A Novel Method of Electric Field Estimation by using Spherical Dielectric Scatterer

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***Abstract*— To evaluate the noise source of electric equipment, the magnetic near field is often measured practically. The EMC rule, however, regulates generally the limited field strength in far electric field. In the case, the far electric field strength is not always corresponding to the magnetic near field strength because of the complex transmission function from the source to the receiving antenna. The authors have been developing the new electromagnetic field measurement system based on the Modulated Scattering Technique (MST) in order to map the radiated noise distribution. A dielectric sphere is used as the scatterer instead of a conventional metallic dipole element to improve the field invasiveness and to obtain the isotropic polarization for the incident wave. In this paper, the scattered electric field by the dielectric sphere on the MST system was theoretically investigated to confirm the factors that control the measurement sensitivity. The calculated result showed that the dielectric scatterer could generate enough power to detect and agreed with the result of the experimental measurement. The investigation showed that the scatterer volume, the MST modulation ratio, and the scattering efficiency corresponding to the permittivity of the dielectric, controlled the measurement sensitivity of the system.**

Key words: Dielectric, Scatter, Electromagnetic wave, EMC, Modulation

I. INTRODUCTION

The EMC design for electronic equipment becomes more and more important by its downsizing, high frequency driving, and low-power consuming. Although the empirical knowledge and/or various tools of the EMC design are available and have been brought a certain effect, the final review and the performance measurement of the EMC property must be made for the finished product undoubtedly. A near field magnetic probe is practically often used to find the place of the noise source on the product because of its high sensitivity and easy operation. For example, the high-frequency carrier type MI (magneto-impedance) effect prove that could measure the high-frequency magnetic signal in the high spatial resolution with high sensitivity has been developed to map the magnetic near field distribution of the noise from the printed circuit board (PCB) [1].

Meanwhile, the EMC regulatory standards are, in general, stipulated by the electric field strength in the far field for the specific measurement place, for example, a three meter's semi-anechoic chamber or an open site. However, the measured electric far field strength from the noise source does not always correspond to the magnetic near field one because of the complex transmission path between the noise source and the receiving antenna. Furthermore, when the multiple places generating the same frequency noise component were found on the PCB in magnetic near field measurement, it is difficult to determine the dominant noise source for the electric far field.

Modulated scattering technique (MST) is one of the electromagnetic field measurement methods for the arbitrary position in space. MST was firstly proposed on the mid-1950s [2]−[4], and until recent years mainly the scattering element and the signal detecting scheme have been improved and sophisticated [5]−[8].

The authors have developed an electric field measurement system based on MST to map the field distribution of the noise source. As the modulated scattering device in our system, a dielectric sphere instead of the conventional metallic dipole is used. The dielectric scatterer could realize the low invasiveness for the electromagnetic environment in comparison with the metallic dipole. Also, the employment of the sphere shape of the scatterer could bring the isotropic property to the incident wave polarization, so that the measurement system should to be simplified [9]. A few studies have been mentioned such an isotropic scatterer because of the difficulty to realize the MST modulation by it. We implement the MST modulation using the mechanical vibration scheme.

In this paper, the detection processes of the scattering wave are theoretically represented by the formulation based on the principle of MST. And the antenna propagation model is introduced in order to obtain the measurement sensitivity of electric field by the dielectric sphere as an MST scatterer. Finally, the influence of each system parameter for the detection sensitivity is discussed.

II. Modulated Scatterer Technique

Figure 1 shows a block diagram of a typical MST measurement system. The transmitting antenna, Tx, creates the field pattern to be measured. The MST system includes a scatterer as the field sensor of which scattering intensity is modulated to distinguish the scattering wave from the direct wave. The scatterer could be modulated mechanically, electrically, or optically so that the scattering efficiency might be changed by the external control signal that is also used for the synchronous detection circuit. The modulated scattering signal is received by an auxiliary receiving antenna, Rx, with superimposing on the direct wave from Tx. The objective electric field strength at the position of the scatterer could be estimated by the scattered component discriminated by the synchronous detection circuit and the distance between the scatterer and Rx.

In the MST system, the size of the scatterer is fundamentally smaller and simpler than another field detector such as a $\lambda/2$ dipole antenna, so that the low invasiveness and high resolution could be realized.

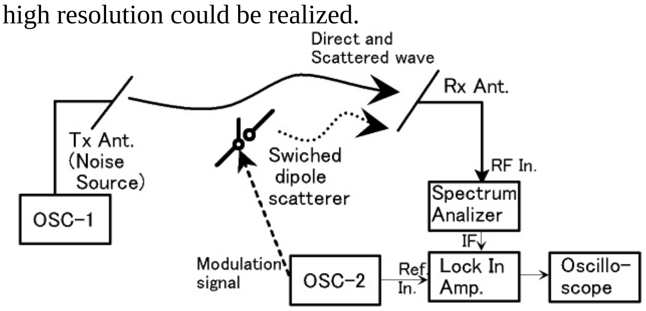

Fig. 1 Block diagram of MST measurement system

III. Spherical Dielectric Scatterer

In a conventional MST method, a metallic dipole scatterer is often used because the scattering power is easily modulated. As shown in Fig. 2(a), the current is induced along the metallic dipole in the radiated electromagnetic field. Accordingly, the re-radiating wave scatters from the dipole by the induced current. As a typical modulation scheme the diode switch is inserted to the center of the dipole. Turning on and off the diode by the bias voltage could change the impedance of the dipole and modulate the scattering power. Meanwhile, the spherical dielectric scatterer in the alternative electric field polarized and the displacement current flows as shown in Fig. 2(b). As an electric switching scheme destroys the isotropic polarization of the spherical scatterer, a mechanical vibration along the field incline is employed as the modulated method in our MST system.

When the dimension of the scatterer is enough smaller than the objective wavelength, the displacement current could approximate to that in an infinitesimal dipole. The intensity of scattered wave arose from the equivalent infinitesimal dipole should depend on the polarization of which strength corresponds to the relative permittivity of the dielectric. Also the relative permittivity would be the index for the disturbance for the surrounding field, so that the permittivity of the dielectric scatterer is the significant parameter for both the field sensitivity and the invasiveness in this MST measurement system.

In addition, the spherical shape of the scatterer has the advantage of easy polarization arrangement in a measuring procedure [9]. The spherical dielectric scatterer has the isotropic polarization for the incidental electromagnetic wave field, so that the measurement polarization could be determined only by that of the receiving antenna. Meanwhile, for the metallic dipole scatterer, the scattering intensity changes by the angle between the dipole element and the polarization of the incident field, and also by the angle between the dipole and the receiving antenna.

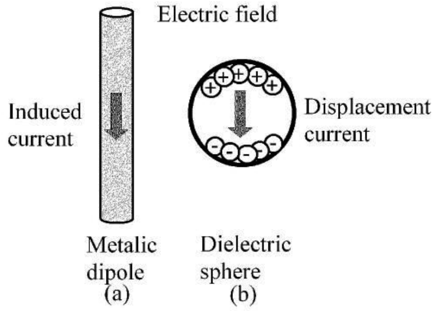

Fig. 2 Current flow in the element (a) metallic dipole, (b) dielectric sphere

IV. Theoretical Analysis of Detecting Sensitivity

A. Scattering Power

The scattering power by the spherical dielectric can be calculated from Poynting power and a scattering cross section. Poynting power, S (W/m^2), at the position in electric field strength, E (V/m), is denoted as $S=E^2/120\pi$. Meanwhile, when Rayleigh scattering condition ($2a<\lambda/10$) is satisfied for the radius of a dielectric sphere, a (m), and the incident wavelength, λ (m), the scattering cross section, σ (m^2), of the scatterer is given in following equation [10][11]:

$$\sigma= (8\pi/3)\{(\varepsilon_r-1)/(\varepsilon_r+2)\}^2(2\pi/\lambda)^4a^6 \quad , \qquad (1)$$

where ε_r, is the relative permittivity of the scatterer.

Amount of the scattering power by the dielectric sphere, Ws (W), is the product of the scattering cross section and Poynting power,

$$\begin{aligned} W_S &= \sigma S \\ &= (8\pi/3)\ \{(\varepsilon_r-1)/(\varepsilon_r+2)\}^2(2\pi/\lambda)^4a^6(E^2/120\pi) \\ &= (1/45)\ (\varepsilon_r-1)/\ (\varepsilon_r+2)\}^2(2\pi/\lambda)^4a^6E^2\ . \qquad (2)\end{aligned}$$

A numerical example is Ws=0.48x10^{-14} (W), for a practical case, a=25x10^{-3} (m), ε_r=10, λ=1 (m), E=1x10^{-3} (V / m).

B. Electric Field Strength by Scatterer

The total power of the scattering mentioned above is not radiated uniformly to space in this case. For an enough small dielectric scatterer compared with an objective wavelength, the electric field distribution generated by the scatterer could approximate that by an equivalent infinitesimal dipole. The calculation of the scattering field could be simplified by introducing the expression of the antenna theory. The electric field directivity by the infinitesimal dipole in the far field is well-known to appear as the eight-shape for the cross section parallel to the direction of the current in the dipole, Z-Z', as shown in Fig. 3. The electric field strength, E_r (V/m), along the maximum field direction O-Y is denoted as follows [12]:

$$E_r=(45W_S)^{0.5}/r \quad , \qquad (3)$$

where W_S (W) is the fed power to the dipole and r (m) is the distance from the imaginary dipole center.

From Eq. (2) and (3), the following equation is obtained.

$$E_r= \{(\varepsilon_r-1)/(\varepsilon_r+2)\}(2\pi/\lambda)^2a^3\, E/r \qquad (4)$$

For the above numerical example, the maximum field strength is calculated by Eq. (4), as $0.46\text{x}10^{-6}$ (V/m), i.e. -6.7 (dBμV/m) at the distance of 1 (m) from the scatterer.

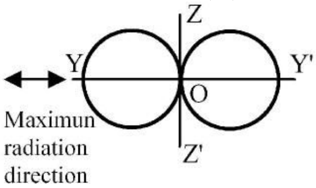

Fig. 3 Radiation field directivity from the infinitesimal dipole

C. Receiving Voltage in MST Approach

Then, the detection of the modulated scattered wave by MST approach should be considered. The electric field strength denoted in Eq. (4) represents to be an input signal value for the MST synchronous detection circuit, and the signal is modulated with the MST modulation factor, m ($0<m<1$), in the mechanical vibrating frequency. The scattered signal component after discriminating from the direct wave by the synchronous detection might correspond to the value of mE_r.

Finally, the available voltage by a receiving antenna that is located r (m) distance away from the scatterer could be obtained as the product of Eq. (4) and m/K as follows:

$$V_R=\{(\varepsilon_r-1)/(\varepsilon_r+2)\}(2\pi/\lambda)^2a^3\,(E/r)(m/K) \ , \qquad (5)$$

where K (1/m) is the receiving antenna factor.

For the above numerical calculation example, the received power, $W_R=V_R^2/50$ (W), for 50 Ω load connected to the receiving antenna is calculated as $W_R=0.42\text{x}10^{-18}$ (W) assuming $m=0.1$ and $K=10$. The power of this example is almost the same level of the thermal noise in the room temperature, $0.4\text{x}10^{-18}$ (W) (=-154 dBm), with the resolution bandwidth (RBW) of 100 Hz for a spectrum analyzer detection. The value indicates that it is possible to identify the scattered field practically.

V. Experimental Measurement

As the calculated numerical example suggests that the scatterer could generate the detectable electric field, the scattering wave by a dielectric sphere is experimentally measured. Figure 4 shows the configuration of the measurement equipment, and the measurement conditions is also shown in Table 1. The RF semi-anechoic chamber, which is filed on FCC as a three-meter standard EMC measurement site, is used for the experiment. The floor of the chamber is covered with RF-absorbers in order to reduce the electromagnetic reflection at the ground plane. The scatterer is mechanically vibrated by a voice coil motor (VCM). The arc motion of the VCM is transformed to the linear motion by the linear slider. The linear position information is picked up by the linear encoder connected to the slider, and then the signal from the encoder compensates the input power to the VCM. The superposed scattered and direct wave is received simultaneously and only the scattered component can be discriminated by a lock-in amplifier.

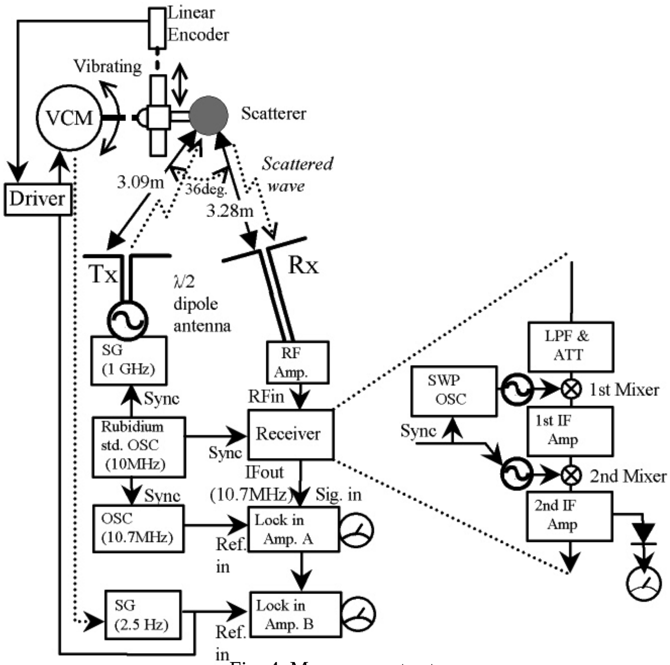

Fig. 4 Measurement setup

TABLE I
MEASUREMENT CONDITIONS

(1)	Frequency		1000 MHz
(2)	Feeding power		-0.21 dBm
(3)	Antenna	Transmit	λ/2 dipole
		Receive	Bi-log
(4)	Axis in measurement results	Vertical	arbitrary units
		Horizontal	$(\varepsilon_r-1)/(\varepsilon_r+2)a^3$
(7)	Distance Between scatterer and antenna	Transmit	3.09 m
		Receive	3.28 m
(8)	Scatterers' permittivity and diameter	s1:Teflon	ε_r=2.0 2a=19.1 mm
		s2:Alumina	ε_r=9.7 2a=20.8 mm, 10.6 mm
		s3:Stainless steel	ε_r=infinite 2a=19.1 mm, 9.5 mm

Figure 5 plots the measured results of scattering field for five spherical scatterers of which the permittivity and the diameter are different. The scatterers have the different relative permittivity and the diameter. In order to correct the difference, the horizontal axis of Fig. 5 is the product of the term of the relative permittivity and the cube of the scatterer's radius, a^3, based on Eq. (5). Equation (5) expects for measured values to be on a straight line passing through the origin, and the measured values almost agree. The precise measurement of the dimension and the material property for scatterers would to be investigated in future.

VI. Discussion

A. *Effect of the Relative Permittivity*

The term related to the relative permittivity of the scatterer for receiving voltage denoted in Eq. (5) is

$$(\varepsilon_r-1)/(\varepsilon_r+2) \quad . \qquad (6)$$

This term should represent the scattering efficiency for the relative permittivity. Figure 6 shows the change of the value of this term for the relative permittivity, ε_r. The figure 6 indicates that the scattering efficiency, $0<(\varepsilon_r-1)/(\varepsilon_r+2)<1$, is attributed to the extent of the relative permittivity, $1<\varepsilon_r<$infinity. The value of the term, $(\varepsilon_r-1)/(\varepsilon_r+2)$, reached 0.9 no longer for the relative permittivity of $\varepsilon_r=30$, so that the extremely higher relative permittivity of the material is not necessary in this MST system.

Another MST modulation scheme instead of the mechanical vibration with a fixed permittivity scatterer, would be realized by changing the relative permittivity in some way for instance by a pyroelectric scatterer. In this case, the extent of the relative permittivity seems to be suitable in the vicinity of 5-10 because of the compatibility of the large variation and absolute value for the scattering efficiency, $(\varepsilon_r-1)/(\varepsilon_r+2)$ as shown in Fig. 6.

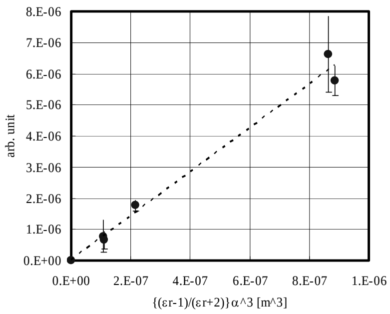

Fig. 5 Measured scattering electric field strength for different scatterers of which relative permittivity is compensated by the radius

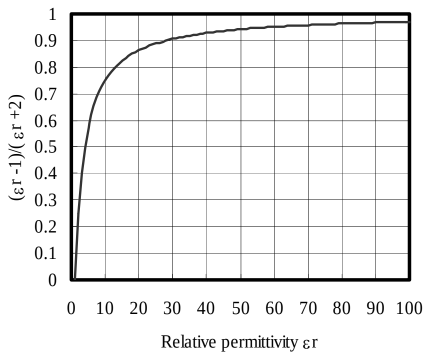

Fig. 6 Scattering efficiency change by relative permittivity

B. *Other Sensitivity Parameters*

From Eq. (5), the received power increases by 18 dB when the radius of the scatterer doubles. The fact insists that the volume of the scatterer should be a significant parameter for the measurement sensitivity. The size of the scatterer, however, should be limited to keep Rayleigh scattering condition in the MST system. Furthermore, the scatterer could not increase in size inordinately from the point of view of the spatial resolution. Conversely, the scatterer size might decrease to meet the Rayleigh scattering condition for the high frequency, short wavelength region. In this case, the substantial decline of sensitivity could be expected to be relaxed because the shorter wavelength acts to increase the sensitivity as shown in Eq. (5).

The MST modulation factor is also a parameter to control the scattering field strength. From Eq. (5), the received power increases in 6 dB when the MST modulation factor doubles. The MST modulation factor, m, could be set with no relation to the wavelength in the extent of $0<m<1$. The modulation factor of m=1 corresponding to the maximum sensitivity, indicates the states for [present or absent] of scattering. One of the challenges of developing the system is how to realize the modulation factor m close to 1 by improvement of the material characteristics and the modulating scheme of the system.

VII. Summary

The received signal strength by the MST approach using a dielectric spherical scatterer was calculated. The result shows the detectable level of scattering wave is generated. The scattered signal was practically verified by the experimental measurement in agreement with the calculation result. The relative permittivity of 5-10 was adequate for the dielectric scatterer in this MST system. In order to improve the sensitivity in this system, the MST modulation factor and the size of a scatterer was found to be significant.

Acknowledgments

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