Estimation of Current Distribution on Multi-layer Printed Circuit Board by Near-field Measurement

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Abstract

A method to estimate the current distribution on multi-layer printed circuit board (PCB) by measuring the near-field distribution is proposed. Microstrip transmission line on the PCB is divided into segments which are small compared with the wavelength. An electric field integral equation (EFIE) is established to relate the near-field to the current on these segments. The current is estimated by measuring the near-field, evaluating the mutual impedance between the current segments, and solving the EFIE. Experimental results are presented and compared with the numerical results confirming the validity of the proposed method.

1. Introduction

The problem of electromagnetic interference between the electric circuits and devices becomes more and more serious because the clock frequency of the electric circuits is increasing greatly, and the high-density packaging and multi-layer printed circuit board (PCB) technologies are widely applied to the PCB design. When the problem occurs in an electric device, it is required to know the electric current distribution on the PCB of the electric device in advance, in order to identify the location where the undesired electromagnetic wave is radiated to take measures against the interference by revising the PCB design or using shielding techniques.

The current distribution on PCB can be measured directly by using a magnetic probe such as a small loop antenna. However, it is difficult to estimate the current distribution of the multi-layer PCB because the measured magnetic field is produced by not only the current flowing on the top layer but also that on other layers under the probe. Therefore, it is required to distinguish the radiation caused by the current on different layers.

In the previous related researches, the equivalent source approach has been studied [1]-[7]. This approach was originally used to calculate the radiation from aperture antennas where the aperture of antennas was replaced by equivalent magnetic currents located at equally spaced meshes of a 2-dimensional plane in [1]-[3]. The electric current was then used as the equivalent source in solving the radiation problem of aperture sources [4]-[5]. In these researches, a coupling equation was established between the electric field radiated by the equivalent currents and the value of the equivalent currents by using the free space Green's function. The value of equivalent current was evaluated by measuring the near electric field and solving the coupling equation. A uniform wire-mesh composed of magnetic dipoles was used as equivalent source to investigate radiation of small printed antennas [6], and the method was then improved by using a Tikhonov regularization technique [7]. The near field radiated by the magnetic dipoles was evaluated analytically and the current distribution on the wire-mesh was obtained by measuring the near magnetic field and solving the analytical equation reversely. The equivalent source is an effective method to evaluate far field by measuring near field distribution of a radiation source. However, although the current of the equivalent source can be evaluated, real current distribution on the radiator, such as the PCB, is still unknown.

The objective of present study is to estimate the current distribution on the microstrip transmission lines on different layers of a multi-layer PCB. In this research, the PCB is assumed to be composed of microstrip lines and lumped circuit elements. The current on the microstrip line is divided into electric current segments with unknown magnitude and phase. Because of the presence of the dielectric substrates and complicated structure of the microstrip lines, the coupling equation between the radiated field and the expanded electric currents is evaluated by finite differential time-domain (FDTD) method which is an effective full-model analysis method for easily modeling various configurations of the PCB. The unknown current segments are evaluated by measuring near-field and calculating coupling equation.

2. Approach

Let us consider a general case of a multi-layer PCB, as shown in Figure 1, which has two layers and some lumped elements are implemented on the microstrip transmission line. The objective is to estimate the current flowing on the transmission line of both the top layer and the middle layer.

The model of the multi-layer PCB for current estimation is shown in Figure 2. All the lumped elements are removed because they do not radiate electromagnetic field. The microstrip transmission line is divided into current segments which are electrically small. When the current on each segment has a distribution of $\mathbf{f}_j(r)$, the current distribution on the transmission line is expanded in terms of the expansion function as

$$\mathbf{I}(\mathbf{r}) = \sum_{j=1}^{N} I_j \mathbf{f}_j(\mathbf{r}) \tag{1}$$

where I_j is the unknown coefficient to be evaluated, N is the total number of the divided segments, and the expansion function $\mathbf{f}_j(r)$ is a pulse function, expressed as

$$\mathbf{f}_j(\mathbf{r}) = \begin{cases} 1, & \mathbf{r} \in \text{segment } j \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

The electric field integral equation (EFIE)

$$\mathbf{E}(\mathbf{r}) = \int \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{I}(\mathbf{r}') d\mathbf{r}' \tag{3}$$

is introduced to relate electric near-field $\mathbf{E}(\mathbf{r})$ to the current $\mathbf{I}(\mathbf{r})$ on these segments, where $\bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}')$ is dyadic Green's function satisfying the boundary condition of the multi-layer substrate. If the electric near-field is measured, the current can be evaluated when the Green's function is known.

The equations

$$V_i = \sum_{j=1}^{N} Z_{ij} I_j \qquad (i = 1 \sim M) \tag{4}$$

can be derived by combining Equation (1) to (3), where Z_{ij} is the mutual impedance between the jth current segment $\mathbf{f}_j$ and the dipole probe at ith position, which is required to be evaluated numerically. V_i is the voltage received by the dipole probe at each measuring point i, and M is the number of the measuring points.

Because the structure of the PCB is usually complicated in practice, Z_{ij} is hardly expressed by using an analytical closed form because of the complicated dielectric substrate. In this research, Z_{ij} is evaluated numerically using the FDTD method. Figure 3 shows the analysis model for FDTD analysis. For a current segment i having distribution of $\mathbf{f}_j$ with unit coefficient, the radiated tangential components of electric field at the Yee cells inside the scan plane where the near-field is measured by the dipole probe are calculated and stored in advance. The FDTD calculation is performed N times until the radiated field on the scanning plane for all the current segments are obtained. The impedance matrix in Equation (4) is evaluated by

$$Z_{ij} = \frac{1}{I_j} \sum_{k=1}^{K} \int \mathbf{E}_k(\mathbf{r}) \cdot \mathbf{w}_i(\mathbf{r}) d\mathbf{r} \tag{5}$$

in the sense of reaction between the probe at position of i and the current segment j, where $\mathbf{w}(r)$ is a piecewise sinusoidal function expressing the current distribution on the dipole probe, K is number of Yee cells included in the dipole surface, and the integration is carried out along the dipole to evaluate the received voltage. Figure 4 shows positions of the probe and Yee cells to describe how the electric field radiated by current segment j is coupled by the probe at position of i.

Because V_i is obtained from the measurement and Z_{ij} is calculated, the unknown current coefficients I_j can be obtained

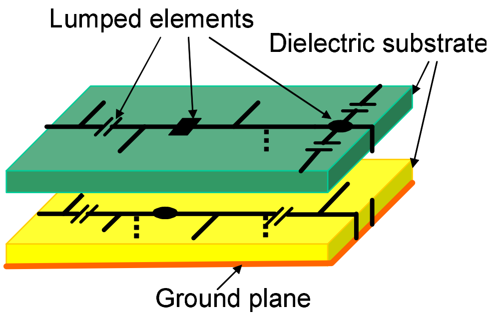

Fig. 1: Multi-layer PCB.

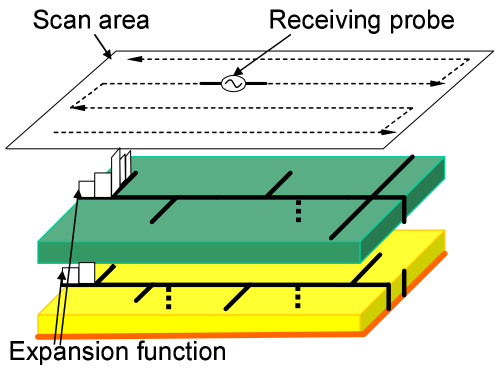

Fig. 2: Expansion of current on transmission line and near-field measurement area.

by solving the equation (4), which is expressed in a matrix equation form as,

$$[\boldsymbol{Z}][\boldsymbol{I}] = [\boldsymbol{V}] \tag{6}$$

where $[Z]$ is a $M \times N$ impedance matrix, $[I]$ is a N element vector and $[V]$ is a M element vector. Usually, the number of measurement points M is larger than the number of segments N. Therefore, the matrix equation is solved by using generalized matrix inversion as,

$$[I] = ([Z]^H [Z])^{-1} [Z]^H [V] \qquad (M \geq N) \tag{7}$$

where $[Z]^H$ is Hermitian conjugate matrix of $[Z]$.

3. Measurement Results

A 2-layer PCB is used as the PCB model for current estimation whose geometry is shown in Figure 5 and Table 1. Figure 6 shows the microstrip configuration on each layer. Figure 7 shows the location number of the current segments on the microstrip line. Current segments from 1 to 16 correspond to the current on the microstrip line of the middle layer, and current segments form 17 to 28 correspond to the current on the microstrip line of the top layer. The microstrip line is excited by a voltage of continuous wave at 1.5 GHz between

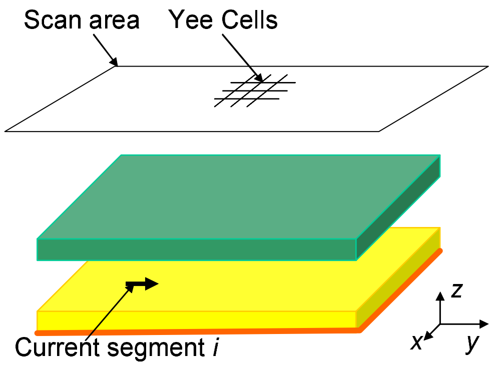

Fig. 3: FDTD analysis model for evaluating tangential electric field on probe scanning area radiated by a current segment i.

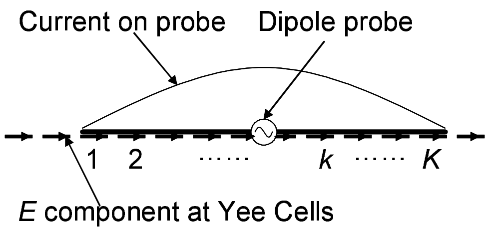

Fig. 4: Positions of probe and Yee cells.

the ground and the segment 17 on the top layer, while the microstrip line on the middle layer is not fed directly and the current on this layer is generated by the electromagnetic coupling with current on the top layer. Of course, the feed position is an unknown information which is not required in the estimation procedure.

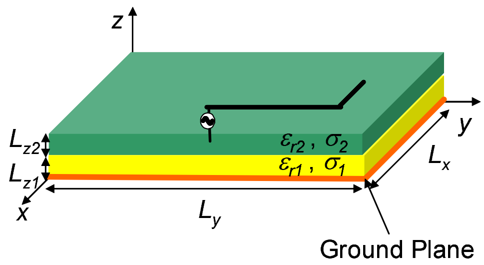

Fig. 5: 2-layer PCB for experiment of current estimation.

TABLE 1: CONFIGURATION OF 2-LAYER PCB SHOWN IN FIGURE 5.

frequency [GHz]	1.5
L_x, L_y, L_{z1}, L_{z2} [λ]	0.5, 0.5, 0.002, 0.016
ε_{r1}, ε_{r2}	4.4, 4.4
σ_1, σ_2 [S/m]	2.13×10^{-3}, 2.13×10^{-3}

The scanning plane for the near field measurement is shown in Figure 8. The dipole probe has a total length of $2l_p$ and the

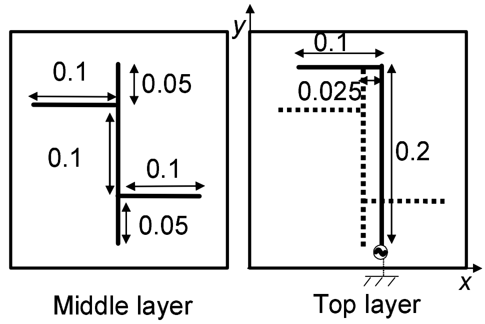

Fig. 6: Geometry of microstrip line on each layer in 2-layer PCB shown in Figure 5.

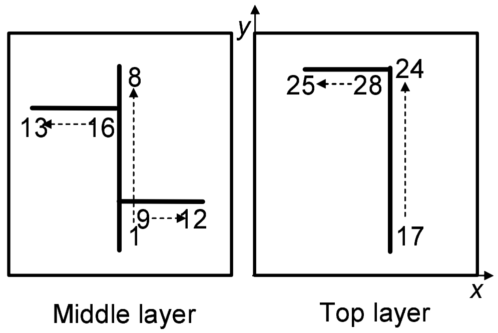

Fig. 7: Current segment number on microstrip line of 2-layer PCB shown in Figure 5.

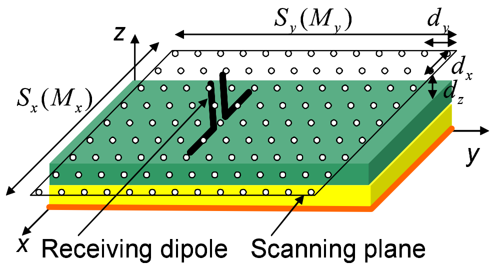

Fig. 8: Geometry of scanning plane for measuring near-field above the PCB.

radius of b. The distance between the surface of top layer and the scanning plane is d_z. The scanning plane has an area of $S_x \times S_y$ corresponding to scan points of $M_x \times M_y$. The interval of the measuring points are d_x and d_y in x and y directions, respectively. The received signal by the probe dipole is modulated with optical carrier and is transmitted to a demodulator through an optical fiber instead of RF cable to reduce the interference to the measured current distribution.

The measurement parameters are shown in Table 2

Figure 9 shows the relative magnitude of the estimated current distribution. FDTD solution of the current distribution is also plotted for comparison, where the feed point is assumed

TABLE 2: MEASUREMENT PARAMETERS FOR CURRENT ESTIMATION OF PCB.

L_x, L_y [λ]	0.3, 0.3
M_x, M_y	13, 13
l_p [λ]	0.2
d_z [λ]	0.025

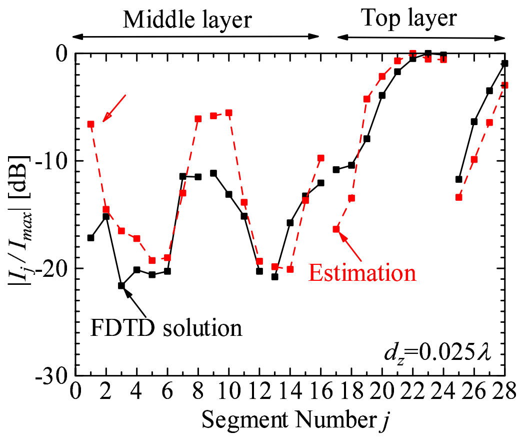

Fig. 9: Relative magnitude of estimated current distribution.

to be known. A acceptable agreement is obtained for most current segments. The Error on segments 1 and 17 is relatively large because the position of the two segments is near the feed point which is not considered in the estimation model. The current distribution at the discontinuous points near junction of stubs is hardly estimated accurately because the complicated near-field distribution at these points is difficult to be measured accurately. The accuracy of the estimated current on the middle layer suffers the measurement error of the near-field easily because electromagnetic coupling between the middle layer and the top layer is weak, and a small error on the received voltage can cause a large relative error on the estimated current on the middle layer.

4. SUMMERY

A method to estimate the current distribution by measuring the near-field distribution has been proposed and applied to estimation of current distribution on the microstrip transmission lines on a multi-layer PCB. Current distribution of a 2-layer microstrip line has been estimated experimentally, and the experimental results have been compared with the numerical solution to confirm the validity of the method. The present method is practicable because the physical location and configuration of microstrip lines and the lumped circuit elements on the PCB are usually known information in practice.

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