is larger than the measured value because 1 V p-p sine wave was used as the noise source. Almost the same spectra was obtained using other two models.

Figure 8 is the near magnetic field distribution simulated by Model B. The figure shows the intensity distribution of the magnetic field ($H_z$) on the x-y plane 1 mm beneath the board. The magnetic field $H_z$ is made by the x-direction or y-direction currents. Thus, we may compare Figure 8 with Figure 6 directly. Figure 8 shows good agreement with Figure 6 regarding the field distribution around upper and lower edges of the board. While there is a little difference between the figures around right and left edges of the board, this can be explained due to the imperfect symmetry of the experimental board. Almost the same distribution were obtained using Model C. But Mode A showed a little different field distribution, because the modeling of the outer space permittivity was not correct.
Fig. 8. Simulated near magnetic field map by Model B at 170 MHz.

Figure 9 shows the current distributions of the ground layer simulated by Model C. The inner plane current (Figure 9 (a)) is quite different from the outer plane current (Figure 9 (b)). On the inner plane, the standing wave of the half-wavelength mode appears in the x-direction. The standing wave is not localized near the board edge but it spreads over the inner plane. On the other hand, the noise current on the outer plane is small and the standing wave is not generated. The power layer currents flow at the same intensity as and to the opposite direction to the ground layer currents. The current distributions of Model A and Model B were almost the same as the inner plane current of Model C.

The computation time remarkably increased from Model A, Model B to Model C because of increasing the number of simulation elements. The time was 4-10 times longer in Model B and 20-100 times longer in Model C than that in Model A. For the purpose of rough estimation, Model A is effective because of time efficiency. Model B or Model C is preferable for precise discussion on the near field distribution or the effect of metal thickness.

Although the above analysis treated the main peak near 170 MHz, the simulation can be extended to higher frequency and to a board with arbitrary shape. The resonance frequency of a parallel plate waveguiding system are given by

\[ f_r = \frac{c}{2\sqrt{\varepsilon_r}} \sqrt{\frac{m^2}{a} + \frac{n^2}{b}} \]  

(1)

where \( a \) and \( b \) are the length of the sides of the plate, \( c \) is the light velocity in free space, \( m \) and \( n \) are the mode numbers [4],[5]. The simulated radiation peak frequency for rectangle boards showed good agreement with the calculated one using equation (1). The current distributions at each frequency are shown in Figure 10 for arbitrary resonance modes.

Figure 9. Current distribution on the inner (a) and the outer (b) planes of the ground layer (Model C). The same intensity and the opposite direction currents flow on planes of the power layer.

Figure 10. Current distributions for general resonance modes. Arrows show the current intensity and direction.
DISCUSSION

Current Distribution

According to the above-mentioned analysis, the noise currents in the power and ground layers are illustrated three-dimensionally, as shown in Figure 11. The main noise current flows only on the inner planes. The inner currents have the standing wave shape. The inner currents are not localized near the board edges but spread over the inner planes. The inner currents in the power and ground layers flow in the differential-mode.

This noise distribution is considered to be generated by the following process. When the IC is switched, the current flows from the power layer to the ground layer as the through-current, or from the power or ground layer alternately to the load. The currents in the power and ground layers have opposite phase and flow to the opposite direction each other. The opposite direction currents become stable in terms of energy as they come close to each other. Therefore, the noise currents are concentrated on the inner planes to reduce the total energy. The inner currents interfere due to the multiple reflection at the board edges. Finally the standing waves are generated on the inner planes at specific resonant frequencies, as shown in Figure 11.

![Figure 11. Three-dimensionally illustrated noise current distribution in the power and ground layers.](image)

Noise Reduction Method

Based on the noise current distributions and the current generation process, we examined several noise reduction methods. Two of reduction methods are presented below.

One is the method of decreasing the power to ground layer gap. Although this method has been known empirically in the multilayer board, the reduction condition and mechanism have not been known [5]. We have studied the gap distance dependence of the radiation intensity using the board without signal trace. Figure 12 shows the gap distance dependence of the maximum radiation intensity around 170 MHz derived by simulation and measurement. The graph indicates the slopes of the curves are about 20 dB/decade. This means that the radiation intensity is proportional to the gap distance. This gap dependence can be explained by the increase of the cancellation between the inner plane currents.

![Figure 12. The power to ground layer gap dependence of the normalized far electric field.](image)

The other is a decoupling technique for the power and ground planes. We have studied the method to reduce the power and ground plane resonance. Capacitors near board edges decreased the resonance when they were arranged with an appropriate spacing. However, they activated other radiation noise. It was found that capacitors near ICs were effective to reduce the extra noise. When appropriate capacitance for the edge capacitors and for the near-IC capacitors were selected, the radiation noise from the power and ground layers was reduced drastically without exciting the extra noise. Figure 13 shows the noise intensity dependence on the edge capacitance $C_e$ and the near-IC capacitance $C_o$. The chart shows there is the most suitable area of $C_e$ and $C_o$ in a high capacitance range for the noise reduction.

![Figure 13. Decoupling capacitance dependence of the radiation from the power and ground layers. $C_e$ and $C_o$ denote the capacitance placed near board edges and near active devices, respectively.](image)
CONCLUSION

Radiation noise current distributions in the power and ground layers in multilayer PCB were analyzed by the far electric and near magnetic field measurements and the moment method simulation. The analysis, considering the difference between the front and back surfaces of the metal layers, showed the noise current distributions three-dimensionally.

The radiation from the power and ground layers was extracted as a dominant radiation source in the far electric field spectrum. The near magnetic field measurement showed that the main field distributed on the outside along the board edge with a standing wave shape. The result suggests the main noise current flows not on the board surface but in the inside of the board.

The moment method simulation was carried out using three models. In the last model, a metal layer was modeled as two metal planes spaced at the distance of the layer thickness to consider the metal layer thickness. The model shows that the main noise current flows only on the inner planes of the layers in the differential-mode. Noise current distributions on the inner planes were shown for every resonance mode.

Two noise reduction methods were discussed based on the noise current distributions. The noise reduction by decreasing the power to ground layer gap was confirmed with the gap distance dependence and the reduction mechanism. A decoupling technique was proposed to reduce the power and ground layer radiation drastically.

REFERENCES


