A Modeling of Slot on the PCB Ground Plane by Using Genetic Algorithm

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Abstract

Modeling a slot at a ground plane is studied when a signal trace runs over it. Supposing the slot would work as a slot line with some terminal loads, we propose an experimental method to determine the parameters of the slot-line model by using a genetic algorithm (GA). At first, time-domain responses of the transmission line were measured by using a time-domain reflectometer (TDR). Then using GA, we determined a likely equivalent circuit and its parameters so as to agree with the measured and computed responses. As equivalent circuits of radiation impedance, parallel-CR, parallel-LR, series-CR, and series-LR circuits were assumed in advance. And we set possible ranges of their parameters and effective permittivity of the slot line too. Under such condition, GA determined the most likely model and parameters. By using the proposed method, it is expected to estimate a far-field emission pattern and to discover the mechanism of far-field emission and signal integrity.

1 Introduction

With the demand of high-density wiring on a printed circuit board (PCB), signal traces crossing slots in a ground plane are found. The slots are formed by a boundary of different voltage power planes. Such configuration models showing the interconnection of PCBs cause serious EMC problems. That is, they worsen a far-field emission and signal integrity. To overcome these problems, it is required to make clear the behavior of the slot on the ground plane.

In this paper we consider PCB models shown in Fig. 1. A signal line on a substrate runs over a slot existing in a ground plane. In model (a), the ground plane is perfectly divided by the slot, i.e., the slot is put between two transmission lines on one board. Model (b) shows the model where the ground plane is connected at both upper and bottom edges. Figure 1 (c) is the one where the ground plane is connected only at the bottom edge. We have confirmed that the slot behaves as a slot transmission line in [1]. Considering the duality of a slot line and a strip line, we found that the end of the slot in model (b) can be treated as an open circuit. Therefore, the model of model (b) can be treated as a transmission line with open stabs as shown in Fig. 2, where $Z_{emit}$ is an open circuit. In model (c), the slot goes through the upper edge, so that radiation may be caused there. We here consider the role of the slot end as some impedance containing a radiation effect. We propose an experimental method to determine parameters of such model by using a genetic algorithm (GA) [2].

2 Theory

2.1 Transmission Line model

We derive reflection and transmission characteristics of the strip line by using a chain matrix. Let $\beta$ be a propagation constant, $F_l(\beta, l)$ be a chain matrix of the transmission line of length $l$, $F_o(\beta, l)$ be a chain matrix of an open stab of length $l$, and $F_z(\beta, l, Z_{emit})$ be a chain matrix of a stab of length $l$, which is loaded with impedance $Z_{emit}$. $F_l$, $F_o$, $F_z$ are written by

$$F_l(\beta, l) = \begin{bmatrix} \cos(\beta l) & jZ_o\sin(\beta l) \\ j\sin(\beta l) & Z_o \cos(\beta l) \end{bmatrix}$$  (1)
Figure 1. Microstrip line on ground plane with slot

\[ F_i(\beta, l) = \begin{bmatrix} 1 & 1 \\ jZ_o \cot(\beta l) & 1 \end{bmatrix} \] (2)

\[ F_z(\beta, l, Z_{emitt}) = \begin{bmatrix} 1 & \frac{1}{Z_o + jZ_{emitt} \tan(\beta l)} \\ \frac{Z_o}{Z_{emitt} + jZ_o \tan(\beta l)} & 1 \end{bmatrix} \] (3)

The total chain matrix \( F \) is calculated by

\[ F = F_i(\beta_{strip}, l_1)F_o(\beta_{slot}, l_2)F_z(\beta_{slot}, l_3, Z_{emitt})F_i(\beta_{strip}, l_4) \] (4)

The reflection coefficient \( S_{11} \) is calculated by using a chain matrix:

\[ S_{11} = \frac{F_{11} + F_{12}/Z_o - F_{21}Z_o - F_{22}}{F_{11} + F_{12}/Z_o + F_{21}Z_o + F_{22}} \] (5)

Parallel-CR, parallel-LR, series-CR, and series-LR may be considered as an equivalent circuit of radiation impedance. Let the value \( Cir \) be an index of the circuit types; 1 denotes a parallel-CR, 2 denotes a parallel-LR, 3 denotes a series-CR, and 4 denotes a series-LR. Let \( R \) be a resistance of the radiation impedance and \( LC \) be an inductance with the parallel-CR or series-CR and a capacitance with the parallel-LR or series-LR. Thus, the time domain reflection waveform for a step pulse \( V_{calc} \) can be written as a function of a \( Cir \), \( R \), \( LC \), \( Z_{slot} \), and \( \epsilon_{eff \ slot} \).
Table 1. Possible ranges of parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Possible range</th>
<th>Divisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit type of the radiation impedance</td>
<td>Cir</td>
<td>1(parallel-CR), 2(parallel-LR), 3(series-CR), or 4(series-LR)</td>
<td>4 (2bits)</td>
</tr>
<tr>
<td>Resistance of the radiation impedance</td>
<td>R</td>
<td>$10^{-1} - 10^{3},\Omega$</td>
<td>512 (9bits)</td>
</tr>
<tr>
<td>Inductance or capacitance of the radiation impedance</td>
<td>LC</td>
<td>$10^{-15} - 10^{-10},\text{H or F}$</td>
<td>512 (9bits)</td>
</tr>
<tr>
<td>Characteristic impedances of the slot line</td>
<td>$Z_{\text{slot}}$</td>
<td>$50 - 150,\Omega$</td>
<td>128 (7bits)</td>
</tr>
<tr>
<td>Effective relative permittivity of the slot line</td>
<td>$\varepsilon_{\text{eff},\text{slot}}$</td>
<td>$1 - 3$</td>
<td>128 (7bits)</td>
</tr>
</tbody>
</table>

$V_{\text{calc}}(\text{Cir}, R, LC, Z_{\text{slot}}, \varepsilon_{\text{eff},\text{slot}}, t) = \int_{0}^{T} F^{-1}(S_{11}) \, dt$, \hspace{1cm} (6)

where $F^{-1}$ shows inverse Fourier transformation.

The reflection waveform for a step pulse is obtained experimentally by using a time-domain reflectometer (TDR). Let $V_{\text{meas}}(t)$ be an experimentally-obtained waveform for a period $T$. The minimum square error $E_{\text{val}}$ can be defined by the following equation:

$E_{\text{val}}(\text{Cir}, R, LC, Z_{\text{slot}}, \varepsilon_{\text{eff},\text{slot}}) = \int_{0}^{T} (V_{\text{meas}}(t) - V_{\text{calc}}(\text{Cir}, R, LC, Z_{\text{slot}}, \varepsilon_{\text{eff},\text{slot}}, t))^2 \, dt$ \hspace{1cm} (7)

A genetic algorithm finds the $\text{Cir}$, $R$, $LC$, $Z_{\text{slot}}$, and $\varepsilon_{\text{eff},\text{slot}}$ so as to achieve the minimum $E_{\text{val}}$:

$E_{\text{val}}(\text{Cir}, R, LC, Z_{\text{slot}}, \varepsilon_{\text{eff},\text{slot}}) \rightarrow 0$ \hspace{1cm} (8)

When the $E_{\text{val}}$ becomes small enough, an optimized $\text{Cir}$, $R$, $LC$, $Z_{\text{slot}}$, and $\varepsilon_{\text{eff},\text{slot}}$ indicate the type of equivalent circuit and the parameters.

3 Experiments

3.1 Model

We conducted an experiment to discuss the validity of our method. We made the PCB models shown in Fig. 1(c), which were of a glass-epoxy material (FR4) with a permittivity of 4.7 and a thickness of 1.6 mm. The width of the pattern trace was 3 mm. Therefore, the characteristic impedance was about 50 $\Omega$. The width of the slot was 1 mm, and was in orthogonal directions to the pattern trace. SMA connectors were attached to the ends of the trace through vias.

3.2 TDR Measurement

One terminal of the strip line was excited by a step pulse at a rise time of 45 ps, with a repeat late of 20 ms and an amplitude of 200 mV. The other terminal was ended with a 50-$\Omega$ load. A digitizing oscilloscope of bandwidth 20 GHz and equivalent sampling interval 1.22 ps was used to acquire the waveforms at the feeding terminal. The obtained waveform is shown in Fig. 4.

3.3 Execution of GA

Based on the experimental waveform, the GA found unknown parameters. The possible ranges of the parameters and the divisions of those ranges are shown in Table 1. For example, based on the $\varepsilon_{\text{eff},\text{slot}}$, the GA searched between $\varepsilon_{\text{eff},\text{slot}}=1$ and $\varepsilon_{\text{eff},\text{slot}}=3$ with step (3-1)/128=0.015748. Because the $\varepsilon_{\text{eff},\text{slot}}$ was divided in the $128 = 2^7$ steps, the genes based on the $\varepsilon_{\text{eff},\text{slot}}$ consisted of 7 bits. The total genes consisted of $2 + 9 + 9 + 7 + 7 = 34$ bits. After 10,000 iterations, the evaluation function converged through mutations and crossovers. The calculation time was 74 seconds with a 2.4 GHz processor. Figure 3 shows the transient of the evaluation function and candidate values.

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The best-fitted parameters are shown in Table 2. The waveform calculated by the obtained parameters is shown in Fig. 4. In the period 1.2 to 1.5 nS, the experimental values did not agree with the calculated ones. We think that the divisions should be enhanced.

### 4 Conclusion

We described a method for finding an equivalent circuit and its parameters for a slot in a ground plane, where a signal line crosses, using a genetic algorithm. Experiments show the potentiality of using a GA for EMC modeling based on our results. Based on EMC modeling, selecting an equivalent circuit and the parameters for it has traditionally depended on the person’s skill. Though by using this method, the selection can be done automatically.

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### REFERENCES