Simulation of the Coupling of an External Electromagnetic Field to the PCB Traces in SPICE Simulator

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Abstract – In the paper the response of PCB structure to an electromagnetic field has been investigated. Employing active transmission line model the analytical expressions were derived for waveforms of current sources. An illustrative example of trace on PCB terminated by ECL gates and illuminated by double exponential has been presented.

1 Introduction

Various time-domain models exist for predicting the induced voltages and currents by coupling of electromagnetic waves to Printed Circuit Board (PCB). The more exact of these are based on 3-D analysis (e.g. FT-DT) of electromagnetic field, however they still require great computational resources if applied to practical problems.

Hence the coupling phenomenon of an external electromagnetic field to a PCB is usually modeled by electromagnetic plane wave incident on a system of transmission lines, with PUL parameters calculated from PCB structure, placed in free-space above perfectly conducting plane. Next incident electric field is converted to distributed voltage and current sources located along the line e.g. [1]. Such a line we call Active Lossy Transmission Line (ALTL). It appears however [2] that such an approach is too simple some times and can provide erroneous results.

Recently in [3] was proposed the method for solving this problem. Basing on the general theory of planarly layered media, were derived analytical frequency-domain expressions describing horizontal electric field component on the substrate surface and vertical electric field component in the substrate. These expressions were simplified by low-frequency approximation and next transform to the time-domain. Such an approach permits for taking into account distortion of electromagnetic wave in tree layer medium (air, substrate, and conductor) and therefore more realistic simulation [2].

Figure 1: Model of the ALTL as connection of PLTL and current source $j_1(t)$ and $j_2(t)$.

2 Theory

Our approach will be explained, for simplicity, on the case of single lossy TL, but it can be extended for the case of the multiconductor TL. In the ALTL model in Fig.1 current $i_1(t)$ and $i_2(t)$, which are the sums of $j_1(t)$, $j_2(t)$ and respectively input and output PLTL model currents, have to control the internal PLTL field incident on PCB traces into functions describing the current sources.

2.1. Model of an active lossy transmission line

The aim of this paper is to propose a subcircuit, modeling an ALTL in SPICE, consisting of a model of Passive Lossy Transmission Line (PLTL) and two current sources connected in parallel to the input and output PLTL ports. Moreover we give, basing on [3], a procedure of conversion of an external electromagnetic field incident on PCB traces into functions describing the current sources.

The telegrapher’s equations, for an active transmission line has the following form

$$\frac{\partial u}{\partial \tau} = Ri + L \frac{\partial i}{\partial \tau} - e, \quad \frac{\partial i}{\partial \tau} = Ru + C \frac{\partial u}{\partial \tau} - j$$

(1)

Eqs. (1) can be solved by the method of successive approximation [5]. The solution can be written in the form:

$$i_1(0, \tau) = S_1(\tau) \ast i_1(0, \tau) + S_2(\tau) \ast i_2(t, \tau) - j_1(\tau)$$

$$i_2(t, \tau) = S_2(\tau) \ast i_1(0, \tau) + S_1(\tau) \ast i_2(t, \tau) + j_2(t)$$

(2)
In (2) $S_1(τ)$, $S_2(τ)$ are scattering parameters of the line and $i_+, i_-$ are backward and forward current waves respectively. Functions $j_1$, $j_2$ represent distributed current and voltage sources. For the case of transmission line with the small loses ($Rl/Zc < \pi$) first order approximation of the solution (2) is simple, exact enough [5] and poses the form

$$S_1(τ) = \frac{b}{2} e^{-\frac{1}{2} |1(τ) - 1(τ - 2)|}, \quad S_2(τ) = e^{-\frac{1}{2} |1(τ)|},$$

$$j_1(τ) = \frac{1}{e^{-\frac{1}{2} |1(ξ)| - (ξ, τ - ξ)dξ},$$

$$j_2(τ) = \frac{1}{e^{-\frac{1}{2} |1(ξ)| - (ξ, τ + ξ)dξ},$$

(3)

where

$$a = \frac{1}{2} \left[ Z_c G + Y_c R \right], \quad b = \frac{1}{2} \left[ Z_c G - Y_c R \right],$$

$$RLGC \cdot \text{line parameters}$$

$$Y_c = Z_c l = \frac{C}{L}, \quad T = l\sqrt{LC}, \quad 0 \leq y \leq \frac{z}{l};$$

$$τ = l\sqrt{T}, \quad l - \text{line length}$$

$$j(y, τ) = Y_0 e(y, τ, τ),$$

Functions $j_1(τ)$, $j_2(τ)$ (3) are specified current waveforms of the two independent current sources shown in Fig.1. Controlled current sources marked in Fig.1 as $j_1, j_2$ has the form

$$j_1(τ) = S_1(τ) * i_1(0, τ) + S_2(τ) * i_1(1, τ),$$

$$j_2(τ) = S_1(τ) * i_1(0, τ) + S_2(τ) * i_2(1, τ).$$

(4)

Relationships (4), in which the stars denote convolution, can be easily modeled in SPICE by means of lossless transmission lines and first order circuits. Basing on eqs. (2), (4) and Fig.1 an equivalent circuit for ALTL has been created in SPICE. The separate problem area formulas describing conversion of external electromagnetic field into current sources $j_1(τ)$, $j_2(τ)$, we will discuss this in the next point.

### 2.2 External electromagnetic field

Distributed sources $e_0(x, y, z, t)$, $j_0(x, y, z, t)$, for k-th conductor, depend on electric field vector and are described by known formulas e.g.[4] in following manner:

$$e_0(x, y, z, t) = E_r(x, y, z, t) - \frac{∂}{∂z} \left[ E_r(x, y, z, t) dx \right],$$

$$j_0(x, y, z, t) = C \frac{∂}{∂l} \left[ E_r(x, y, z, t) dx \right],$$

(5)

where

$E_r(x, y, z, t)$ - horizontal component of the electric field for k-th conductor,

$$E_r(x, y, z, t) = \left( e_r, a_r, + e_r, a_r, \right) E_{m, f}.$$
This PCB structure is illuminated by an electro-
magnetic plane wave incident at the different angles. The greatest electromagnetic noise can be observed in three cases. In the first case, referred as endfire excitation [4], angles are \( \theta_p = 90^\circ \), \( \phi_p = 0^\circ \), \( \theta_E = 90^\circ \) and resulting output voltages of the lines \( v(4), v(5), v(6) \) (see Fig.3) are shown on the lower plot of the Fig.4. The upper plot of this figure shows output voltages of ECL gates \( v(41), v(51), v(61) \) (see Fig.3).

In the second case, referred as sidefire excitation [4], angles are \( \theta_p = 180^\circ \), \( \phi_p = 0^\circ \), \( \theta_E = 0^\circ \) and resulting output voltages of the lines \( v(4), v(5), v(6) \) (see Fig.3) are shown on the lower plot of the Fig.5. The upper plot of this figure shows output voltages of ECL gates \( v(41), v(51), v(61) \) (see Fig.3).

In the third case, referred as broadside excitation [4], angles are \( \theta_p = 90^\circ \), \( \phi_p = 0^\circ \), \( \theta_E = 90^\circ \) and resulting output voltages of the lines \( v(4), v(5), v(6) \) (see Fig.3) are shown on the lower plot of the Fig.6. The upper plot of this figure shows output voltages of ECL gates \( v(41), v(51), v(61) \) (see Fig.3).

Voltages from the range (-1V, -2.1V) represents logical “1” and from range (-1.6V, -2V) logical “0”. The voltage at the level -1.4V is intermediate non-stable state. In all cases electromagnetic noise causes switching phenomena between logical “0” and “1” at the output of the ECL gates or introduce the gate in intermediate state.

### 3 Results

As a test we consider an example of structure shown in Fig.1. The traces possessing coordinates \( y_1=-300 \), \( y_2=0 \), \( y_3=100 \), \( x_1=x_2=x_3=625 \) with thickness \( t_1=t_2=t_3=30 \) and widths \( w_1=60 \), \( w_2=100 \), \( w_3=100 \) have lengths of 20 cm. They are placed on common substrate with \( \varepsilon_r =4.7 \) and conductance of the traces is \( \sigma =5.6E7 \) [m·Ω⁻¹]. The traces are excited by double-exponential pulse (EMP) with parameters \( E_m=-3kV/m \) and time constants of 1 ns and 20 ns. ECL gates and their pull-down networks (see Fig.3) terminate the traces.

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### 4 Conclusions

This paper present a simple SPICE model for transient analysis of the coupled transmission lines excited by an external field. The main result of the paper are derived formulas (3) and (7) describing the lumped current sources \( j_1(t), j_2(t) \) connected to the input and output ports of lossy PLTL. In these formulas function \( f_o(t) \), which describes the time dependence of the electric field may be arbitrary. Hence not only double-exponential pulse excitation may be con-sidered. The advantages of SPICE environment together with proposed model of the ALTL permits for simulation and investigation of practical problems, which arise in electromagnetic environment. The obtained results permit for the first time the more exact SPICE modeling and simulation of nonhomogeneous structures (PCB) illuminated by electromagnetic plane wave. As it was mentioned in introduction low-frequency approximation of electric field was adopted from [3], actually we work on full range frequency approximation, which can be included to time-domain simulation and the results are promising.
Figure 4: Output voltages for the endfire case.

Figure 5: Output voltages for the sidefire case.

Figure 6: Output voltages for the broadside case.

References


