Hybrid Approach of SPM and Matrix-Inversion to Estimate Current Distribution of High-Oder Mode

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1. Introduction

Problems of electromagnetic interference (EMI) between electronic devices are becoming more and more serious because operating clock frequency of electronic devices is increasing rapidly and high-density printed circuit board (PCB) technologies have been widely applied to the PCB design for the past few years. In order to suppress the EMI between electronic devices, it is important to know electric current distribution which causes the EM radiation in advance. The electric current on the PCB can be classified into two types, i.e. common-mode and differential-mode current [1], [2]. The common-mode current causes the EM radiation, but the differential-mode current does not because of the cancellation of inverse phases of the current distribution. Consequently, phase information of the currents on PCB is as important as the amplitude information when detecting source positions of the EMI. Therefore, it is necessary to estimate both the amplitude and the phase of current distribution on the PCB.

Many approaches to estimate current distribution on PCB have been studied [3]-[5]. One of the methods is the SPM method, which was further improved and demonstrated numerically by estimating location of multiple current sources with phase difference in [6]. However, the method was only valid in detection of current distribution of the basic harmonic mode, where it was assumed each current had a constant phase distribution.

In this report, a new hybrid approach which combines the SPM method and the matrix-inversion method is proposed to enhance the capability of the SPM method to detect the amplitude and phase information of current distribution of high-order mode, where phase variation occurs in each current source. The experimental results are compared with the numerical results to show the accuracy of the estimation. Firstly, the SPM method and the hybrid method are described in details in Section 2. Parameters of analysis and experimental results are given in section 3 and finally the conclusion is drawn in Section 4.

2. Hybrid Approach for Estimating Current Distribution

Let us consider electronic circuits or devices, which look like a combination of electric current sources (actual sources) in terms of radiation as illustrated in Fig. 1. Electric field on a measurement plane above the electronic circuit is measured using a near-field measurement system. The electric field radiated by the actual sources at i^{th} measurement point on the measurement plane is denoted by e_i and the electric field distribution can be then expressed in a vector form as

$$\mathbf{E} = [e_1, e_2, \cdots, e_i, \cdots, e_M]^T, \qquad \ldots (1)$$

where M is total number of the measurement points and T represents transpose operation of the matrix. Next, we consider a virtual volume consisting of many small hypothetical current sources as shown in Fig. 2. The sources are located uniformly in the volume. Total number of sources is N^{tot}. The notation f_{ij} is used as the electric field which is radiated from the j^{th} hypothetical current source and received at the i^{th} measurement point. Electric field distributions created by all hypothetical current sources at the measurement plane can be obtained numerically via numerical or analytical method and they can be expressed in a compact form as

$$\mathbf{F}_j = [f_{1j}, f_{2j}, \cdots, f_{ij}, \cdots, f_{Mj}]^T. \qquad \ldots (2)$$

A. *SPM Method*

The SPM method is used to estimate the current distribution by finding a set of equivalent current sources which radiate an identical electric or magnetic field distribution with the measured one. The correlation coefficient of the measured electric fields (**E)** and the calculated one (**F**$_j$) are evaluated. The correlation coefficient, determining similarity between the measured and the calculated field distributions on the measurement plane, is expressed as

$$P_{\mathrm{SPM}}(\theta_h) = \arg\max\left\{ \frac{\langle \mathbf{E}, \mathbf{G}(\theta_h) \rangle}{\sqrt{\langle \mathbf{E}, \mathbf{E} \rangle}\sqrt{\langle \mathbf{G}(\theta_h), \mathbf{G}(\theta_h) \rangle}} \right\}, \quad \mathbf{G}(\theta_h) = \left(\mathbf{F}_j + \sum_{j'=1}^{N'} \mathbf{F}_{j'} \right) e^{j\theta_h}, \quad \ldots (3)$$

where $j \in (\Omega - \Omega')$ and $j' \in \Omega'$, Ω and Ω' are sets of the hypothetical current sources and the selected ones, respectively. P_{SPM} is the correlation coefficient, **E** is the measured field distribution given by (1) and **F**$_j$ is the electric field distribution created by the hypothetical current source that has not yet been selected in the calculation. **F**$_{j'}$ is the electric field distribution created by the hypothetical current sources that have been already selected in the previous calculation step. θ_h represents phase of hypothetical current sources.

In the process of estimating locations of the equivalent current sources, a hypothetical current source having the maximum correlation coefficient of the calculated field **F**$_j$ with the measured field **E** is selected as the equivalent current source in each calculation step. N' is the number of selected hypothetical current sources at the present step of the calculation. The selection process of the equivalent current sources continues until the number of selected current sources reaches to the number of N_s.

B. *Hybrid approach of SPM and matrix-inversion method*

In the original SPM method, amplitude of all the hypothetical current sources is assumed to be the same. To find the real amplitude of equivalent current sources and estimate strength of radiated EM fields, the SPM method is combined with the matrix-inversion method. The procedure of estimation is as follows.

1. The correlation coefficients when phase of hypothetical current sources is varied from 0° to 360°, are determined according to the procedure of the SPM method described in subsection A.
2. The equivalent current sources associated with the maximum or peak of the correlation coefficients are utilized as new current sources in the matrix-inversion method. The number of current sources is reduce to N^h, where $N^h << N^{tot}$.
3. Amplitude and phase of equivalent current sources are then determined by solving the following matrix equation by matrix inversion:

$$\sum_{j=1}^{N^h} Z_{ij} I_j = V_i, \qquad (i = 1, 2, \ldots, M) \qquad \ldots (4)$$

where, Z_{ij} represents mutual impedance between the i^{th} probe and j^{th} equivalent current source, V_i denotes measured voltage at i^{th} probe, I_j denotes coefficient of j^{th} equivalent current source to be solved, M and N^h are number of measurement points and equivalent current sources obtained from the SPM method, respectively. Although the matrix-inversion method gives an inaccurate result due to the ill-posed nature of the matrix when the number of equivalent current sources increases, this problems can be alleviated by reducing the number of coefficients to be determined via the SPM method.

3. Experimental Parameters and Results

Current distribution of TM_{12} mode of a patch antenna is detected at frequency of 2.2 GHz in the experiment. Dimensions of the patch antenna are shown in Fig. 2 (left). A rectangular metal plate with the size of 136 x 144 mm was placed at h_p = 9 mm from the larger ground plate. Measurement plane of electric field is 0.1λ above the first plate, where λ is the wavelength at 2.2 GHz. Size of measurement area and estimation area is 30 x 30 cm. Spacing between two measurement points is kept to be 0.073λ. Hypothetical current sources are virtually placed on the plane of small metal plate. The effect of the ground plane is taken into consideration by placing images of current sources with opposite directional vector of the actual currents on the plane at $-h_p$. Parameters of hypothetical current sources are summarized in Table I.

Table I. Parameters of hypothetical current sources (λ @ 2.2 GHz).

Spacing between hypothetical current sources	0.03λ
Length of hypothetical current sources	0.03λ
Number of hypothetical current sources	34 x 34 = 1156
Phase of hypothetical current sources	$\theta_h = -180^o \sim 180^o$
Number of selected equivalent current sources	$N_s = 100$

Experiment setup of near-field measurement is shown in Fig. 2 (right). A small dipole probe with an optical modulator is used as the receiving probe. The signal received by the probe is then modulated by the optical modulator and delivered to an optical/electrical demodulator through an optical fibre instead of a coaxial cable to reduce the electromagnetic disturbance of the cable to the measured electric field distribution. A network analyzer is used to feed the measured device and receive the signal from the dipole probe.

Fig. 3 (left) shows the correlation coefficients calculated by the SPM method using experimental and numerical electric field distributions. The numerical field distribution above the patch antenna was calculated by Finite-Difference Time-Domain (FDTD) method [4], while the experimental one was obtained by actual measurement using the experiment setup as described. It is obvious that peaks of correlation coefficients locate at $\theta_h = 40^o$ and $\theta_h = -150^o$, which correspond to the actual phase of current distribution on the patch antenna. It is also shown that the simulation result has a good agreement with the experimental result, which implies that the SPM method has a good accuracy of prediction. Fig. 3 (right) shows the equivalent current distribution obtained by the SPM method when $\theta_h = 40^o$ and $\theta_h = -150^o$. It is found that locations of selected equivalent current sources are almost the same with that of the actual sources and current distributions of two modes are obviously observed. Figs. 4 (left) and (right) show the current distributions obtained by the hybrid method and numerically calculated by the FDTD method. It is shown that amplitude of currents has a peak at the place around feeding point, which agrees with that obtained by the FDTD method.

4. Conclusions

A new hybrid approach of combining the SPM and the matrix-inversion method to estimate current distribution of high-order mode has been proposed. It was shown that the current distribution can be estimated by using the hybrid approach with a moderate accuracy. The hybrid method gives a robust way to estimate current distribution of high-order mode, providing an approach to detect the source for EM radiation on PCB.

References

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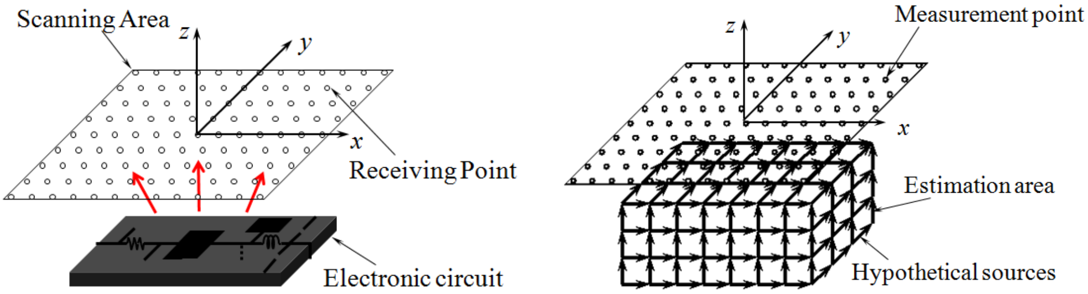

Figure 1: Measurement model (left) and equivalent problem (right).

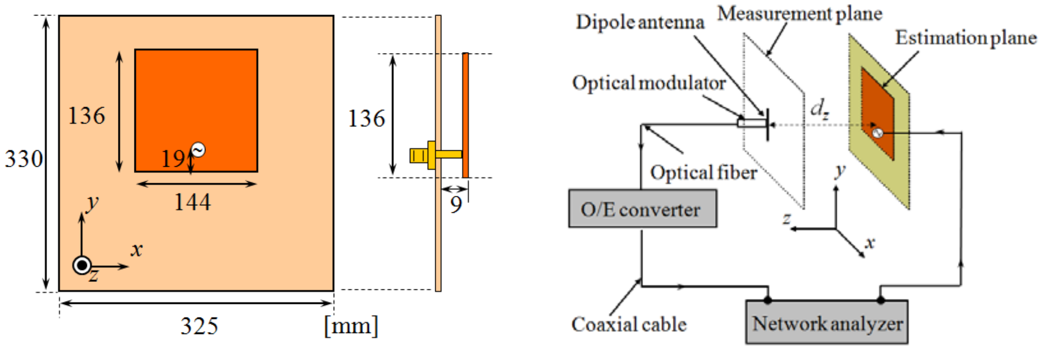

Figure 2: Rectangular patch antenna as a DUT (left) and experiment setup of near-field measurement (right).

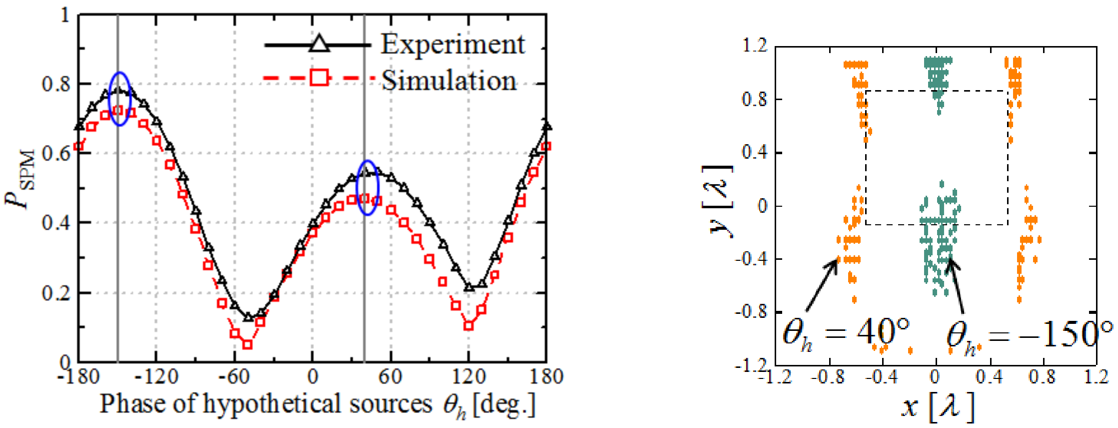

Figure 3: Correlation coefficient (left) and current distribution (right) estimated by SPM method.

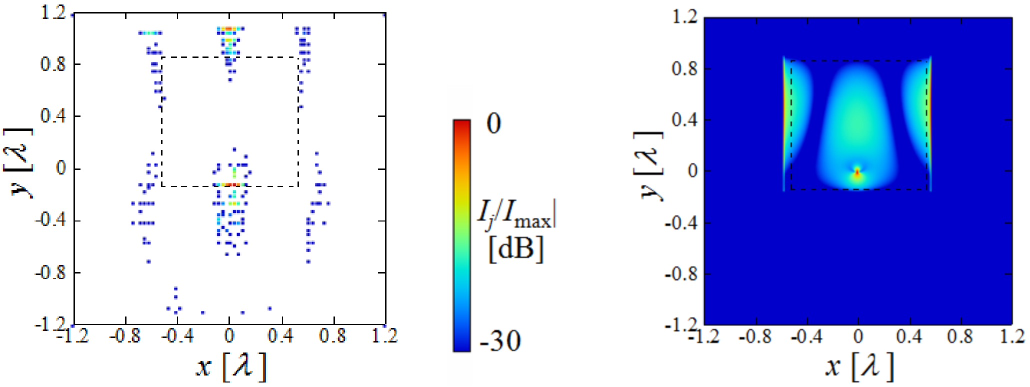

Figure 4: Current distribution estimated by hybrid method (left) and calculation results by FDTD method (right).