Experimental Characterization and Circuit Modeling of Power/Ground Planes with Discontinuities

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Abstract
Power/ground planes of an integrated circuit package with discontinuities are experimentally characterized by using high-frequency measurement techniques, (i.e., time domain transmission/reflectometry and frequency-domain vector network analyzer). Then they are modeled with frequency-variant distributed circuits. The accuracy of the frequency-variant circuit model is verified by comparing SPICE-based simulation with VNA-based s-parameter-measurement data and commercial field-solver (HFSS)-based numerical simulation up to 26.5GHz. Thereby, it is shown that the integrated circuit package performance can be accurately as well as efficiently evaluated by using the proposed circuit model.

1. Introduction
As the level of integrated circuits becomes more and more increased, physical spacing between the lines are much tighter. Moreover, the high-frequency operation of them significantly reduces the circuit design margin such as timing, jitter, ISI (inter-symbol interference, and etc.) One of the significant problems is the simultaneous switching noise due to the integrated circuit power/ground planes. Recently most of the high-performance integrated circuits employ the dedicated power/ground planes in order to stabilize the circuit reference potentials. Thus, whether the power/ground planes meet the circuit performance or not should be accurately characterized as well as evaluated in the early phase of a circuit design.

In a real package, the power ground planes have many discontinuities due to vias and clearances which significantly distort the current return paths, followed by signal integrity degradation [1][2]. Moreover, their electrical performances are frequency-dependent as well as process-dependent. Thus an accurate characterization and circuit model that can reflect the frequency-variant characteristics and process-variations are essential. Particularly, without considering the process-dependent model parameter variations, a blind numerical simulation using commercial field solver or nominal layout-based parameter determination may cause a substantial error.

In this work, the power/ground planes are modeled with grid-type RLC circuit cells [3]. The frequency-variant transmission line effects and discontinuities are taken into account with 4-ladder circuit model and fringing effects [4]. The transmission line circuit model parameters are characterized by using the high-frequency measurements, i.e., TDR/TDT(time domain reflectometry/transmission)-based time domain wave measurements and VNA(vector network analyzer)-based frequency domain s-parameter measurements, followed by the frequency-variant 4-ladder circuit model parameters determinations [4]. The accuracy of the frequency-variant circuit model is verified by comparing SPICE-based simulation with VNA-based s-parameter-measurement data and commercial field-solver (HFSS)-based numerical simulation up to 26.5GHz.

2. Power/Ground Plane Circuit Model Parameters
In order to reflect the process-dependent model parameter-variations, test patterns are sectioned and physical dimensions are determined. Then average dimensions are employed for the model parameter determinations. The dielectric constant between the metals is not pure material but a compound one which is mixed with the epoxy and epoxy resin. Thus it is determined by measuring the time-domain reflection/transmission waves of various transmission line test patterns. Then capacitance parameters are determined by using a commercial field solver.

Unlike the capacitance, the resistance and inductance are frequency-dependent. That is, skin effect, metal roughness, and proximity effect may be substantial in high-frequency. Thus, the high-frequency s-parameters are measured by using VNA for the various transmission line test patterns. Then the transmission line parameters such as characteristic impedance and propagation constant are directly determined by using the s-parameters, followed by transmission line circuit model parameters [5][6]. Based on these measurement data, frequency-variant transmission line circuit model parameters are determined [4]. The four ladder RLC cell parameters can be determined with

\[
R_{eq} = \frac{1}{\omega \sigma \mu} \left[ \frac{1}{\delta_{hf}} + \frac{1}{\delta_{dc}} \right] \left( R_{eq} - \mu \frac{\delta_{hf}}{\delta_{dc}} \right) \quad (1)
\]

\[
L = \frac{1}{\omega^2 \mu} \left[ \frac{1}{\delta_{hf}} + \frac{1}{\delta_{dc}} \right] \left( \frac{R_{eq} - R_{eq}(U + \xi_{hf})}{\delta_{hf} - \delta_{dc}} \right) \quad (2)
\]

\[
\xi = \frac{1}{\omega \mu} \left[ \frac{1}{\delta_{hf}} + \frac{1}{\delta_{dc}} \right] \left( \frac{R_{eq} - R_{eq}(U + \xi_{hf})}{\delta_{hf} - \delta_{dc}} \right) \quad (3)
\]

\[
\xi = \frac{1}{\omega \mu} \left[ \frac{1}{\delta_{hf}} + \frac{1}{\delta_{dc}} \right] \left( \frac{R_{eq} - R_{eq}(U + \xi_{hf})}{\delta_{hf} - \delta_{dc}} \right) \quad (4)
\]

\[
\xi = \frac{1}{\omega \mu} \left[ \frac{1}{\delta_{hf}} + \frac{1}{\delta_{dc}} \right] \left( \frac{R_{eq} - R_{eq}(U + \xi_{hf})}{\delta_{hf} - \delta_{dc}} \right) \quad (5)
\]

where \( t_1, t_2, d, \) and \( \sigma \) indicate the power plane thickness, ground plane thickness, dielectric thickness, and copper conductivity, respectively. The \( \delta_{hf}, \delta_{dc}, \) and \( \xi_{hf} \) indicate a skin depth at 26.5GHz, critical skin depth at which the metal roughness effect occurs, and a constant ratio, respectively.

3. Discontinuity Power/Ground Parameter Determination
The discontinuities of the power/ground planes have a significant effect on the impedance of the path. That means the simultaneous switching and resonance frequency of the system may vary with the discontinuities. Thus, the discontinuity effects have to be taken into account for the package performance evaluation. In order to test the various discontinuity effects, a plane model with discontinuities are assumed as shown in Fig. 1. Then 2-port s-parameters are determined by using the circuit model, VNA-based measurements, and 3D-field solver. As shown in Fig. 2, for the planes without discontinuity, the s-parameters of the frequency-variant circuit model have excellent agreement with VNA-based measurement data. However, the discontinuity effect may have a significant effect as shown in Fig. 3.

a) Fringing Effect due to Discontinuity
Since the discontinuity may significantly modulate the electric field, the fringing effect has to be taken into account. The fringing capacitances are determined by using a commercial 3-dimensional field solver.

b) Discontinuity Circuit Modeling
An arbitrary discontinuity structure can be simply approximated by many grid cells as shown in Fig. 4. Since a cell size should be less than one tenth of the significant wave length, the cell size of the circuit model has been determined with 500 \( \mu \text{m} \times 500 \mu \text{m} \). However, in the edge regions with discontinuities, a cell size has been determined with much smaller cell of 73.25 \( \mu \text{m} \times 73.25 \mu \text{m} \). The 4-ladder circuit model parameters are summarized in Table 1.

\[
R_{eq} = \frac{1}{\omega \sigma \mu} \left[ \frac{1}{\delta_{hf}} + \frac{1}{\delta_{dc}} \right] \left( R_{eq} - \mu \frac{\delta_{hf}}{\delta_{dc}} \right) \quad (1)
\]

\[
L = \frac{1}{\omega^2 \mu} \left[ \frac{1}{\delta_{hf}} + \frac{1}{\delta_{dc}} \right] \left( \frac{R_{eq} - R_{eq}(U + \xi_{hf})}{\delta_{hf} - \delta_{dc}} \right) \quad (2)
\]
4. S-parameter-based Model Verification

In order to verify the power/ground plane circuit model, the test pattern of 10mm×10mm is measured by using VNA and simulated by using 3D field solver (HFSS). Note, all the material parameters for the 3D field solver such as the metal roughness effect, resistivity, and dielectric constants are experimentally characterized. Otherwise, blind 3D numerical simulations using nominal values cause a substantial error. Then the measurement data are compared with HSPICE-based circuit simulation data using the proposed frequency-variant circuit model (see Fig. 5).

As shown in Fig. 5, the frequency-variant circuit model with discontinuities shows excellent agreement with the 3D-field solver data up to 26.5GHz. Thereby, the power/ground planes with discontinuities can be very efficiently as well as accurately evaluated.

5. Conclusion

A frequency-variant circuit model for the power/ground planes of integrated circuit packages is developed. The frequency-variant circuit model parameters are determined by using the experimental characterizations. It was shown that blind numerical simulations using 3D-field solver and conventional constant circuit model may cause substantial error. Further, metal roughness and discontinuity effects which are considered to be inherent in a real package system are taken into account in the circuit model. The model accuracy is experimentally verified up to the high frequency (up to 26.5 GHz) with the high-frequency measurements. Note, the computation time of the circuit model is 100 times faster than that of the 3D-field solver. Thus, the proposed circuit model can be very usefully employed for a package performance evaluation.

Reference