IBIS-Model-Based Signal Transient Simulation of Frequency-Variant Transmission Lines with Non-Linear Driver

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Abstract
Efficient signal transient characterization method for frequency-variant transmission lines with non-linear drivers are presented. IBIS model for a non-linear driver is generated by employing TSMC 0.18 μm process-based parameters. The frequency-variant characteristics of the transmission lines are modeled with 4-vertically stacked RLC-ladder circuit. The transmission line circuit model parameters are determined by using high-frequency measurements, i.e., TDR/TDT and VNA. Thereby, it is shown that the signal transient responses of the frequency-variant transmission line circuits with non-linear drivers can be efficiently as well as accurately evaluated with the proposed technique.

1. Introduction
With the advanced semiconductor process technology, i.e., nanotechnology, the level of integration and the operating frequency of integrated circuits drastically increase. In such high-performance integrated circuits, the signal integrity degradation due to interconnect lines becomes a crucial issue [1].

With the operating frequency of the chip increased, interconnect lines have to be treated as a transmission line. Further, it is well known that the transmission line parameters are frequency-dependent due to skin effect, proximity effect, induced eddy current, and conductive substrate effect. Thus, in order to accurately design the circuits, frequency-dependent interconnect line model is essential [2][3]. In addition, note, the non-linear driver characteristics cannot be accurately represented with the conventional RC circuit (i.e., a kind of linear circuit) model. In reality, SPICE like circuit model is the best in order to characterize the transmission lines with non-linear drivers. However, in general, not only is the SPICE circuit model not open in the public domain but also it is not computationally efficient enough. In order to overcome the problems, the non-linear drivers/receivers (buffer) are modeled with an IBIS model as schematically described in Fig. 1 [4]. Thereby, the responses of the transmission line circuits with non-linear drivers can be accurately evaluated.

In this paper, the frequency-variant transmission line characteristics are modeled with 4-vertically stacked RLC-ladder circuit [3]. The transmission line circuit model parameters are determined by using high-frequency measurement data (i.e., TDR/TDT-based time domain waves and VNA-based s-parameters). Then the frequency-variant transmission line circuits are combined with IBIS models which are generated by using TSMC 0.18 μm process-based device model parameters. Thereby, it is shown that the signal transient responses of the frequency-variant transmission line circuits with non-linear drivers can be efficiently as well as accurately evaluated with the proposed technique.

2. Generation of IBIS Model
Integrated circuit I/O drivers which are composed of MOS transistors and other non-linear devices are inherently non-linear circuits which may have a considerable effect on the circuit performance. As an example, the SPICE-responses of a CMOS inverter are compared with that of a simple linear RC circuit model. As shown in Fig. 2(a) simple RC model does not reflect the non-linear characteristics of the inverter. On the contrary, the IBIS model shows excellent agreement with SPICE simulation. In this work, the IBIS model for all the non-linear drivers are generated by using TSMC 0.18 μm process-based device model parameters.

3. Frequency-Variant Transmission Line Circuit Model
The frequency-variant transmission lines are modeled with vertically stacked 4-ladder RLC circuit as shown in Fig. 3 [3]. The frequency-variant transmission line parameters and material parameters are determined by using high-frequency measurements.

1) Determination of Capacitance
In order to determine the dielectric constant and transmission line parameters of microstrip line in Fig. 4, test pattern are designed and fabricated. Then the average dimensions of physical structures are determined by the SEM-based-measured cross-section data. First, the flight time of 17mm and 19.625mm line is measured with TDR/TDT in order to determine the effective dielectric constant. The dielectric constant can be determined by

![Fig. 1. SPICE circuit model and basic structure of IBIS model.](image1)

![Fig. 2. CMOS inverter response (a) SPICE(CMOS) vs. RC model, (b) SPICE(CMOS) vs. IBIS model.](image2)

![Fig. 3. Frequency-variant transmission line model.](image3)

![Fig. 4. Structure of test pattern (a) thru and microstirp line, (b) cross-section of test pattern.](image4)
\[ v_{\text{signal}} = \frac{L_{\text{dc}}}{2L_{f}} \approx \frac{c}{\sqrt{\varepsilon_r}}, \quad \varepsilon_r \approx \left(\frac{2R_f - c}{\ell_{\text{dc}}}\right)^2. \] (1)

Alternatively, the effective dielectric constant can be determined by using s-parameter data \( (S_{21} \text{ phase difference}) \) [5]. As summarized in Table 1, the effective dielectric constant is 3.72. The capacitance of interconnect lines can be determined by using effective dielectric constant, average dimensions, and commercial Filed Solver.

Table 1. Effective dielectric constant using experimental measurements.

<table>
<thead>
<tr>
<th>Patterns</th>
<th>( \Delta \ell ) [( \mu m )]</th>
<th>( \varepsilon_{r, \text{eff}} )</th>
<th>( \varepsilon_{r, \text{off}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 mm</td>
<td>109.38</td>
<td>3.720</td>
<td>3.69</td>
</tr>
<tr>
<td>19.695 mm</td>
<td>127.34</td>
<td>3.757</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>3.72</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2) Determination of Resistance and Inductance

The resistances can be determined by employing a proportional constant, \( \xi_x \), which can be calculated by [3]

\[ R_x = \alpha_x R_c, \quad \xi_x = \xi_x^1 + \xi_x^2 + \xi_x^3 + 1, \quad \xi_x^2 = \frac{R_x}{R_c} \quad (i = 1, 2, 3), \quad \xi_x^3 > 1. \] (2)

The resistance is frequency variant due to the skin effect which is given by [6].

\[ R(f) = \frac{1}{w\sqrt{\mu_0 f}} = \frac{1}{\sigma w \delta}, \] (3)

where \( l, \omega, \sigma \) is line length, line width, and conductivity, respectively. In reality, the conventional skin effect is modulated due to metal roughness effect in high frequency (see Fig. 5). Taking this effect into account, more accurate frequency-dependent resistance can be modeled by

\[ R(f) = \frac{1}{w\sqrt{\mu_0 f}} \cdot \left( X_{\text{roughness}} \right), \quad X_{\text{roughness}} = \frac{\delta}{\delta(f)}, \] (4)

where \( X_{\text{roughness}} \) indicates the metal roughness effect. Similarly, introducing a proportional constant, \( \xi_{L_x} = L_x / L_{c_x}, \quad (i = 1, 2) \), the inductance parameters can be determined as shown in below [3],

\[ L_x = \frac{R_x (\xi_x^1 + \xi_x^2 + \xi_x^3 + 1)(1 + 1/\xi_x^3)}{\omega \delta}, \] (5)

\[ L_{L_x} = \frac{R_x (\xi_x^1 + \xi_x^2 + \xi_x^3 + 1)}{\omega \delta}, \]

where \( R_x \) is the resistance at the highest frequency. It is determined by equation (4). Since the internal inductance of low frequency is

\[ L_{L_x}^{-\text{internal}} = L_{L_x}^{-\text{total}} - L_{L_x}^{-\text{external}}, \] (6)

assuming the inductance variation is linear in a given frequency range, a proportional constant, \( \alpha_x \), can be determined by solving following equations

\[ L_x = L_{L_x}^{-\text{external}} / \alpha_x = (L_{L_x}^{-\text{total}} - L_{L_x}^{-\text{external}}) / \alpha_x, \] (7)

\[ \left( \frac{1}{\xi_x^1} + \left( \frac{1}{\xi_x^2} \right)^2 + \frac{1}{\xi_x^3} + \left( \frac{1}{\xi_x^4} \right)^2 + \frac{1}{\xi_x^5} + 1 \right)^2 = \frac{1}{\alpha_x}, \] (8)

4. Model Verification and Discussions

The frequency-variant transmission lines with non-linear drivers are simulated by combining the frequency-variant circuit model with the IBIS models. Then the responses are benchmarked with SPICE-based circuit simulations. As shown in Fig. 6(a), the proposed model shows excellent agreement with SPICE-based non-frequency-variant transmission line models. In contrast, both the non-frequency-variant transmission line model and linear driver model shows large discrepancy with the frequency-variant model-based responses.

5. Conclusion

In this work, a novel frequency-dependent transmission line circuit model is proposed and its model parameters are determined by using high-frequency measurements. The non-linear drivers are represented with IBIS models. Thereby, the signal transient responses of frequency-dependent transmission lines with non-linear drivers can be accurately as well as efficiently evaluated with the proposed technique. It was shown that the frequency-variant proposed model shows excellent agreement with SPICE-based circuit simulations.

Reference