

# Estimation of Current Distribution on Multiple Coherent Sources by Using Improved SPM Method

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**Abstract** In this paper, the *improved sampled pattern matching* (SPM) method is proposed. The method is based on the substitution of the original device by an equivalent set of small current sources, which radiate the same near-field. The correlation coefficient, which determines the similarity between the measured field and calculated field in the improved SPM method, does not require the absolute operation so that the phase term of equivalent sources is also taken into account. The validity of proposed method is shown by performing the estimation of the locations of two coherent EM sources with different initial phases. The results show that the improved SPM method can estimate accurately the location of current sources. Finally, the phase difference is also identified and compared with the experiment results to demonstrate the validity of the proposed method.

**Keywords** SPM method, correlation coefficient, source identification, phase difference

## 1 Introduction

The problem of electromagnetic interference between electrical circuits and devices is becoming more and more serious because the clock frequency of the electrical circuits is increasing rapidly and high-density printed circuit board (PCB) technologies are widely used in most of the electronic devices nowadays. In order to suppress the electromagnetic interference between the devices, it is necessary to know the electric current distribution on the electronic circuits in designing the electronic devices. The currents on a PCB can be a common-mode currents or a differential-mode currents [1, 2]. The common-mode current are actually radiating higher electromagnetic noise than differential-mode current. Consequently, the phase information of current in a PCB have to be retrieved accurately by current-estimation approach from the measured near-field.

The current-estimation approaches which the distribution of current sources are estimated by finding the equivalent current sources which radiate identical electric- or magnetic-field distribution compared to the measured results have been proposed in many way. Regué used a genetic algorithm to generate equivalent set of current sources (referred as elemental dipoles) and calculated the far-field from the determined radiating sources [3]. Despite a genetic algorithm can reduce the local minimum trap, the computational cost of this approach is quite expensive. The approach called the *sampled pattern matching* (SPM) method is proposed by Saotome et. al. [4]. The SPM method is a technology used to create the magnetoencephalograph in the field of biological magnetism in which the frequency of signals is actually not much high. The SPM method has also been used in the high-frequency application such as the estimation of unrequired electromagnetic sources in the electronic devices [5]. In the SPM method, the current source distribution is found

by selecting one by one the equivalent current source which has the largest correlation coefficient between the measured field and the radiated fields from equivalent sources. However, the estimation of equivalent current sources is difficult when phase difference between emission sources exists in the conventional SPM method because the phase information of sources is destroyed by the absolute operation of complex correlation coefficients. This problem can be improved by using the scalar correlation coefficient instead of the complex one so that the phase term of equivalent current source can be taken into account.

The SPM method is improved in this paper, which is capable of estimating equivalent current sources with phase difference between two EM emission sources exists. The theoretical basis for the SPM method and improved SPM method is detailed in Section II. Parameter of calculation and analysis model are presented in Section III. The results by conventional SPM method and improved SPM method are compared and discussed in Section IV. Finally, the conclusion is given in Section V.

## 2 Theory

Let us consider an electronic circuit or device radiating the electromagnetic field into free space as illustrated in Fig. 1. For the planar scanning case, the near-field measurement is performed over a planar surface assumed to be parallel with the source plane. The electric field at each receiving point can be calculated by the numerical method or measured by the practical measurement method. The electric field radiated from the current source to the receiving point  $i$  is denoted by  $e_i$ . The field distribution at the measurement plane is then expressed in the vector form

$$\mathbf{E} = [e_1, e_2, \dots, e_i, \dots, e_M]^T, \quad (1)$$

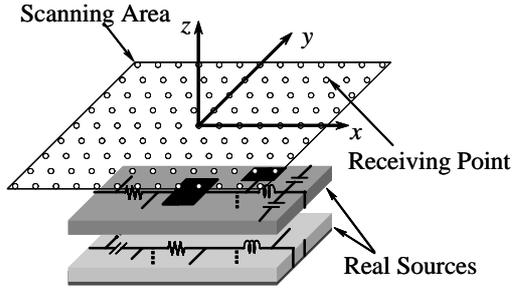


Figure 1: Planar Scanning model for electric field measurement.

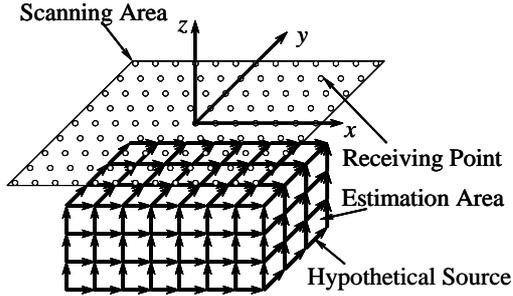


Figure 2: Arrangement of hypothetical current sources in the estimation area.

where  $M$  is the total number of receiving points,  $T$  is the transpose operation of matrix. The method of moments (MoM) [6] is used to calculate electric fields at every receiving point.

Next, let us consider the estimation area which encompass the current sources as shown in Fig. 2. The hypothetical current sources are placed uniformly into the estimation area along the  $x$ ,  $y$ , and  $z$  direction respectively. The total number of hypothetical current sources is then  $N=N_x \times N_y \times N_z$ . The electric field distributions, which are created by the hypothetical current sources at the scanning plane, is calculated from the method of moments. Using the notation  $f_{ij}$  for the electric field radiated from the hypothetical current source  $j$  into the receiving point  $i$ , the electric field distribution created by the hypothetical current source  $j$  is then expressed as

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

## 2.1 SPM method

During the process of the estimation of equivalent current sources in SPM method, the hypothetical current source, which shows the maximum correlation coefficient calculated by the similarity of the measured electric fields and calculated electric fields at the scanning plane will be selected one by one. The total number of selected hypothetical current sources is set to  $N_s$ . The selection of hypothetical current sources is terminated when all of  $N_s$  current sources are selected. The correlation coefficient calculated from the calculated and

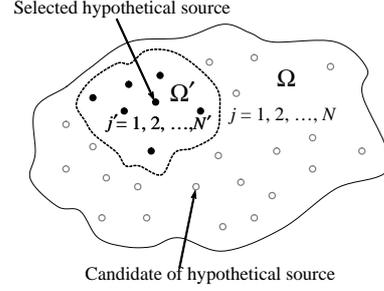


Figure 3: Set of hypothetical sources.

measured electric field distribution is expressed by using the Cauchy-Schwarz inequality. In the conventional SPM method, the correlation coefficient is determined as a result of complex inner product expressed as

$$P_{\text{SPM}} = \arg \max \left\{ \frac{|\langle \mathbf{E}, \mathbf{G} \rangle|}{\sqrt{\langle \mathbf{E}, \mathbf{E} \rangle} \sqrt{\langle \mathbf{G}, \mathbf{G} \rangle}} \right\}, \quad (3)$$

where,

$$\mathbf{G} = \mathbf{F}_j + \sum_{j'=1}^{N'} \mathbf{F}_{j'}, \quad (4)$$

$$j \in (\Omega - \Omega') \quad \text{and} \quad j' \in \Omega'.$$

where,  $P_{\text{SPM}}$  is the correlation coefficient calculated by the calculated and measured electric field distribution.  $\mathbf{F}_j$  is the electric field distribution calculated from the hypothetical current source that has not yet been selected in the process of estimation.  $\mathbf{F}_{j'}$  is the electric field distribution calculated from the hypothetical current sources that have been already selected in the previous turn of calculation.  $\Omega$  is a set of candidates of the hypothetical current sources as illustrated in Fig. 3.  $\Omega'$  is a set of selected hypothetical current sources.  $N'$  is the number of selected hypothetical current sources. The process of selection of the hypothetical current sources continues until  $N'$  reaches  $N_s$ . The inner product of complex vector in (3) is defined as follows.

$$\langle \mathbf{A}, \mathbf{B} \rangle = \sum_{i=1}^M a_i^* b_i \quad (5)$$

The inner product in (5) results in a complex value in the conventional SPM method. Consequently, the absolute value of numerator of (3) must be evaluated for the correlation coefficient. This causes the phase information of the electric field distribution radiated from the hypothetical current source to vanish in the above expression.

## 2.2 Improved SPM method

In the conventional SPM method, the phase of the electric field distribution is not taken into account because of the phase information is destroyed during the evaluation of absolute value for correlation coefficient. The inner product is then redefined to be determined as a

real value in the improved SPM method, i.e. the inner product is represented as follows.

$$\langle \mathbf{A}, \mathbf{B} \rangle = \sum_{i=1}^M \text{Re}(a_i^* b_i) \quad (6)$$

The absolute operation is not required in the proposed method. The correlation coefficient is then expressed as

$$P_{\text{SPM}}(k) = \arg \max \left\{ \frac{\langle \mathbf{E}, \mathbf{G}(k) \rangle}{\sqrt{\langle \mathbf{E}, \mathbf{E} \rangle} \sqrt{\langle \mathbf{G}(k), \mathbf{G}(k) \rangle}} \right\} \quad (7)$$

$$\mathbf{G}(k) = \left( \mathbf{F}_j + \sum_{j'=1}^{M'} \mathbf{F}_{j'} \right) e^{j\Delta\varphi} \quad (8)$$

where  $P_{\text{SPM}}(k)$  is the correlation coefficient when the phase of hypothetical current source is equal to  $\Delta\varphi$ . The phase term  $e^{j\Delta\varphi}$  of electric field distribution is also taken into account during the evaluation of correlation coefficient. By using the new definition of correlation coefficient, the phase of hypothetical current sources are fully taken into account in the estimation procedure.

### 3 Analysis model

Two half-wavelength dipoles with the  $y$ -polarization are placed in the estimation area as shown in Fig. 4. The parameters of the dipoles are indicated in the table 1. The phase difference between two current sources is  $120^\circ$  or  $\pi/3$  in radians. The analysis frequency is set to 2.42 GHz throughout all numerical experiments.

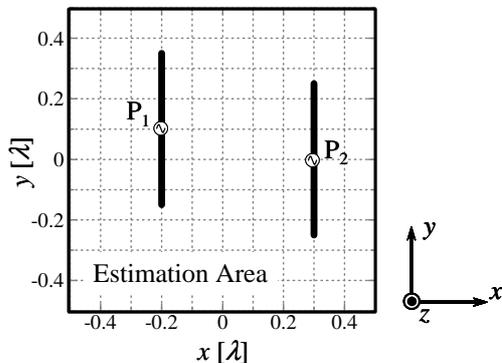


Figure 4: Location of real sources.

Table 1: Parameters of current sources.

feed location	P <sub>1</sub>	(-0.2λ, 0.1λ)
	P <sub>2</sub>	(0.3λ, 0)
initial phase	(θ <sub>1</sub> , θ <sub>2</sub> )	(0°, 120°)
analysis frequency	(f <sub>1</sub> , f <sub>2</sub> )[GHz]	(2.42, 2.42)

The analysis model for the estimation of the current source distribution is illustrated in the Fig. 5. The parameters for the analysis model are summarized in the

table 2. The measurement area is aligned in the  $x$ - $y$  plane and located at  $z = 0$ . The total measurement points  $M$  is  $15 \times 15 = 225$ . The  $y$ -polarized electric fields are only measured at each measurement point. The estimation area is assumed to be a plane parallel to the measurement area. The distance of the measurement area  $d_z$  is  $0.15\lambda$  far from the estimation area. Here, we define "SNR" (signal to noise ratio) to be the ratio between the maximum receiving voltage at  $d_z = \lambda$  and the receiving noise voltage. SNR is fixed to 20 dB in the calculations.

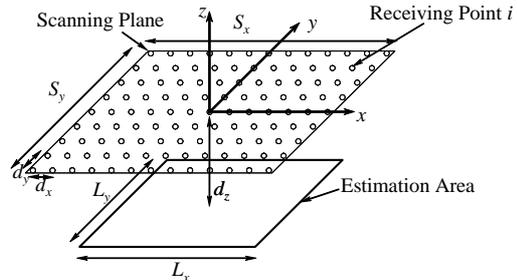


Figure 5: Simulation model.

Table 2: parameters of analysis model.

measurement area	( $S_x, S_y$ )	(1.05λ, 1.05λ)
total number of measurement points	( $s_x, s_y$ )	(15, 15)
space between measurement points	( $d_x, d_y$ )	(0.075λ, 0.075λ)
distance from source plane	$d_z$	0.15λ
length of current source	$l_s$	0.03λ
number of current sources	$N$	35 × 35 = 1225
phase of current sources	$\Delta\varphi$	0° ~ 360°
total number of selections	$N_s$	100

## 4 Results

In this section, the results obtained by conventional SPM method and improved SPM method are compared. The correlation coefficients are also calculated and used to estimate the location of equivalent current sources, and identify the phase difference between sources. Finally, the estimation results when the phase difference varied is shown and discussed.

### 4.1 Comparison between two SPM methods

The estimation result by using conventional SPM method is shown in the Fig. 6. It can be obviously seen that the location of the equivalent current sources do not coincide with the location of real emission sources. The hypothetical current sources nearby the source with initial phase of  $120^\circ$  have never been selected in

the estimation process because the conventional SPM method uses the absolute operation which destroys the phase information of the source with initial phase of  $120^\circ$ . Consequently, the conventional SPM method can not be applied to estimate the current source in this case.

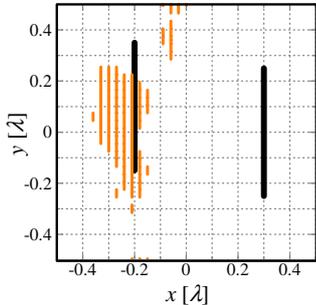


Figure 6: Estimation result by SPM method.

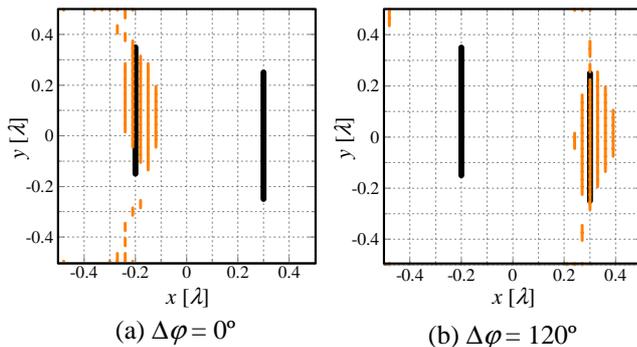


Figure 7: Estimation result by improved SPM method (left :  $k\Delta\varphi = 0^\circ$ , right :  $k\Delta\varphi = 120^\circ$ )

In the improved SPM method, the information of the phase term remains because the absolute calculation of the correlation coefficient is not performed. The results obtained when the phases of the hypothetical current sources are fixed to  $0^\circ$  and  $120^\circ$ , respectively, are demonstrated in the Fig. 7(a) and (b). As can be seen in Fig. 7, the location of equivalent current sources estimated coincide with the location of the real source with the initial phase corresponding to the phase of hypothetical source. If the phase of hypothetical current sources is fixed to  $0^\circ$ , the locations of selected equivalent sources coincide with the location of the real emission source which have the initial phase of  $0^\circ$ . Similarly, when the phases of hypothetical current sources are fixed to  $120^\circ$ , the distribution of the selected equivalent current sources which have the initial phase of  $120^\circ$  is obtained. Therefore, the equivalent sources are estimated in the way that the phase of hypothetical current sources are the same to that of the real emission sources.

## 4.2 Identification of phase difference between two sources

After all of the possible equivalent current sources ( $N' = N_s$ ) are selected in the estimation process, The resultant correlation coefficient  $P_{\text{SPM}}$  is used to identify the phase difference  $k\Delta\varphi$  between two sources. The phase of the hypothetical current source is varied from  $-180^\circ$  to  $180^\circ$  with the phase interval of  $30^\circ$ . The result of correlation coefficient is shown in the Fig. 8. It is obvious that the correlation coefficient reaches the peak when the phase of the hypothetical current sources is the same as the phase of real source and there are two peaks in the result which corresponds to the number of the real emission sources. Thus, the phase difference between any real sources can be estimated by determining the phase difference of hypothetical current sources which are used to calculate the correlation coefficient. So, the improved SPM method is proved to be applicable to estimate the location of sources with the distinct phases effectively.

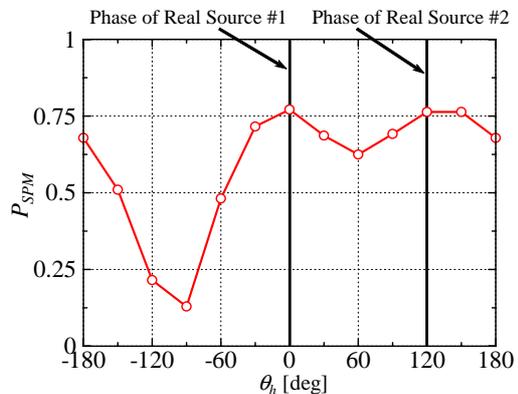


Figure 8: Correlation coefficients calculated by improved SPM method when the initial phases of sources are  $0^\circ$  and  $120^\circ$ , respectively.

## 4.3 Measurement using improved SPM method

To demonstrate the validity of the improved SPM method, the near-field measurements were done and the current estimation was performed. The near-field measurement system is shown in Fig 9. In the near-field measurement system, a dipole with an optical modulator was used as the probe. The signal received by the probe was modulated by an optical modulator and transmitted to an optical/electrical demodulator through an optical fiber instead of through a radio-frequency coaxial cable to reduce the interference with the measured current distribution. The dipole probe was moved by a planar scanner at a constant distance  $d_z$  between the probe and surface of the measured device. A network analyzer was used to feed the measured device and received the signal from the dipole probe. Two dipole antennas are used as a device radiating electromagnetic wave with different incident phase.

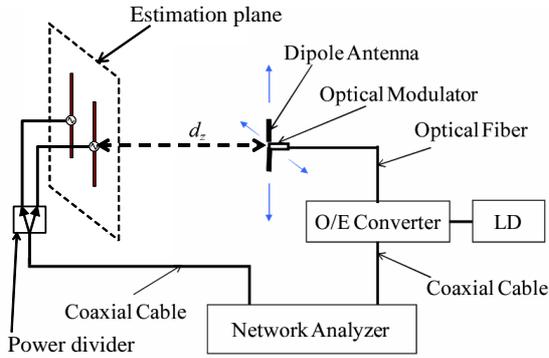


Figure 9: Near-field measurement system.

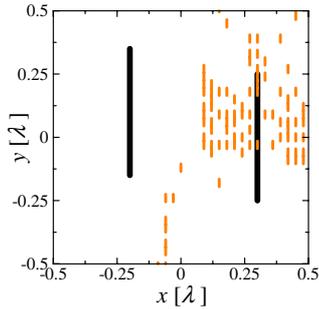


Figure 10: Estimation result by conventional SPM method.

The arrangement of dipoles is shown in Fig. 4. Two coaxial cables with different length are connected to the power divider at the output port of network analyzer and they are utilized to realize the phase difference between two dipole antennas. The parameters of current estimation is the same as described in the previous subsection and summarized in Table 1. The electric field distribution over the plane which is  $0.1\lambda$  far from estimation plane is measured by using optical modulating probe described in the section III. The measured field distribution are then used to estimate the location of current sources by using the improved SPM method.

The results of estimated location of current sources obtained by using conventional SPM method and improved SPM method are shown in Fig. 10, and Fig. 11, respectively. It can be seen that the the estimated location of current sources by using conventional SPM method do not coincident with the location of real sources, while the improved SPM method give a quite reasonable estimation results. Therefore, the validity of improved SPM method is demonstrated.

## 5 Concluding remarks

The improved SPM method is proposed and applied to estimate the locations of multiple sources with distinct initial phases. In the improved SPM method, the correlation coefficient is determined as a real value and the absolute operation is not required in the calculation.

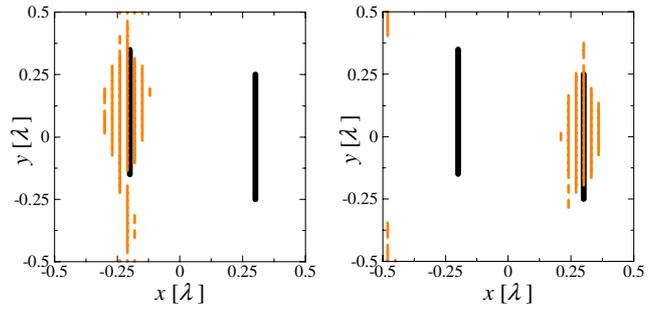


Figure 11: Estimation results by improved SPM method. (left:  $\theta_h = 0^\circ$ , right:  $\theta_h = -100^\circ$ )

Therefore, the phase term of the electric field distribution radiated by the hypothetical sources is taken account into the calculation of the improve SPM method. The phase difference between multiple sources is identified by the peaks of correlation coefficients calculated after all of the equivalent current source are selected in the estimation procedure. Finally, The locations of multiple sources with distinct initial phase have been estimated by using the numerical or experimental results and the phase differences between sources is identified, which confirms the validity of the improved SPM method.

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