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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.
Key words   SPM method, correlation coefficient, near-field measurement, current estimation

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 neccessary 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 current or a differential-mode cur-

rent [1], [2]. The common-mode current may be a source of electromagnetic noise, but the differential-mode current is never. Consequently, the phase information of current on a PCB is as important as the amplitude in recognizing the reason of electromagnetic interference. Therefore, it is necessary to estimate both the amplitude and phase of current distribution of a PCB.

In the previous studies, the equivalent source approach has been studied as the current estimation method [3]-[11]. The equivalent source approach was originally used to calculated the radiation from aperture antennas, which are replaced by the equivalent magnetic current located at equally spaced meshes of a two-dimensional plane [3], [4]. The electric current was also used as the equivalent source instead of the equivalent magnetic current to solve the radiation problem of aperture sources [5]. In these studies, 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. In [6], [7], the coupling equation between the radiated field and the expanded electric currents is evaluated by the finite-difference time-domain (FDTD) method, and the current distribution on the location-specific wire segments on the multilayer PCB is then estimated. The current distribution on the wire mesh or the unknown current segments are obtained by solving the matrix equation with direct inversion methods or iterative methods such as conjugate gradient method (CGM). However, the results are seriously sensitive to noises produced in the measurement system due to the fact that the matrix is almost ill-conditioned for the equivalent electric current approach. The distance between the estimation plane and measurement plane must be small enough to obtain a high signal-to-noise ratio (SNR) in order to give an accurate estimation results.

Another approach to estimate the distribution of current sources by finding the equivalent current sources which radiate the identical electric- or magnetic-field distribution compared to the measured results has been proposed. Regué used a genetic algorithm to generate equivalent set of current sources (refered as elemental dipoles) and calculated the far-field from the determined radiating sources [9]. Despite a genetic algorithm can reduce the local minimum trap, the computational cost of this approach is quite expensive. The *sampled pattern matching* (SPM) method is proposed by Saotome et. al. [10], which is a method used to create the magnetoencephalograph in the field of biological magnetism at low frequency. The SPM method has also been used in the high-frequency application such as the estimation of unrequired electromagnetic sources in the electronic devices [11]. 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 improved SPM method is proposed in this paper. The improved SPM method is capable of estimating equivalent current sources when the phase difference between two EM emission sources exists. The conventional SPM method and improved SPM method are introduced in Section II. The parametric study is performed for the effect of size of measurement plane, number of sampling points, phase defference to the estimation accuracy are discussed in Section IV. Finally, the conclusion is given in Section V.

2. SPM method and improvement

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 is measured over a plane parallel with the source plane. The electric field on the receiving point can be determined by the numerical method or be 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

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

where M is the total number of receiving points, T is the transpose operation of matrix. The method of moments (MoM) [12] 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
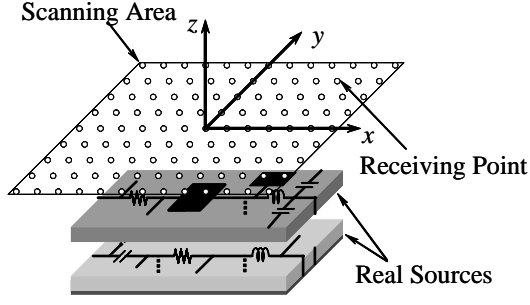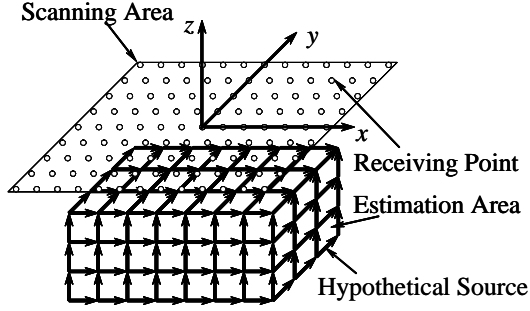
1   Planar Scanning model for electric field measurement.

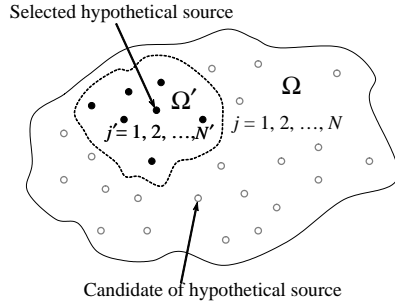2   Arrangement of hypothetical current sources in the estimation area.

3   Set of hypothetical sources.

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

2.1 SPM method

In the process of the estimation of equivalent current sources in SPM method, the hypothetical current source, which has the maxmimum correlation coefficient calculated by the similarity of the measured electric fields and calculated electric fields at the scanning plane will be selected out one by one. If the total number of selected hypothetical current sources is N_s, the selection of hypothetical current sources is terminated when all of N_s current sources are selected out. The correlation coefficient calculated from the calculated and 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

$$P_{\mathrm{SPM}} = \arg\max\left\{ \frac{|\langle \mathbf{E}, \mathbf{G}\rangle|}{\sqrt{\langle \mathbf{E}, \mathbf{E}\rangle}\sqrt{\langle \mathbf{G}, \mathbf{G}\rangle}} \right\}, \tag{3}$$

where,

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

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

where, P_{SPM} is the correlation coefficient between the electric field distribution created by a hypothetical current source and measured electric field distribution. $\mathbf{F}_j$ is the electric field distribution created by the hypothetical current source that has not yet been selected in the process of estimation. $\mathbf{F}_{j'}$ is the electric field distribution created by the hypothetical current sources that have been already selected in the previous turn of calculation. Ω is a set of candidates of the hypothetical current sources as illustrated in Fig. 3. Ω' 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.

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

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.

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

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

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

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

where $P_{\mathrm{SPM}}(k)$ 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 and results

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 $120°$ or $\pi/3$ in radians. The analysis frequency is set to 2.42 GHz throughout all numerical experiments.
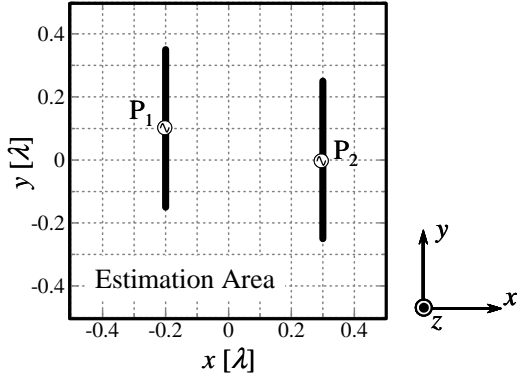

4　Location of real sources.

1　Parameters of current sources.

feed location	P_1	$(-0.2\lambda, 0.1\lambda)$
	P_2	$(0.3\lambda, 0)$
initial phase	(θ_1, θ_2)	$(0°, 120°)$
analysis frequency	(f_1, f_2)[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 and the hypothetical current sources are indicated in the table 2 and 3, respectively. 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 0.15λ 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.
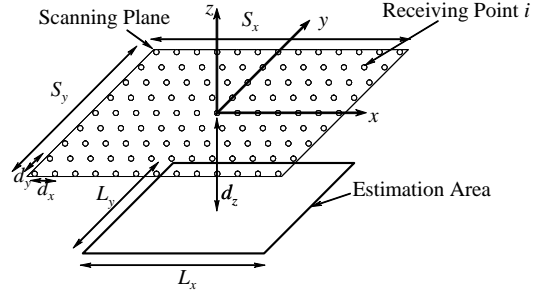

5　Simulation model.

2　parameters of analysis model.

measurement area	(S_x, S_y)	$(1.05\lambda, 1.05\lambda)$
total number of measurement points	(s_x, s_y)	$(15, 15)$
space between measurement points	(d_x, d_y)	$(0.075\lambda, 0.075\lambda)$
distance from source plane	d_z	0.15λ

3　parameters of hypothetical current sources.

length of current source	l_s	0.03λ
number of current sources	N	$35\times35 = 1225$
phase of current sources	$\Delta\varphi$	$0° \sim 360°$
total number of selections	N_s	100

3.1　Comparison between conventional and improved 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 $120°$ 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 intial phase of $120°$. Consequently, the conventional SPM method can not be applied to estimate the current source in this case.
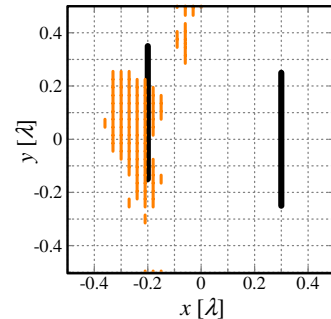

6　Estimation result by SPM method.

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
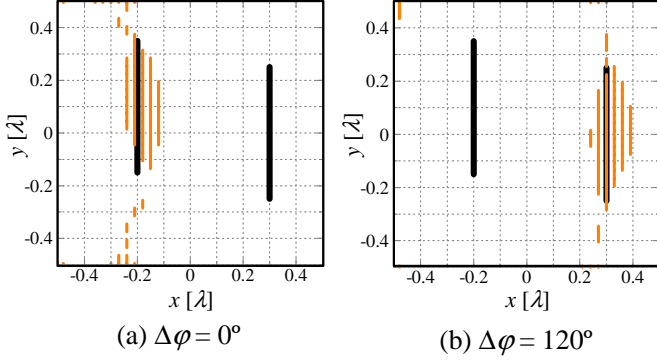
(a) $\Delta\varphi = 0^\circ$ (b) $\Delta\varphi = 120^\circ$

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

the phases of the hypothetical current sources are fixed to 0° and 120°, 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°, the locations of selected equivalent sources coincide with the location of the real emission source which have the initial phase of 0°. Similarly, when the phases of hypothetical current sources fixed to 120°, the distribution of the selected equvalent current sources which have the initial phase of 120° 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.

3. 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_{SPM} is used to identify the phase difference $\Delta\varphi$ between two sources. The phase of the hypothetical current source is varied from -180 to 180° with the phase interval of 30°. 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.

3. 3   Estimation results of phase difference

The estimation results, when the initial phase of first dipole is fixed to 0° and the initial phase of second dipole
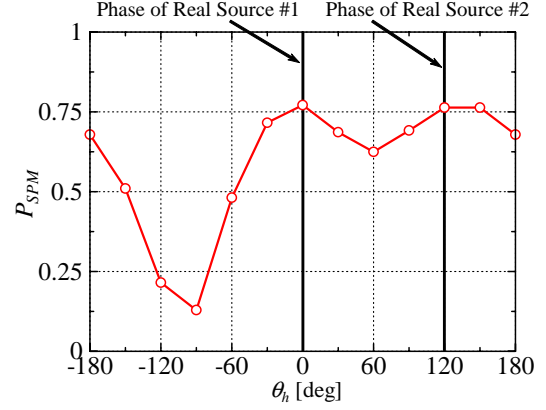

8   Correlation coefficients calculated by improved SPM method when the initial phases of sources are 0° and 120°, respectively.

is varied from 30° to 120°, is shown in Fig. 9. The parameters of analysis model (Table II) and the parameters of hypothetical current sources (Table III) are not changed except that the distance of measurement plane is fixed to 0.05λ instead of 0.15λ. The parameters of current source is summarized in Table 4.

4   Parameters of current sources.

feed location	P_1	$(-0.2\lambda, 0.1\lambda)$
	P_2	$(0.3\lambda, 0)$
initial phase	(θ_1, θ_2)	$(0^\circ, 30^\circ \sim 180^\circ)$
analysis frequency	(f_1, f_2)[GHz]	$(2.42, 2.42)$

It is shown that when the phase difference between sources is less than 90°, only one peak of correlation coefficients can be observed. Thus, the phase difference can not be identified. When the phase difference between sources is larger than 90°, the peaks of correlation coefficients become more apparent and identification of phase difference can be calculated straightforward. Consequently, it is difficult to identify the phase difference by the improved SPM method when the phases of sources are close together. However, the locations of equivalent current sources are still estimated accurately enough, which can be utilized to find the way to suppress the undesired EM field from the view of electromagnetic compatibility.

3. 4   Effect of size of measurement plane

After the validity of the improved SPM method is proved, it was applied to identified the phase difference between two sources as same as in the previous section except that the size of measurement plane is varied. The size of measurement plane is varied from 1λ, 2λ and 3λ square while the parameters of current sources (Table I) and the parameters of hypothetical current sources (Table III) are fixed. The sampling points is set to 0.05λ. The analysis parameters are
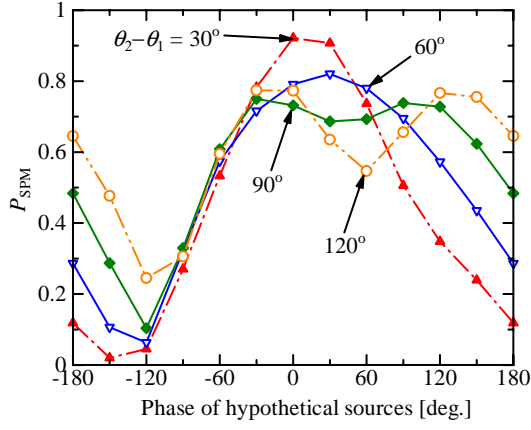
9 Correlation coefficients calculated by improved SPM method when the initial phase of first source is fixed to 0° and the other is varied from 30° to 180°.

5 parameters of measurement.

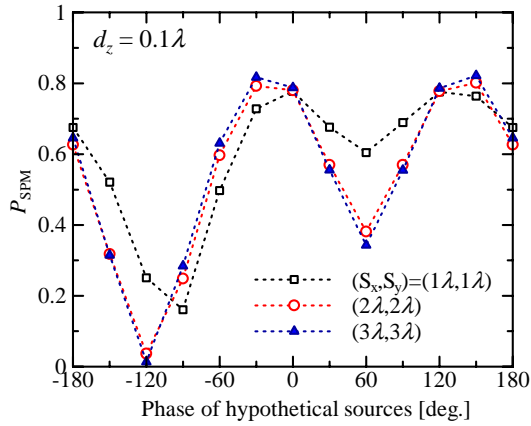| measurement area | (S_x, S_y) | $(1\lambda, 1\lambda)$ |
		$(2\lambda, 2\lambda)$
		$(3\lambda, 3\lambda)$
total number of measurement points	(s_x, s_y)	$(21, 21)$
		$(41, 41)$
		$(61, 61)$
distance between measurement points	(d_x, d_y)	$(0.05\lambda, 0.05\lambda)$
distance from source plane	d_z	$0.1\lambda, 0.5\lambda, 1\lambda$

10 Correlation coefficients when the distance of measurement plane is fixed to 0.1λ and the size of the measurement plane are is altered.

summarized in Table 5.

The correlation coefficient of equivalent current estimation calculated by using the improved SPM method when the distance of measurement plane from source plane is set to 0.1λ, 0.5λ and 1λ, are shown in Fig. 10, 11, and 12, respectively. As shown in Fig. 10, when the distance of measurement plane is small ($d_z = 1\lambda$), the phase difference between current sources can be distinctly identified by the phase difference of hypothetical sources in the correlation coefficient
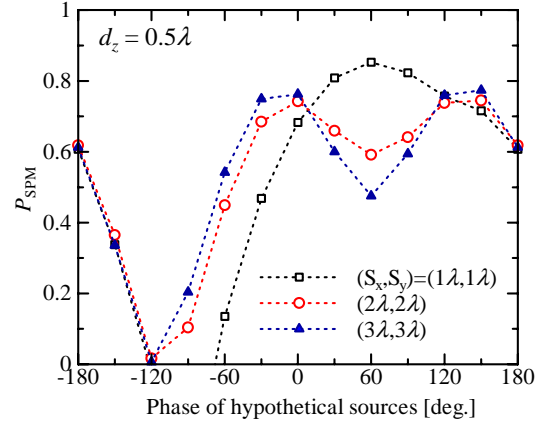

11 Correlation coefficients when the distance of measurement plane is fixed to 0.5λ and the size of the measurement plane are is altered.
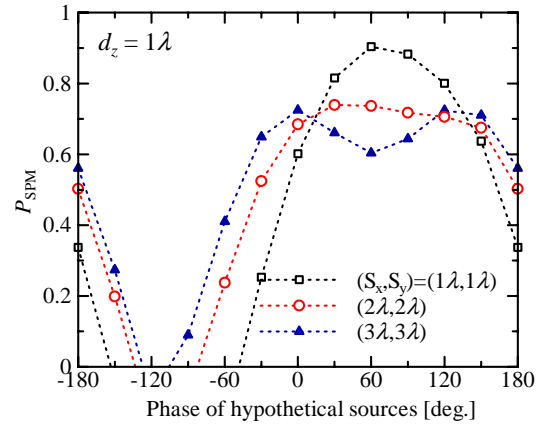

12 Correlation coefficients when the distance of measurement plane is fixed to 1λ and the size of the measurement plane are is altered.

results. Two peaks of correlation coefficients are even more obvious when the size of measurement plane is enlarged as in the case of 2λ and 3λ square in the size of measurement plane. When $d_z = 0.5\lambda$, the accuracy of estimation decreases because the size of measurement plane is not large enough to capture the informations of electric field distribution to be used in the estimation. Only one peak in the correlation coefficient is observed and the estimation result is not accurate. However, this problem can be solved by enlarge the measurement plane. The further declination in accuracy also appears in the result when $d_z = 1\lambda$. The size of measurement plane have to be enlarged to 3λ square to give an accurate result of correlation coefficient when $d_z = 1\lambda$.

3.5 Effect of number of sampling points

Next, the number of sampling points on the measurement plane is varied from 0.05λ to 0.5λ while the other parameters is fixed. The size of measurement plane is fixed to 1λ square, and the distance between measurement plane and source plane is set to 0.1λ The parameters of current sources

(Table I) and the parameters of hypothetical current sources (Table III) are fixed. The parameters of measurement are summarized in Table 6.

6   parameters of measurement.

measurement area	(S_x, S_y)	$(1\lambda, 1\lambda)$
total number of measurement points	(s_x, s_y)	(21, 21)
		(11, 11)
		(9, 9)
		(6, 6)
		(5, 5)
		(3, 3)
space between measurement points	(d_x, d_y)	$(0.05\lambda, 0.05\lambda)$
		$(0.1\lambda, 0.1\lambda)$
		$(0.125\lambda, 0.125\lambda)$
		$(0.2\lambda, 0.2\lambda)$
		$(0.25\lambda, 0.25\lambda)$
		$(0.5\lambda, 0.5\lambda)$
distance from source plane	d_z	0.1λ

The estimation result is shown in Fig. 13. It is seen that two peaks of correlation coefficients are observed even when the number of sampling points is quite large. However, there is a phase shift in the results when the number of sampling points is 0.2λ and 0.25λ. The correlation coefficient when $d_x = d_y = 0.5\lambda$ is significantly large compared with the other cases but the estimation result is not accurate and only one peak of correlation coefficient can be observed. As a consequence, if the size of measurement plane is set to 1λ, the number of sampling points should be equal or less than 8 points per wavelength in order to obtain an accurate estimation result.
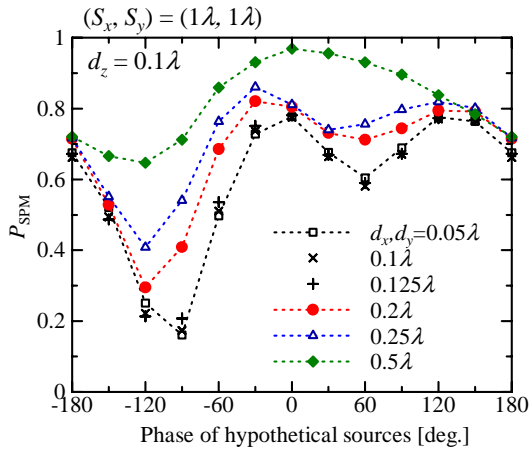

13   Correlation coefficients when the sampling points at the measurement plane is varied from 0.01λ to 0.5λ.
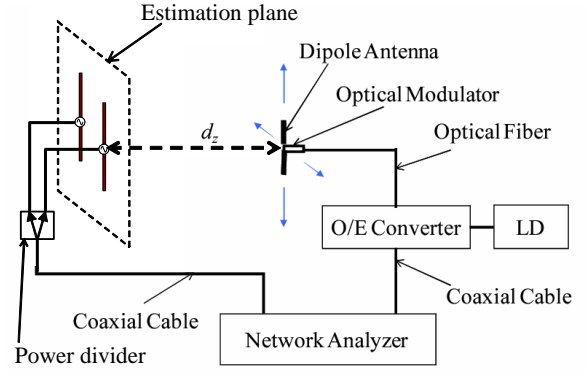

14   Near-field measurement system.

3.6   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 14. 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. 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 0.1λ 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. 15, and Fig. 16, 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 resonable estimation results. Therefore, the validity of improved SPM method is demonstrated.
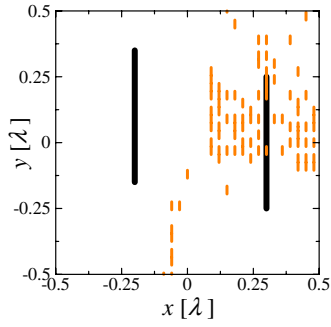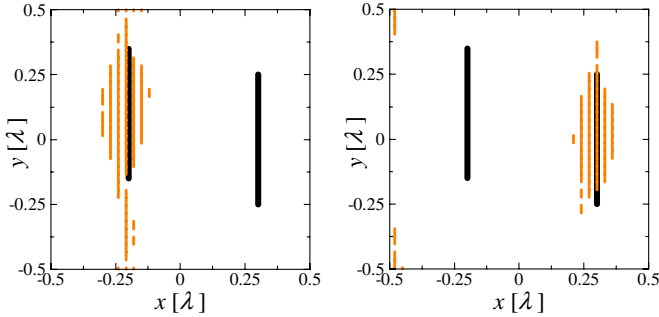
15　Estimation result by conventional SPM method.

16　Estimation results by improved SPM method. (left: $\theta_h = -100°$, right: $\theta_h = 0°$)

4.　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. 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 guideline has been given to show how to determine the measurement parameters to measure the near field to estimate the current distribution, such as the measurement distance, the measurement plane area, and the number of sampling points on the measurement plane. The phase difference between multiple sources is identified by the peaks of correlation coefficients calculated after all of the equivalent current sources 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 difference between sources is identified, which confirms the validity of the improved SPM method.

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