Via and Reference Discontinuity Impact on High-Speed Signal Integrity

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Abstract— An efficient and consistent model for the signal trace with reference discontinuities has been devised. It has been verified that the signal trace model can be used to compute the noise coupling between signal traces and reference planes.

Keywords— *reference discontinuity, noise coupling, via transition*

I. INTRODUCTION

The increasing speed of digital circuit and the increasing density of printed circuit board (PCB) layouts often results in more challenging signal integrity problems. The increasing speed of signal requires a more tight noise margin and strict signal integrity. At the same time, the increasing density of layout of digital circuit increases the difficulty in routing of signal traces. In today's high-speed multi-layer designs, it is very common that signal traces change reference planes several times. The discontinuities of signal return current at the via transitions and terminations of signal traces are very prevailing, as shown in Figure 1. The signal reference discontinuities affect the signal quality and the timing of the signals flowing through the traces significantly, and also induce noises on reference planes and on other nearby signal traces. Therefore, the reference planes and signal traces are getting more coupled each other. This is becoming a bottleneck in high speed digital systems.

Figure 1. Noise coupling between signal traces and power/ground planes in current multi-layer systems

Previously, several analytical approaches such as the method of moments (MoM) and the finite difference time domain (FDTD) have been utilized to investigate signal via coupling to power/ground planes [1], [2]. The underlying physics has been analyzed and solved within the framework of radial transmission lines [3], [4]. Also, several circuit models have been proposed to describe the coupling between power systems and signal traces [5], [6]. Power systems in the circuit

models have been represented as the cavity resonator model or a simple SPICE model. However, the previous analytical approaches are too much time-consuming and too complex to be adapted in most practical applications. Moreover, in any approach of those analytical methods and circuit models, it is not known where and when the dominant coupling will occur, and the whole structure of both the reference planes and the signal trace has to be considered simultaneously to find how much the reference planes and signal traces are coupled each other. If the factors and the mechanism associated with the coupling phenomenon are revealed, the estimation of coupling will be much easier and the estimation time will be much shorter.

The coupling of the simultaneous switching noise (SSN) voltage on power/ground planes to signal traces has been rigorously investigated and clarified, based on analytical equations in our previous work [7]. It has been noticed that the proposed model allows that power/ground planes and signal traces can be analyzed separately in order to estimate the coupling. Now, in this paper, it has also been found that the signal current flowing through via transition induces noise voltages on power/ground planes, just as the switching current does. And then the noise voltage on power/ground planes induces noise voltages sequentially on nearby other signal traces. Using a simple and consistent model of a signal trace with reference discontinuities, the impact of reference discontinuities on the coupling to the power/ground planes and nearby other signals has been investigated.

II. NOISE COUPLING THROUGH REFERENCE DISCONTINUITIES

A. Noise Coupling from Signal Traces to Power/Ground Planes

To estimate the effect of reference discontinuity in signal traces, an efficient and consistent model for reference discontinuity is required. Figure 2 (a), (b) show the discontinuities of return current paths at the termination of a signal trace referenced to power plane, and at the via layer transition. When a return current path is broken by a reference change, the return current path is completed by displacement current. The displacement current suffers from the high impedance between plane pair, and the effect of reference path

discontinuity can be considered as a kind of impedance mismatching. In Figure 2, the broken return current paths have been simply modeled as self impedances between plane pair at the location of reference changes. The self impedances at via transitions and terminations referenced to a power plane have to be given individually, and added to the model of the signal trace. This simple model can be used to compute the noise coupling from a signal trace to reference planes as well as to estimate signal integrity in the signal trace itself.

Figure 2. (a) Model of signal trace routed with referenced to power plane (b) Model of signal trace with changing layers through via transition

A vertical current flow through a signal trace at the location of a reference change induces electromagnetic fields and noise voltages between a reference plane pair, just as a switching current does. To obtain the coupled noise voltage to reference planes by a vertical signal current, it is important to obtain the exact quantity of the vertical current.

Figure 3. (a) Noise coupling to reference planes by signal currents (b) Calculation of current flow through a via transition (c) Calculation of current flow through a termination

The simple reference discontinuity model was used to derive the quantity of the vertical signal current at the reference changes of via transitions and terminations. In Figure 3, the current into a signal trace from a signal source is represented as I_s , and the vertical current through via transition and through termination were represented as I_{via} and I_{term} , respectively. The via current I_{via} can be obtained from the reflection constant Γ before via transition, as shown in Figure 3 (b). On the other hands, ABCD matrix was made up to calculate the current through the termination with a reference change in Figure 3 (c). The termination current I_{term} is equal to I_s divided by 'D' parameter. Each vertical current flow at the via transition and at the termination is calculated with Equation (1).

$$I_{via} = \frac{(1-\Gamma)e^{-\alpha l}}{1-\Gamma e^{-2\alpha l}} I_s, \quad I_{term} = \frac{I_s}{D} \quad (1)$$

The coupled noise voltage on the reference plane pair can be obtained by considering the vertical currents through a via transition and a termination as switching currents. Then, the total coupled noise voltage on the reference plane pair is equal to the sum of the noise voltage induced by the current through the via transition $V_{pg}(I_{via})$ and the noise voltage induced by the current through the termination $V_{pg}(I_{term})$, as shown in Equation (2).

$$V_{pg_total} = V_{pg}(I_{via}) + V_{pg}(I_{term}) \quad (2)$$

B. Noise Coupling from Power/Ground Planes to Signal Traces

After noise voltages are induced on reference planes by a switching current or a signal trace, the noise voltages on reference planes induce noise voltage on other signal traces again. When a signal trace is routed with referenced to a noisy power/ground plane pair, the boundary condition of the signal trace has to be selected carefully [7].

Figure 4. Signal trace changing layers through via transition and terminated with impedances Y1, Y2

Figure 4 shows a signal trace between a noisy plane pair when it changes layers through a via transition and is terminated with arbitrary admittance Y_1 and Y_2 . I_{term1} and I_{term2} represent the currents on the signal trace at terminations. If the impressed noise voltages on the signal trace by noisy reference planes are represented as $V(0)$, $V(a)$, and $V(b)$ at terminations and the via transition, then the boundary condition for the signal transmission is given as Equation (3). It is noticed that the noise on reference planes at the termination and the via

transition ($V(0)$, $V(a)$, and $V(b)$) is acting as a electromagnetic sources and inducing a propagating wave along the signal trace.

$$\begin{aligned} v_1'(0) &= j\omega L Y_1 (v(0) + V(0)), \\ v_2'(a) &= -j\omega L Y_2 (v(a) + V(a)), \\ v_1(b) + V_1(b) &= v_2(b) + V_2(b), \\ v_1'(b) &= v_2'(b) \end{aligned} \quad (3)$$

The solution of wave equation with the boundary condition of Equations (3) can be obtained by considering the voltage induced at terminations and the voltage induced at the via transition separately. If we define $\psi(x)$ as a solution with boundary conditions defined in Equations (4), and $\phi(x)$ as a solution with boundary conditions defined in Equations (5), then the sum of $\psi(x)$ and $\phi(x)$, $v(x) = \psi(x) + \phi(x)$, is a solution with the boundary condition defined by Equations (3).

$$\begin{aligned} \psi'(0) - j\omega L Y_1 (\psi(0) + V(0)) &= 0 \\ \psi'(a) + j\omega L Y_2 (\psi(a) + V(a)) &= 0 \end{aligned} \quad (4)$$

$$\begin{aligned} \phi_1'(0) - j\omega L Y_1 \phi_1(0) &= 0 \\ \phi_1'(b) &= \phi_2'(b) \\ \phi_2(b) - \phi_1(b) &= V_1(b) - V_2(b) \\ \phi'(a) + j\omega L Y_2 \phi(a) &= 0 \end{aligned} \quad (5)$$

The general solutions of $\psi(x)$ and $\phi(x)$ are given as follow equations.

$$\psi(x) = A \cosh \gamma x + B \sinh \gamma x$$

where,

$$\begin{aligned} A &= \frac{V_0 \omega^2 L^2 Y_1 Y_2 \sinh \gamma a - j\omega L Y_1 V_0 \gamma \cosh \gamma a - j\omega L Y_2 V_a}{\Delta} \\ B &= \frac{-V_0 \omega^2 L^2 Y_1 Y_2 \cosh \gamma a + j\omega L Y_1 V_0 \gamma \sinh \gamma a + \omega^2 L^2 Y_1 Y_2 V_a}{\Delta} \end{aligned} \quad (6)$$

$$\phi_1(x) = A \cosh \gamma x + B \sinh \gamma x$$

$$\phi_2(x) = C \cosh \gamma x + D \sinh \gamma x$$

where,

$$\begin{aligned} A &= \frac{V_b \gamma^2 \sinh \gamma(b-a) - j\omega L Y_1 V_b \gamma \cosh \gamma(b-a)}{\Delta} \\ B &= \frac{j\omega L Y_1}{\gamma} A \\ C &= A + V_b \cosh \gamma b \\ D &= B - V_b \sinh \gamma b \end{aligned} \quad (7)$$

The parameters γ , V_0 , V_a , V_b , and Δ are given as Equations (8).

$$\begin{aligned} \gamma &= \sqrt{(R + j\omega L)(G + j\omega C)} \\ V_0 &= V(0), \quad V_a = V(a), \quad V_b = V_1(b) - V_2(b) \\ \Delta &= j\omega L (Y_1 + Y_2) \gamma \cosh \gamma a + \gamma^2 \sinh \gamma a - \omega^2 L^2 Y_1 Y_2 \sinh \gamma a \end{aligned} \quad (8)$$

Therefore it is possible to obtain the general solution $v(x)$ of the voltage propagating along a signal trace induced by the noise voltage on reference planes. It is the sum of $\psi(x)$ and $\phi(x)$, where $\psi(x)$ is the voltage induced at termination and $\phi(x)$ is the voltage induced at the via transition. Consequently, the total voltage $v_t(x)$ measured on the signal trace is the sum of $v(x)$ and the voltage $V(x)$ directly impressed by noisy reference planes, as shown in Equation (9).

$$v_t(x) = V(x) + \psi(x) + \phi(x) \quad (9)$$

Above analytical equations are simply applied to the case even when the signal trace is outside of a plane pair. Although the noise field between a plane pair cannot affect a signal trace at outside of plane pair directly, the signal is still affected by the field at terminations and at via transitions.

III. NUMERICAL RESULTS

Figure 5. Test vehicle structure. All measurements are in mm. (a) Layout (b) Cross section (c) Top view of probing pad and termination pad at ports

In order to verify the model of signal trace with reference discontinuity, some test vehicles were designed and fabricated and S-parameter measurements have been done up to 10GHz in frequency domain. Figure 5 (a), (b) illustrates the layout and cross section of one of the test vehicles. It consists of four layers with dimensions of 50mm×50mm and FR4 was used as

dielectric material with permittivity $\epsilon_r=3.8$. A signal trace exists on inner layers between power plane and ground plane, and has the characteristic impedance of 50Ω . Both ports are connected between the signal trace and the ground plane. Figure 5 (c) shows the pad structure for G-S-G probing and the signal termination. It has been found that the pad structure for probing has strong effect on the measured results. The distance from the probing point to ground vias and the signal line is quite long, which will increase the current loop significantly. Non-ideal probing pads with finite area give non-ideal effects on the measured results. To exclude the effect of the probing pads, a full-wave simulation using HFSS has been done with and without the non-ideal probing pads, respectively. In the simulation without probing pads, the ports with very small size have been placed precisely at the observation point.

Figure 6. (a) Comparison of measurement and HFSS simulation with pad structures (b) Comparison of HFSS simulation without pad structures and the devised model for reference discontinuities

Figure 6 shows the comparison between the measurement, simulation, and the model for the signal trace with reference discontinuities shown in Figure 2 (b). From the model, the 2-port ABCD parameters of the signal trace model were computed using Equation (10) and converted to S-parameters. It is found that the simulated results with probing pads agrees well with the measured results and the simulated results without probing pads agrees well with the results calculated from the model of Figure 2. With this procedure, the model of a signal trace with reference discontinuities has been verified.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh \gamma l & Z_0 \sinh \gamma l \\ \gamma_0 \sinh \gamma l & \cosh \gamma l \end{bmatrix} \times \begin{bmatrix} 1 & Z_1 \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cosh \gamma l & Z_0 \sinh \gamma l \\ \gamma_0 \sinh \gamma l & \cosh \gamma l \end{bmatrix} \times \begin{bmatrix} 1 & Z_2 \\ 0 & 1 \end{bmatrix} \quad (10)$$

Next, to compute the coupling between signal traces and reference planes using the model of signal trace with reference discontinuity, two test samples have been considered. A signal current flow through a signal trace induces the noise voltage between reference planes, and the noise voltage between planes induces sequentially the noise voltage on other signal traces. When a signal current ' I_s ' is incident to a signal trace at port1, the noise voltages induced on the reference plane pair and on nearby another signal trace are observed at port 2 of samples in Figure 7 (a) and (b), respectively. The noise transfer mechanism is summarized in Figure 7 (c). Firstly, the vertical

current flows at via transitions and terminations are calculated using Equation (1). From the values of the via current ' I_{via} ' and the termination current ' I_{term} ', the induced noise voltage on the reference plane pair is computed using the cavity resonator model. It is known that the noise voltage induced on a rectangular plane pair by a switching current is given by Equation (11). By substituting the value of ' I_{via} ' and ' I_{term} ' to Equation (11), the noise voltage induced on the reference plane pair ' V_{pg} ' can be computed. Secondly, the voltages impressed on other nearby signal traces by the reference noise voltage are calculated at the locations of the signal terminations and via transitions. Knowing the values of ' V_0 ', ' V_a ', and ' V_b ' in Equation (6)–(9) leads to find the noise voltages induced on other signal traces.

Figure 7. (a) Test sample to estimate the noise voltage ' V_{pg} ' induced on reference plane by a signal trace (b) Test sample to estimate the noise voltage ' V_{s2} ' induced on another signal trace by a signal trace (c) Noise transfer mechanism (a signal trace → reference planes → another signal trace)

$$V_{pg}(i, j) = \frac{j\omega\mu d i_s}{ab} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{\epsilon_m^2 \epsilon_n^2}{k_{mn}^2 - k^2} \cos \frac{m\pi x_i}{a} \sin c \frac{m\pi x_j}{2a} \times \cos \frac{n\pi y_i}{b} \sin c \frac{n\pi y_j}{2b} \cos \frac{m\pi x_j}{a} \sin c \frac{m\pi x_i}{2a} \cos \frac{n\pi y_j}{b} \sin c \frac{n\pi y_i}{2b} \quad (11)$$

where, (x_i, y_i) and (x_j, y_j) are the coordinates of the port 1 and port 2, respectively. $k = k' - jk''$ with $k' = \omega\sqrt{\mu\epsilon}$ and $k'' = \omega\sqrt{\mu\epsilon}(\tan \delta/2 + r/2d)$, $k_{mn}^2 = (m\pi/2)^2 + (n\pi/2)^2$, where

m, n are propagating modes in the cavity, $\mu, \epsilon, \tan\delta$ are the permeability, permittivity and loss tangent of the dielectric material, respectively, $r = \sqrt{2/(\omega\mu\sigma)}$ in which σ is the conductivity of the metallization, and $\epsilon_m, \epsilon_n=1$ for $m,n=0$ and $\sqrt{2}$, otherwise.

We have calculated the transfer impedance (Z_{21}) and compared it with the simulated transfer impedance using a full-wave simulator (HFSS), as shown in Figure 8. The transfer impedance describes the ratio of the coupled noise voltage (V_{pg}, V_{s2}) to the signal current incident into a signal trace (I_{s1}). The coupling between signal traces and reference planes can be represented as this transfer impedance. From Figure 8, it is noticed that the transfer impedances calculated using the model of the signal trace with reference discontinuities show very good agreement with the results from the full-wave simulation. It has been verified that if a current flow through a vertical signal path between reference planes is known, the noise voltage on the reference planes induced by the current can be computed by considering the current as a switching current. Also, the coupling from the reference plane to other signal traces is given as derived in Section III-B.

Figure 8. Comparison between results calculated from the model equation and the results simulated using HFSS

- (a) Transfer impedance in the test sample of Figure 7-(a)
- (b) Transfer impedance in the test sample of Figure 7-(b)

IV. CONCLUSION

An efficient and consistent model for the signal trace with reference discontinuity has been devised. It has been shown that the model can represent the reference discontinuity effect on the signal integrity quite well. The signal trace model has been used to calculate the current flow at signal discontinuities, and by considering the vertical current flow across reference planes as a switching current, the noise coupling between a signal traces and reference planes has been estimated. With these procedures, the effects of reference discontinuities on the coupling between signal traces and reference planes have been investigated, and the coupling mechanism has been illuminated. The model for noise coupling through reference discontinuities of signal traces was verified up to 10GHz by comparison with measured results and full-wave simulated results.

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