Experimental Characterisations of Coupled Transmission Lines

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Abstract

Coupled transmission lines are experimentally characterised by using 4-port s-parameter measurements in the broad frequency band (up to more than the 20GHz). The test patterns are designed and fabricated by using a BGA package process. Symmetrical coupled transmission lines are decoupled into two eigen modes that can be readily determined from the measured s-parameters. Then signal transient and crosstalk noise are directly determined from the measured s-parameters. It is shown that not only are the transmission line parameters frequency-variant, but also the frequency-variant effects and non-ideal characteristics of transmission lines have substantial effect on the signal transients and crosstalk noises.

1. Introduction

As the circuit operation frequency and the level of the integration of integrated circuits drastically increase, integrated circuit packages have a substantial effect on the circuit performance [1]-[4]. Signal transient variations and electromagnetic coupling noises concerned with package interconnect lines significantly deteriorate signal integrity. As a result, the circuit design margin becomes extremely stringent. Thus, circuit designers must exercise extra caution in accurately verifying signal integrity concerned with integrated circuit package interconnect lines [2].

As the physical length of interconnect lines become comparable to the wave lengths of the fundamental and harmonic frequency of a digital signal, the interconnect lines have to be treated as a transmission line. The transmission line parameters are frequency-variant due to skin effect and proximity effect [3]. Further, they show many non-ideal phenomena owing to the inherent process variation, metal roughness [4], non-ideal skin effect, and compound dielectrics [5]. Thus, in order to design high-speed circuits, the experimental verifications of the transmission lines over a broad frequency band are essential. Thereby, accurate design rules for the high-performance system design can be established and the various EDA tools can be benchmarked with the experimental data base.

Many techniques concerned with the experimental transmission line characterisations have been reported in literatures [3],[6]-[11]. However, all these techniques may not be accurate enough for the characterisations of today’s IC interconnect lines or package interconnect lines since they are based on a single line or inaccurate inductive parameter determination.

In this work, test patterns for the two coupled transmission line characterisations are designed and fabricated by using a BGA package process. Then 4-port s-parameters are measured over the 20GHz by using 2-port VNA. Symmetrical coupled transmission lines are decoupled into two eigen modes that can be readily determined from the measured s-parameters. Then signal transient and crosstalk noise are directly determined from the measured s-parameters. It is shown that not only are the transmission line parameters frequency-variant, but also the frequency-variant effects and non-ideal characteristics of transmission lines have substantial effect on the signal transients and crosstalk noises.

2. Experimental Characterisation of Transmission Lines

The test pattern layout and its cross-section are shown in Figure 1. Note, the bottom of the metals is not smooth but rough (see Figure 1-(b)). The thickness of the rough portion of the metal is comparable to the skin depth at a significant frequency (e.g., at a several GHz). Further, the nominal drawn dimensions have large process variations (see Figure 1-(c)). Particularly, since the metal is not a square but a trapezoid, signal coupling (crosstalk noise) may not be accurately determined without experimental verification.
The s-parameters for the 4-port test patterns are measured by using 2-port vector network analyzer (Agilent 8510C VNA) connected with two Cascade Microtech GSSG probe tips (150um pitch). The measured 4-port s-parameters can be represented by a 4x4 matrix,

\[
\begin{bmatrix}
 S_{11} & S_{12} & S_{13} & S_{14} \\
 S_{21} & S_{22} & S_{23} & S_{24} \\
 S_{31} & S_{32} & S_{33} & S_{34} \\
 S_{41} & S_{42} & S_{43} & S_{44} 
\end{bmatrix}
\]  

(1)

The measured s-parameters are shown in Figure 2. Note, since the structure is symmetrical, the same port-reflections and coupling parameters between the ports are averaged for data analysis.

3. S-Parameter-Based Signal Transient and Crosstalk Noise

Since the transmission line parameters are in general frequency-variant, the frequency-dependent transmission line characteristics cannot be directly employed for the general purpose circuit simulator (i.e., SPICE). In order to investigate the frequency-variant characteristics of the transmission line parameters, the transmission line equations are decoupled into modal transmission lines by using the modal analysis. Then, the coupled transmission line system is expressed as the linear combination of the eigen modes. For example, if the first line of the two coupled lines as shown in Figure 3 is switching from logic 0 to logic 1 and the second line is in a quiet state, the signals on the respective lines due to switching (i.e., $↑0$) can be readily determined by using a symbolic operation

(2)

(3)

Note, the line of interest for the switching mode is marked with a square box. Other switching cases such as (“$↑↓$”) and (“$↑↑$”) can be similarly determined.

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Note, the line of interest for the switching mode is marked with a square box. Other switching cases such as (“$↑↓$”) and (“$↑↑$”) can be similarly determined.
\[ H_{\text{even}}(x, \omega) = \frac{1}{2} \left( T_{\text{even}} - T_{\text{odd}} \right), \]

where
\[
T_{\text{even}}(x, \omega) = \frac{Z_{\text{even}}}{Z_{\text{even}} + Z_G} \exp(-\gamma_{\text{even}} x) + \rho_{L1} \exp(-\gamma_{\text{even}} (2l-x)) \frac{1 - \rho_{L1} \rho_{L2} \exp(-2\gamma_{\text{even}} l)}{1 - \rho_{L1} \rho_{L2} \exp(-2\gamma_{\text{even}} l)}
\]

\[
T_{\text{odd}}(x, \omega) = \frac{Z_{\text{odd}}}{Z_{\text{odd}} + Z_G} \exp(-\gamma_{\text{odd}} x) + \rho_{L1} \exp(-\gamma_{\text{odd}} (2l-x)) \frac{1 - \rho_{L1} \rho_{L2} \exp(-2\gamma_{\text{odd}} l)}{1 - \rho_{L1} \rho_{L2} \exp(-2\gamma_{\text{odd}} l)}
\]

\[
\rho_{L1} = \frac{Z_L - Z_{\text{even}}}{Z_L + Z_{\text{even}}}, \quad \rho_{L2} = \frac{Z_L - Z_{\text{odd}}}{Z_L + Z_{\text{odd}}},
\]

\[
\rho = \frac{Z_{\text{odd}} - Z_{\text{even}}}{Z_{\text{odd}} + Z_{\text{even}}}
\]

where \( \rho_{L1}(\omega) \) and \( \rho_{L2}(\omega) \) are the reflection coefficient of the i-th line at generator and the reflection coefficient of the i-th line at load, respectively. The propagation constants ( \( \gamma_{\text{even}}(\omega) \) and \( \gamma_{\text{odd}}(\omega) \) ) and characteristic impedance ( \( Z_{\text{even}}(\omega) \) and \( Z_{\text{odd}}(\omega) \) ) of the single line can be determined from the measured s-parameters. That is, decoupling the coupled s-parameters, the modal transmission line parameters can be determined as in a single line [8]

\[
e^{-j\omega l} = \left[ 1 - \frac{S_{11}^2 + S_{21}^2}{2S_{21}} \pm \sqrt{ \left( \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{21}} \right)^2 - \frac{(2S_{11})^2}{(2S_{21})^2}} \right]^{-1}
\]

\[
Z^2 = Z_0 \left( \frac{1 + S_{11}^2}{1 - S_{11}^2} \right) - S_{21}^2
\]

where the measurement reference impedance ( \( Z_0 \) ) is 50\( \Omega \). During the extraction of both complex parameters (i.e., \( \gamma(\omega) \) and \( Z(\omega) \)) , the cyclically mapped phase outputs of the s-parameter have to be converted to the true radian measurement phase which can be any real value.

Thus, the frequency-variant transfer functions can be accurately determined in terms of s-parameters by using (10) and (11). In contrast, pulsed input signal can be formulated in frequency domain with delayed step functions [12]

\[
V_i(\omega) = \sum_{n=1}^{\infty} \sum_{k=1}^{\infty} A_n t_z \text{sinc} \left( \frac{\omega t_z}{2} \right) \exp \left( -j\frac{\omega t_z}{2} \right) \exp \left( -j\frac{\omega k - 1}{n} \right)
\]

where \( n \), \( t_z \) and \( t_f \) are the number of delayed step functions, the rise time, and fall time of a pulsed signal, respectively. Since both the transfer function and input function are formulated in frequency domain, the time domain transient response and crosstalk noise of the lines can be determined by the inverse Fourier transform as shown below

\[
v_i(t) = F^{-1} \left[ V_i(\omega) \cdot H_{\text{even}}(\omega) \right]
\]

The s-parameter-measurement-based signal transient wave shapes and crosstalk noises are compared with those of the SPICE simulations.
accurately determined in the odd mode (↑↓) switching, where the capacitive-effects are prominent.

The crosstalk noises for the “↑0” switching lines are shown in Figure 5. SPICE simulations using constant transmission line parameters show large deviation from the s-parameter-measurement-based ones. Note, the constant-parameter-based SPICE simulation too much overestimates the crosstalk noises in its magnitudes and its wave shapes are totally different with the s-parameter-measurement-based ones. Thus, it may cost too much.

Figure 5. Crosstalk of the “↑0” switching (VDD=1[V], t_i=50[ps], t_f=50[ps], T=1[ns]).

4. Conclusion

In this paper, for the accurate characterisations of the integrated circuit package transmission lines, test patterns are designed and fabricated by using a BGA package process. Then, the signal transients and crosstalk noises are accurately as well as directly determined by using the measured 4-port s-parameters. It was shown that not only are the transmission line parameters frequency-variant but also the frequency-variant transmission line characteristics have substantial effects on the high-speed signal transients and crosstalk noises. The conventional SPICE simulation using the distributed circuit model based on the constant circuit model parameters are not accurate enough since they do not reflect the frequency variant transmission line effects and non-ideal transmission line characteristics.

5. References